AERO-F Manual

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1 INTRODUCTION

AERO-F is a domain decomposition based, parallel, three-dimensional, compressible, Euler/Navier-Stokes solver based on finite volume and finite element type discretizations on unstructured meshes constructed with tetrahedra. It can model both single-phase and multi-phase flow problems where the fluid can be either a perfect gas (and possibly going through porous media), stiffened gas, barotropic liquid governed by Tait's equation of state (EOS), or a highly explosive system describable by the Jones-Wilkins-Lee (JWL) EOS. For this purpose, it is equipped with various numerical methods and the level set technique. It can also solve multi-fluid problems whether they involve multi-phase flows or not.

AERO-F can perform steady and unsteady, inviscid (Euler) and viscous (Navier-Stokes), laminar and turbulent flow simulations. For turbulent flow computations, it offers one- and two-equation turbulence models, static and dynamic LES and Variational Multi-Scale (VMS)-LES, as well as DES methods, with or without a wall function.

AERO-F operates on unstructured body-fitted meshes, or on fixed meshes that can embed discrete representations of surfaces of obstacles around and/or within which the flow is to be computed. The body-fitted meshes and the embedded discrete surfaces can be fixed, move and/or deform in a prescribed manner (for example, as in forced oscillations), or be driven via interaction with the structural code **AERO-S**. In the case of body-fitted meshes, the governing equations of fluid motion are formulated in the arbitrary Lagrangian Eulerian (ALE) framework. In this case, large mesh motions are handled by a corotational approach which separates the rigid and deformational components of the motion of the surface of the obstacle, and robust mesh motion algorithms that are based on structural analogies. In the case of embedded surfaces, which can have complex shapes and arbitrary thicknesses, the governing equations of fluid motion are formulated in the Eulerian framework and the wall boundary or transmission conditions are treated by an embedded boundary method.

In **AERO-F**, the spatial discretization combines a second-order accurate Roe, HLLE, or HLLC upwind scheme for the advective fluxes and a Galerkin centered approximation for the viscous fluxes. This semi-discretization can also achieve a fifth-order spatial dissipation error and a sixth-order spatial dispersion error — and therefore fifth-order spatial accuracy — and possibly a sixth-order spatial accuracy. Time-integration can be performed with first- and second-order implicit, and first, second, and fourth-order explicit algorithms which, when performing in the ALE setting, satisfy their discrete geometric conservation laws (DGCLs).

AERO-F embeds **AERO-FL**, a module for solving linearized fluid equations. This module shares with **AERO-F** the semi-discretization schemes outlined above. Currently, the **AERO-FL** module can be used to compute linearized inviscid flow perturbations around an equilibrium solution, predict linearized inviscid aeroelastic (fluid-structure) responses assuming a modalized structure, compute aeroelastic snapshots in either the time or frequency domains to construct a POD (proper orthogonal decomposition) basis, generate an aeroelastic ROM (reduced-order model) in the frequency domain, and compute aeroelastic ROM solutions in the time-domain assuming a modalized structure.

AERO-F can also be used to perform flow computations past accelerating or decelerating obstacles, and steady, inviscid or viscous sensitivity analyses with respect to a set of aerodynamic and/or shape parameters. It is also equipped to communicate with a structural/thermal analyzer to perform aeroelastic, aerothermal, and aerothermoelastic analyses by state-of-the-art fluid-structure-thermal staggered solution algorithms.

AERO-F is essentially a comprehensive external flow solver. As such, it is not yet equipped with all boundary condition treatments that are characteristic of internal flow problems. Nevertheless, it can handle a class of such problems.

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2 INSTALLATION

The installation of **AERO-F** on a given computing system requires the availability on that system of the following tools:

`C++` compiler `g++`	Version 4.1.2 or higher.
`Fortran` compiler `gfortran`	Version 4.1.2 or higher.

`Flex` utility	Version 2.5 or higher. `Flex` is a lexical analyser required for building the parser of **AERO-F**'s ASCII Input Command Data file.
`Bison` utility	Version 2.3 or higher. `Bison` is a parser generator required for building the parser of **AERO-F**'s ASCII Input Command Data file.
`CMake` utility	Version 2.6 or higher. `CMake` is a cross-platform open-source build system. It is comparable to the Unix `Make` program in that the build process is ultimately controlled by configuration files (`CMakeLists.txt`). However unlike `Make`, it does not directly build the final software but instead generates standard build files such as makefiles for Unix and projects/workspaces for Windows Visual C++. The `CMake` version 2.6 utility can be obtained from http://www.cmake.org. (Note: a "README.cmake" file discussing details on `CMake` options for code configuration and installation is available).

and following libraries:

`BLAS` library	`BLAS` is a set of Basic Linear Algebra Subprograms required by various operations performed in **AERO-F**.
`MPI` library `openmpi`	Version 1.2.6 or higher. `Open MPI` is a high-performance implementation of the Message Passing Interface (MPI) required for performing interprocessor communication, among others. More specifically, **AERO-F** requires an MPI-2 implementation such as the one provided by the Open MPI project.
`OpenMP` API	Open Multi-Processing is an Application Programming Interface (API) that supports multi-platform shared memory multiprocessing programming in C, C++ and Fortran on many architectures, including Unix. As an option, **AERO-F** can be compiled with `OpenMP` to enable multi-threaded execution.

In addition, the POD (Proper Orthogonal Decomposition) and ROM (Reduced-Order Modeling) capabilities of the linearized module **AERO-FL** of **AERO-F** require the availability on the host computing system of the following libraries:

`LAPACK` library	`LAPACK` is a high-performance Linear Algebra PACKage with advanced solvers.
`ARPACK` library	`ARPACK` is the Arnoldi PACKage for the solution of large-scale symmetric, nonsymmetric, and generalized eigenproblems.
`ScaLAPACK` library	`ScaLAPACK` is also known as the Scalable LAPACK. This library includes a subset of LAPACK routines redesigned for distributed memory MIMD parallel computers.
`BLACS` library	`BLACS` (Basic Linear Algebra Communication Subprograms) is a linear algebra oriented message passing interface designed for linear algebra.

Furthermore, the embedded computational framework of **AERO-F** requires the availability on the host computing system of the following libraries:

`Boost` library	The `Boost` C++ libraries are a collection of free libraries that extend the functionality of C++.

To install **AERO-F**, follow the procedure specified below:

- From the directory containing the source code of **AERO-F**, type "`cmake` ." (without the " "). Note the space and the "." after the command `cmake`. The "." specifies the current directory.

- Watch the computer screen and verify that all invoked libraries were found and all build options were correct. A sample computer screen output of the `cmake` command is:

```
-- The C compiler identification is GNU
-- The CXX compiler identification is GNU
-- Check for working C compiler: /usr/bin/gcc
-- Check for working C compiler: /usr/bin/gcc -- works
-- Detecting C compiler ABI info
-- Detecting C compiler ABI info - done
-- Check for working CXX compiler: /usr/bin/c++
-- Check for working CXX compiler: /usr/bin/c++ -- works
-- Detecting CXX compiler ABI info
-- Detecting CXX compiler ABI info - done
-- The Fortran compiler identification is GNU
-- Check for working Fortran compiler: /usr/bin/gfortran
-- Check for working Fortran compiler: /usr/bin/gfortran  -- works
-- Detecting Fortran compiler ABI info
-- Detecting Fortran compiler ABI info - done
-- Checking whether /usr/bin/gfortran supports Fortran 90
-- Checking whether /usr/bin/gfortran supports Fortran 90 -- yes
-- Looking for Fortran cblas_dgemm
-- Looking for Fortran cblas_dgemm - not found
-- Looking for Fortran sgemm
-- Looking for Fortran sgemm - found
-- Looking for include files CMAKE_HAVE_PTHREAD_H
-- Looking for include files CMAKE_HAVE_PTHREAD_H - found
-- Looking for pthread_create in pthreads
-- Looking for pthread_create in pthreads - not found
-- Looking for pthread_create in pthread
-- Looking for pthread_create in pthread - found
-- Found Threads: TRUE
-- A library with BLAS API found.
-- Looking for Fortran cheev
-- Looking for Fortran cheev - found
-- A library with LAPACK API found.
-- Found MPI: /usr/lib/openmpi/lib/libmpi_cxx.so
-- Building for system type: Linux.
-- ARPACK library /usr/lib/libarpack.so found.
-- SCALAPACK library /usr/lib/libscalapack-openmpi.so found.
-- BLACS library /usr/lib/libblacs-openmpi.so,/usr/lib/libblacsF77init-openmpi.so fou
-- Boost version: 1.42.0
-- Will compile with MPI API /usr/lib/openmpi/include/usr/lib/openmpi/include/openmpi

=================================================
           Summary of build options
-------------------------------------------------
Distributed Execution:    YES
Aeroelastic:              YES
Embedded framework:       YES
Modal capability:         YES
Parallel SVD capability:  YES
Build type:               Release
Extra link flags:
=================================================

-- Configuring done
-- Generating done
-- Build files have been written to: /home/pavery/Codes/Fluid
```

- If necessary, edit the `CMakeCache.txt` file to include the file paths to all required and desired optional components that were not automatically found by `cmake`. Typically, the compilers, the utilities `Flex` and `Bison`, the libraries `MPI`, `BLAS` and `LAPACK`, and the API `OpenMP` will be automatically found. However, it

may be necessary to specify the paths for the libraries `ARPACK`, `ScaLAPACK`, `BLACS` and `Boost`.
- Then, also from the directory containing the source code of **AERO-F**, type `make`.

The successful completion of the procedure described above leads to the creation in the bin/ directory of **AERO-F**'s executable aerof.

Next: Objects, Previous: Installation

3 OVERVIEW

- Object oriented input
- Syntactic rules
- Comments
- Which problems can AERO-F actually solve?

Next: Syntactic rules, Up: Overview

3.1 OBJECT ORIENTED INPUT

The structure of the text input data file follows closely the internal structure of AERO-F. As a result, this file contains a list of objects that define the problem to be solved and the numerical techniques selected for its resolution. Sample objects that are currently supported are: `Problem`, `Input`, `Output`, `Equations`, `Preconditioner`, `ReferenceState`, `BoundaryConditions`, `MultiPhase`, `Space`, `Time`, `Aeroelastic`, `Forced`, `Accelerated`, `MeshMotion`, `Linearized`, and `Newton`. These objects can depend themselves on other lower-level objects. All are defined in Objects.

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3.2 SYNTACTIC RULES

Here are the rules followed in this document.

1. Keywords are printed like `this`.
2. Metasyntactic variables (i.e. text bits that are not part of the syntax, but stand for other text bits) are printed like *this*.
3. A metasyntactic variable ending by *-int* refers to an integer value.
4. A metasyntactic variable ending by *-real* refers to a real value.
5. A metasyntactic variable ending by *-str* refers to a string enclosed in double quotes (`""`).
6. A metasyntactic variable ending by *-id* refers to an identifier.
7. A metasyntactic variable ending by *-obj* refers to an object.
8. For conciseness, three dots (...) replace an object definition.

The definition of an object starts with the keyword `under` followed by the name of the object. The members of an object are enclosed within curly braces (`{}`). For example,

```
under Problem {
  Type = Steady;
  Mode = Dimensional;
}
```

is a valid syntax for the object `Problem`. Alternatively, it can also be written as

```
Problem.Type = Steady;
Problem.Mode = Dimensional;
```

Notes:

1. a semicolon (`;`) is required after each assignment;
2. the ordering of the objects as well as the ordering within an object do not matter.

Next: Which problems can AERO-F actually solve?, Previous: Syntactic rules, Up: Overview

3.3 COMMENTS

Both C and C++ style comments are supported and can be used in the input data file to comment out selected text regions:

1. the text region comprised between `/*` and `*/` pairs is ignored;
2. the remainder of a line after a double slash `//` is ignored.

These commands do not have the described effects inside double quotes.

Previous: Comments, Up: Overview

3.4 WHICH PROBLEMS CAN AEROF-NAME ACTUALLY SOLVE?

AERO-F can be used to perform:

- A steady or unsteady, inviscid or viscous flow computation around a fixed obstacle.
- Steady or unsteady natural convection (buoyancy) computations.
- A steady or unsteady, inviscid or viscous flow computation around a rigid or flexible obstacle set in accelerated motion.
- An unsteady, inviscid or viscous flow computation around a rigid or flexible obstacle set in a prescribed motion (forced oscillations).
- An unsteady, inviscid or viscous aeroelastic computation.
- A steady or unsteady viscous aerothermal flow computation involving a fixed obstacle.
- Steady or unsteady natural convection (buoyancy) computations coupling viscous fluid flow and heat transfer analyses.
- A steady or unsteady viscous aerothermoelastic flow computation involving a flexible obstacle.
- Any of the above computations in the presence of porous media when the fluid is modeled as a perfect gas.
- An unsteady linearized Euler flow perturbation computation in the time-domain, where the fluid is modeled as a perfect gas.
- An unsteady linearized Euler-based aeroelastic computation in which the structure is represented by a truncated set of its natural modes and the fluid is modeled as a perfect gas.
- A construction of a time- or frequency-domain POD basis when the fluid is modeled as a perfect gas and trained for obstacle vibrations.
- A construction of a time- or frequency-domain POD basis by linear interpolation between two given sets of POD basis vectors, when the fluid is modeled as a perfect gas.
- A construction of a fluid ROM trained for obstacle vibrations, when the fluid is modeled as a perfect gas.
- A time-domain ROM flow computation in which the flow is expressed in a POD basis, when the fluid is modeled as a perfect gas.
- A construction of an aeroelastic ROM in which the structure is currently represented by a truncated set of its natural modes and the fluid is modeled as a perfect gas and trained for structural vibrations.

- A time-domain aeroelastic ROM computation in which the flow is expressed in a POD basis and the structure is represented by a truncated set of its natural modes, when the fluid is modeled as a perfect gas.
- A steady or unsteady multi-fluid problem with or without a multi-phase flow component where any fluid can be modeled by the Equation Of State (EOS) of a perfect or stiffened gas, Tait's EOS for a barotropic liquid, or the JWL EOS. Viscous effects are currently implemented only for the case of multi-perfect-gas problems. The number of fluid media is arbitray. However, **AERO-F** can currently handle only three different fluid-fluid interfaces which furthermore must be between a same fluid — referred to in this User's Reference Manual as the “primary” fluid — and any one of three other fluids. In this case, the primary fluid must be identified by *fluid-id-int* = 0.
- A steady, inviscid or viscous sensitivity analysis around a specified steady-state flow solution with respect to a specified set of flow and shape parameters, when the fluid is modeled as a perfect gas.

Next: Examples, Previous: Overview

4 OBJECTS

This chapter describes each object that can be inserted in the **AERO-F** input file and its syntax. The default value of each object member or parameter is given between square brackets (`[ ]`). The list of currently available objects is given below.

- Accelerated
- Aeroelastic
- Boundaries
- BoundaryConditions
- BoxFix
- ClippingDynamic
- ClippingDynamicVMS
- ConeFix
- Deforming
- DES
- Dynamic
- DynamicVMS
- EmbeddedFramework
- Equations
- Explicit
- Fixes
- FluidModel
- Forced
- GasModel
- Heaving
- Hydro
- Implicit
- InitialConditionsEmbedded
- InitialConditionsMultiPhase
- InitialState
- Inlet
- Input
- JWLModel
- LESModel
- LevelSet

- Linearized
- LinearSolver
- LiquidModel
- MeshMotion
- MultiPhase
- NavierStokes
- Newton
- Outlet
- Output
- Pade
- Pitching
- Plane
- Point
- PorousMedium
- Postpro
- Preconditioner
- Probes
- ProbingNode
- SolverPreconditioner
- Problem
- ReferenceState
- Restart
- RotationAxis
- Smagorinsky
- Space
- SpaceTurbulenceModel
- SpalartAllmaras
- SparseGrid
- Sphere
- SphereFix
- SurfaceData
- Surfaces
- Symmetry
- ThermalConductivityModel
- Time
- TimeVelocity
- Tripping
- TurbulenceClosure
- Velocity
- ViscosityModel
- VMS
- VolumeData
- VolumeInitialConditions
- Volumes
- WALE
- Wall

Next: Input, Up: Objects

4.1 DEFINING THE PROBLEM TYPE

Object: **Problem**

The `Problem` object sets the type, mode, and few other global parameters of the problem to be solved. Its syntax is:

```
under Problem {
  Type = type-id;
  Mode = mode-id;
  Prec = prec-id;
  Framework = framework-id;
  SolveFluid = solvefluid-flag;
}
```

with

type-id [`Steady`]:

`Steady`
: Steady-state flow computation around a fixed obstacle (local time-step).

`Unsteady`
: Unsteady flow computation around a fixed obstacle (global time-step).

`AcceleratedUnsteady`
: Accelerated unsteady flow computation around a fixed obstacle (global time-step). See Accelerated.

`SteadyAeroelastic`
: Steady-state aeroelastic computation (local time-step). See Aeroelastic.

`UnsteadyAeroelastic`
: Unsteady aeroelastic computation (global time-step). See Aeroelastic.

`AcceleratedUnsteadyAeroelastic`
: Accelerated unsteady aeroelastic computation (global time-step). See Aeroelastic and Accelerated.

`SteadyAeroThermal`
: Steady-state aerothermal (thermostructure-thermofluid) flow computation around a fixed obstacle (local time-step).

`UnsteadyAeroThermal`
: Unsteady aerothermal (thermostructure-thermofluid) flow computation around a fixed obstacle (global time-step).

`SteadyAeroThermoElastic`
: Steady-state aerothermoelastic flow computation (local time-step). See Aeroelastic.

`UnsteadyAeroThermoElastic`
: Unsteady aerothermoelastic flow computation (global time-step). See Aeroelastic.

`Forced`
: Forced oscillations (unsteady flow) computation around a rigid or flexible obstacle (global time-step). See Forced.

`UnsteadyLinearized`
: Unsteady flow perturbation using a linearized computational model. Currently, this option assumes that the flow is modeled by the linearized Euler equations. If the perturbation is due to a structural motion and is input as such, *mode-id* must be set to `Dimensional` when using this option.

`UnsteadyLinearizedAeroelastic`
: Unsteady linearized aeroelastic computation (using a linearized computational model). Currently, this option assumes that the flow is modeled by the linearized Euler equations and the structure by a modal representation. When using this option, *mode-id* must be set to `Dimensional`.

`PODConstruction`
: Construction of a POD basis from computed snapshots.

`PODInterpolation`

Construction of a POD basis by interpolation between two or more sets of POD basis vectors specified, together with their respective Mach numbers and angles of attack, in `PODData` (see Input). This file should also contain the Mach number and angle of attack at which the interpolated POD basis is desired. The size of the POD basis to be constructed must be specified in `NumPOD` (see Linearized). Do not forget to output the computed POD basis using the `PODData` command in Postpro.

`ROBInnerProduct`

Computation of all inner products between the elements of a set of Reduced-Order Bases (ROBs) $\{V_j\}_{j=1}^{N_V}$ inputted to **AERO-F** in `Input.PODData`. If `Time.Form = Descriptor`, the inner products are computed with respect to the matrix of cell volumes A as follows

$$P_{ij} = V_i^T A V_j$$

On the other hand, if `Time.Form = NonDescriptor`, the inner products are computed with respect to the identity matrix I as follows

$$P_{ij} = V_i^T V_j$$

The data is loaded into **AERO-F** and the above inner products are computed using a strategy that optimizes the computational resources. The resulting matrices P_{ij} are outputted in `Output.ROBInnerProduct`.

`ROM`

Construction of a fluid ROM, given a POD basis specified in `PODData` (see Input), or time-domain ROM fluid simulation in which the flow is expressed in a POD basis specified in `PODData` (see Input). See Linearized.

`ROMAeroelastic`

Construction of an aeroelastic ROM, or time-domain aeroelastic ROM simulation in which the flow is expressed in a POD basis and the structure is represented by a truncated set of its natural modes. See Linearized.

`SteadySensitivityAnalysis`

Computation of the gradients, at a specified steady-state flow solution, of aerodynamic design criteria with respect to flow parameters such as the free-stream conditions (Mach number, angle of attack, and sideslip angle) and design variables such as shape design parameters (see Sensitivities).

`SparseGridGeneration`

Pre-computation and tabulation in the sparse grid format specified in SparseGrid of information specified in MultiPhase.

`1D`

One-dimensional computation in spherical, cylindrical, or Cartesian coordinates of a spherically symmetric unsteady two-phase flow problem using the finite volume method with an exact two-phase Riemann solver (`MultiPhase.Method = FiniteVolumeWithExactTwoPhaseRiemann`).

mode-id [`NonDimensional`]:

`NonDimensional`

In this case, all input data is interpreted as being for the non-dimensionalized variables, and all solutions are outputted in non-dimensional form. AERO-F non-dimensionalizes the computational input and variables as follows:

1. coordinates in x-, y- and z-directions:

$$\underline{x} = \frac{x}{L_{reference}}$$

2. time:

$$\bar{t} = \frac{t\, u_{reference}}{L_{reference}}$$

3. density:

$$\bar{\rho} = \frac{\rho}{\rho_{reference}}$$

4. velocity:

$$\underline{\bar{u}} = \frac{\underline{u}}{u_{reference}}$$

5. pressure:

$$\overline{P} = \frac{P}{\rho_{reference} u^2_{reference}}$$

6. temperature:

$$\overline{T} = \frac{c_v T}{u^2_{reference}}$$

where the subscript $_{reference}$ designates a reference value.

AERO-F computes

$u_{reference}$ internally as follows. For a perfect gas,

$$u_{reference} = M_{reference}\sqrt{\gamma\frac{p_{\infty}}{\rho_{reference}}}$$

For a barotropic liquid,

$$u_{reference} = M_{reference}\sqrt{\frac{((k_1+k_2 p_0)(k_1+k_2 p)^{k_2-1})^{\frac{1}{k_2}}}{\rho_0}}$$

where p_0, ρ_0, k_1 and k_2

For a highly explosive gas modeled by the JWL equation of state,

$$u_{reference} = M_{reference} c(\rho_{reference}, p_{infty})$$

where c is the speed of sound.

are defined in LiquidModel . (see ReferenceState).

`Dimensional`
: Input parameters and output solutions are in dimensional form. This is the default and only mode available for problems involving a structural code or a steady-state sensitivity analysis.

prec-id [`NonPreconditioned`]:

`NonPreconditioned`
: The dissipation terms of the convective fluxes of the solution scheme are not preconditioned.

`LowMach`
: The dissipation terms of the convective fluxes of the solution scheme are equipped with the low-Mach Turkel preconditioner. For steady-state calculations, the inertia (or pseudo-time-derivative) terms (see Preconditioner) can also be preconditioned if desired by making the request in the `Time` object (see Time).

framework-id [`BodyFitted`]:

`BodyFitted`
: In this case, the CFD grid must be body-fitted and the governing fluid equations are formulated in the Arbitrary Lagrangian Eulerian setting which can handle both static (fixed) and dynamic (moving and deforming) grids.

`Embedded`
: In this case, the obstacle must be embedded in the CFD grid, and the fluid equations are formulated in the Eulerian setting and solved by an embedded boundary method for CFD.

solvefluid-flag [`On`]:

This flag is only relevant for nonlinear problems.

`On`
: In this case, the specified simulation is carried out as usual.

`Off`
: In this case, only the component of the simulation associated with the ALE mesh motion/deformation or motion/deformation of embedded surfaces is carried out, and therefore the flow solution is skipped. This option is useful only for verifying, assessing, or debugging the mesh motion strategy and/or algorithm chosen in MeshMotion and the dynamics of embedded surfaces when *framework-id* = `Embedded`.

Notes:

1. explicit time-integration is not recommended for low-Mach flows for computational efficiency reasons;
2. the `Embedded` framework is operational only if **AERO-F** was compiled and linked with the **PhysBAM-Lite** library.

Next: 1DGrid, Previous: Problem, Up: Objects

4.2 DEFINING THE INPUT FILES

Object:	**Input**

The several input files that are required by AERO-F are specified within the `Input` object. Its syntax is:

```
under Input {
  Prefix = prefix-str;
  Connectivity = connectivity-str;
  Geometry = geometry-str;
  Decomposition = decomposition-str;
  CpuMap = cpumap-str;
  Matcher = matcher-str;
  EmbeddedSurface = embeddedsurface-str;
  WallDistance = walldistance-str;
  GeometryPrefix = geometryprefix-str;
  Solution = solution-str;
```

```
    Levelset = levelset-str;
    Position = position-str;
    StrModes    =  strmodes-str;
    RestartData = restartdata-str;
    Perturbed = perturbsolution-str;
    PODData = poddata-str;
    ShapeDerivative = shapederivative-str;
    under 1DRestartData { ... }
  }
```

with

prefix-str [`""`]:

String that is prefixed to all input file names. For example, if *prefix-str* is set to `"data/"` and *connectivity-str* is set to `"wing.con"`, AERO-F looks for a connectivity file named `"data/wing.con"`.

connectivity-str [`""`]:

Name of the binary connectivity file produced by the SOWER program.

geometry-str [`""`]:

Name of the binary geometry file produced by the SOWER program. However if `Problem.Type` = `1D`, this becomes the name of the ASCII file storing a one-dimensional grid in the following format:

```
number_of_nodes_in_the_grid
distance_of_node_1_to_the_center_of_the_sphere
distance_of_node_2_to_the_center_of_the_sphere
.
.
.
distance_of_last_node_to_the_center_of_the_sphere
```

decomposition-str [`""`]:

Name of the binary decomposition file produced by the SOWER program.

cpumap-str [`""`]:

Name of the ASCII CPU map file produced by the SOWER program.

matcher-str [`""`]:

Name of the binary matcher file produced by the MATCHER program (required for simulations involving a structural code).

embeddedsurface-str [`""`]:

Name of the ASCII file describing in the **XPost** format a discrete representation of a surface to be embedded in the CFD grid, and around/or within which the flow is to be computed. Currently, the embedded discrete surface must be made of triangles. If it is closed, the triangles must be defined such that their normals are outward to the medium they enclose.

walldistance-str [`""`]:

Name of the binary distance-to-the-wall file. This file is required for turbulent flow simulations performed with the one-equation Spalart-Allmaras turbulence model or the DES method (see TurbulenceModel). This file contains for every mesh point its distance to the closest solid wall. This distance is used in the Spalart-Allmaras turbulence model in order to provide the correct asymptotic behavior of the turbulence variable in the near wall regions. The ASCII **XPost** version of this file is always produced when the software CD2TET is used. The conversion into binary format can be performed with the SOWER software (see Hints_and_tips).

geometryprefix-str [`""`]:

This entry specifies the prefix name for all of the files describing the connectivity, geometry, decomposition, CPU map, distance-to-the-wall (when the Spalart-Allmaras turbulence model or the DES method is employed) generated by **SOWER** for a given fluid mesh. Hence, specifying *geometryprefix-str* is equivalent (and therefore an alternative) to specifying all of *connectivity-str*, *geometry-str*, *decomposition-str*, *cpumap-str*, and *walldistance-str* (when applicable). If any one of these members is specified simultaneously with *geometryprefix-str*, its value takes precedence over that implied by *geometryprefix-str*.

solution-str [`""`]:

Name of the binary solution (i.e. conservative variables) file obtained from a previous simulation from which AERO-F starts. If this file is not specified, AERO-F starts from a uniform flow (see Restart) and in particular the variable `Output.Restart.Solution`).

levelset-str [`""`]:

This information is relevant only for multi-phase flow problems (see MultiPhase). The content of *levelset-str* can be the name of the binary level set solution file obtained from a previous multi-phase flow simulation from which AERO-F starts. If this file is not specified, AERO-F starts from the initial solution specified in InitialConditionsMultiPhase.

position-str [`""`]:

Name of the binary file containing the position (i.e. x,y,z node coordinates) of the mesh as outputted during a previous simulation and from which AERO-F is to start. If this file is not specified, AERO-F starts from the mesh position stored in *geometry-str* (see Restart and in particular the variable `Output.Restart.Position`).

strmodes-str [`""`]:

Name of the binary file containing the initial position of the fluid mesh, a set of natural structural frequencies, and the set of fluid mesh positions compatible with the corresponding set of natural structural modes. This information is required here if the computation and output of the corresponding generalized forces is requested in the object `Postpro` (see Postpro).

restartdata-str [`""`]:

Name of the ASCII restart file obtained from a previous simulation. This file allows AERO-F to continue a simulation that was successfully completed or was for some reason interrupted (see Restart and in particular the variable `Output.Restart.RestartData`).

perturbsolution-str [`""`]:

Name of the binary file containing a perturbed flow solution needed for linearized flow calculations. This file can be generated, for example, by running AERO-F or AERO-S with one perturbed parameter. For full-order calculations, this parameter can be any reasonable input parameter. For reduced-order computations, only a parameter such as the displacement of the body which pertains to the sources of excitations used to construct the ROM should be considered. AERO-FL computes the initial perturbation in the flow as the difference between this flow solution and the equilibrium flow solution that must be specified in `Input.Solution` (see Input). If this file is not specified, the initial perturbation is set to 0.

poddata-str [`""`]:

Except when `Problem.Type` = `PODInterpolation` or `Problem.Type` = `ROBInnerProduct`, this is the name of the binary file containing a set of POD basis vectors that could have been generated by AERO-FL (see Linearized) in a previous run where the `Problem.Type` was set to `PODConstruction`. When `Problem.Type` = `PODInterpolation`, *poddata-str* is the name of the text file specifying the number of precomputed POD bases to be interpolated, the names of the binary files containing each one of these bases, their respective Mach numbers and angles of attack, and the Mach number and angle of attack at which interpolation is desired. The format of this text file is examplified below.

Example:

```
3
PODData.d/podVecs4.freq0.499.2_4.df5e3.30snap.100pod
PODData.d/podVecs4.freq0.520.2_6.df5e3.30snap.100pod
PODData.d/podVecs4.freq0.700.2_5.df5e3.30snap.100pod
0.499  0.520  0.700
0.550
2.4 2.6 2.5
2.45
```

The first line specifies the number of precomputed POD bases to be interpolated. Each of the following three lines specifies the path and name of the file containing a precomputed POD basis to be interpolated. The following line specifies the three Mach numbers at which the POD bases to be interpolated are precomputed, in the order in which these bases are specified. The next line specifies the interpolation Mach number. The following line specifies the three angles of attack at which the POD bases to be interpolated are precomputed, in the order in which these bases are specified. The last line specifies the interpolation angle of attack. When `Problem.Type` = `ROBInnerProduct`, *poddata-str* is the name of the text file specifying the number of precomputed Reduced-Order Bases (ROBs) whose inner products are to be computed when `Problem.Type` = `ROBInnerproduct`, the maximum number of these ROBs to be loaded into memory at a time, and the names of the binary files containing each one of these ROBs. The format of this text file is examplified below.

Example:

numFiles-int maxLoadFiles-int
ROB1File-str
ROB2File-str
...

where *numFiles-int* denotes the number of ROB files listed starting on the second line of the file *poddata-str*, *maxLoadFiles-int* denotes the maximum number of ROB files to be loaded in memory at a time, *ROB1File-str* is the (path and) name of the file containing the first ROB, *ROB2File-str* the (path and) name of the file containing the second ROB, etc.

shapederivative-str [""]:

Name of the binary file containing essentially $\frac{d\mathbf{X}_\Gamma}{ds_j}$, the derivatives of the mesh position $\mathbf{X}$ with respect to a number of shape design variables s_j at the fluid/structure boundary Γ (see SensitivityAnalysis and Sensitivities). This information is generated as follows. First, an **XPost**-type ASCII file containing the following information is created. This ASCII file starts with an **XPost**-like header (see below), followed by the total number of grid points in the CFD mesh (and not the number of fluid grid points on the fluid/structure interface). Then, the information $\frac{d\mathbf{X}_\Gamma}{ds_j}$ is specified in this ASCII file for each shape design parameter s_j, one parameter at a time, in block form. First, the index j of s_j is specified on a separate line starting from $j = 0$ (zero). Then, all grid points of the CFD mesh are considered in the same ordering as that adopted in the corresponding **XPost** geometry file. On each line corresponding to grid point i, the derivatives $\frac{dx_i}{ds_j}$, $\frac{dy_i}{ds_j}$, and $\frac{dz_i}{ds_j}$ (where x_i, y_i, and z_i denote the coordinates of the grid point i) are provided. If the grid point i is an "interior" point, these derivatives are set to zero. An example of the ASCII file described above is given below.

```
Vector <file name> under load for FluidNodes
<vector size = total number of grid points in the CFD mesh>
0
0.000000 0.000000 0.000000
    .        .        .
    .        .        .
    .        .        .
dx_i/ds_0  dy_i/ds_0  dz_i/ds_0
    .        .        .
    .        .        .
    .        .        .
0.000000 0.000000 0.000000
1
0.000000 0.000000 0.000000
    .        .        .
    .        .        .
    .        .        .
dx_i/ds_1  dy_i/ds_1  dz_i/ds_1
    .        .        .
    .        .        .
    .        .        .
0.000000 0.000000 0.000000
2
0.000000 0.000000 0.000000
    .        .        .
    .        .        .
    .        .        .
dx_i/ds_2  dy_i/ds_2  dz_i/ds_2
    .        .        .
    .        .        .
    .        .        .
```

Then, the ASCII file described above is converted to a distributed binary file using the **SOWER** code and generated mesh partition.

`1DRestartData`:

Allows the local initialization of a three-dimensional flow computation with the results of a spherically symmetric one-dimensional unsteady two-phase flow computation.

Notes:

1. as mentioned in the SOWER manual, there is no need to specify the ending number for the binary files;
2. if the name of the input files `Solution`, `Position`, `RestartData`, or `1DRestartData` starts by a slash (`/`), the variable `Prefix` is not used for these files.

- 1DRestartData

Up: Input

4.2.1 INITIALIZING A 3D SIMULATION LOCALLY WITH 1D SPHERICALLY SYMMETRIC DATA

Object:	**1DRestartData**

The `1DRestartData` object initializes a three-dimensional flow computation locally with the results of a spherically symmetric one-dimensional unsteady two-phase flow computation identified by a simulation tag *1Dsimulation-id-int*.

The syntax of this object is:

```
under 1DRestartData[1Dsimulation-id-int] {
  File =  file-str;
  X0 = x0-real;
  Y0 = y0-real;
  Z0 = z0-real;
  under FluidIDMap{ ... }
}
```

with

file-str [`""`]:

Name of the ASCII file containing the results of a previously performed spherically symmetric one-dimensional unsteady two-phase flow computation. It is subject to `Input.Prefix`.

x0-real [0.0]:

x-coordinate of the center of the spherical region where the flow is to be initialized by the spherically symmetric results stored in *file-str*.

y0-real [0.0]:

y-coordinate of the center of the spherical region where the flow is to be initialized by the spherically symmetric results stored in *file-str*.

z0-real [0.0]:

z-coordinate of the center of the spherical region where the flow is to be initialized by the spherically symmetric results stored in *file-str*.

`FluidIDMap`:

This object can be used to map the fluid identification integers of a one-dimensional two-phase flow simulation to those of the three-dimensional flow computation locally initialized by the results of that one-dimensional simulation.

- FluidIDMap

Up: 1DRestartData

4.2.1.1 MAPPING A SET OF FLUID IDENTIFICATION TAGS TO ANOTHER ONE

Object:	**FluidIDMap**

The `FluidIDMap` object can be used to map the fluid identification integers of a one-dimensional two-phase flow simulation identified by its simulation tag *1Dsimulation-id-int* to those of the three-dimensional flow computation locally initialized by the results of that one-dimensional simulation.

The syntax of this object is:

```
under FluidIDMap[FluidIDDonor-int] {
  FluidIDReceptor =  fluidIDreceptor-int;
}
```

with

fluidIDreceptor [—]:

Integer identifying the fluid medium to be initialized using data from the fluid medium identified in the spherically symmetric one-dimensional two-phase flow simulation by the integer *FluidIDDonor-int*.

Next: Output, Previous: Input, Up: Objects

4.3 GENERATING A ONE-DIMENSIONAL SPHERICALLY SYMMETRIC GRID

Object:	**1DGrid**

The `1DGrid` object allows the user to generate in **AERO-F** a uniform, one-dimensional grid for a spherically symmetric problem instead of inputting it in `Input.Geometry`, and specify the coordinate system in which to solve this problem. The first point of this grid is always located at the origin of the coordinate system. Using 1DRestartData, the flow results obtained on this grid can be applied in a spherical region of a three-dimensional domain centered at an arbitrary point.

The syntax of this object is:

```
under 1DGrid {
  NumberOfPoints =  numberofpoints-int;
  Radius         =  radius-real;
  Coordinates    =  coordinates-id;
}
```

with

numberofpoints [0]:

> Number of grid points to be generated.

radius-real [0.0]:

> radius of the spherical region to be represented by a one-dimensional grid.

coordinates-id [`Spherical`]:

`Spherical`
: In this case, the spherically symmetric one-dimensional computational problem is solved in spherical coordinates.

`Cylindrical`
: In this case, the spherically symmetric one-dimensional computational problem is solved in cylindrical coordinates.

`Cartesian`
: In this case, the spherically symmetric one-dimensional computational problem is solved in Cartesian coordinates.

Next: Surfaces, Previous: 1DGrid, Up: Objects

4.4 DEFINING THE OUTPUT FILE

Object:	**Output**

The `Output` object mainly defines the name of the files used for post-processing (see the SOWER manual) and restart purposes. The output information requested by the object `Probes` is typically generated in an ASCII format. That requested by all other objects within the `Output` object is almost always generated in a binary format; therefore, its exploitation requires post-processing by **SOWER** (see SOWER's User's Reference Manual).

The syntax of this object is:

```
under Output {
  under Postpro { ... }
  under Probes { ... }
  under Restart { ... }
}
```

`Postpro`:

> Specifies the computational results to output.

`Restart`:

> Specifies the data to be saved for possible restart later.

- Postpro
- Probes
- Restart

Next: Probes, Up: Output

4.4.1 EXPLOITING THE COMPUTATIONAL RESULTS

Object:	**Postpro**

The syntax of the `Postpro` object is:

```
under Postpro {
  Prefix = prefix-str;
  Frequency = frequency-int;
  Density = density-str;
  TavDensity = tavdensity-str;
  Mach = mach-str;
  TavMach = tavmach-str;
  HWTMach  = hwtmach-str;
  Pressure = pressure-str;
  TavPressure = tavpressure-str;
  DeltaPressure = deltapressure-str;
  HydroStaticPressure = hydrostaticpressure-str;
  HydrodynamicPressure = hydrodynamicpressure-str;
  Temperature = temperature-str;
  TavTemperature = tavtemperature-str;
  TemperatureNormalDerivative = tempnormder-str;
  HeatFluxPerUnitSurface = heatfluxus-str;
  HeatFlux = heatflux-str;
  TotalPressure = totalpressure-str;
  TavTotalPressure = tavtotalpressure-str;
  LiftandDrag = liftanddrag-str;
  TavLiftandDrag = tavliftanddrag-str;
  Vorticity = vorticity-str;
  TavVorticity = tavvorticity-str;
  NuTilde = nutilde-str;
  K = k-str;
  Eps = eps-str;
  EddyViscosity = eddyviscosity-str;
  DeltaPlus = deltaplus-str;
  CsDLES    = csdles-str;
  TavCsDLES = tavcsdles-str;
  CsDVMS    = csdvms-str;
  TavCsDVMS = tavcsdvms-str;
  MutOverMu = mutomu-str;
  SkinFriction = skinfriction-str;
  TavSkinFriction = tavskinfriction-str;
  Velocity = velocity-str;
  TavVelocity = tavvelocity-str;
  VelocityMagnitude =  velocitymagnitude-str;
  HWTVelocityMagnitude =  hwtvelocitymagnitude-str;
  Displacement = displacement-str;
  ModalDisplacement = modaldisplacement-str;
  GeneralizedDisplacement = generalizeddisplacement-str;
  TavDisplacement = tavdisplacement-str;
  FlightDisplacement = fldisplacement-str;
  LocalFlightDisplacement = lfldisplacement-str;
  Force = force-str;
  GeneralizedForce = generalizedforce-str;
  TavForce = tavforce-str;
  HydroStaticForce = hydrostaticforce-str;
  HydroDynamicForce = hydrodynamicforce-str;
  Residual = residual-str;
  TimeInterval = timeinterval-real;
  Length = length-real;
  Surface = surface-real;
```

```
    XM = xm-real;
    YM = ym-real;
    ZM = zm-real;
    PODData = poddata-str;
    ROBInnerProduct =  robinnerproduct-str;
    ROM =  rom-str;
    Philevel = philevel-str;
    FluidID = fluidID-str;
    StateVector = statevector-str;
    StateVectorSensitivity      = statevectorsensitivity-str;
    DensitySensitivity = densitysensitivity-str;
    MachSensitivity = machsensitivity-str;
    TemperatureSensitivity = temperatursensitivity-str;
    PressureSensitivity = pressuresensitivity-str;
    TotalPressureSensitivity = totalpressuresensitivity-str;
    VelocitySensitivity = velocitysensitivity-str;
    DisplacementSensitivity = displacementsensitivity-str;
    ForceSensitivity = forcesensitivity-str;
    SparseGrid = sparsegrid-str;
    MaterialVolumes = matvols-str;
    BubbleRadius = bubbleradius-str;
    CPUTiming = cputiming-str;
  }
```

with

prefix-str [`""`]:

String that is prefixed to all post-processing file names.

frequency-int [`0`]:

The frequency (every so many time-iteration) at which the output files are written. If the frequency is set to zero, the output files are only written at the last time-iteration. When the frequency is set to a nonzero value, the output files are also written at the last time-iteration.

density-str [`""`]:

Name of the binary file that contains the sequence of nodal density values.

tavdensity-str [`""`]:

Name of the binary file that contains the sequence of time-averaged nodal density values (useful particularly in LES simulations).

mach-str [`""`]:

Name of the binary file that contains the sequence of nodal Mach number values.

hwtmach-str [`""`]:

Name of the binary file that contains the sequence of nodal “hybrid wind tunnel” (see Accelerated and Figure HWT) Mach number values (relevant only for accelerated or decelerated flow simulations). The hybrid wind tunnel Mach number is defined as the Mach number based on the difference between the local velocity and the ALE (moving) grid velocity — that is, the relative Mach number with respect to the ALE frame.

tavmach-str [`""`]:

Name of the binary file that contains the sequence of time-averaged nodal Mach number values (useful particularly in LES simulations).

pressure-str [""]:

Name of the binary file that contains the sequence of nodal pressure values. If *gravity-real* and *depth-real* have nonzero values (see Hydro), then the pressure values are the sum of the hydrostatic and hydrodynamic pressure values.

pressurecoefficient-str [""]:

Name of the binary file that contains the sequence of nodal pressure coefficient values. These are defined in **AERO-F** only when the fluid is modeled as a perfect gas. If for some reason *gravity-real* and *depth-real* have nonzero values (see Hydro), then the pressure values used for this output are the sum of the hydrostatic and hydrodynamic pressure values.

tavpressure-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal pressure values (useful particularly in LES simulations).

hydrostaticpressure-str [""]:

Name of the binary file that contains the sequence of nodal hydrostatic pressure ($\rho g h$) values.

hydrodynamicpressure-str [""]:

Name of the binary file that contains the sequence of nodal hydrodynamic pressure values.

deltapressure-str [""]:

Name of the binary file that contains the sequence of pressure variations with respect to the free-stream pressure (useful particularly for Low-Mach simulations).

temperature-str [""]:

Name of the binary file that contains the sequence of nodal temperature values.

tavtemperature-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal temperature values (useful particularly in LES simulations).

tempnormder-str [""]:

Name of the binary file that contains the sequence of temperature normal derivative ($\vec{\nabla} T \cdot \vec{n}$) nodal values for (moving) isothermal wall boundaries and zero elsewhere.

heatfluxus-str [""]:

Name of the binary file that contains the sequence of heat flux per unit surface ($-\kappa \vec{\nabla} T \cdot \vec{n}$) nodal values for (moving) isothermal wall boundaries and zero elsewhere.

heatflux-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the heat flux exchanged through (moving) isothermal wall boundaries ($-\int_S \kappa \vec{\nabla} T \cdot \vec{n} d\sigma$).

totalpressure-str [""]:

Name of the binary file that contains the sequence of nodal total pressure values.

tavtotalpressure-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal total pressure values (useful particularly in LES simulations).

liftanddrag-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the drag, which is the force in the direction parallel to the free-stream velocity;
6. the lift, which is defined here as the force in the direction orthogonal to the vector defined by the yaw angle in the x-y plane;
7. the lift, which is defined here as the force in the direction orthogonal to the vector defined by the angle of attack in the x-z plane.

tavliftanddrag-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the time-averaged drag, which is the force in the direction parallel to the free-stream velocity;
6. the time-averaged lift, which is defined here as the force in the direction orthogonal to the vector defined by the yaw angle in the x-y plane;
7. the time-averaged lift, which is defined here as the force in the direction orthogonal to the vector defined by the angle of attack in the x-z plane.

vorticity-str [""]:

Name of the binary file that contains the sequence of nodal vorticity values.

tavvorticity-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal vorticity values (useful particularly for LES simulations).

nutilde-str [""]:

Name of the binary file that contains the sequence of nodal $\tilde{\nu}_t$ (field variable in the Spalart-Allmaras turbulence model) values.

k-str [""]:

Name of the binary file that contains the sequence of nodal k (turbulent kinetic energy in the $k-\epsilon$ model) values.

eps-str [""]:

Name of the binary file that contains the sequence of nodal ϵ (turbulent kinetic energy dissipation rate in the $k-\epsilon$ model) values.

eddyviscosity-str [""]:

Name of the binary file that contains the sequence of nodal eddy viscosity values.

deltaplus-str [""]:

Name of the binary file that contains the sequence of nodal non-dimensional wall distance values (only available if a wall function is used, see Wall).

csdles-str [""]:

Name of the binary file that contains the sequence of nodal values of the *dynamic* Smagorinski coefficient C_s computed during a dynamic LES simulation.

tavcsdles-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal values of the *dynamic* Smagorinski coefficient C_s computed during a dynamic LES simulation.

csdvms-str [""]:

Name of the binary file that contains the sequence of nodal values of the *dynamic* Smagorinski coefficient C_s' computed during a dynamic VMS-LES simulation.

tavcsdvms-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal values of the *dynamic* Smagorinski coefficient C_s' computed during a dynamic VMS-LES simulation.

mutomu-str [""]:

Name of the binary file that contains the sequence of nodal values of the ratio of turbulent viscosity and molecular viscosity (available for all turbulence simulations except VMS-LES).

skinfriction-str [""]:

Name of the binary file that contains the sequence of nodal values of the skin friction coefficient.

tavskinfriction-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal values of the skin friction coefficient.

velocity-str [""]:

Name of the binary file that contains the sequence of nodal velocity vectors.

tavvelocity-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal velocity vectors (useful particularly for LES simulations).

velocitymagnitude-str [""]:

Name of the binary file that contains the sequence of nodal velocity magnitudes (useful particularly for low-Mach multi-phase simulations).

hwtvelocitymagnitude-str [""]:

Name of the binary file that contains the sequence of nodal “hybrid wind tunnel” (see Accelerated and Figure HWT) velocity magnitudes (relevant only for accelerated or decelerated flow simulations). The hybrid wind tunnel velocity magnitude is defined as the magnitude of the difference between the velocity and the speed of the accelerating or decelerating moving grid — that is, the magnitude of the relative velocity with respect to the ALE frame.

displacement-str [""]:

Name of the binary file that contains the sequence of nodal displacement vectors.

modaldisplacement-str [""]:

Name of the ASCII file that contains the sequence of modal displacements obtained during a linearized flow or aeroelastic computation.

generalizeddisplacement-str [""]:

Name of the ASCII file that contains the sequence of generalized displacements (generalized coordinates associated with a structural Reduced-Order Basis (ROB)) obtained during a linearized aeroelastic or aeroelastic ROM computation.

tavdisplacement-str [""]:

Name of the binary file that contains the sequence of time-averaged nodal displacement vectors (useful particularly in LES simulations).

fldisplacement-str [`""`]:

Name of the binary file that contains the sequence of nodal flight displacement vectors. For accelerated flight and landing gear simulations, the flight displacement is defined as the difference between the usual mesh displacement and the product $V_\infty t$ where t denotes time — that is, the displacement with respect to a frame moving at the free-stream velocity.

lfldisplacement-str [`""`]:

Name of the binary file that contains the sequence of nodal local flight displacement vectors. For accelerated flight, the local flight displacement is defined as the difference between the usual mesh displacement and the rigid body displacement associated with the direction of acceleration — that is, the deformational component of the mesh displacement. For landing flight simulations, it is defined as the difference between the usual mesh displacement and the rigid body displacement in rolling direction.

force-str [`""`]:

Name of the ASCII file that contains for all the time-steps:

1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the force in the x-direction;
6. the force in the y-direction;
7. the force in the z-direction;
8. the moment along the x-direction;
9. the moment along the y-direction;
10. the moment along the z-direction;
11. the energy transferred to the structure.

Note: if *gravity-real* and *depth-real* have nonzero values (see Hydro), then the force values are the sum of the hydrostatic and hydrodynamic force values.

generalizedforce-str [`""`]:

Name of the ASCII file containing the generalized force(s) associated with the structural mode(s) specified under the object `Input` (see Input) or with the forced oscillation mode (which is not necessarily a natural structural mode) specified or implied under the object `Forced` (see Forced), in the following format:

1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the generalized force associated with the first input mode shape;
6. the generalized force associated with the second input mode shape;
7. ... ;
8. the generalized force associated with the last mode shape;

Note: when the simulation of a forced oscillation is specified under the object `Forced` (see Forced), a requested generalized force computation is performed with respect to the forced oscillation “mode” (which is not necessarily a natural structural mode), unless a set of natural structural modes are specified in *StrModes* under the object `Input` (see Input), in which case the generalized forces are computed with respect to these specified natural structural modes.

tavforce-str [""]:

(Useful particularly in LES simulations). Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the time-averaged force in the x-direction;
6. the time-averaged force in the y-direction;
7. the time-averaged force in the z-direction;
8. the time-averaged moment along the x-direction;
9. the time-averaged moment along the y-direction;
10. the time-averaged moment along the z-direction;
11. the time-averaged energy transferred to the structure.

hydrostaticforce-str [""]:

Name of the ASCII file that contains the components of the hydrostatic force in the x-, y-, and z-directions.

hydrodynamicforce-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the hydrodynamic force in the x-direction;
6. the hydrodynamic force in the y-direction;
7. the hydrodynamic force in the z-direction;
8. the hydrodynamic moment along the x-direction;
9. the hydrodynamic moment along the y-direction;
10. the hydrodynamic moment along the z-direction;
11. the hydrodynamic energy transferred to the structure.

liftanddrag-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the physical time;
3. the subcycling factor;
4. the number of Newton iterations;
5. the drag, which is the force in the direction parallel to the free-stream velocity;
6. the lift, which is defined here as the force in the direction orthogonal to the vector defined by the yaw angle in the x-y plane;
7. the lift, which is defined here as the force in the direction orthogonal to the vector defined by the angle of attack in the x-z plane.

residual-str [""]:

Name of the ASCII file that contains for all the time-steps:
1. the time-step number;
2. the elapsed time;

3. the relative nonlinear residual;
4. the CFL number.

timeinterval-real [ ]:

> This is an alternative option to *frequency-int* for specifying when to write a result in an output file. Essentially, *timeinterval-real* is an output time-step Δt_{out} which controls the frequency at which the output files are written as follows. Let m be a positive integer set initially to 0, and incremented by 1 after each output time-iteration is reached. Then, output is performed at each time-iteration $t^n \geq m \times \Delta t_{out}$.
>
> When *timeinterval-real* is specified to a strictly positive value, the output files are always written at the last computed time-iteration. If both *frequency-int* and *timeinterval-real* are specified, *frequency-int* is ignored.

length-real [`1.0`]:

> Reference length used in the computation of the moment coefficients.

surface-real [`1.0`]:

> Reference surface used in the computation of the force and moment coefficients.

xm-real [`0.0`]:

> x-coordinate of the point around which the moment coefficients are computed.

ym-real [`0.0`]:

> y-coordinate of the point around which the moment coefficients are computed.

zm-real [`0.0`]:

> z-coordinate of the point around which the moment coefficients are computed.

poddata-str [`""`]:

> Name of the binary file to contain the computed POD basis vectors which are always output in non-dimensional form in order to be invariant with changes in altitude.

robinnerproduct-str [`""`]:

> Name of the ASCII file to contain the inner products computed between the Reduced-Order Bases (ROBs) specified in `Input.PODData` when `Problem.Type` = `ROBInnerProduct`. The format of this output file is examplified below.
>
> Example:
>
> *ROB1Id-int ROB2Id-int*
> *ROB1Id-1TimesROB2Id-1-real ROB1Id-1TimesROB2Id-2-real* ...
>   *ROB1Id-2TimesROB2Id-1-real ROB1Id-2TimesROB2Id-2-real* ...
>   ...
>   *ROB2Id-int ROB3Id-int*
> *ROB2Id-1TimesROB3Id-1-real ROB2Id-1TimesROB3Id-2-real* ...
>   *ROB2Id-2TimesROB3Id-1-real ROB2Id-2TimesROB3Id-2-real* ...

...

where *ROBiId-int* and *ROBjId-int* identify the i -th and j -th ROBs in the file specified in `Input.PODData`, and *ROBiId-kTimesROBjId-l-real* is the inner product $V_{i,k}^T M V_{j,l}$, where M is the matrix of cell volumes A if `Time.Form` = `Descriptor`, and M is the identify matrix I if `Time.Form` = `NonDescriptor`.

rom-str [`""`]:

Name of ASCII file where to output in the format described in Appendix B (see ROM) the matrices defining a fluid or aeroelastic ROM.

philevel-str [`""`]:

Name of the binary file that contains the sequence of nodal level set values.

fluidID-str [`""`]:

Name of the binary file that contains the sequence of nodal integer values identifying the fluid media covering these nodes (see VolumeData and FluidModel).

statevector-str [`""`]:

Name of the binary file that contains the sequence of nodal fluid state vector values. These solution snapshots are always stored as non-dimensional quantities. In particular, they can be used to construct a POD basis (see Problem).

statevectorsensitivity-str [`""`]:

Name of the binary file that contains the sequence of the sensitivities of the nodal fluid state vector values with respect to the specified variables.

densitysensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal density values with respect to specified variables.

machsensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal Mach number values with respect to specified variables.

temperaturesensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal temperature values with respect to specified variables.

pressuresensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal pressure values with respect to specified variables. If *gravity-real* and *depth-real* have nonzero values (see Hydro), the pressure values referred to here are those corresponding to the sum of the hydrostatic and hydrodynamic pressure values.

totalpressuresensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal total pressure values with respect to specified variables.

velocitysensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal velocity vectors with respect to specified variables.

displacementsensitivity-str [`""`]:

Name of the binary file that contains the sequence of sensitivities of nodal displacement vectors with respect to specified variables.

forcesensitivity-str [`""`]:

Name of the ASCII file that contains the sequence of sensitivities of the aerodynamic forces and moments with respect to specified variables, in the following format:

1. the sensitivity analysis step number;
2. the active specified variable: “1” for a shape parameter, “2” for the Mach number, “3” for the angle of attack, and “4” for the yaw angle (see Inlet);
3. the force in the x-direction;
4. the force in the y-direction;
5. the force in the z-direction;
6. the moment along the x-direction;
7. the moment along the y-direction;
8. the moment along the z-direction;
9. sonic boom (currently not supported and therefore set to zero);
10. the sensitivity of the force in the x-direction with respect to the specified variable;
11. the sensitivity of the force in the y-direction with respect to the specified variable;
12. the sensitivity of the force in the z-direction with respect to the specified variable;
13. the sensitivity of the moment along the x-direction with respect to the specified variable;
14. the sensitivity of the moment along the y-direction with respect to the specified variable;
15. the sensitivity of the moment along the z-direction with respect to the specified variable;
16. sensitivity of the sonic boom with respect to the specified variable (currently not supported and therefore set to zero).

sparsegrid-str [`""`]:

Name of the ASCII file that contains computational data tabulated in sparse grid format. If the tabulated data is to be stored across multiple files, *sparsegrid-str* is the common prefix to all these files whose names will be *sparsegrid-str*.x, with x ranging from 1 to the number of files.

matvols-str [`""`]:

Name of the ASCII file that contains the sequence of volumes occupied by each fluid medium during a simulation. The format of this file is as follows:

1. the time-step number;
2. the current time-instance;
3. the volume occupied by the fluid medium whose ID is 0;
4. the volume occupied by the fluid medium whose ID is 1;

5. ...
6. the volume occupied by the fluid medium whose ID is the highest;
7. the volume occupied by the obstacle;
8. the total volume of the computational domain.

bubbleradius-str [`""`]:

Name of the ASCII file that contains the time-history of the radius of the spherical interface associated with a one-dimensional computation of a spherically symmetric unsteady two-phase flow problem (see Problem`.Type` = `1D`).

cputime-str [`""`]:

Name of the ASCII file that contains a comprehensive report on the elasped CPU time associated with the performed simulation. The information in this report is updated in a cumulative fashion at the frequency specified in *frequency-int*.

Notes:

1. as mentioned in Problem, the output mode (non-dimensional or dimensional) is governed by the variable `Problem.Mode`;
2. in the files containing the sensitivities of nodal flow quantities with respect to specified variables, the specific variables are identified by tags: “1” for a shape parameter, “2” for the Mach number, “3” for the main angle of attack, and “4” for the yaw angle of attack; the integer tag is placed before its corresponding result set; the results are outputted on a tag basis and for a given tag, on a node basis; the sensitivities with respect to shape parameters are outputted in the order in which these parameters are specified in the file `Input.ShapeDerivative` (see Input).
3. The binary sensitivity analysis result files can be post-processed by **SOWER** and visualized by **XPost** as all other binary output results files.

Next: Restart, Previous: Postpro, Up: Output

4.4.2 PROBING NODAL RESULTS

Object:	**Probes**

The object `Probes` is used to request outputting, **for every time-step** of a simulation, a specified scalar or vector result (called here the “probed” result) at one or several nodes of the fluid mesh or other locations in the computational domain. The current list of scalar and vector results supported by this object can be found in the definition of its syntax given below. A mesh node or other location in the computational domain where the output is desired is identified in an object such as `Node1` within this object.

The syntax of the object `Probes` is:

```
under Probes {
  Prefix       = prefix-str;
  Density      = density-str;
  Pressure     = pressure-str;
  Temperature  = temperature-str;
  Velocity     = velocity-str;
  Displacement = displacement-str;
  under Node1{ ... }
}
```

with

prefix-str [""]:

String that is prefixed to all post-processing file names.

density-str [""]:

Name of the ASCII file that contains for each time-step the sequence of density values at the nodes or other locations identified in an object of the type `Node1`.

pressure-str [""]:

Name of the ASCII file that contains for each time-step the sequence of pressure values at the nodes or other locations identified in an object of the type `Node1`.

temperature-str [""]:

Name of the ASCII file that contains for each time-step the sequence of temperature values at the nodes or other locations identified in an object of the type `Node1`.

velocity-str [""]:

Name of the ASCII file that contains for each time-step the sequence of velocity vector values at the nodes or other locations identified in an object of the type `Node1`.

displacement-str [""]:

Name of the ASCII file that contains for each time-step the sequence of displacement vector values at the nodes or other locations identified in an object of the type `Node1`.

`Node1`:

Identification of a mesh node or other location in the computational domain where to probe computational results.

Notes:

1. as mentioned in Problem, the output mode (non-dimensional or dimensional) is governed by the variable `Problem.Mode`;
2. all output files requested under this object are generated in an ASCII format;
3. currently, the user can specify up to 50 nodes or other locations in the computational domain where to probe scalar and/or vector computational results;
4. the ASCII format of an output file associated with a probed scalar result field is as follows (one line per time-step):

```
[SCALAR_RESULT]
(1) time-step identification number
(2) physical time
(3) value of the specified scalar result at the node specified in Node1
(4) value of the specified scalar result at the node specified in Node2
    ...
```

5. the ASCII format of an output file associated with a probed vector result field is as follows (one line per time-step):

```
[VECTOR_RESULT]
(1) time-step identification number
(2) physical time
(3) value of the x-component of the specified vector result at the node specified i
(4) value of the y-component of the specified vector result at the node specified i
(5) value of the z-component of the specified vector result at the node specified i
(6) value of the x-component of the specified vector result at the node specified i
(7) value of the y-component of the specified vector result at the node specified i
(8) value of the z-component of the specified vector result at the node specified i
    ...
```

- ProbingNode

Up: Probes

4.4.2.1 PROBING NODE

Object:	**Node**

The object `Node` (with an integer appended to the last letter of this word) is used to identify a node of the mesh or a location in the computational domain where to output a probed computational result.

The syntax of the object `Node` (with an integer appended to the last letter of this word) is:

```
under node-obj {
ID = id-int;
LocationX = locationx-real;
LocationY = locationy-real;
LocationZ = locationz-real;
}
```

with

id-int [—]:

Global identification number (as in the **XPost** mesh file) of a node of the fluid mesh at which a computational result is to be probed at each time-step of an **AERO-F** simulation.

locationX-real [—]:

x coordinate of a location in the computational domain at which a computational result is to be probed at each time-step of an **AERO-F** simulation.

locationY-real [—]:

y coordinate of a location in the computational domain at which a computational result is to be probed at each time-step of an **AERO-F** simulation.

locationZ-real [—]:

z coordinate of a location in the computational domain at which a computational result is to be probed at each time-step of an **AERO-F** simulation.

Note:

1. currently, the user can specify up to 50 nodes or locations where to probe scalar and/or vector computational results;
2. if at any point in time the chosen node or location in the computational domain is covered by the obstacle, the computational result at this probe is set to its free-stream value.

Previous: Probes, Up: Output

4.4.3 SAVING THE COMPUTATIONAL RESULTS FOR LATER

Object:	**Restart**

The `Restart` object specifies the name of the files that are written during (if the value of `Output.Restart.Frequency` is different from zero) and at the end of the computation. These files are only needed if one wishes to restart AERO-F (see Input). The syntax of the `Restart` object is:

```
under Restart {
  Prefix = prefix-str;
  Solution = solution-str;
  Position = position-str;
  LevelSet = levelset-str;
  RestartData = restartdata-str;
  Frequency = frequency-int;
  TimeInterval = timeinterval-real;
}
```

with

prefix-str [`""`]:

String that is prefixed to all restart file names.

solution-str [`"DEFAULT.SOL"`]:

Name of the binary solution (i.e. conservative variables) file.

position-str [`"DEFAULT.POS"`]:

Name of the binary position (i.e. x,y,z node coordinates) file. This file is written if a “ping-pong” step, “modal ping-pong” step, aeroelastic, forced vibration, or accelerated flight simulation is performed.

levelset-str [`"DEFAULT.LS"`]:

Name of the binary file containing the “conservative” level set variable $\rho\phi$. This file can be specified only for multi-phase flow simulations (see MultiPhase).

restartdata-str [`"DEFAULT.RST"`]:

Name of the ASCII restart file .

frequency-int [`0`]:

The frequency (every so many time-iteration) at which the restart files are re-written (each save overwrites the previous one). In the case of an aerothermal, aeroelastic, or aerothermoelastic simulation with the

AERO-S code, this value must be specified in the AERO-S input file.

timeinterval-real [ ]:

This is an alternative option to *frequency-int* for specifying when to update a restart file. Essentially, *timeinterval-real* is a restart update time-step Δt_{up} which controls the frequency at which the restart files are updated as follows. Let m be a positive integer set initially to 0, and incremented by 1 after each update time-iteration is reached. Then, the update of the restart files is performed at each time-iteration $t^n \geq m \times \Delta t_{up}$. When *timeinterval-real* is specified to a strictly positive value, the restart files are always written at the last computed time-iteration. If both *frequency-int* and *timeinterval-real* are specified, *frequency-int* is ignored. This option is not recommended when performing a coupled-field simulation using also the AERO-S code.

Next: Velocity, Previous: Output, Up: Objects

4.5 SPECIFYING THE ATTRIBUTES OF THE MESH SURFACES DEFINED IN THE COMPUTER-AIDED DESIGN MODEL

Object:	**Surfaces**

During the process of generating a fluid mesh from a computer-aided design model, several surfaces can be defined and grouped according to a user-specified id number. The `Surfaces` object specifies these surfaces in preparation for defining their attributes. Its syntax is:

```
under Surfaces {
  under SurfaceData[surface-id-int] { ... }
  ...
}
```

with

surface-id-int [`None`]:

ID number of a surface or group of surfaces.

`SurfaceData`:

Specifies the attributes of the mesh surfaces.

- SurfaceData

Up: Surfaces

4.5.1 SPECIFYING THE ATTRIBUTES OF THE MESH SURFACES

Object:	**SurfaceData**

The `SurfaceData` object defines the attributes to be assigned to the surface identified by the specified surface tag *surface-id-int*.

The syntax of this object is:

```
under SurfaceData[surface-id-int] {
  Nx  =  Nx-real;
  Ny  =  Ny-real;
  Nz  =  Nz-real;
  ComputeForces = computef-flag;
  SeparateForces = separatef-flag;
  ComputeHeatFlux = computehf-flag;
  SeparateHeatFlux = separatehf-flag;
  VelocityID = velocity-id-int;
  Type = type-id-;
  Temperature = temp-real;
}
```

with

Nx-real [`0.0`]:

This information is relevant only when the target simulation involves mesh motion. If at least one of the parameters *Nx-real* or *Ny-real* or *Nz-real* (see below) is non zero, the tagged surface (or group of surfaces) is declared a sliding plane and *Nx-real* specifies the value of the x-component of the normal to this sliding plane. In this case, the nodes in the declared sliding plane are constrained to move within this plane — that is, the component of their displacement field along the specified normal to the sliding plane is constrained to zero. If the declared sliding plane is also a symmetry plane and *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion), it is strongly recommended in this case to specify the `Symmetry` object within the `MeshMotion` object (see Symmetry).

Ny-real [`0.0`]:

This information is relevant only when the target simulation involves mesh motion. If at least one of the parameters *Nx-real* or *Ny-real* or *Nz-real* (see below) is non zero, the tagged surface (or group of surfaces) is declared a sliding plane and *Ny-real* specifies the value of the y-component of the normal to this sliding plane. In this case, the nodes in the declared sliding plane are constrained to move within this plane — that is, the component of their displacement field along the specified normal to the sliding plane is constrained to zero. If the declared sliding plane is also a symmetry plane and *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion), it is strongly recommended in this case to specify the `Symmetry` object within the `MeshMotion` object (see Symmetry).

Nz-real [`0.0`]:

This information is relevant only when the target simulation involves mesh motion. If at least one of the parameters *Nx-real* or *Ny-real* or *Nz-real* (see below) is non zero, the tagged surface (or group of surfaces) is declared a sliding plane and *Nz-real* specifies the value of the z-component of the normal to this sliding plane. In this case, the nodes in the declared sliding plane are constrained to move within this plane — that is, the component of their displacement field along the specified normal to the sliding plane is constrained to zero. If the declared sliding plane is also a symmetry plane and *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion), it is strongly recommended in this case to specify the `Symmetry` object within the `MeshMotion` object (see Symmetry).

computef-flag [ ]:

`True`

In the absence of this command, and when requested under the `Output.Postpro` object, AERO-F computes the total aerodynamic forces (lift, drag, forces and moments, time-averaged counterparts, etc.) generated by all "moving" surfaces except moving inlet and outlet boundaries. Setting this command to `True` adds to the total the contribution of the specified tagged surface (or group of surfaces).

`False`
: In the absence of this command, and when requested under the `Output.Postpro` object, AERO-F computes the total aerodynamic forces (lift, drag, forces and moments, time-averaged counterparts, etc.) generated by all "moving" surfaces except moving inlet and outlet boundaries. Setting this command to `False` removes from the total the contribution of the specified tagged surface (or group of surfaces).

separatef-flag [`False`]:

`True`
: In this case, the aerodynamic forces (lift, drag, forces and moments, time-averaged counterparts, etc.) generated by the tagged surface (or group of surfaces) are output in a separate file, assuming that such a result is requested under the `Output.Postpro` object. The name of each output file associated with the tagged surface (or group of surfaces) is set to the filename of the corresponding result specified under `Output.Postpro` with a postfix set to the surface id number.

`False`
: In this case, the aerodynamic forces (lift, drag, forces and moments, time-averaged counterparts, etc.) generated by the tagged surface (or group of surfaces) are not computed and output in a separate file.

computehf-flag [ ]:

`True`
: In the absence of this command, and when requested under the `Output.Postpro` object, **AERO-F** computes the total heat flux through all “moving” isothermal wall boundaries. Setting this command to `True` adds to the total the contribution of the specified tagged surface (or group of surfaces).

`False`
: In the absence of this command, and when requested under the `Output.Postpro` object, **AERO-F** computes the total heat flux through all “moving” isothermal wall boundaries. Setting this command to `False` removes from the total the contribution of the specified tagged surface (or group of surfaces).

separatehf-flag [`False`]:

`True`
: In this case, the heat flux values through the tagged surface (or group of surfaces) are outputted in a separate file, assuming that such a result is requested under the `Output.Postpro` object. The name of each output file associated with the tagged surface (or group of surfaces) is set to the filename of the corresponding result specified under `Output.Postpro` with a postfix set to the surface id number.

`False`
: In this case, the heat flux values through the tagged surface (or group of surfaces) are not outputted in a separate file.

velocity-id-int [`None`]:

ID number of a prescribed velocity data-set including the rotation or translation axis, the center of rotation, and the angular or translational velocity (see Velocity, RotationAxis). This option can be used to prescribe the velocity field of a rotating or translating surface in a viscous flow simulation. In the case of an aeroelastic computation, if the tagged surface is at the fluid-structure interface, the prescribed velocity field is superposed to the velocity field of the transmission condition at this interface.

type-id [ ]:

`Adiabatic`
: In this case, the surface identified by the specified surface tag is treated as an adiabatic surface (wall).

`Isothermal`
: In this case, the surface identified by the specified surface tag is treated as an isothermal surface (wall) where the constant temperature is specified in `SurfaceData.Temperature` (see below).

The default value of *type-id* is the value set in `Wall.Type` (see Wall).

temp-real [—]:

Temperature of the surface identified by the specified surface tag if this surface is specified as an isothermal wall in `SurfaceData.Type` (see above). Attention should be paid to inputting this temperature, when desired, in the same system of units as that of the ideal gas constant R (see GasModel) and the remainder of the input file.

Next: Volumes, Previous: Surfaces, Up: Objects

4.6 SPECIFYING ROTATIONAL AND TRANSLATIONAL VELOCITY FIELDS

Object:	**Velocity**

Axes of rotation or translation are defined using this object to facilitate the prescription of the velocity field of the grid points lying on a rotating or translating surface (see Surfaces). The syntax of this object is:

```
under Velocity{
  under RotationAxis[rotation-id-int] { ... }   ...
}
```

with

`RotationAxis`:

Specifies rotational and translational velocity fields.

rotation-id-int [`None`]:

ID number of a rotation or translation data-set.

- RotationAxis

Up: Velocity

4.6.1 SPECIFYING ROTATIONAL AND TRANSLATION VELOCITY FIELDS (CONTINUE)

Object:	**RotationAxis**

The `RotationAxis` object defines the parameters of the specified rotation/translation data-set. Its syntax is:

```
under RotationAxis[rotation-id-int] {
  Nx  =  Nx-real;
  Ny  =  Ny-real;
  Nz  =  Nz-real;
  X0  =  X0-real;
```

```
        Y0   =  Y0-real;
        Z0   =  Z0-real;
        InfiniteRadius = infiniteradius-flag;
        Omega = omega-real;

      }
```

with

Nx-real [`0.0`]:

The x-component of the normalized rotation axis or translation vector.

Ny-real [`0.0`]:

The y-component of the normalized rotation axis or translation vector.

Nz-real [`0.0`]:

The z-component of the normalized rotation axis or translation vector.

X0-real [`0.0`]:

The x-coordinate of the center of rotation.

Y0-real [`0.0`]:

The y-coordinate of the center of rotation.

Z0-real [`0.0`]:

The z-coordinate of the center of rotation.

infiniteradius-flag [`False`]:

`False`
: When this flag is set to `False`, the vector specified above is interpreted as the normalized axis of rotation.

`True`
: When this flag is set to `True`, the vector specified above is interpreted as the normalized direction of translation.

omega-real [`0.0`]:

When *infiniteradius-flag* is set to `False`, *omega-real* is the angular velocity. When *infiniteradius-flag* is set to `True`, *omega-real* becomes the magnitude of the translational velocity.

Next: ReferenceState, Previous: Velocity, Up: Objects

4.7 SPECIFYING THE ATTRIBUTES OF THE MESH VOLUMES DEFINED IN THE COMPUTER-AIDED DESIGN MODEL

Object:	**Volumes**

During the process of generating a fluid mesh from a computer-aided design model, several volumes (sets of mesh elements) can be defined and grouped according to a user-specified id number. The `Volumes` object specifies these volumes in preparation for defining their attributes. Its syntax is:

```
under Volumes{
  under VolumeData[volume-id-int] { ... }
  ...
}
```

with

volume-id-int [`None`]:

ID number of a volume or group of volumes.

`VolumeData`:

Specifies the attributes of the mesh volumes.

- VolumeData

Up: Volumes

4.7.1 SPECIFYING THE ATTRIBUTES OF THE MESH VOLUMES

Object:	**VolumeData**

The `VolumeData` object specifies the attributes of a region of the computational domain (subset of the mesh elements) identified by the integer *volume-id-int*. It can also be used to set the initial conditions of a multi-fluid (which includes the particular case of a single fluid with porous media) or multi-phase flow problem. The syntax of this object is:

```
under VolumeData[volume-id-int] {
  Type = type-str;
  FluidID = fluid-id-int;
  under PorousMedium { ... }
  under InitialState { ... }
}
```

with

type-str [`Fluid`]:

`Fluid`
Specifies that the volume identified by *volume-id-int* is occupied by a fluid. The fluid which initially occupies this volume is identified by its integer identifcation number *fluid-id-int*; its material properties are set in FluidModel, and its initial state is specified in InitialState.

`Porous`
Specifies that the volume identified by *volume-id-int* is occupied by a porous medium whose properties are described in the `PorousMedium` object.

fluid-id-int [—]:

Integer identification (ID) number of the fluid medium which initially occupies the volumic region identified by *volume-id-int*. This is the same ID used in FluidModel to set the material properties of this fluid medium.

`PorousMedium`:

Defines the properties of the porous medium occupying the volumic region of the computational domain identified by *volume-id-int* if *type-str* is set to `PorousMedium`.

`InitialState`:

Defines the initial conditions of the fluid initially occupying the volumic region of the computational domain identified by *volume-id-int* if *type-str* is set to `Fluid`.

- PorousMedium
- InitialState

Next: InitialState, Up: VolumeData

4.7.1.1 SPECIFYING THE PROPERTIES OF A POROUS MEDIUM

Object:	**PorousMedium**

The `PorousMedium` object specifies the porosity properties of a volume that is identified by its id number and declared a porous medium. In this volume, the fluid flow is described by a generalized momentum equation based on the Brinkman-Forchheimer-Extended Darcy model. Essentially, the following sink term

$$(\alpha_i|\mathbf{u}| + \beta_i)u_i$$

is added to the i^{th} momentum equation.

The nonlinear component in the above term is called the Forchheimer term. The linear component is the usual Darcy term.

For turbulence runs, the turbulence kinetic energy k and dissipation rate ϵ of the flow through the porous media are computed as follows:

$$k = (3/2)I_{dr}^2|\mathbf{u}|^2$$

$$\epsilon = \frac{C_\mu^{3/4}k^{3/2}}{L_{dr}}$$

where, I_{dr} and L_{dr} are user-supplied coefficients representing the average turbulence intensity and length scale respectively, and $C_\mu = 0.09$. Using these values of k and ϵ , the eddy viscosity $\nu_t = C_\mu k^2/\epsilon$ is computed.

The syntax of this object is:

```
under PorousMedium {
  Ix  =  ix-real;
  Iy  =  iy-real;
  Iz  =  iz-real;
  Jx  =  jx-real;
  Jy  =  jy-real;
```

```
    Jz  =  jz-real;
    Kx  =  kx-real;
    Ky  =  ky-real;
    Kz  =  kz-real;
    Alphax = alphax-real;
    Alphay = alphay-real;
    Alphaz = alphaz-real;
    Betax  = betax-real;
    Betay  = betay-real;
    Betaz  = betaz-real;
    Idr =  idr-real;
    Ldr =  ldr-real;
  }
```

with

ix-real [`1.0`]:

The x-component of the x-axis of the local coordinate system.

iy-real [`0.0`]:

The y-component of the x-axis of the local coordinate system.

iz-real [`0.0`]:

The z-component of the x-axis of the local coordinate system.

jx-real [`0.0`]:

The x-component of the y-axis of the local coordinate system.

jy-real [`1.0`]:

The y-component of the y-axis of the local coordinate system.

jz-real [`0.0`]:

The z-component of the y-axis of the local coordinate system.

kx-real [`0.0`]:

The x-component of the z-axis of the local coordinate system.

ky-real [`0.0`]:

The y-component of the z-axis of the local coordinate system.

kz-real [`1.0`]:

The z-component of the z-axis of the local coordinate system.

alphax-real [`0.0`]:

Resistance coefficient of the Forchheimer term in the local x-direction. It has the dimension of mass/length ^{4} .

alphay-real [`0.0`]:

Resistance coefficient of the Forchheimer term in the local y-direction. It has the dimension of mass/length ^{4}.

alphaz-real [`0.0`]:

Resistance coefficient of the Forchheimer term in the local z-direction. It has the dimension of mass/length ^{4}.

betax-real [`0.0`]:

Resistance coefficient of the Darcy term in the local x-direction. It has the dimension of mass/length ^{3} /time.

betay-real [`0.0`]:

Resistance coefficient of the Darcy term in the local y-direction. It has the dimension of mass/length ^{3} /time.

betaz-real [`0.0`]:

Resistance coefficient of the Darcy term in the local z-direction. It has the dimension of mass/length ^{3} /time.

idr-real [`0.01`]:

Coefficient representing average turbulent intensity in the porous media. This is used to compute the turbulence kinetic energy *k*.

ldr-real [`0.1`]:

Coefficient representing the length scale of turbulence in the porous media (~0.1 times a characterstic passage dimension). This is used to compute the turbulence dissipation rate ϵ .

Notes:

1. currently, flow through a porous medium is supported only when the fluid is modeled as a perfect gas in the remainder of the computational domain;
2. currently, turbulence through a porous medium is supported only when a RANS turbulence model is selected for the remainder of the computational domain.

Previous: PorousMedium, Up: VolumeData

4.7.1.2 SPECIFYING AN INITIAL STATE FOR A MULTI-FLUID COMPUTATION

Object:	**InitialState**

In the context of a multi-fluid flow problem, this object can be used to specify the parameters of a uniform initial state in a region of the computational domain identified outside this object. Its syntax is:

```
under InitialState {
    Mach = mach-real;
    Velocity = velocity-real;
    Alpha = alpha-real;
    Beta = beta-real;
    Density = density-real;
    Pressure = pressure-real;
    Temperature = temperature-real;
  }
```

with

mach-real [—]:

Initial Mach number. To be specified only if the velocity magnitude is not specified.

velocity-real [—]:

Initial velocity magnitude. To be specified only if the Mach number is not specified.

alpha-real [—]:

Initial angle of attack.

beta-real [—]:

Initial yaw angle.

density-real [—]:

Initial density. Needs to be specified for a perfect gas, stiffened gas, and a fluid modeled by the JWL equation of state. For a barotropic liquid, this parameter needs to be specified only if no pressure value is specified (it is discarded if a pressure value is simultaneously specified).

pressure-real [—]:

Initial density. Needs to be specified for a perfect gas, stiffened gas, and a fluid modeled by the JWL equation of state. For a barotropic liquid, this parameter needs to be specified only if no density value is specified.

temperature-real [—]:

Initial temperature. Needs to be specified only for a barotropic liquid. It is discarded if it is specified for any other fluid.

Next: Equations, Previous: Volumes, Up: Objects

4.8 DEFINING THE REFERENCE STATE

Object:	**ReferenceState**

The `ReferenceState` object allows to specify some of the quantities used for non-dimensionalizing the governing equations. Its syntax is:

```
under ReferenceState {
  Density = density-real;
```

```
    Temperature = temp-real;
    Reynolds = reynolds-real;
    Length = length-real;
    Mach = mach-real;
  }
```

with *density-real* [—];

Reference density (required for simulations with variations of boundary conditions in time. See BoundaryConditions). If it is not specified it is set internally to the boundary value.

temp-real [—]:

Reference temperature (required for non-dimensional viscous simulations with the Sutherland viscosity model).

reynolds-real [—]:

Reynolds number (required for non-dimensional viscous simulations). Its definition is based on the reference length, reference velocity, and reference density (see Problem).

length-real [`1.0`]:

Reference length which is used to non-dimensionalize the mesh. The Reynolds number is based on this length.

Mach-real [—]:

Reference Mach number that should be specified only if the inlet Mach number is not specified in Inlet or specified to zero in `Inlet.Mach`. Otherwise, the reference Mach number is automatically set to the non zero value of the free-stream Mach number specified in `Inlet.Mach`. Hence, specifying the reference Mach number is useful primarily when the inlet Mach number is zero as in a shock-tube problem.

Note:

1. the reference state conditions that cannot be specified by this command but are perceived needed for the flow computation are set internally by the code to the corresponding boundary values.

Next: MultiPhase, Previous: ReferenceState, Up: Objects

4.9 DEFINING THE EQUATIONS TO BE SOLVED

Object:	**Equations**

The `Equations` object defines the type of equations to be solved. Its syntax is:

```
under Equations {
  Type = type-id;
  GravityX = gravityx-real;
  GravityY = gravityy-real;
  GravityZ = gravityz-real;
  under FluidModel[fluid-id-int] { ... }
  under ViscosityModel { ... }
  under TurbulenceClosure { ... }
}
```

with

type-id [`Euler`]:

`Euler`
: Inviscid flow simulation based on the compressible Euler equations.

`NavierStokes`
: Viscous flow simulation based on the compressible Navier-Stokes equations.

gravityx-real [`0.0`]:

Value of the gravity field in the x-direction, if any.

gravityy-real [`0.0`]:

Value of the gravity field in the y-direction, if any.

gravityz-real [`0.0`]:

Value of the gravity field in the z-direction, if any.

`FluidModel`:

Defines the properties of the fluid in a single-phase flow problem. The corresponding syntax is defined in the *FluidModel* object (see FluidModel).

fluid-id-int[—]

Integer identifier of a fluid medium.

`ViscosityModel`:

Specifies the viscosity model to be used in a viscous flow problem.

`TurbulenceClosure`:

Specifies the turbulence model as either a RANS or LES model.

- FluidModel
- ViscosityModel
- TurbulenceClosure

Next: ViscosityModel, Up: Equations

4.9.1 SPECIFYING A FLUID MODEL

Object:	**FluidModel**

The object `FluidModel`[*fluid-id-int*], where *fluid-id-int* is an integer identifying a fluid medium, can be used to specify an equation of state (EOS) for this medium and its parameters. The user can choose between the EOS of a perfect gas, stiffened gas, Tait's EOS which typically models a compressible barotropic liquid, and the Jones-Wilkins-Lee (JWL) EOS which typically models a highly explosive gas. Currently, viscous effects are implemented only for a perfect gas. The syntax of these objects is:

```
under FluidModel[fluid-id-int] {
  Fluid = fluidtype-id;
  PressureCutOff = pressurecutoff-real;
  under GasModel { ... }
  under LiquidModel { ... }
  under JWLModel { ... }
}
```

with

fluid-id-int [ ]:

Integer number identifying a fluid medium. When the problem involves a single fluid, *fluid-id-int* must be set to 0 (which is done by default). When it involves multiple fluids, *fluid-id-int* must be assigned in a consecutive manner (no gap) starting with 0. **AERO-F** can handle a multi-fluid problem with an arbitrary number of fluid media. However, **AERO-F** can currently handle only three different fluid-fluid interfaces which furthermore must be between a same fluid — referred to in this User's Reference Manual as the "primary" fluid — and any one of three other fluids. In this case, the primary fluid must be identified by *fluid-id-int* = 0.

fluidtype-id [`PerfectGas`]:

`PerfectGas`
: The fluid is modeled as a perfect gas.

`StiffenedGas`
: The fluid is modeled as a stiffened gas.

`Liquid`
: The fluid is modeled as a barotropic liquid governed by Tait's EOS.

`JWL`
: The fluid is modeled as a highly explosive gas governed by the Jones-Wilkins-Lee EOS.

pressurecutoff-real [0.0]:

Lower threshold for the pressure. This limit value of the pressure can be used to avoid artificial cavitation due to discretization error for a given EOS. Essentially, if the computed value of the pressure field becomes lower than the specified threshold value, it is set to the specified threshold value. The dimensional or non-dimensional mode of this parameter should be consistent with the mode of the simulation (see Problem).

`GasModel`:

Specifies the parameters of a perfect or stiffened gas.

`LiquidModel`:

Specifies the model for a compressible liquid and its parameters.

`JWLModel`:

Specifies the model for a highly explosive gas and its parameters.

- GasModel
- LiquidModel
- JWLModel

Next: LiquidModel, Up: FluidModel

4.9.1.1 SPECIFYING THE EQUATION OF STATE OF A PERFECT OR STIFFENED GAS

Object:	**GasModel**

The object `GasModel` is currently restricted to the equation of state (EOS) of a stiffened gas which can be written as

$$p = (\gamma - 1)\rho e - \gamma p_{sg}$$

$$h = c_p T$$

where p , ρ , T , e and h denote the pressure, density, temperature, internal energy per unit mass and internal enthalpy per unit mass, respectively, and γ , p_{sg} and c_p are the ratio of specific heats, a pressure constant, and the specific heat at constant pressure, respectively. For example, in the case of water which can be modeled as a stiffened gas, p_{sg} represents the molecular attraction between water molecules.

The EOS of an ideal (perfect) gas is a particular case of the EOS of a stiffened gas obtained by setting $p_{sg} = 0$, which leads to

$$p = (\gamma - 1)\rho e = \rho R T$$

where R is the ideal gas constant.

The specific heats at constant volume and constant pressure are given by

$$c_v = \frac{R}{\gamma - 1} \quad c_p = R + c_v = \frac{\gamma}{\gamma - 1} R$$

respectively.

The syntax of this object is:

```
under GasModel {
  SpecificHeatRatio               = gamma-real;
  IdealGasConstant                = R-real;
  PressureConstant                = psg-real;
  SpecificHeatAtConstantPressure = cp-real;

}
```

with

gamma-real [`1.4`]:

Ratio of specific heats γ . It must be specified for both a stiffened gas and a perfect gas.

R-real [`287.1`]:

Ideal gas constant (hence, must be specified only for a perfect gas, instead of the specific heat at constant pressure). It is used by **AERO-F** only in dimensional simulations where a temperature boundary condition is specified, or a temperature output is requested, or Sutherland's viscosity model is used. In such cases, this constant must be specified in the same system of units as all other input data (its default value is equal to $287.1\ m^2/s^2/K$ and therefore should be used only when the units of this default value are consistent with the system of units chosen for all other input data).

psg-real [`0.0`]:

Stiffened gas pressure constant p_{sg} expressed in pressure units consistent with the system of units used by all other input data. For a perfect gas, this constant is zero (default value).

cp-real [`---`]:

Stiffened gas specific heat at constant pressure expressed in units consistent with the system of units used by all other input data. It need not be specified for a perfect gas (instead, the ideal gas constant is specified for a perfect gas).

Note:

1. if a temperature boundary condition is specified, or the temperature field is outputted, or Sutherland's viscosity model is used, special attention should be paid to ensure that: for a dimensional simulation, the ideal gas constant *R-real* is specified for a perfect gas and the specific heat at constant pressure is specified for a stiffened gas in the same system of units as the temperature and all other input data.

Next: JWLModel, Previous: GasModel, Up: FluidModel

4.9.1.2 SPECIFYING THE TAIT EQUATION OF STATE

Object:	**LiquidModel**

The object `LiquidModel` is currently restricted to Tait's barotropic equation of state (EOS)

$$p = p_c + \alpha \rho^{\beta}, \quad p(\rho_0) = p_0$$

$$h = c_p T$$

where p , ρ , T , and h denote the pressure, density, temperature and internal enthalpy per unit mass, respectively, p_c , α and β are three constants, (ρ_0, p_0) is a reference state, and c_p is the specific heat at constant pressure. The Tait EOS also assumes that the bulk modulus *K* is anaffine function of the pressure

$$K = \rho \frac{dp}{d\rho} = k_1 + k_2 p$$

where k_1 and k_2 are two constants.

The constants p_c and β are determined from the knowledge of k_1 and k_2 as follows

$$p_c = -\frac{k_1}{k_2} \qquad \beta = k_2$$

and the constant α is determined from the knowledge of the reference state (ρ_0, p_0) as follows

$$\alpha = \frac{p_0 + \frac{k_1}{k_2}}{\rho_0^{k_2}}$$

The specific heat at constant pressure of a fluid modeled by Tait's EOS is given by

$$c_p = \left(\frac{1}{\rho_\infty T_\infty}\right)\left(\frac{k_2}{k_2-1}\right)\left(p_0 + \frac{k_1}{k_2}\right)\left(\frac{\rho_\infty}{\rho_0}\right)^{k_2}$$

where ρ_∞ and T_∞ are the free-stream density and temperature, respectively, specified or set by **AERO-F** as explained in Inlet.

The syntax of the object `LiquidModel` is:

```
under LiquidModel {
  k1       = k1-real;
  k2       = k2-real;
  Pressure = referencepressure-real;
  Density  = referencedensity-real;
  Burnable = burnable-id;
}
```

with

k1-real [`2.07e9`]:

One of the two constants defining the behavior of the bulk modulus. Its default value is $2.07e9\ Kg/m/s^2$ and corresponds to water. However, even for water, this default value should be used only when its units are consistent with the system of units chosen for all other input data.

k2-real [`7.15`]:

Second constant defining the behavior of the bulk modulus. This constant is non-dimensional. Its default value is 7.15 and corresponds to water.

referencepressure-real [—]:

This reference pressure value must be chosen in agreement with the reference density value (see below), and expressed in pressure units consistent with the system of units used by all other input data. It can be found in a thermodynamic table.

referencedensity-real [—]:

This reference density value must be chosen in agreement with the reference pressure value (see above), and expressed in density units consistent with the system of units used by all other input data. It can be found in a thermodynamic table.

burnable-flag [False];

`True`
Specifies that the fluid identified by *fluid-id-int* (see FluidModel) is burnable (see ProgrammedBurn).
`False`
Specifies that the fluid identified by *fluid-id-int* (see FluidModel) is not burnable (see ProgrammedBurn).

Notes:

1. the reference pressure and density are not independent: they must correspond to a physical state — the user can set them by looking at thermodynamic tables;
2. it is best to set the reference pressure and density to their free-stream values.

Previous: LiquidModel, Up: FluidModel

4.9.1.3 SPECIFYING THE JWL EQUATION OF STATE

Object:	**JWLModel**

This object can be used to specify the parameters of the Jones-Wilkins-Lee equation of state (EOS) which can be written as

$$p = \omega\rho\epsilon - A_1\left(1 - \frac{\omega\rho}{R_1\rho_0}\right)e^{-\frac{R_1\rho_0}{\rho}} - A_2\left(1 - \frac{\omega\rho}{R_2\rho_0}\right)e^{-\frac{R_2\rho_0}{\rho}}$$

where p denotes the pressure of the fluid medium, ρ its density, ϵ its internal energy per unit mass, ω is a non-dimensional constant, A_1 and A_2 are two constants with pressure units, R_1 and R_2 are two non-dimensional constants, and ρ_0 is a constant with a density unit.

The syntax of this object is:

```
under JWLModel {
  Omega = omega-real;
  A1 = a1-real;
  R1 = r1-real;
  A2 = a2-real;
  R2 = r2-real;
  ReferenceDensity = referencedensity-real;
}
```

with

omega-real[0.4]

First constant defining the behavior of the JWL EOS. It is non-dimensional. Its default value is 0.4.

a1-real[0.0]

Second constant defining the behavior of the JWL EOS. It has the dimension of a pressure and therefore should be expressed in pressure units consistent with the system of units used by all other input data.

r1-real[1.0]

Third constant defining the behavior of the JWL EOS. It is non-dimensional. Its default value is 1.0.

a2-real[0.0]

Fourth constant defining the behavior of the JWL EOS. It has the dimension of a pressure and therefore should be expressed in pressure units consistent with the system of units used by all other input data.

r2-real[1.0]

Fifth constant defining the behaviour of the JWL EOS. It is non-dimensional. Its default value is 1.0.

referencedensity-real[1.0]

Last constant defining the behaviour of the JWL EOS. It has the dimension of a density and therefore should be expressed in density units consistent with the system of units used by all other input data. Its default value is $1.0~Kg/m^3$ and therefore should be used only when the units of this default value are consistent with the system of units chosen for all other input data.

Next: ThermalConductivityModel, Previous: FluidModel, Up: Equations

4.9.2 SPECIFYING THE VISCOSITY MODEL

Object:	**ViscosityModel**

The object `ViscosityModel` can be used to specify a viscosity model. Its syntax is:

```
under ViscosityModel {
  Type                             = type-id;
  SutherlandConstant               = cst-real;
  SutherlandReferenceTemperature = temp-real;
  DynamicViscosity                 = dynavisc-real;
  BulkViscosity                    = bulkvisc-real;
}
```

with

type-id [`Sutherland`]:

Identifies the Sutherland viscosity model *for an ideal gas*, or a constant dynamic viscosity (in space and time).

`Sutherland`
: Sutherland's viscosity law. For an ideal gas, a widely used formula is

$$\mu = \frac{\mu_0 \sqrt{T}}{1 + T_0/T}$$

where Sutherland's constants μ_0 and T_0 are specified below.

`Constant`
Constant viscosity model applicable to all equations of state supported by**AERO-F**. It is recommended for dimensionless analyses.

cst-real [`1.458e-6`]:

Sutherland's constant μ_0 . Its default value is $1.458e - 6 \text{ Kg/msK}^{\frac{1}{2}}$ and corresponds to air. However, even for air, this default value should be used only when its units are consistent with the system of units chosen for all other input data.

temp-real [`110.6`]:

Sutherland's reference temperature T_0 . When performing a non-dimensional simulation, this temperature must be specified in the same system of units as the reference temperature `ReferenceState.Temperature`. Its default value is $110.6K$ and corresponds to air. However, even for air, this default value should be used only when its units are consistent with the system of units chosen for all other input data.

dynavisc-real [`---`]:

Dynamic viscosity coefficient (assumed to be constant).

bulkvisc-real [`0`]

Bulk viscosity coefficient (assumed to be constant) when the fluid is not assumedto satisfy Stoke's hypothesis (zero bulk viscosity).

Notes:

1. special attention should be paid to the consistency of the units of *cst-real* and *R-real* (see GasModel), and the units of all other data in the remainder of the input file;
2. Sutherland's viscosity law is not recommended for dimensionless analyses because it results in a non-uniform dynamic viscosity that can become inconsistent with the Reynolds nunmber specified in `ReferenceState.Reynolds`.

Next: TurbulenceClosure, Previous: ViscosityModel, Up: Equations

4.9.3 THERMAL CONDUCTIVITY MODEL

Object:	**ThermalConductivityModel**

The object `ThermalConductivityModel` can be used to specify the behavior of the heat conductivity coefficient k of a fluid. If this fluid is barotropic — that is, governed by Tait's equation of state (EOS) — or if it is a stiffened gas, it is assumed to be characterized by two constants: a constant dynamic viscosity μ that is set in `ViscosityModel.DynamicViscosity`, and a constant specific heat at constant pressure c_p that is set in `GasModel.SpecificHeatAtConstantPressure` or implied by the constants set in LiquidModel. If on the other hand it is a perfect gas, it is characterized at least by one constant, the ideal gas constant set in `GasModel.IdealGasConstant`, as its dynamic viscosity can be either a constant or governed by Sutherland's viscosity law (see ViscosityModel).

For any of the above discussed fluids, k , μ and c_p are related by the Prandtl number

$$P_r = \frac{c_p \mu}{k}$$

Hence, the heat conductivity coefficient k can be specified either directly, or via a constant Prandtl number (including for dimensional simulations). If k is constant, it can be specified directly using `ThermalConductivity.HeatConductivity`. If it is specified via a constant Prandtl number in `ThermalConductivity.Prandtl`, it is computed as

$$k = \frac{c_p \mu}{P_r}$$

where the specific heat ratio at constant pressure c_p is that specified in `GasModel.SpecificHeatAtConstantPressure` or implied by the parameters set in LiquidModel, and μ is specified in ViscosityModel.

Hence, note that if μ is constant, specifying a constant Prandtl number is equivalent to specifying a constant conductivity coefficient.

The syntax of this object is:

```
under ThermalConductivityModel{
  Type                              = type-id;
  HeatConductivity                  = heatcond-real;
  Prandtl                           = prandtl-real;
}
```

with

type-id [`ConstantPrandtl`]:

Specifies whether the heat conductivity coefficient k is inputted directly or via the Prandtl number (and the specific heat at constant pressure and dynamic viscosity specified elsewhere, as indicated above).

`ConstantConductivity`
: In this case, the constant heat conductivity coefficient k is inputted directly in *heatcond-real* (see below).

`ConstantPrandtl`
: In this case, the constant heat conductivity coefficient k is inputted via the Prandtl number which is assumed to be constant (see below).

heatcond-real [`0.0`]:

Heat conductivity coefficient (assumed to be constant).

prandtl-real [`0.72`]:

Prandtl number (assumed to be constant).

Previous: ThermalConductivityModel, Up: Equations

4.9.4 SPECIFYING THE TURBULENCE CLOSURE

Object:	**TurbulenceClosure**

For viscous flow simulations, the type of turbulence closure is defined within the `TurbulenceClosure` object. Its syntax is:

```
under TurbulenceClosure {
  Type = type-id;
  PrandtlTurbulent = coefficient-real;
  under TurbulenceModel { ... }
  under LESModel { ... }
  under Tripping{ ... }
}
```

with

type-id [`None`]:

`None`
The compressible Navier-Stokes equations are solved without any additional model.

`TurbulenceModel`
The averaged compressible Navier-Stokes equations are solved with an eddy viscosity turbulence model (see TurbulenceModel).

`LESModel`
The compressible Navier-Stokes equations are solved with a large eddy simulation model (see LESModel).

coefficient-real [0.9]:

Subgrid-scale Prandtl number which is assumed to be constant.

`TurbulenceModel`:

Speficies the eddy viscosity model to be used in the computation.

`LESModel`:

Specifies the LES model to be used in the computation.

`Tripping`:

Specifies the box within the computational domain in which the turbulence model is to be used.

- TurbulenceModel
- LESModel
- Tripping

Next: LESModel, Up: TurbulenceClosure

4.9.4.1 SPECIFYING THE EDDY VISCOSITY MODEL

Object:	**TurbulenceModel**

For turbulent flow simulations based on the averaged Navier-Stokes equations augmented by an eddy viscosity model, the type of the turbulence model is defined within the `TurbulenceModel` object. Its syntax is:

```
under TurbulenceModel {
  Type = type-id;
  under SpalartAllmaras { ... }
  under DES { ... }
}
```

with

type-id [`SpalartAllmaras`]:

`SpalartAllmaras`
: One-equation Spalart-Allmaras turbulence model.

`DES`
: Detached eddy simulation method based on the Spalart-Allmaras model. See Appendix C for a description of the mesh requirements (see DESMESH).

`KEpsilon`
: Two-equation $k-\epsilon$ turbulence model.

`SpalartAllmaras`:

Specifies either the original form of the Spalart-Allmaras turbulence model, or its modified form known as the fv3 model.

- SpalartAllmaras
- DES

Next: DES, Up: TurbulenceModel

4.9.4.1.1 SPECIFYING THE FORM OF THE SPALART-ALLMARAS TURBULENCE MODEL

Object:	**SpalartAllmaras**

This object allows the user to specify one of two forms of the Spalart-Allmaras turbulence model. Its syntax is:

```
under SpalartAllmaras{
  Form  = form-id;
}
```

with

form-id [`Original`]:

`Fv3`

Specifies the modified form of the Spalart-Allmaras turbulence model known as the fv3 form. This form was devised to prevent negative values of the source term that were experienced early on with the original form of this turbulence model. It is not recommended for low Reynolds number problems, say below $100,000$, because of its unusual transition behavior in this flow regime.

`Original`
Specifies the original form of the Spalart-Allmaras turbulence model.

Previous: SpalartAllmaras, Up: TurbulenceModel

4.9.4.1.2 SPECIFYING THE FORM OF THE DES METHOD

Object:	**DES**

This object allows the user to specify one of two forms of the DES method. Its syntax is:

```
under DES{
  Form  = form-id;
}
```

with

form-id [`Original`]:

`Fv3`
Specifies the DES method based on the modified form of the Spalart-Allmaras turbulence model known as the fv3 form. This form was devised to prevent negative values of the source term that were experienced early on with the original form of this turbulence model. It is not recommended for low Reynolds number problems, say below $100,000$, because of its unusual transition behavior in this flow regime.

`Original`
Specifies the DES method based on the original form of the Spalart-Allmaras turbulence model.

Next: Tripping, Previous: TurbulenceModel, Up: TurbulenceClosure

4.9.4.2 SPECIFYING THE LES MODEL

Object:	**LESModel**

For turbulent flow simulations based on the Navier-Stokes equations augmented by a large eddy simulation model, the type of the LES model is defined within the `LESModel` object. Its syntax is:

```
under LESModel {
  Type = type-id;
  Delta = delta-id;
  under Smagorinsky { ... }
  under Dynamic { ... }
  under VMS { ... }
  under DynamicVMS { ... }
  under WALE { ... }
}
```

with

type-id [`VMS`]:

`Smagorinsky`
: The classical filtering and Smagorinsky Eddy Viscosity model are used to separate the coarse and fine-scales and model the effect of the latter.

`Dynamic`
: The classical filtering and variable-constant (obtained using the Germano Identity) Smagorinksy Eddy Viscosity model is used to separate the coarse and fine scales, and model the effect of the latter on the coarse scales.

`VMS`
: The variational multiscale approach is used to separate the large and small resolved scales and to model the effect of the unresolved scales in the small resolved scales equation using a Smagorinksy Eddy Viscosity model.

`DynamicVMS`
: The VMS method is equipped with a variational analogue of the Germano identity to compute a variable constant in the Smagorinksy Eddy Viscosity model.

`WALE`
: The Wall-Adapting Local Eddy Viscosity (WALE) model is used for the eddy-viscosity.

delta-id [`Volume`]:

`Volume`
: In this case, for a given tetrahedron $\mathrm{T}_l,$ the filter width Δ used to compute the eddy viscosity is set to

$$\Delta = Vol(\mathrm{T}_l)^{1/3}$$

`Side`
: In this case, for a given tetrahedron T_l , the filter width Δ

used to compute the eddy viscosity is set to the size of the largest side of this tetrahedron.

`Smagorinsky`:

Specifies the classical filtering and Smagorinsky Eddy Viscosity model for separating the coarse and fine-scales and modeling the effect of the latter.

`Dynamic`:

Specifies the classical filtering and variable-constant (obtained using the Germano Identity) Smagorinsky Eddy Viscosity model for separating the coarse and fine-scales and modeling the effect of the latter on the coarse scales.

`VMS`:

Specifies the variational multiscale approach for separating the large and small resolved scales and modeling the effect of the unresolved scales in the small resolved scales equation using a Smagorinksy Eddy Viscosity model.

`DynamicVMS`:

Specifies the VMS method equipped with a variational analogue of the Germano identity to compute a variable constant in the Smagorinksy Eddy Viscosity model.

`WALE`:

Specifies the Wall-Adapting Local Eddy Viscosity (WALE) model for representing the eddy-viscosity.

- Smagorinsky
- Dynamic
- VMS
- DynamicVMS
- WALE

Next: WALE, Up: LESModel

4.9.4.2.1 SPECIFYING THE PARAMETERS OF THE SMAGORINSKY EDDY VISCOSITY MODEL

Object:	**Smagorinsky**

The `Smagorinsky` object specifies the parameters of the Smagorinsky LES model. Its syntax is:

```
under Smagorinsky{
  Cs = coefficient-real;
}
```

with

coefficient-real [0.1]:

Usual Smagorinsky coefficient C_s used in computing the eddy viscosity

$$\nu_T = (C_s\Delta)^2\sqrt{2S_{ij}S_{ij}}$$

Next: Dynamic, Previous: Smagorinsky, Up: LESModel

4.9.4.2.2 SPECIFYING THE PARAMETERS OF THE WALL-ADAPTED LOCAL EDDY VISCOSITY MODEL

Object:	**WALE**

The `WALE` object specifies the parameters of the WALE LES model. Its syntax is:

```
under WALE{
  Cw = coefficient-real;
}
```

with *coefficient-real* [0.325]:

WALE coefficient C_w used in computing the eddy viscosity

$$\nu_t = \frac{\overline{\rho}(C_w\Delta)^2(S^d_{ij}S^d_{ij})^{3/2}}{(S_{ij}S_{ij})^{5/2} + (S^d_{ij}S^d_{ij})^{5/4}}$$

where S^d_{ij} is the symmetric part of the square of the velocity gradient tensor and S_{ij} is the deformation tensor of the resolved field.

Next: VMS, Previous: WALE, Up: LESModel

4.9.4.2.3 SPECIFYING THE PARAMETERS OF THE DYNAMIC LES MODEL

Object:	**Dynamic**

The `Dynamic` object specifies the parameters of Germano's dynamic LES model. Its syntax is:

```
under Dynamic{
  under Clipping { ... }
}
```

with

`Clipping`
: The upper bound for the C_s coefficient and upper and lower bounds for the turbulent Prandtl number Pt can be specified in this object.

- ClippingDynamic

Up: Dynamic

4.9.4.2.3.1 SPECIFYING BOUNDS FOR THE DYNAMIC LES MODEL

Object:	**Clipping**

The `Clipping` object specifies the upper bound for the C_s coefficient and the upper and lower bounds for the turbulent Prandtl number Pt in Germano's dynamic LES model.

Its syntax is:

```
under Clipping{
  CsMax = coefficient-real1;
  PtMin = coefficient-real2;
  PtMax = coefficient-real3;
}
```

with *coefficient-real1* [0.4]:

This value mulitplied by the filter width `Delta` is used as a clipping upper bound for the dynamically evaluated $C_s\Delta$ products.

coefficient-real2 [0.5]:

This serves as a clipping lower bound for the dynamically evaluated Prandtl numbers Pt .

coefficient-real3 [1.6]:

> This serves as a clipping upper bound for the dynamically evaluated Prandtl numbers Pt .

Next: DynamicVMS, Previous: Dynamic, Up: LESModel

4.9.4.2.4 SPECIFYING THE PARAMETERS OF THE VMS TURBULENCE MODEL

Object:	**VMS**

The `VMS` object specifies the parameters of the variational multiscale LES model. Its syntax is:

```
under VMS{
  Csprime = coefficient-real;
  AgglomerationLayer= layer-integer;
  AgglomerationDepth = depth-integer;
}
```

with

coefficient-real [0.1]:

> Fine-scale Smagorinsky coefficient C_s' used in computing the eddy viscosity

$$\nu_T' = (C_s'\Delta)^2\sqrt{2S_{ij}'S_{ij}'}$$

layer-integer [1]:

> Characterizes the size of a macro-cell in an agglomeration. A value of 1 results in each macro-cell containing a cell and (a subset of) its neighbors. A value of 2 results in each macro-cell containing a cell, (a subset of) its neighbors, and (a subset of) the neighbors of these neighbors, etc...

depth-integer [1]:

> This is the number of recursive clustering steps to be performed for generating the agglomeration used for constructing the projector of the VMS-LES method.

Previous: VMS, Up: LESModel

4.9.4.2.5 SPECIFYING THE PARAMETERS OF THE DYNAMIC VMS LES MODEL

Object:	**DynamicVMS**

The `DynamicVMS` object specifies the parameters of the dynamic variational multiscale LES model. Its syntax is:

```
under DynamicVMS{
  Type = type-id;
  Csprime = csprime-real;
  AgglomerationLayer= layer-integer;
  AgglomerationDepth1= depth-integer1;
  AgglomerationDepth2= depth-integer2;
```

```
    under Clipping { ... }
  }
```

with

type-id [D1VMSLES]:

`D1VMSLES`
: A Dynamic VMS-LES method based on the “difference” variational analogue of Germano's identity (and therefore closest to the original version of Germano's identity). Here, the Smagorinsky subgrid-scale parameters are solved for dynamically by employing least-squares on the equations obtained by differencing the conservation equations associated with two different grid sizes.

`D2VMSLES`
: A robust Dyamic VMS-LES method which resorts to the least-squares solution of the “stacked” conservation equations associated with two different grid sizes to compute the Smagorinsky subgrid-scale parameters dynamically.

csprime-real [0.1]:

Fall-back fine-scale Smagorinsky coefficient adopted when the computed dynamic constant falls outside the interval $[0, 0.3]$.

layer-integer [1]:

Characterizes the size of a macro-cell in an agglomeration. A value of 1 results in each macro-cell containing a cell and (a subset of) its neighbors. A value of 2 results in each macro-cell containing a cell, (a subset of) its neighbors, and (a subset of) the neighbors of these neighbors, etc...

depth-integer1 [1]:

This is the number of recursive clustering steps to be performed for constructing the first-level agglomeration — that is, the agglomeration used for constructing the basic projector of the dynamic VMS-LES method.

depth-integer2 [*depth-integer1* + 1]:

This is the number of recursive clustering steps to be performed for constructing the second-level agglomeration — that is, the agglomeration used for constructing the projector used in the variational analogue of the Germano identity in the dynamic VMS-LES method.

`Clipping`
: The upper bound for the C'_s coefficient and upper and lower bounds for the turbulent Prandtl number Pt' can be specified in this object.

- ClippingDynamicVMS

Up: DynamicVMS

4.9.4.2.5.1 SPECIFYING BOUNDS FOR THE DYNAMIC VMS TURBULENCE MODEL

Object:	**Clipping**

The `Clipping` object specifies the upper bound for the C_s' coefficient and the upper and lower bounds for the turbulent Prandtl number Pt' in the dynamic VMS turbulence model.

Its syntax is:

```
under Clipping{
  CsMax = coefficient-real1;
  PtMin = coefficient-real2;
  PtMax = coefficient-real3;
}
```

with *coefficient-real1* [0.4]:

> This value mulitplied by the filter width `Delta` is used as a clipping upper bound for the dynamically evaluated $C_s'\Delta'$ products.

coefficient-real2 [0.5]:

> This serves as a clipping lower bound for the dynamically evaluated Prandtl numbers Pt' .

coefficient-real3 [1.6]:

> This serves as a clipping upper bound for the dynamically evaluated Prandtl numbers Pt' .

Previous: LESModel, Up: TurbulenceClosure

4.9.4.3 TRIPPING TURBULENCE

Object:	**Tripping**

Turbulence can be tripped by specifying a domain outside which the turbulent eddy viscosity is set to zero to model a laminar flow. The syntax of this command is:

```
under Tripping {
  under Box1 { ... }
}
```

`Box1`:

> Defines a box within the computational domain (see BoxFix).

Next: BoundaryConditions, Previous: Equations, Up: Objects

4.10 DEFINING THE MULTI-PHASE COMPONENT OF A FLOW PROBLEM AND SPECIFYING ITS SOLUTION METHOD

Object:	**MultiPhase**

The `MultiPhase` object is used to define a multi-phase flow problem or problem component and choose a multi-phase flow solver. The material interface is assumed to be well approximated by a free surface where one fluid can only apply a pressure on the other fluid, and to be initially a closed contact surface. The available multi-phase flow solvers are based either on the ghost fluid method, or on the finite volume method with exact, local, two-phase Riemann solvers. The level set technique is used for capturing the material interface.

The syntax of this object is:

```
under MultiPhase{
  LevelSetReinitializationFrequency = lsreinitfreq-int;
  LevelSetMethod = lsmethod-id;
  PhaseChange = phasechange-str;
  Method = method-str;
  RiemannComputation = riemanncomputation-str;
  under SparseGrid{ ... }
  under InitialConditions { ... }
}
```

with

lsreinitfreq-int [0]:

Specifies the reinitialization frequency for the computation of the level set function(s). (By default, the computation of the level set function(s) is not reinitialized. Furthermore, for one-dimensional computations, it is not reinitialized either).

lsmethod-id [`Conservative`]:

`Conservative`

In this case: (a) the level set equation is given by

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho u \phi) = 0$$

where ρ and u denote the density and velocity vector of the fluid at a given point, respectively, and ϕ denotes the level set function at that point; (b) it is solved by the same finite volume method specified for the solution of the flow problem.

`HJWENO`

This option is available only for the one-dimensional computation of a spherically symmetric unsteady two-phase flow problem. In this case: (a) the level set equation is given by the Hamilton-Jacobi equation

$$\frac{d\phi}{dt} + u\frac{d\phi}{dx} = 0$$

where u denotes the velocity of the fluid at a given point and ϕ denotes the level set function at that point;

(b) it is discretized in space by a fifth-order WENO scheme, and discretized in time by the same scheme specified for the time-discretization of the flow problem.

`Scalar`

This option is available only for the one-dimensional computation of a spherically symmetric unsteady two-phase flow problem. In this case: the level set equation is given by

$$\frac{dx_I}{dt} = u(x_I, t)$$

where x_I denotes the position of the material interface and $u(x_I, t)$ denotes the fluid velocity at that

position, at a given time t ; (b) this ordinary differential equation is solved by the fourth-order time-accurate, four-stage, Runge-Kutta scheme. This is the most accurate level set method among all three methods available for one-dimensional computations.

method-str [`GhostFluidForThePoor`]:

`GhostFluidForThePoor`
: In this case, the level set method is used to capture the interface, and the multi-phase flow equations are solved by the “Ghost Fluid method for the Poor”. This option can be used when running gas-gas simulations, where gas is a perfect or stiffened gas. It can also be used for solving liquid-liquid multi-phase problems if all liquids are assumed to be barotropic and are modeled by Tait's equation.

`FiniteVolumeWithExactTwoPhaseRiemann`
: In this case, the level set method is used to capture the interface, and the multi-phase flow equations are solved by the finite volume method with exact, local, two-phase Riemann solvers. This option can be used to solve fluid-fluid problems where either fluid can be modeled as a perfect gas, stiffened gas, barotropic liquid (Tait's equation of state), or by the JWL equation of state. It is particularly useful when simulating fluid-fluid problems characterized by large contact discontinuities across the interfaces.

phasechange-str[`RiemannSolution`]:

This parameter is relevant only when *method-str* is set to `FiniteVolumeWithExactTwoPhaseRiemann`.

`None`
: No special numerical treatment is applied to the state of a node that changes phase from one time-step to the following one.

`RiemannSolution`
: One of the two interface states obtained by the solution of the appropriate Riemann problem is used to replace the state of a node that changes phase from one time-step to the following one.

`Extrapolation`
: An extrapolation procedure is used to populate the state of a node that changes phase from one time-step to the following one.

riemanncomputation-str[`SecondOrder`]:

This parameter is relevant only when the multi-phase flow problem involves an interface between two media where at least one of them is modeled by the JWL equation of state and applies to this interface only.

`FirstOrder`
: The Riemann invariants of the relevant Riemann problem are numerically computed using a first-order ODE integrator.

`SecondOrder`
: The Riemann invariants of the relevant Riemann problem are numerically computed using a second-order ODE integrator.

`TabulationRiemannInvariant`
: When `Problem.Type` is set to anything but `SparseGridGeneration` (see Problem), this option, which is highly recommended in this case because of its computational efficiency, requests the exploitation of a sparse grid tabulation to interpolate the values of the Riemann invariants of the relevant Riemann problem. This tabulation is specified in SparseGrid. On the other hand when `Problem.Type` is set to `SparseGridGeneration` (see Problem), this option specifies that the Riemann invariants are to be tabulated in a sparse grid according to the parameters specified in the SparseGrid.

`TabulationRiemannProblem`
: When `Problem.Type` is set to anything but `SparseGridGeneration` (see Problem), this option requests the exploitation of a sparse grid tabulation to interpolate directly the solutions of the relevant Riemann problems. This tabulation is specified in SparseGrid. On the other hand when `Problem.Type` is set to `SparseGridGeneration` (see Problem), this option specifies that the solutions of the Riemann problems are to be tabulated in a sparse grid according to the parameters specified in the SparseGrid.

`InitialConditions`:

Defines the regions occupied by two fluids by initializing the level set function(s), and sets the initial conditions of each fluid in its region of the computational domain.

Note:

1. currently, **AERO-F** can handle only three different fluid-fluid interfaces which furthermore must be between a same fluid — referred to in this User's Reference Manual as the “primary” fluid — and any one of three other fluids. In this case, the primary fluid must be identified in FluidModel by *fluid-id-int* = 0.

- SparseGrid
- InitialConditionsMultiPhase

Next: SparseGrid, Up: MultiPhase

4.10.1 SPECIFYING THE INITIAL CONDITIONS OF A MULTI-PHASE FLOW COMPUTATION

Object:	**InitialConditions**

The level set function and the state of each fluid of a multi-phase flow computation are initialized using this object. The initialization of each level set function is performed by specifying the geometry of a surface that separates initially two fluids. Within the region it occupies, the state of each fluid is initialized to a uniform flow whose parameters are specified in this object.

The syntax of the `InitialConditions` object is:

```
under InitialConditions {
  under Sphere[sphere-id-int] { ... }
  ...
  under Plane[plane-id-int] { ... }
  ...
  under Box[box-id-int] { ... }
}
```

with

sphere-id-int[—]

ID number of a sphere.

plane-id-int[—]

ID number of a plane.

box-id-int[—]

ID number of a box.

`Sphere`:

Defines a geometric sphere and the initial conditions for the flow within (see Box).

`Plane`:

Defines a geometric plane and the initial conditions for the flow within the region of the computational domain it implies (see Plane).

^ `Box`:

Defines a geometric box and the initial conditions for the flow within the region of the computational domain it implies (see Box).

Notes:

1. the VolumeData object offers the possibility to initialize the states of two fluids separated by rigid or flexible walls. The user is allowed to specify initial conditions using both the `VolumeData` object and the present object.
2. **AERO-F** initializes the solution of a multi-phase flow problem in several overwriting steps as follows: first, the states of all grid points are initialized to the values of the free-stream conditions; next, the states of all grid points belonging to a specific set of volume IDs are initialized as specified in the associated VolumeData object; next, the states of all grid points in each region of the computational domain implied by each plane specified in Plane[*plane-id-int*] are initialized as requested in the corresponding `InitialConditions` object; finally, the states of all grid points located inside each sphere specified in Box[*sphere-id-int*] are initialized as requested in the corresponding `InitialConditions` object.

- Sphere
- Plane
- Box

Next: Box, Up: InitialConditionsMultiPhase

4.10.1.1 DEFINING A GENERIC SPHERE FOR A MULTI-PHASE FLOW COMPUTATION

Object:	**Sphere**

The `Sphere` object (with an integer number appended to the last letter of this word) specifies the location and size of a spherical region, as well as the initial condition parameters for the flow inside this region. The syntax of this object is:

```
under Sphere[sphere-id-int] {
  FluidID = fluid-id-int;
  Center_x = center_x-real;
  Center_y = center_y-real;
  Center_z = center_z-real;
  Radius = radius-real;
  under InitialState{ ... }
  under ProgrammedBurn{ ... }
}
```

with *sphere-id-int*[—]

Integer identification number of the sphere defined in this object.

fluid-id-int [—]:

ID of the fluid medium for which the initial conditions specified in this sphere apply to.

center_x-real [0.0]:

Coordinate of the center of the sphere along the x axis.

center_y-real [0.0]:

Coordinate of the center of the sphere along the y axis.

center_z-real [0.0]:

Coordinate of the center of the sphere along the z axis.

radius-real [—]:

Radius of the sphere.

`InitialState`:

Specifies the initial state of the fluid occupying the sphere defined above.

`ProgrammedBurn`:

Specifies the parameters of a programmed burn of a highly explosive, burnable material located within the sphere defined above.

- InitialState
- ProgrammedBurn

Up: Sphere

4.10.1.1.1 SPECIFYING THE PARAMETERS OF A PROGRAMMED BURN

Object:	**ProgrammedBurn**

The `ProgrammedBurn` object specifies the parameters of a programmed burn of a highly explosive, burnable material (see LiquidModel) located within a region specified by a geometrical object (see Box, Sphere) of **AERO-F**. Its syntax is:

```
under ProgrammedBurn {
IgnitionX0 = ignition-x0-real;
IgnitionY0 = ignition-y0-real;
IgnitionZ0 = ignition-z0-real;
E0 = detonation-energy-real;
ChapmanJouguetDensity = cj-density-real;
ChapmanJouguetPressure = cj-pressure-real;
ChapmanJouguetDetonationVelocity = cj-detonation-speed-real;
BurnedEOS = burned-fluidID-int;
UnburnedEOS = unburned-fluidID-int;
IgnitionTime = ignition-time-real;
Ignite = ignite-flag;
}
```

with

ignition-x0-real [0.0]:

x-coordinate of the ignition point.

ignition-y0-real [0.0]:

> y-coordinate of the ignition point.

ignition-z0-real [0.0]:

> z-coordinate of the ignition point.

detonation-energy-real [—]:

> Initial internal energy of the explosive material (prior to detonation).

cj-density-real [-1.0]:

> Chapman-Jouguet density of the explosive material behind the detonation wave (just after detonation). If not provided (by default), **AERO-F** automatically computes the value of *cj-density-real*.

cj-pressure-real [-1.0]:

> Chapman-Jouguet pressure of the explosive material behind the detonation wave (just after detonation). If not provided (by default), **AERO-F** automatically computes the value of *cj-pressure-real*.

cj-detonation-speed-real [-1.0]:

> Chapman-Jouguet speed of the detonation wave. If not provided (by default), **AERO-F** automatically computes the value of *cj-denotation-speed-real*.

burned-fluidID-int [—]:

> Integer ID of the fluid medium representing the burned explosive products.

unburned-fluidID-int [—]:

> Integer ID of the fluid medium representing the unburned explosive.

ignition-time-real [0.0]:

> Time at which the explosive material is ignited.

ignite-flag [True]:

`True`
> In this case, the explosive material is ignited.

`False`
> In this case, the explosive material is not ignited during the simulation. A typical usage of this option would be during the restarting of a three-dimensional simulation that involved a programmed burn.

Next: Plane, Previous: Sphere, Up: InitialConditionsMultiPhase

4.10.1.2 DEFINING A GENERIC BOX FOR A MULTI-PHASE FLOW COMPUTATION

Object:	**Box**

The `Box` object (with an integer number appended to the last letter of this word) specifies the location and size of a boxy region, as well as the initial condition parameters for the flow inside this region. The syntax of this object is:

```
under Box[box-id-int] {
  FluidID = fluid-id-int;
  X0 = x0-real;
  Y0 = y0-real;
  Z0 = z0-real;
  X1 = x1-real;
  Y1 = y1-real;
  Z1 = z1-real;
  under InitialState{ ... }
  under ProgrammedBurn{ ... }
}
```

with *box-id-int*[—]

Integer identification number of the box defined in this object.

fluid-id-int [—]:

ID of the fluid medium for which the initial conditions specified in this box apply to.

x0-real [`0.0`]:

x-coordinate of the lower left corner of the box.

y0-real [`0.0`]:

y-coordinate of the lower left corner of the box.

z0-real [`0.0`]:

z-coordinate of the lower left corner of the box.

x1-real [`0.0`]:

x-coordinate of the upper right corner of the box with *x1-real* > *x0-real*.

y1-real [`0.0`]:

y-coordinate of the upper right corner of the box with *y1-real* > *y0-real*.

z1-real [`0.0`]:

z-coordinate of the upper right corner of the box with *z1-real* > *z0-real*.

`InitialState`:

Specifies the initial state of the fluid occupying the box defined above.

`ProgrammedBurn`:

Specifies the parameters of a programmed burn of a highly explosive material located within the box defined above.

- InitialState

- ProgrammedBurn

Previous: Box, Up: InitialConditionsMultiPhase

4.10.1.3 DEFINING A GENERIC PLANE FOR A MULTI-PHASE FLOW COMPUTATION

Object:	**Plane**

The `Plane` object defines a plane by a point and a normal vector, and specifies the initial conditions in the region of the computational domain toward which the normal vector points to. The syntax of this object is:

```
under Plane[plane-id-int] {
  FluidID = fluid-id-int;
  Point_x = point_x-real;
  Point_y = point_y-real;
  Point_z = point_z-real;
  Normal_x = normal_x-real;
  Normal_y = normal_y-real;
  Normal_z = normal_z-real;
  under InitialState{ ... }
}
```

with

plane-id-int[—]

Integer identification number of the plane defined in this object.

fluid-id-int [—]:

ID of the fluid medium for which the initial conditions specified here apply to.

point_x-real [0.0]:

Coordinate of the point in the plane along the x axis.

point_y-real [0.0]:

Coordinate of the point in the plane along the y axis.

point_z-real [0.0]:

Coordinate of the point in the plane along the z axis.

normal_x-real [0.0]:

Component of the normal to the plane along the x axis.

normal_y-real [0.0]:

Component of the normal to the plane along the y axis.

normal_z-real [0.0]:

Component of the normal to the plane along the z axis.

`InitialState`:

Specifies the initial state of the fluid occupying the region of the computational fluid domain identified above.

- InitialState

4.10.2 TABULATING DATA IN SPARSE GRID FORMAT FOR SPEEDING UP MULTI-PHASE COMPUTATIONS

Object:	**SparseGrid**

To accelerate the solution of flow problems involving a medium modeled by a complex and computationally intensive equation of state (EOS), the object `SparseGrid` offers the possibility of tabulating some data in sparse grid format (see TAB), or exploiting it when readily available. This data can be either the Riemann invariants along a characteristic curve, or the solutions of two-phase Riemann problems. When using this object to tabulate the solutions of two-phase Riemann problems, one fluid is assumed to be modeled by the JWL EOS and must be specified in FluidModel[0], and the other is assumed to be a perfect or stiffened gas and must be specified in FluidModel[1].

The syntax of this object is:

```
under SparseGrid {
  FileName = filename-str;
  NumberOfFiles = numfiles-int;
  Verbose = verbose-int;
  NumberOfInputs = numinputs-int;
  NumberOfOutputs = numoutputs-int;
  Input1Minimum = in1min-real;
  Input1Maximum = in1max-real;
  NumberOfDomains1 = numdomains1-int;
  ...
  Input6Minimum = in6min-real;
  Input6Maximum = in6max-real;
  NumberOfDomains6 = numdomains6-int;
  MinimumNumberOfPoints = minnumpts-int;
  MaximumNumberOfPoints = maxnumpts-int;
  DegreeDimAdapt = degdimadapt-real;
  RelativeAccuracy = relacc-real;
  AbsoluteAccuracy = absacc-real;
}
```

with

filename-str [""]:

Specifies the path and name of the file containing the tabulated data. If this data was stored across multiple files, *filename-str* is the common prefix to all names of these files.

numfiles-int [0]:

Specifies the number of files to be loaded to access the entire tabulated data.

verbose-int [0]:

This integer ranges from 0 (no output) to 9 (maximum output) and specifies the level of data reporting (on the screen) when tabulating data in sparse grid format or exploiting it.

numinputs-int [2]:

Number of input variables of the vector function to be tabulated. For example, *numinputs-int* = 2 when the Riemann invariants are tabulated, and *numinputs-int* = 6 when the Riemann solutions are tabulated (see TAB).

numoutputs-int [2]:

Number of outputs (components of the vector function) to be tabulated (seeTAB).

numdomains1-int [1]:

Specifies the uniform splitting of the domain of the first input variable into *numdomains1-int* subdomains. If this number is greater than 1, it automatically multiplies the number of expected sparse grids by *numdomains1-int*.

in1min-real [0.0]:

Specifies the lower bound of the first input variable.

in1max-real [1.0]:

Specifies the upper bound of the first input variable.

minmumpts-int [100]:

Minimum number of data points to be generated in each (see Note below) sparse grid.

maxnumpts-int [100]:

Maximum number of data points to be generated in each (see first Note below) sparse grid (however, this maximum can be slightly exceeded by **AERO-F**).

degdimadapt-real [0.75]:

This parameter, which should be given a value between 0.0 and 1.0, specifies the desired degree of dimensional adaptivity of all generated sparse grids (TAB).

relacc-real [1.0e-3]:

Specifies the desired level of relative accuracy to be delivered by the sparse grid tabulation.

absacc-real [1.0e-1]:

Specifies the desired level of absolute accuracy to be delivered by the sparse grid tabulation.

Note:

1. to accelerate the sparse grid tabulation of functions, the user can split the domain of each i -th input variable into an arbitrary number of subdomains parameterized above by n_i = *numdomains* i *-int*. In this

case, the function is tabulated in a number of sparse grids equal to $\prod_{i=1}^{N} n_i$, where $N =$ *numinputs-int*.

Next: Preconditioner, Previous: MultiPhase, Up: Objects

4.11 DEFINING THE BOUNDARY CONDITIONS

Object:	**BoundaryConditions**

The different boundary conditions are specified within the `BoundaryConditions` object. Its syntax is:

```
under BoundaryConditions {
  under Inlet { ... }
  under Outlet { ... }
  under Wall { ... }
  under Hydro { ... }
}
```

with

`Inlet`:

Defines the inflow boundary conditions.

`Outlet`:

Defines the outflow boundary conditions. This object can be omitted if the inflow and outflow states are the same.

`Wall`:

Defines the wall boundary conditions.

`Hydro`:

Specifies a list of additional parameters for a hydro-computation. These are used to define the far-field boundary conditions and to compute the hydrostatic and hydrodynamic pressure and force fields. Its syntax is defined by the *Hydro* object (see Hydro). This object can be omitted if irrelevant.

Notes:

1. if `Problem.Mode` is set to `Dimensional`, the inflow pressure and density must be specified for an aerodynamic computation and the inflow pressure and temperature for a hydro-computation;
2. if an outflow condition is not specified but needed for the flow computation, it is set to the inflow condition;
3. the boundary conditions are specified for the "run-type" variables. Hence, if `Problem.Mode` is set to `Dimensional`, the specified boundary conditions are applied "as-is" to the dimensional variables. On the other hand, if `Problem.Mode` is set to `NonDimensional`, the specified boundary conditions are applied "as-is" to the non-dimensional variables.

- Inlet
- Outlet
- Wall
- Hydro

4.11.1 DEFINING THE FAR-FIELD INLET CONDITIONS

Object:	**Inlet**

The `Inlet` object defines the far-field inlet state. Its syntax is:

```
under Inlet {
  Type = type-id;
  Mach = mach-real;
  Velocity = velocity-real;
  Alpha = alpha-real;
  Beta = beta-real;
  Density = density-real;
  Pressure = pressure-real;
  Temperature = temperature-real;
  NuTilde = nutilde-real;
  K = k-real;
  Eps = eps-real;
}
```

with

type-id [`External`]:

`External`
: External flow computation with free-stream conditions in all far-fields.

`Internal`
: Designates a special class of problems in which the pressure is specified at the outlet boundary, the density and velocity vector in the case of a perfect gas and the temperature and velocity vector in the case of a barotropic liquid are specified at the inlet boundary, and both boundaries are subsonic. This class of problems arises in some internal flow applications, which explains the choice of the word “Internal”. AERO-F being essentially an external flow solver, it does not offer in this case an explicit and straightforward mechanism for specifying the velocity field at the subsonic inlet boundary. However, for a perfect gas, this can be accomplished in the dimensional case by setting the Mach number and the inlet pressure, and in the non-dimensional case by setting the Mach number only, as described below. For a barotropic liquid, it can be accomplished in both dimensional and non-dimensional cases by setting the Mach number only.

$$PERFECT\ GAS\ ---\ DIMENSIONAL\ CASE$$

First, it is noted that because the outlet boundary is subsonic, the true pressure at the inlet is not specified but propagated numerically from the outlet boundary to the inlet boundary during the solution procedure. Hence, the inlet pressure that can be specified in the input file should be considered only as a “knob”. In this case, it turns out that the free-stream Mach number is also a knob. Now, given the velocity vector to be specified at the inlet boundary, one can compute its modulus.

This modulus, v , is related to the pressure and Mach number via

$$v = M\sqrt{\frac{\gamma p}{\rho}}$$

where M , γ , p , and ρ designate the Mach number, ratio of specific heats, pressure, and density, respectively.

Hence, (after specifying the legitimate density at the inlet boundary) one begins by choosing the Mach number and the pressure at the subsonic inlet boundary so that v is equal to the modulus of the desired velocity vector.

Then, the angles of attack *alpha-real* and *beta-real* are set to obtain the desired components of this velocity vector.

Clearly, there are many (M,p) combinations that lead to the same v . Since in this case both M and p are only knobs, all combinations are in principle valid. However, those combinations with a Mach number knob that is far away from a reasonable value associated with v can lead to numerical difficulties.

$$PERFECT\ GAS\ ---\ NON-DIMENSIONAL\ CASE$$

In this case, AERO-F considers the inlet density to be the reference density (which is to be considered as the inlet density to be specified), the modulus of the inlet velocity vector

$$v_{inlet}$$

to be the modulus of the reference velocity vector (which is to be considered as the modulus of the inlet velocity vector to be prescribed), the outlet pressure to be the reference pressure (which is to be considered the outlet pressure to be prescribed), and the artificial inlet pressure knob to be the reference pressure too (warning: in this context, the reference pressure is not to be confused with the non-dimensionalization pressure). It follows that AERO-F automatically sets

$$\bar{\rho}_{inlet} = 1; \quad \bar{v}_{inlet} = 1$$

$$\bar{p}_{inlet} = \bar{p}_{outlet} = \frac{p_{reference}}{\rho_{reference} v^2_{reference}} = \frac{1}{\gamma M^2_{reference}}$$

From a discussion similar to that of the dimensional case described above, it follows that in the non-dimensional case, the user needs to input only the reference Mach number and the angles of attack *alpha-real* and *beta-real*. Furthermore, from the above explanation, it also follows that the reference Mach number should be set to

$$M_{reference} = v_{inlet}\sqrt{\frac{\rho_{inlet}}{\gamma p_{outlet}}}$$

Then, by default, the free-stream Mach number is set to the reference Mach number (see below).

$$BAROTROPIC\ LIQUID\ ---\ DIMENSIONAL\ CASE$$

For a barotropic fluid, the pressure and density are not independent variables. Hence, in this case, the primitive variables are the density (or pressure), velocity field, and temperature. The modulus of the inlet velocity vector is given by

$$v = M\sqrt{\frac{1}{\rho_0}((k_1 + k_2p_0)(k_1 + k_2p)^{k_2-1})^{\frac{1}{k_2}}}$$

where

$$p_0, \rho_0, k_1, k_2$$

are the “reference” pressure, “reference” density, and the two constants used for defining the barotropic equation of state of the fluid. Because the outlet boundary is subsonic, the pressure — and therefore the density — at the inlet is not specified but propagated numerically from the outlet boundary to the inlet boundary during the solution procedure. The free-stream Mach number is a knob. Given the velocity vector to be specified at the inlet boundary, one can compute its modulus.

From the above formula, it follows that, after specifying the pressure at the outlet boundary, one chooses the Mach number so that v is equal to the modulus of the desired velocity vector. Then, one sets the angles of attack *alpha-real* and *beta-real* to obtain the desired components of this velocity vector. One also specifies the temperature at the inlet boundary.

$$BAROTROPIC\ LIQUID\ ---\ NON-DIMENSIONAL\ CASE$$

In this case, AERO-F considers the outlet density to be the reference density, and the modulus of the inlet velocity vector to be the modulus of the reference velocity vector. At the inlet, it computes the reference temperature using the formula given in `Problem`. Thus AERO-F automatically sets

$$\bar{\rho}_{outlet} = 1; \quad \bar{v}_{inlet} = 1$$

while the non-dimensionalized temperature is set by the user. Also, AERO-F automatically sets the artificial inlet density to

$$\bar{\rho}_{inlet} = 1$$

In addition, the user must specify the reference Mach number so that

$$M_{reference} = \frac{v_{inlet}}{\sqrt{\alpha k_2 \rho_{outlet}^{k_2-1}}}$$

where $\alpha = \frac{1}{\rho_0^{k_2}}(p_0 + k_1/k_2)$

In both dimensional and non-dimensional cases, for this class of flow problems, AERO-F enforces the true inlet and outlet boundary conditions in a weak sense unless it is compiled with the flag STRONG_INLET_BC set ON.

mach-real [—]:

Free-stream Mach number. To be specified only if a free-stream velocity (see below) is not specified. If omitted and a free-stream velocity is not specified instead, this Mach number is automatically set to the reference Mach number. If both a free-stream Mach number and a free-stream velocity are specified,

AERO-F chooses to run with the specified free-stream Mach number.

velocity-real [—]:

Free-stream velocity (magnitude). To be specified — whether a dimensional or non-dimensional simulation is desired — only if a free-stream Mach number (see above) is not specified. If both a free-stream Mach number and a free-stream velocity are specified, **AERO-F** chooses to run with the specified free-stream Mach number.

alpha-real [—]:

Angle of attack (in degrees) defined in the x-z plane as follows: rotate the free-stream velocity vector around the z-axis until it intersects the x-z plane. The angle of attack is then the angle between the x-axis and the rotated vector and is measured positively when rotating from x to z. It is equal to zero if the flow is parallel to the x-axis. (Think of a spherical coordinate system).

beta-real [—]:

Yaw angle (in degrees) defined in the x-y plane as follows: project the free-stream velocity vector on the x-y plane. The yaw angle is then the angle between the x-axis and the projected vector, and is measured positively when rotating from x to y. It is equal to zero if the flow is parallel to the x-axis. (Think of a spherical coordinate system).

density-real [—]:

Density. It is required if `Problem.Mode` is set to `Dimensional` and `FluidModel.Fluid` is set to `Gas`. When running a `Dimensional` hydro-simulation (fluid modeled as a barotropic liquid or stiffened ga or stiffened gass), the far-field density is not specified as it is set automatically using the equation of state and the far-field pressure (see LiquidModel).

pressure-real [—]:

Pressure. It is required if `Problem.Mode` is set to `Dimensional` and `FluidModel.Fluid` is set to `Gas`. When running a `Dimensional` hydro-simulation (fluid modeled as a barotropic liquid or stiffened gas), if the far-field pressure is not specified, it is set to the “reference” pressure specified in `LiquidModel` (and then the far-field density is automatically set to the “reference” density) (see LiquidModel).

temperature-real [—]:

Temperature. It must be specified when the fluid is modeled as a barotropic liquid (that is, when `FluidModel.Fluid` is set to `Liquid`), and only in this case. If `Problem.Mode` is set to `Dimensional`, this temperature must be specified in Kelvin (in this case, the user should verify that the ideal gas constant R (see GasModel) is specified in the same system of units as all other input data). If `Problem.Mode` is set to `NonDimensional`, this specified temperature is interpreted as the value of the non-dimensionalized free-stream temperature.

nutilde-real [see below]:

Field variable of the one-equation Spalart-Allmaras turbulence model whose implementation in **AERO-F** does not include the trip term which usually starts it up. The default value of this parameter in the non-dimensional case is *nutilde-real* = 0.1. Its default value in the dimensional case is *nutilde-real* = $0.1 \times \nu = 0.1 \times \mu/\rho$, where ν is the laminar kinematic viscosity of the fluid, ρ is its density, and μ

is its dynamic viscosity (see ViscosityModel). These default values provide fully turbulent boundary and shear layers while avoiding numerical difficulties.

k-real [—]:

Turbulent kinetic energy in the two-equation $k-\epsilon$ turbulence model (required if `Problem.Mode` is set to `Dimensional`).

eps-real [—]:

Turbulent kinetic energy dissipation rate in the two-equation $k-\epsilon$ turbulence model (required if `Problem.Mode` is set to `Dimensional`).

Note:

1. some internal flow problems are characterized by sudden time-variations of the boundary conditions. For such problems, the initial state of the flow in a certain region is uniform but not equal to the state defined by the boundary condition (an assumption that is otherwise always made by AERO-F). The problem of opening the valve of a pressurized tank is such an example. It is possible to simulate such flow problems with AERO-F in dimensional mode, using the following two-step procedure. First, the desired initial state (for example, inside the tank) is computed by setting the boundary condition artificially to the desired uniform initial state (desired inside the tank). Next, a second simulation is performed by restarting from the outcome of the first simulation. In the second simulation, the reference Mach number, reference density, and reference temperature must be set to the desired initial state because the data saved by AERO-F for re-use in a restart is always saved in non-dimensional form. If these reference values are not specified as described, AERO-F will dimensionalize the saved data by the value of the boundary condition specified in the second simulation to model the sudden variation.

Next: Wall, Previous: Inlet, Up: BoundaryConditions

4.11.2 DEFINING THE FAR-FIELD OUTLET CONDITIONS

Object:	**Outlet**

The `Outlet` object defines the far-field outlet state. Its syntax is:

```
under Outlet {
  Type = type-id;
  Mach = mach-real;
  Velocity = velocity-real;
  Alpha = alpha-real;
  Beta = beta-real;
  Density = density-real;
  Pressure = pressure-real;
  Temperature = temperature-real;
  NuTilde = nutilde-real;
  K = k-real;
  Eps = eps-real;
}
```

with

type-id [`External`]:

`External`
: External flow computation with free-stream conditions in all far-fields.

`Internal`
: Designates a special class of problems in which the pressure is specified at the outlet boundary, the density and velocity vector in the case of a perfect gas and the temperature and velocity vector in the case of a barotropic liquid are specified at the inlet boundary, and both boundaries are subsonic. This class of problems arises in some internal flow applications, which explains the choice of the word “Internal”. AERO-F being essentially an external flow solver, it does not offer in this case an explicit and straightforward mechanism for specifying the velocity field at the subsonic inlet boundary. However, for a perfect gas, this can be accomplished in the dimensional case by setting the Mach number and the inlet pressure, and in the non-dimensional case by setting the Mach number only, as described below. For a barotropic liquid, it can be accomplished in both dimensional and non-dimensional cases by setting the Mach number only.

$$PERFECT\ GAS\ ---\ DIMENSIONAL\ CASE$$

First, it is noted that because the outlet boundary is subsonic, the true pressure at the inlet is not specified but propagated numerically from the outlet boundary to the inlet boundary during the solution procedure. Hence, the inlet pressure that can be specified in the input file should be considered only as a “knob”. In this case, it turns out that the free-stream Mach number is also a knob. Now, given the velocity vector to be specified at the inlet boundary, one can compute its modulus.

This modulus, v , is related to the pressure and Mach number via

$$v = M\sqrt{\frac{\gamma p}{\rho}}$$

where M , γ , p , and ρ designate the Mach number, ratio of specific heats, pressure, and density, respectively.

Hence, (after specifying the legitimate density at the inlet boundary) one begins by choosing the Mach number and the pressure at the subsonic inlet boundary so that v is equal to the modulus of the desired velocity vector.

Then, the angles of attack *alpha-real* and *beta-real* are set to obtain the desired components of this velocity vector.

Clearly, there are many (M, p) combinations that lead to the same v . Since in this case both M and p are only knobs, all combinations are in principle valid. However, those combinations with a Mach number knob that is far away from a reasonable value associated with v can lead to numerical difficulties.

$$PERFECT\ GAS\ ---\ NON-DIMENSIONAL\ CASE$$

In this case, AERO-F considers the inlet density to be the reference density (which is to be considered as the inlet density to be specified), the modulus of the inlet velocity vector

$$v_{inlet}$$

to be the modulus of the reference velocity vector (which is to be considered as the modulus of the inlet velocity vector to be prescribed), the outlet pressure to be the reference pressure (which is to be considered the outlet pressure to be prescribed), and the artificial inlet pressure knob to be the reference pressure too (warning: in this context, the reference pressure is not to be confused with the non-dimensionalization pressure). It follows that AERO-F automatically sets

$$\bar{\rho}_{inlet} = 1; \quad \bar{v}_{inlet} = 1$$

$$\bar{p}_{inlet} = \bar{p}_{outlet} = \frac{p_{reference}}{\rho_{reference} v^2_{reference}} = \frac{1}{\gamma M^2_{reference}}$$

From a discussion similar to that of the dimensional case described above, it follows that in the non-dimensional case, the user needs to input only the reference Mach number and the angles of attack *alpha-real* and *beta-real*. Furthermore, from the above explanation, it also follows that the reference Mach number should be set to

$$M_{reference} = v_{inlet}\sqrt{\frac{\rho_{inlet}}{\gamma p_{outlet}}}$$

Then, by default, the free-stream Mach number is set to the reference Mach number (see below).

$$BAROTROPIC\ LIQUID\ ---\ DIMENSIONAL\ CASE$$

For a barotropic fluid, the pressure and density are not independent variables. Hence, in this case, the primitive variables are the density (or pressure), velocity field, and temperature. The modulus of the inlet velocity vector is given by

$$v = M\sqrt{\frac{1}{\rho_0}((k_1 + k_2 p_0)(k_1 + k_2 p)^{k_2 - 1})^{\frac{1}{k_2}}}$$

where

$$p_0, \rho_0, k_1, k_2$$

are the “reference” pressure, “reference” density, and the two constants used for defining the barotropic equation of state of the fluid. Because the outlet boundary is subsonic, the pressure — and therefore the density — at the inlet is not specified but propagated numerically from the outlet boundary to the inlet boundary during the solution procedure. The free-stream Mach number is a knob. Given the velocity vector to be specified at the inlet boundary, one can compute its modulus.

From the above formula, it follows that, after specifying the pressure at the outlet boundary, one chooses the Mach number so that v is equal to the modulus of the desired velocity vector. Then, one sets the angles of attack *alpha-real* and *beta-real* to obtain the desired components of this velocity vector. One also specifies the temperature at the inlet boundary.

$$BAROTROPIC\ LIQUID\ ---\ NON-DIMENSIONAL\ CASE$$

In this case, AERO-F considers the outlet density to be the reference density, and the modulus of the inlet velocity vector to be the modulus of the reference velocity vector. At the inlet, it computes the reference temperature using the formula given in `Problem`. Thus AERO-F automatically sets

$$\bar{p}_{outlet} = 1; \quad \bar{v}_{inlet} = 1$$

while the non-dimensionalized temperature is set by the user. Also, AERO-F automatically sets the artificial inlet density to

$$\bar{\rho}_{inlet} = 1$$

In addition, the user must specify the reference Mach number so that

$$M_{reference} = \frac{v_{inlet}}{\sqrt{\alpha k_2 \rho_{outlet}^{k_2-1}}}$$

where $\alpha = \frac{1}{\rho_0^{k_2}}(p_0 + k_1/k_2)$

In both dimensional and non-dimensional cases, for this class of flow problems, AERO-F enforces the true inlet and outlet boundary conditions in a weak sense unless it is compiled with the flag STRONG_INLET_BC set ON.

mach-real [—]:

Free-stream Mach number. To be specified only if a free-stream velocity (see below) is not specified. If omitted and a free-stream velocity is not specified instead, this Mach number is set to the reference Mach number. If both a free-stream Mach number and a free-stream velocity are specified, **AERO-F** chooses to run with the specified free-stream Mach number.

velocity-real [—]:

Free-stream velocity (magnitude). To be specified — whether a dimensional or non-dimensional simulation is desired — only if a free-stream Mach number (see above) is not specified. If both a free-stream Mach number and a free-stream velocity are specified, **AERO-F** chooses to run with the specified free-stream Mach number.

alpha-real [—]:

Angle of attack (in degrees) defined in the x-z plane as follows: rotate the free-stream velocity vector around the z-axis until it intersects the x-z plane. The angle of attack is then the angle between the x-axis and the rotated vector and is measured positively when rotating from x to z. It is equal to zero if the flow is parallel to the x-axis. (Think of a spherical coordinate system).

beta-real [—]:

Yaw angle (in degrees) defined in the x-y plane as follows: project the free-stream velocity vector on the x-y plane. The yaw angle is then the angle between the x-axis and the projected vector, and is measured positively when rotating from x to y. It is equal to zero if the flow is parallel to the x-axis. (Think of a spherical coordinate system).

density-real [—]:

Density. It is required if `Problem.Mode` is set to `Dimensional` and `FluidModel.Fluid` is set to `Gas`. When running a `Dimensional` hydro-simulation (fluid modeled as a barotropic liquid or stiffened ga or stiffened gass), the far-field density is not specified as it is set automatically using the equation of state and the far-field pressure (see LiquidModel).

pressure-real [—]:

Pressure. It is required if `Problem.Mode` is set to `Dimensional` and `FluidModel.Fluid` is set to `Gas`. When running a `Dimensional` hydro-simulation (fluid modeled as a barotropic liquid or stiffened gas), if the far-field pressure is not specified, it is set to the “reference” pressure specified in `LiquidModel` (and then the far-field density is automatically set to the “reference” density) (see LiquidModel).

temperature-real [—]:

Temperature. It must be specified when the fluid is modeled as a barotropic liquid (that is, when `FluidModel.Fluid` is set to `Liquid`), and only in this case. If `Problem.Mode` is set to `Dimensional`, this temperature must be specified in Kelvin (in this case, the user should verify that the ideal gas constant R (see GasModel) is specified in the same system of units as all other input data). If `Problem.Mode` is set to `NonDimensional`, this specified temperature is interpreted as the value of the non-dimensionalized free-stream temperature.

nutilde-real [—]:

Field variable of the one-equation Spalart-Allmaras turbulence model whose implementation in **AERO-F** does not include the trip term which usually starts it up. The default value of this parameter in the non-dimensional case is *nutilde-real* = 0.1. Its default value in the dimensional case is *nutilde-real* = $0.1\times \nu = 0.1\times \mu/\rho $, where ν is the laminar kinematic viscosity of the fluid, ρ is its density, and μ is its dynamic viscosity (see ViscosityModel). These default values provide fully turbulent boundary and shear layers while avoiding numerical difficulties.

k-real [—]:

Turbulent kinetic energy in the two-equation $k-\epsilon$ turbulence model (required if `Problem.Mode` is set to `Dimensional`).

eps-real [—]:

Turbulent kinetic energy dissipation rate in the two-equation $k-\epsilon$ turbulence model (required if `Problem.Mode` is set to `Dimensional`).

Note:

1. some internal flow problems are characterized by sudden time-variations of the boundary conditions. For such problems, the initial state of the flow in a certain region is uniform but not equal to the state defined by the boundary condition (an assumption that is otherwise always made by AERO-F). The problem of opening the valve of a pressurized tank is such an example. It is possible to simulate such flow problems with AERO-F in dimensional mode, using the following two-step procedure. First, the desired initial state (for example, inside the tank) is computed by setting the boundary condition artificially to the desired uniform initial state (desired inside the tank). Next, a second simulation is performed by restarting from the outcome of the first simulation. In the second simulation, the reference Mach number, reference density, and reference temperature must be set to the desired initial state because the data saved by AERO-F for

re-use in a restart is always saved in non-dimensional form. If these reference values are not specified as described, AERO-F will dimensionalize the saved data by the value of the boundary condition specified in the second simulation to model the sudden variation.

Next: Hydro, Previous: Outlet, Up: BoundaryConditions

4.11.3 DEFINING THE WALL CONDITIONS

Object:	**Wall**

For viscous simulations, three different types of solid wall are currently supported and defined within the `Wall` object whose syntax is:

```
under Wall {
  Type = type-id;
  Integration = integration-id;
  Temperature = temp-real;
  Delta = delta-real;
}
```

with

type-id [`Adiabatic`]:

`Adiabatic`
: Adiabatic wall.

`Isothermal`
: Isothermal wall with temperature set to `Wall.Temperature`.

integration-id [ ]:

`WallFunction`
: Modeling by the discretized governing equations up to a distance `Wall.Delta` from the wall. The region of the boundary layer that is not resolved by the mesh is modeled by Reichardt's nonlinear wall function (available for all Navier-Stokes simulations with or without turbulence models).

`Full`
: Modeling by the discretized governing equations up to the wall (not available for Navier-Stokes simulations with the $k-\epsilon$ turbulence model). In this case, it is strongly recommended to have the first layer of elements above the wall located at $y^+ \approx 1$.

If *integration-id* is not specified, AERO-F sets *integration-id* to `Full` for Navier-Stokes simulations without turbulence modeling and to `WallFunction` for Navier-Stokes simulations with turbulence modeling (including LES).

temp-real [—]:

Wall temperature (required for an isothermal wall).

delta-real [—]:

Distance of the fictitious computational domain to solid walls (required for a modelisation with the wall function). This global parameter is kept constant during the computation and can be set and verified using

the following guidelines:
* In principle, the suitability of a specific value of *delta-real* can be assessed only a posteriori, by checking the values of the y^+ of the corresponding solution as explained below. Hence, one begins with a trial value of *delta-real* then adjusts it after one or more additional runs.
* A good first trial value of *delta-real* can be obtained as follows. Typically, the non-dimensional value of the friction velocity is of the order of 1/20, and the non-dimensional value of the dynamic viscosity coefficient is of the order of 1. Using these typical values, the formula relating the y^+ to y, the non-dimensional friction velocity and the non-dimensional dynamic viscosity becomes

$$y^+ = Re\frac{\bar{y}}{20}$$

where Re denotes the Reynolds number and $\bar{y}$ denotes y after non-dimensionalization by the reference length (used for the definition of the Reynolds number). Hence, a first trial value of *delta-real* can be chosen so that $\bar{y} =$ *delta-real* produces a value of y^+ that is within the acceptable limits of the wall function. AERO-F uses Reichardt's law which is valid within all three zones of the boundary layer: the viscous sublayer ($0 \leq y^+ \leq 5$) where the non-dimensional velocity u^+ is a linear function of y^+ , the buffer layer where the relationship is log-linear, and the logarithmic layer where the relationship is logarithmic. However, because of the reasons explained below, the user is advised to verify that *delta-real* is chosen so that

$$30 \leq y^+ \leq 100$$

(see below).

* Check the lower limit of y^+ . In the commonly used applications of wall functions, the meshing should be arranged so that the values of y^+ at all the wall-adjacent mesh points is only slightly above the recommended lower limit between 20 and 30. The real reason is not that the form usually assumed for the wall functions is not valid much below these values (given that Reichardt's law is valid), but the fact that if *delta-real* is positioned too low, the CFD computation will start too close to the wall and its accuracy will depend on the specifics of the chosen turbulence model. If this model does not reproduce correctly the asymptotic behavior of the solution near the wall (for example, the standard LES model or the standard $k-\epsilon$ model), a flawed computation can be expected even though the connection with the wall function is performed at a valid point. On the other hand, the computation may be safe if the dynamic LES model is used instead. In any case, the lower limit given above offers the best chances to correctly resolve the turbulent portion of the boundary layer. It should be noted however that this limit may be impossible to satisfy close to separation or reattachment zones unless y^+ is based upon y*.

* Check the upper limit on y^+ . In the case of moderate Reynolds numbers, where the boundary layer only extends to y^+ of 300 to 500, there is no chance of accurately resolving the boundary layer if the first mesh point is placed at a location with the value of y^+ of 100 or higher.

* Check the resolution of the boundary layer. If boundary layer effects are important, it is recommended that the resolution of the boundary layer is checked after the computation. This can be achieved by a plot of

the ratio between the turbulent to the molecular viscosity, which is high inside the boundary layer. Adequate boundary layer resolution requires at least 8-10 points in the layer. An attempt to address this requirement can be performed a priori by estimating the thickness of the boundary layer assuming the obstacle is locally a flat plate, and using the experiment-based formulae

$$\delta = \frac{5.2x}{\sqrt{Re_x}} \quad \text{(laminar)}$$

and

$$\delta = \frac{0.37x}{Re_x^{0.2}} \quad \text{(turbulent)}$$

where δ denotes the thickness of the boundary layer at the distance x from the leading edge of the plate, and Re_x denotes the Reynolds number based on a length equal to x for this specific purpose.

* For robustness, the mesh spacing and *delta-real* should be such that the distance to the wall is equal to the average value of the wall normal mesh spacing. For some complex flow configurations, the robustness of the solver can be further increased by choosing a larger value of `Wall.Delta` during the first few time iterations, performing a run with this larger value, then restarting from the result of this run and using the suitable value of `Wall.Delta`.
* In any case, the chosen value of the distance to the wall should be validated a posteriori by inspecting the resulting values of the y^+ field as discussed above. This can be done by requesting one restart iteration after setting `Postpro.DeltaPlus` to output the values of y^+ .

Previous: Wall, Up: BoundaryConditions

4.11.4 DEFINING A LIST OF ADDITIONAL PARAMETERS FOR HYDRO-SIMULATION

Object:	**Hydro**

When performing a hydro-computation, a list of additional parameters is needed for computing the far-field pressure and the hydrostatic and hydrodynamic pressure and force fields. This list is currently defined within the `Hydro` object. Its syntax is:

```
under Hydro{
  Depth = depth-real;
}
```

with

depth-real [`0.0`]:

Depth of the origin of the mesh coordinate system.

Next: Space, Previous: BoundaryConditions, Up: Objects

4.12 SETTING THE PARAMETERS OF THE CHOSEN LOW-MACH

PRECONDITIONER

Object:	**Preconditioner**

The `Preconditioner` object specifies the parameters of the low-Mach Turkel preconditioner for the artificial viscosity as well as inertia (or time-derivative, or temporal) terms of the equations to be solved. The preconditioner is local, i.e. its value changes at each node and during the simulation. Its key variable is

$$\beta = min\left(1.0, max(Mach, kM_{local})\right)$$

where M_{local} is the value of the local mach number.

The syntax of the `Preconditioner` object is:

```
under Preconditioner{
  Mach = Mach-real;
  k = k-real;
}
```

with

Mach-real [1.0]:

Minimal value of the preconditioner for the low-Mach Turkel preconditioner. The recommended value is of the order of the characteristic Mach number of the simulation being run. In general, a good choice is a value slightly smaller than the inlet Mach number. However, it can be necessary to set it to a higher value for flows with pockets of very small velocities.

k-real [1.0]:

This parameter characterizes the low-Mach preconditioner for both gas and liquid flows. The recommended value is of the order of unity. However, it can be necessary to set it to a higher value for flows with pockets of very small velocities.

Notes:

1. the user can check that at values of the Mach number in the compressible flow regime, β becomes equal to 1 if the above parameters are reasonably well chosen in which case the preconditioner becomes inactive and therefore does not bother compressible flow computations even when turned on;
2. explicit time-integration is not recommended for low-Mach flows for computational efficiency reasons.

Next: Time, Previous: Preconditioner, Up: Objects

4.13 DEFINING THE SPACE DISCRETIZATION

Object:	**Space**

The finite I volume discretization of the governing equations is defined within the `Space` object. Its syntax is:

```
under Space {
    under NavierStokes { ... }
    under TurbulenceModel { ... }
    under LevelSet { ... }
    under Boundaries { ... }
    under Fixes { ... }
  }
```

with

`NavierStokes`:

> Defines the spatial discretization of the inviscid part of the Euler or averaged Navier-Stokes equations. Its syntax is defined in the *space-obj* object.

`TurbulenceModel`:

> Defines the spatial discretization of the inviscid part of the turbulence model equation(s). Its syntax is defined by the *space-obj* object.

`LevelSet`:

> Defines the spatial discretization of the generalized level set equation(s). Its syntax is defined by the *space-obj* object.

`Boundaries`:

> Defines the options available for the numerical treatment of the far-field boundary conditions.

`Fixes`:

> Defines the few modifications that can be applied to the spatial discretization of the governing equations in order to improve its robustness.

Note:

1. the discretization of the viscous and source terms of the governing equations is always performed by a Galerkin finite element technique.

- NavierStokes
- SpaceTurbulenceModel
- LevelSet
- Boundaries
- Fixes

Next: SpaceTurbulenceModel, Up: Space

4.13.1 NAVIERSTOKES

Object:	**NavierStokes**

The `NavierStokes` object defines the finite volume discretization of the governing Euler or Navier-Stokes equations. Its syntax is:

```
under NavierStokes {
        Flux = flux-id;
        Reconstruction = reconstruction-id;
        AdvectiveOperator = advectiveoperator-id;
        Limiter = limiter-id;
        Gradient = gradient-id;
        Dissipation = dissipation-id;
        Beta = beta-real;
        Gamma = gamma-real;
        Eps = eps-real;
      }
```

with

flux-id [`Roe`]:

`Roe`
: Specifies Roe's numerical flux.

`HLLE`
: Specifies the HLLE (Harten-Lax-van Leer-Einfeldt) numerical flux, which enables the intermediate state to satisfy the so-called entropy and positivity conditions but is more diffusive than Roe's flux. This choice for the numerical flux is available however only when the specified equation of state (EOS) is that of a perfect gas (see FluidModel). If any other EOS is specified in FluidModel, *flux-id* is automatically reset to `Roe` by **AERO-F**.

`HLLC`
: Specifies the HLLC (devised by Toro, HLL for Harten-Lax-van Leer and C for “contact”) numerical flux, which can remain positively conservative and is computationally more efficient than Roe's flux. This choice for the numerical flux is available however only when the specified equation of state (EOS) is that of a perfect gas (see FluidModel). If any other EOS is specified in FluidModel, *flux-id* is automatically reset to `Roe` by **AERO-F**.

reconstruction-id [`Linear`]:

`Constant`
: A constant variation of the solution is assumed within each control volume. This leads to a first-order space-accurate scheme.

`Linear`
: A linear variation of the solution is assumed within each control volume. This leads to at least a second-order space-accurate scheme.

advectiveoperator-id [`FiniteVolume`]:

`FiniteVolume`
: This option is relevant only if *reconstruction-id* is set to `Linear`. In this case, all components of the numerical flux function are computed using the reconstructed values of the primitive variables.

`Galerkin`
: This option is relevant only if *reconstruction-id* is set to `Linear`. In this case, the reconstructed values of the primitive variables may occasionally be non-physical due to the fact that they are computed by extrapolation. They may lead to the appearance of a NaN when used for computing the numerical flux function. To avoid this pitfall and the expensive "if"-type of testing that can prevent it, this option requests that the reconstructed values of the primitive variables be used only in the (Wi - Wj) term of the numerical flux function, and the constant values be used instead in its centered component and upwinding matrix. This is justified by the two following observations about the upwinded flux: a) its centered term is by construction second-order space-accurate and therefore does not need to be evaluated at the reconstructed values of the primitive variables in order to be second-order space-accurate, and b) the evaluation of the

term (Wi - Wj) does not incur the computation of any quantity that can generate a NaN (such as for example, the speed of sound which involves a square root).

limiter-id [`None`]:

`None`
: No limiter is used.

`VanAlbada`
: The one-dimensional limiter developed by van Albada is used.

`Barth`
: The multi-dimensional limiter developed by Barth is used.

`Venkatakrishnan`
: The multi-dimensional limiter developed by Venkatakrishnan (smooth version of Barth's limiter) is used.

`PressureSensor`
: A sensor is used to switch to a constant reconstruction in regions where the flow exhibits large pressure gradients.

gradient-id [`LeastSquares`]:

`LeastSquares`
: A least squares technique is used to compute the nodal gradients for second-order reconstruction. This option is the most robust one, particularly for turbulent flows.

`Galerkin`
: A weighted Galerkin technique is used to compute the nodal gradients for second-order reconstruction.

`NonNodal`
: A "geometrical upwind", non-nodal technique is used to compute the gradients for second-order reconstruction. This option is the least dissipative one.

dissipation-id [`SecondOrder`]:

`SecondOrder`
: This is a misnomer as in this case, the resulting scheme is the standard *beta-real gamma-real* scheme which in the general inviscid case has a second-order dispersion error, a third-order dissipation error and therefore is spatially second-order accurate.

`SixthOrder`
: In this case and for inviscid problems, when *beta-real* is set to 0.333333333333 (1/3), the resulting scheme has a fifth-order spatial dissipation error (with a sixth-order spatial derivative), a sixth-order spatial dispersion error, and therefore is spatially fifth-order accurate. If furthermore *gamma-real* is set to 0, the spatial dissipation error is cancelled and therefore the scheme becomes sixth-order space-accurate. Hence, when this option is used, *beta-real* should be set to 0.333333333333 (1/3).

beta-real [`1/3`]:

Upwinding parameter used in the reconstruction. A value of zero corresponds to a centered reconstruction, while a value of one corresponds to a full upwind one. For a fixed value of *gamma-real* (see below), this parameter controls the second-order spatial dispersion of the scheme and can change its sign. When *beta-real* is set to 0.333333333333 (1/3), the second-order spatial dispersion error is eliminated and the leading spatial dispersion error becomes fourth-order; in this case, the leading spatial discretization error becomes third-order and of the dissipative type and therefore the scheme becomes third-order space-accurate for inviscid problems, if *gamma-real* is set to a non-zero value and *dissipation-id* is set to `SecondOrder`. If *beta-real* is set to 0.333333333333 (1/3), *gamma-real* is set to zero and *dissipation-id* is set to `SecondOrder`, then the scheme becomes fourth-order space-accurate for inviscid problems.

gamma-real [`1.0`]:

> Parameter that controls the spatial numerical viscosity introduced by the chosen numerical flux. A value of one recovers the original flux, while a value less than one decreases the added numerical viscosity. For a fixed value of *beta-real* (see above), this parameter controls the third-order spatial dissipation of the scheme. When *gamma-real* is set to 0, the third-order spatial dissipation error is eliminated and the leading spatial dissipation error becomes fifth-order. In this case, if *dissipation-id* is set to `SecondOrder`, the scheme becomes fourth-order space-accurate at best for inviscid problems when *beta-real* is set to 1/3.

eps-real [`0.1`]:

> Parameter used in Venkatakrishnan's limiter and in the pressure sensor. The limiter becomes more active if this value is reduced.

Note:

1. for the level set equation(s), only the `SecondOrder` option of *dissipation-id* is currently supported.

Next: LevelSet, Previous: NavierStokes, Up: Space

4.13.2 TURBULENCEMODEL

Object:	**TurbulenceModel**

The `TurbulenceModel` object defines the finite volume discretization of the turbulence model equations. Its syntax is:

```
under TurbulenceModel {
  Reconstruction = reconstruction-id;
  AdvectiveOperator = advectiveoperator-id;
  Limiter = limiter-id;
  Gradient = gradient-id;
  Dissipation = dissipation-id;
  Beta = beta-real;
  Gamma = gamma-real;
  Eps = eps-real;
}
```

with

reconstruction-id [`Constant`]:

`Constant`
: A constant variation of the solution is assumed within each control volume. This leads to a first-order space-accurate scheme.

`Linear`
: A linear variation of the solution is assumed within each control volume. This leads to at least a second-order space-accurate scheme.

advectiveoperator-id [`FiniteVolume`]:

`FiniteVolume`
: This option is relevant only if *reconstruction-id* is set to `Linear`. In this case, the flux function is computed using the reconstructed values of the primitive variables.

`Galerkin`
: This option is relevant only if *reconstruction-id* is set to `Linear`. Because they are obtained by extrapolation, the reconstructed values of the primitive variables may occasionally be non-physical. In such a case, they may lead to the appearance of a NaN when used for computing the flux function. To avoid this pitfall and the expensive "if"-type of testing that can prevent it, this option requests that the reconstructed values of the primitive variables be used only in the (Wi - Wj) term of the numerical flux function and that the constant values be used in the centered flux component of this flux function as well as in its associated matrix. This is justified by the two following observations about the upwinded flux: a) its centered flux term is by construction second-order space-accurate and therefore does not need to be evaluated at the reconstructed values of the primitive variables in order to be second-order space-accurate, and b) the evaluation of the (Wi - Wj) term does not incur the computation of any quantity that can generate a NaN (such as for example, the speed of sound which involves a square root).

limiter-id [`None`]:

`None`
: No limiter is used.

`VanAlbada`
: The one-dimensional limiter developed by van Albada is used.

`Barth`
: The multi-dimensional limiter developed by Barth is used.

`Venkatakrishnan`
: The multi-dimensional limiter developed by Venkatakrishnan (smooth version of Barth's limiter) is used.

`PressureSensor`
: A sensor is used to switch to a constant reconstruction in regions where the flow exhibits large pressure gradients.

gradient-id [`LeastSquares`]:

`LeastSquares`
: A least squares technique is used to compute the nodal gradients for second-order reconstruction. This option is the most robust one, particularly for turbulent flows.

`Galerkin`
: A weighted Galerkin technique is used to compute the nodal gradients for second-order reconstruction.

`NonNodal`
: A "geometrical upwind", non-nodal technique is used to compute the gradients for second-order reconstruction. This option is the least dissipative and therefore the preferred one. However, it can slow down convergence.

dissipation-id [`SecondOrder`]:

`SecondOrder`
: This is a misnomer as in this case, the resulting scheme is the standard *beta-real gamma-real* scheme which in the general case has a second-order dispersion error, a third-order dissipation error and therefore is spatially second-order accurate.

`SixthOrder`
: In this case, when *beta-real* is set to 0.333333333333 (1/3), the resulting scheme has a fifth-order spatial dissipation error (with a sixth-order spatial derivative), a sixth-order spatial dispersion error, and therefore is spatially fifth-order accurate. If furthermore *gamma-real* is set to 0, the spatial dissipation error is cancelled and therefore the scheme becomes sixth-order space-accurate. Hence, when this option is used, *beta-real* should be set to 0.333333333333 (1/3).

beta-real [`1/3`]:

> Upwinding parameter used in the reconstruction. A value of zero corresponds to a centered reconstruction, while a value of one corresponds to a full upwind one. For a fixed value of *gamma-real* (see below), this parameter controls the second-order spatial dispersion of the scheme and can change its sign. When *beta-real* is set to 0.333333333333 (1/3), the second-order spatial dispersion error is eliminated, the leading spatial dispersion error becomes fourth-order, and therefore the scheme becomes third-order space-accurate if *gamma-real* is set to a non-zero value and *dissipation-id* is set to `SecondOrder`. If *beta-real* is set to 0.333333333333 (1/3), *gamma-real* is set to zero and *dissipation-id* is set to `SecondOrder`, then the scheme becomes fourth-order space-accurate.

gamma-real [`1.0`]:

> Parameter that controls the spatial numerical viscosity introduced by the chosen numerical flux. A value of one recovers the original flux, while a value less than one decreases the added numerical viscosity. For a fixed value of *beta-real* (see above), this parameter controls the third-order spatial dissipation of the scheme. When *gamma-real* is set to 0, the third-order spatial dissipation error is eliminated and the leading spatial dissipation error becomes fifth-order. In this case, if *dissipation-id* is set to `SecondOrder`, the scheme becomes fourth-order space-accurate at best when *beta-real* is set to 1/3.

eps-real [`0.1`]:

> Parameter used in Venkatakrishnan's limiter and in the pressure sensor. The limiter becomes more active if this value is reduced.

Note:

1. for the level set equation(s), only the `SecondOrder` option of *dissipation-id* is currently supported.

Next: Boundaries, Previous: SpaceTurbulenceModel, Up: Space

4.13.3 LEVELSET

Object:	**LevelSet**

The `LevelSet` object defines the finite volume discretization of the level set equation(s). Its syntax is:

```
under LevelSet {
  Reconstruction = reconstruction-id;
  AdvectiveOperator = advectiveoperator-id;
  Limiter = limiter-id;
  Gradient = gradient-id;
  Dissipation = dissipation-id;
  Beta = beta-real;
  Gamma = gamma-real;
  Eps = eps-real;
}
```

with

reconstruction-id [`Constant`]:

`Constant`
> A constant variation of the solution is assumed within each control volume. This leads to a first-order

space-accurate scheme.

`Linear`
: A linear variation of the solution is assumed within each control volume. This leads to at least a second-order space-accurate scheme.

advectiveoperator-id [`FiniteVolume`]:

`FiniteVolume`
: This option is relevant only if *reconstruction-id* is set to `Linear`. In this case, the flux function is computed using the reconstructed values of the primitive variables.

`Galerkin`
: This option is relevant only if *reconstruction-id* is set to `Linear`. Because they are obtained by extrapolation, the reconstructed values of the primitive variables may occasionally be non-physical. In such a case, they may lead to the appearance of a NaN when used for computing the flux function. To avoid this pitfall and the expensive "if"-type of testing that can prevent it, this option requests that the reconstructed values of the primitive variables be used only in the (Wi - Wj) term of the numerical flux function and that the constant values be used in the centered flux component of this flux function as well as in its associated matrix. This is justified by the two following observations about the upwinded flux: a) its centered flux term is by construction second-order space-accurate and therefore does not need to be evaluated at the reconstructed values of the primitive variables in order to be second-order space-accurate, and b) the evaluation of the (Wi - Wj) term does not incur the computation of any quantity that can generate a NaN (such as for example, the speed of sound which involves a square root).

limiter-id [`None`]:

`None`
: No limiter is used.

`VanAlbada`
: The one-dimensional limiter developed by van Albada is used.

`Barth`
: The multi-dimensional limiter developed by Barth is used.

`Venkatakrishnan`
: The multi-dimensional limiter developed by Venkatakrishnan (smooth version of Barth's limiter) is used.

`PressureSensor`
: A sensor is used to switch to a constant reconstruction in regions where the flow exhibits large pressure gradients.

gradient-id [`LeastSquares`]:

`LeastSquares`
: A least squares technique is used to compute the nodal gradients for second-order reconstruction. This option is the most robust one, particularly for turbulent flows.

`Galerkin`
: A weighted Galerkin technique is used to compute the nodal gradients for second-order reconstruction.

`NonNodal`
: A "geometrical upwind", non-nodal technique is used to compute the gradients for second-order reconstruction. This option is the least dissipative one.

dissipation-id [`SecondOrder`]:

`SecondOrder`
: This is a misnomer as in this case, the resulting scheme is the standard *beta-real gamma-real* scheme which

in the general case has a second-order dispersion error, a third-order dissipation error and therefore is spatially second-order accurate.

`SixthOrder`
: In this case, when *beta-real* is set to 0.333333333333 (1/3), the resulting scheme has a fifth-order spatial dissipation error (with a sixth-order spatial derivative), a sixth-order spatial dispersion error, and therefore is spatially fifth-order accurate. If furthermore *gamma-real* is set to 0, the spatial dissipation error is cancelled and therefore the scheme becomes sixth-order space-accurate. Hence, when this option is used, *beta-real* should be set to 0.333333333333 (1/3).

beta-real [`1/3`]:

Upwinding parameter used in the reconstruction. A value of zero corresponds to a centered reconstruction, while a value of one corresponds to a full upwind one. For a fixed value of *gamma-real* (see below), this parameter controls the second-order spatial dispersion of the scheme and can change its sign. When *beta-real* is set to 0.333333333333 (1/3), the second-order spatial dispersion error is eliminated, the leading spatial dispersion error becomes fourth-order, and therefore the scheme becomes third-order space-accurate if *gamma-real* is set to a non-zero value and *dissipation-id* is set to `SecondOrder`. If *beta-real* is set to 0.333333333333 (1/3), *gamma-real* is set to zero and *dissipation-id* is set to `SecondOrder`, then the scheme becomes fourth-order space-accurate.

gamma-real [`1.0`]:

Parameter that controls the spatial numerical viscosity introduced by the chosen numerical flux. A value of one recovers the original flux, while a value less than one decreases the added numerical viscosity. For a fixed value of *beta-real* (see above), this parameter controls the third-order spatial dissipation of the scheme. When *gamma-real* is set to 0, the third-order spatial dissipation error is eliminated and the leading spatial dissipation error becomes fifth-order. In this case, if *dissipation-id* is set to `SecondOrder`, the scheme becomes fourth-order space-accurate at best when *beta-real* is set to 1/3.

eps-real [`0.1`]:

Parameter used in Venkatakrishnan's limiter and in the pressure sensor. The limiter becomes more active if this value is reduced.

Note:

1. for the level set equation(s), only the `SecondOrder` option of *dissipation-id* is currently supported.

Next: Fixes, Previous: LevelSet, Up: Space

4.13.4 SPECIFYING THE NUMERICAL TREATMENT OF THE FAR-FIELD BOUNDARY CONDITIONS

Object:	**Boundaries**

The `Boundaries` object defines the options available for the numerical treatment of the far-field boundary conditions. Its syntax is:

```
under Boundaries {
  Type = type-id
}
```

with

type-id [`StegerWarming`];

`StegerWarming`
: The fluxes at the far-field boundaries are computed using the StegerWarming scheme. This option is only available when the fluid in the far-field is a perfect gas.

`Ghidaglia`
: The fluxes at the far-field boundaries are computed using Ghidaglia's approach which does not assume that the flux is a homogeneous function of degree one and therefore is applicable to all equations of state supported by **AERO-F**.

`ConstantExtrapolation`
: A constant extrapolation procedure is applied for outgoing variables. This option is recommended when the low-Mach preconditioner (see Problem) is employed (and the Mach number is below 0.01).

Previous: Boundaries, Up: Space

4.13.5 FINE TUNING THE SPATIAL DISCRETIZATION

Object:	**Fixes**

The `Fixes` object defines the few modifications that can be applied to the spatial discretization of the governing equations in order to improve its robustness. Its syntax is:

```
under Fixes {
  under Sphere1 { ... }
  under Box1 { ... }
  under Cone1 { ... }
  Symmetry = symmetry-id;
}
```

with

`Sphere1`:

Defines a sphere in which the value of `NavierStokes.Reconstruction` is automatically set or reverted to `Constant` — that is, in which first-order spatial discretization is automatically enforced.

`Box1`:

Defines a box in which the value of `NavierStokes.Reconstruction` is automatically set or reverted to `Constant` — that is, in which first-order spatial discretization is automatically enforced.

`Cone1`:

Defines a conical frustrum in which the value of `NavierStokes.Reconstruction` is automatically set or reverted to `Constant` — that is, in which first-order spatial discretization is automatically enforced.

symmetry-id [`None`]:

`None`
: No symmetry of the spheres, boxes and cones is performed.

`X`

An additional sphere, box or cone is generated by symmetry with respect to the plane orthogonal to the x-axis and containing the origin.

`Y`

An additional sphere, box or cone is generated by symmetry with respect to the plane orthogonal to the y-axis and containing the origin.

`Z`

An additional sphere, box or cone is generated by symmetry with respect to the plane orthogonal to the z-axis and containing the origin.

Note:

1. currently the user can specify 10 spheres (`Sphere1` to `Sphere10`), 10 boxes (`Box1` to `Box10`), and 10 cones (`Cone1` to `Cone10`).

- SphereFix
- BoxFix
- ConeFix

Next: BoxFix, Up: Fixes

4.13.5.1 DEFINING A GENERIC SPHERE

Object:	**Sphere**

The syntax of the `Sphere` (with an integer appended to the last letter of this word) object is:

```
under Sphere {
  X0 = x0-real;
  Y0 = y0-real;
  Z0 = z0-real;
  Radius = radius-real;
  FailSafe = failsafe-str;
}
```

with

x0-real [`0.0`]:

x-coordinate of the center of the sphere.

y0-real [`0.0`]:

y-coordinate of the center of the sphere.

z0-real [`0.0`]:

z-coordinate of the center of the sphere.

radius-real [`0.0`]:

Radius of the sphere.

failsafe-str [`AlwaysOn`]:

`On` *N*
: In this case, the treatment implied by the Fixes command expires after *N* time-steps, where *N* is a specified integer.

`AlwaysOn`
: In this case, the treatment implied by the Fixes command is permanent.

`Off`
: In this case, the treatment implied by the Fixes is turned off.

Next: ConeFix, Previous: SphereFix, Up: Fixes

4.13.5.2 DEFINING A GENERIC BOX

Object:	**Box**

The syntax of the `Box` (with an integer appended to the last letter of this word) object is:

```
under Box {
  X0 = x0-real;
  Y0 = y0-real;
  Z0 = z0-real;
  X1 = x1-real;
  Y1 = y1-real;
  Z1 = z1-real;
  FailSafe = failsafe-str;
}
```

with

x0-real [`0.0`]:

x-coordinate of the lower left corner of the box.

y0-real [`0.0`]:

y-coordinate of the lower left corner of the box.

z0-real [`0.0`]:

z-coordinate of the lower left corner of the box.

x1-real [`0.0`]:

x-coordinate of the upper right corner of the box with *x1-real* > *x0-real*.

y1-real [`0.0`]:

y-coordinate of the upper right corner of the box with *y1-real* > *y0-real*.

z1-real [`0.0`]:

z-coordinate of the upper right corner of the box with *z1-real* > *z0-real*.

failsafe-str [`AlwaysOn`]:

`On` *N*

In this case, the treatment implied by the Fixes command expires after *N* time-steps, where *N* is a specified integer.

`AlwaysOn`
: In this case, the treatment implied by the Fixes command is permanent.

`Off`
: In this case, the treatment implied by the Fixes is turned off.

Previous: BoxFix, Up: Fixes

4.13.5.3 DEFINING A GENERIC CONICAL FRUSTRUM

Object:	**Cone**

The syntax of the `Cone` (with an integer appended to the last letter of this word) object is:

```
under cone-obj {
  X0 = x0-real;
  Y0 = y0-real;
  Z0 = z0-real;
  Radius0 = radius0-real;
  X1 = x1-real;
  Y1 = y1-real;
  Z1 = z1-real;
  Radius1 = radius1-real;
  FailSafe = failsafe-str;
}
```

with

x0-real [`0.0`]:

x-coordinate of the center of the first circle delimiting the first end of the conical frustrum.

y0-real [`0.0`]:

y-coordinate of the center of the first circle delimiting the first end of the conical frustrum.

z0-real [`0.0`]:

z-coordinate of the center of the first circle delimiting the first end of the conical frustrum.

radius0-real [`0.0`]:

Radius of the first circle delimiting the first end of the conical frustrum.

x1-real [`0.0`]:

x-coordinate of the center of the second circle delimiting the second end of the conical frustrum.

y1-real [`0.0`]:

y-coordinate of the center of the second circle delimiting the second end of the conical frustrum.

z1-real [`0.0`]:

z-coordinate of the center of the second circle delimiting the second end of the conical frustrum.

radius1-real [`0.0`]:

Radius of the second circle delimiting the second end of the conical frustrum.

failsafe-str [`AlwaysOn`]:

`On` *N*
: In this case, the treatment implied by the Fixes command expires after *N* time-steps, where *N* is a specified integer.

`AlwaysOn`
: In this case, the treatment implied by the Fixes command is permanent.

`Off`
: In this case, the treatment implied by the Fixes is turned off.

Next: Newton, Previous: Space, Up: Objects

4.14 DEFINING THE TIME-INTEGRATION

Object: **Time**

The `Time` object specifies how to time-integrate the governing semi-discrete equations. Its syntax is:

```
under Time {
  Form = form-id;
  Type = type-id;
  Prec = prec-id;
  MaxIts = maxits-int;
  Eps = eps-real;
  TimeStep = timestep-real;
  TimeStepAdaptation = timestepadaptation-id;
  MaxTime = maxtime-real;
  Cfl0 = cfl0-real;
  Cfl1 = cfl1-real;
  Cfl2 = cfl2-real;
  CflMax = cflmax-real;
  CflMin = cflmin-real;
  DualTimeStepping = dualtimestepping-str;
  DualTimeCfl = dualtimecfl-real;
  ErrorTolerance = errortolerance-real;
  Ser = ser-real;
  under Implicit { ... }
  under Explicit { ... }
}
```

with

form-id [ ];

Specifies the form of the governing semi-discrete fluid equations to be solved. The chosen form affects the definition of a residual and therefore the meaning of a convergence up to a tolerance specified by `Eps`.

`Descriptor`
: In this case, this form is the classical one which can be written as follows

$$\frac{d}{dt}(A(x)w) + F(w, x, \frac{dx}{dt}) = 0$$

where A denotes the matrix of cell volumes, w denotes the fluid state vector, x denotes the postion of the fluid grid, and F denotes here the algebraic sum of the viscous and convective fluxes. This is the default option for two cases: (1) **linearized snapshot** computations in the frequency or time domain — that is, when `Problem.Type` = `PODConstruction`, and (2) unsteady linearized flow computations — that is, when `Problem.Type` = `UnsteadyLinearized` or `Problem.Type` = `UnsteadyLinearizedAeroelastic`. It is also the **only** option currently available for both of these cases.

`NonDescriptor`

In this case, this form is the following scaled form

$$A(x)^{-1}[\frac{d}{dt}(A(x)w) + F(w, x, \frac{dx}{dt})] = 0$$

where all variables have the same meaning as in the previous case. This weighted form of the governing semi-discrete equations amplifies the contributions of the small cells to the residual. It may lead to some ill-conditioning, particularly for viscous meshes where the cells in the boundary layer are typically much smaller than those in the other regions. For viscous flows, it also makes convergence up to a certain tolerance `Eps` harder, but more meaningful, than in the `Descriptor` case. This option is the default option for all flow computations except for **linearized snapshot** computations in the frequency or time domain, and unsteady linearized flow computations — that is, when `Problem.Type` = `PODConstruction`, `Problem.Type` = `UnsteadyLinearized`, or `Problem.Type` = `UnsteadyLinearizedAeroelastic` — for which the default option is `Descriptor`.

`Hybrid`

In this case, this form is the following scaled form

$$A(x)^{-\frac{1}{2}}[\frac{d}{dt}(A(x)w) + F(w, x, \frac{dx}{dt})] = 0$$

where all variables have the same meaning as in the previous case. This option is not supported however for linearized flow computations.

type-id [`Implicit`];

`Implicit`

Implicit time-integration is used.

`Explicit`

Explicit time-integration is used.

prec-id [`NonPreconditioned`]:

`NonPreconditioned`

For steady-state flow calculations, and for implicit unsteady flow computations performed using dual-time-stepping, the pseudo-inertia (or pseudo-time-derivative) terms of the solution scheme are not preconditioned in this case by the low-Mach Turkel preconditioner.

`LowMach`

In this case, for steady-state flow computations performed using an explicit (see Explicit) or the backward Euler implicit pseudo-time-stepping scheme (see Implicit), and for implicit unsteady flow computations, the pseudo-inertia (or pseudo-time-derivative) terms of the solution scheme are equipped with the low-Mach Turkel preconditioner whose parameters are set in Preconditioner. In the latter sub-case, dual-time-stepping is automatically activated, whether *dualtimestepping-str* is set to `On` or `Off`. This option can be combined with the low-Mach preconditioning of the dissipation terms of the convective fluxes of the solution scheme than can be specified in Problem.

maxits-int [`100`]:

Maximum number of time-steps (or half the number of snapshots per modal impulse — see Running AERO-FL).

eps-real [`1.e-6`]:

Relative decrease of the spatial nonlinear residual (only for steady-state flow simulations).

timestep-real [—]:

Time-step (only for unsteady flow simulations). Setting this variable to a positive value inhibits any subsequent adaptation of the time-step.

timestepsadaptation-id [`CFL`]:

Time-step adaptation strategy. This parameter is relevant only if *timestep-real* is not set to a positive number — that is, a constant time-step is not specified.

`CFL`

In this case, the time-step is adapted according to the current CFL number and residual, using the parameters `Cfl0`, `Cfl1`, `Cfl2`, `CflMax` and `Ser` and the strategy

$$CFL = \min(\max(\max(Cfl1, Cfl2 * it), Cfl0/||R||^{Ser}), CflMax)$$

where $Cfl0$, $Cfl1$, $Cfl2$, $CflMax$ and Ser are parameters explained below, it is the time-iteration index, and R is the spatial residual at time-iteration it .

`ErrorEstimation`

In this case, the time-step is adapted according to an error estimation. This option is applicable only when time-integration is performed using the three-point backward difference scheme — that is, `Implicit.Type` is set to `ThreePointBackwardDifference`. When this option is chosen, the size of the first time-step is computed using CFL = `Cfl0` (see definition below). Subsequently, the size of a time-step is adapted using as error indicator the 2-norm of the difference between the numerical solution predicted using the three point backward difference scheme and that using one step of the forward Euler scheme, as follows

$$factor = \min(\max(\sqrt{\frac{\tau||w^n||_2}{||w^n_{low} - w^n||_2}}, DecFac), IncFac)$$

$$\Delta t^{n+1} = max(factor * \Delta t^n, \Delta t_{min})$$

where τ is a maximum (estimated) relative error tolerated within a time-step and specified in `ErrorTol`, w^n_{low} is computed using w^{n-1} and the forward Euler scheme, Δt_{min} is computed at the first time-step using CFL = `CflMin` (see definition below), and the increase factor $IncFac$ and decrease factor $DecFac$ are given by

$$IncFac = 1.25 + (1.15exp(-\frac{it-2}{3})) \quad DecFac = max(0.2, 0.75 - 1.25exp(-\frac{it-2}{3}))$$

cflmin-real [`1.0`]:

CFL parameter used to determine Δt_{min} in the error estimation based time-step adaptation strategy described above. This parameter is relevant only when `TimeStepAdaptation` = `ErrorEstimation`.

dualtimestepping-str [`Off`]:

This option is relevant only for unsteady implicit analysis. Its default value is `Off`, except when *prec-id* is set to

`LowMach`.

`On`
: Turns on dual-time-stepping, which modifies the tangent operator in Newton's method applied to the solution of the system of nonlinear equations arising at each time-step of an implicit time-discretization of the flow equations. The size of the dual-time-step is governed by the parameter *dualtimecfl-real*. Hence in **AERO-F**, dual-time-stepping can be used together with Newton's method, in the aforementioned context. In general, dual-time-stepping can be expected to slightly reduce the convergence rate of Newton's method, but sufficiently accelerate the iterative solution of the system of linearized equations arising at each Newton iteration to reduce the overall simulation time, particularly in the presence of a low-Mach preconditioner.

`Off`
: Turns off dual-time-stepping. This option is automatically reversed by **AERO-F** to `On` internally, when performing implicit unsteady flow computations with *prec-id* = `LowMach` (see the description of the parameter *prec-id*).

dualtimecfl-real [100]:

Specifies a constant CFL value for computing the size of the dual-time-step when *dualtimestepping-str* is turned `On`.

errortolerance-real [`1e-10`]:

Tolerated (estimated) error during a time-step, when this time-step is adapted according to the error estimation strategy described above. This parameter is relevant only when `TimeStepAdaptation` = `ErrorEstimation`.

maxtime-real [`1.e99`]:

Maximum physical time (only for unsteady flow simulations that do not invlove a structural code). The simulation terminates when either the maximum number of iterations or the maximum time is reached.

cfl0-real [`5.0`]:
cfl1-real [`0.0`]:
cfl2-real [`0.0`]:
cflmax-real [`1000.0`]:
ser-real [`0.7`]:

Values of the parameters $Cfl0$, $Cfl1$, $Cfl2$, $CflMax$ and Ser specifying the CFL-residual time-step adaptation strategy described above.

Note:

1. for one-dimensional two-phase flow computations (`Problem.Type` = `1D`), only explicit time-integration is currently available.

- Implicit
- Explicit

Next: Explicit, Up: Time

4.14.1 DEFINING THE IMPLICIT TIME-INTEGRATION

Object: **Implicit**

The `Implicit` object defines how the system of nonlinear equations is solved at every time-step. Its syntax is:

```
under Implicit {
  Type = type-id;
  MatrixVectorProduct = mvp-id;
  FiniteDifferenceOrder = fdorder-id;
  TurbulenceModelCoupling = tmcoupling-id;
  under Newton { ... }
}
```

with

type-id [`BackwardEuler`]:

`BackwardEuler`
: First-order time-integration based on the backward Euler scheme. This is the default and only time-integrator available for steady-state computations.

`ThreePointBackwardDifference`
: Second-order time-integration based on the three-point backward difference scheme.

mvp-id [`Approximate`]:

`Approximate`
: Relevant only for the case where second-order accuracy in space is specified. In this case, matrix-vector products are based on an approximate Jacobian matrix obtained by linearizing the first-order approximation of the convective flux and the second-order approximation of the diffusive one.

`Exact`
: Matrix-vector products are based on the exact Jacobian matrix. Currently, this option is available only for flow simulations using the body fitted computational framework, the perfect gas Equation of State (EOS), Roe's numerical flux, any flux limiter but the `Venkatakrishnan` limiter (see NavierStokes), any technique except the non-nodal one for computing the gradients when performing second-order reconstruction, and second-order dissipation. Otherwise, and for the generalized level set equation(s), this option reverts to the finite difference option with *fdorder-id* = `FirstOrder`.

`FiniteDifference`
: Matrix-vector products are based on a finite-difference formula of the combined convective and viscous fluxes. This allows to capture the effect of the exact Jacobian matrix without having to compute and to store it.

fdorder-id [`FirstOrder`]:

This option is available only when *mvp-id* (MatrixVectorProduct) is set to FiniteDifference. It specifies the order of the finite difference approximation of the product of the Jacobian matrix of the implicit scheme with a vector, independently from the order of the spatial discretization of the problem.

`FirstOrder`
: In this case, the finite differencing scheme is a first-order finite-difference formula that requires only one residual evaluation per computation.

`SecondOrder`
: In this case, the finite differencing scheme is a more accurate (at least in principle) second-order finite-difference formula that requires however two residual evaluations per computation.

tmcoupling-id [`Weak`]:

This object member is relevant only for simulations with turbulence modeling. The following description of the usage of this parameter refers to a two-by-two block partitioning of the Jacobian of the coupled Navier-Stokes and turbulence model equations, according to the flow and turbulence model unknowns.

`Weak`
: In this case, the Jacobian of the implicit problem is approximated by a blog diagonal matrix. Therefore, the linearized flow and turbulence model equations are decoupled at each step of the Newton method. This also implies that the parameters of the linear equation solver can be adjusted separately for the flow equations using `LinearSolver.NavierStokes`, and the turbulence model equations using `LinearSolver.TurbulenceModel` (see LinearSolver).

`Strong`
: In this case, the Jacobian of the implicit problem accounts for the coupling of the flow and turbulence model equations. Consequently, the fully coupled linearized flow and turbulence model equations are solved at each step of the Newton method. In this case also, the parameters of the linear equation solver must be specified under `LinearSolver.NavierStokes` only, and any input to the object `LinearSolver.TurbulenceModel` is ignored by **AERO-F** (see LinearSolver).

Note:

1. for LES, dynamic LES, VMS-LES, and dynamic VMS-LES computations, the source terms associated with turbulence modeling are explicitized and therefore do not contribute to the Jacobian matrix of the implicit scheme.

- Newton

Previous: Implicit, Up: Time

4.14.2 DEFINING THE EXPLICIT TIME-INTEGRATION

Object:	**Explicit**

The `Explicit` object defines how the system of nonlinear equations is advanced at every time-step using an explicit scheme.

Currently, explicit time-integration is not supported for usage with the AERO-FL module. Hence, the `UnsteadyLinearized`, `UnsteadyLinearizedAeroelastic`, `PODConstruction`, `PODInterpolation`, `ROM` and `ROMAeroelastic` options in the `Problem` object cannot be specified together with explicit time-integration.

The syntax of `Explicit` is:

```
under Explicit {
  Type = type-id;
}
```

with

type-id [`RungeKutta4`];

`RungeKutta4`
: Fourth-order time-accurate, four-stage, Runge-Kutta scheme.

`RungeKutta2`
: Second-order time-accurate, two-stage, Runge-Kutta scheme.

4.15 SOLVING A SYSTEM OF NONLINEAR EQUATIONS

Object:	**Newton**

The use of a Newton method to solve a system of nonlinear equations occurs in the `Implicit` (see Implicit) and `MeshMotion` (see MeshMotion) objects. The syntax of the `Newton` object is:

```
under Newton {
  MaxIts = maxits-int;
  FailSafe = failsafe-str;
  EpsRelRes = epsrelres-real; (or Eps = eps-real;)
  EpsAbsRes = epsabsres-real;
  EpsAbsInc = epsabsinc-real;
  under LinearSolver { ... }
}
```

with

maxits-int [`1`]:

Maximum number of nonlinear iterations.

failsafe-str [`Off`]:

This member is relevant only if `NavierStokes.Reconstruction` is set to `Linear` — that is, for second-order space discretization.

`On`
: In this case, when a negative pressure and/or density is encountered during a Newton iteration, the Newton iteration is repeated with the nodal gradients set to zero at the points where the pressure and/or density are negative. The calculation of the nodal gradients is re-activated however at these points at the next iteration.

`AlwaysOn`
: When the *failsafe-str* is set to `AlwaysOn` and a negative pressure and/or density is encountered during a Newton iteration, the Newton iteration is repeated with the nodal gradients set to zero at the points where the pressure and/or density are negative. In this case, this treatment is maintained at these points in all subsequent Newton iterations.

`Off`
: In this case, when a negative pressure and/or density is encountered during a Newton iteration, AERO-F is stopped and an error message is output on the screen.

epsrelres-real (or *eps-real*) [`0.01`]:

Tolerance for monitoring at each k -th Newton iteration the convergence of the Eucledian norm of the relative value of the nonlinear residual r^k . Convergence of the Newton process is declared whenever either of the following criteria is satisfied

$$\|r^k\|_2 = 0 \qquad \text{or} \qquad \|r^k\|_2 \leq \textit{epsrelres-real}\ \|r^0\|_2$$

or

$$k > 0 \quad \text{and} \quad \|r^k\|_2 \leq \textit{epsabsres-real} \quad \text{and} \quad \|x^k - x^{k-1}\|_2 \leq \textit{epsabsinc-real}$$

where r^0 is the initial value of the nonlinear residual, x^k and r^k are the iterate solution at the k -th Newton iteration and its corresponding residual, respectively, and *epsabsres-real* and *epsabsinc-real* are defined below.

epsabsres-real [`MachinePrecision`]:

Tolerance for monitoring at each k -th Newton iteration the convergence of the Eucledian norm of the (absolute) value of the nonlinear residual r^k . Convergence of the Newton process is declared whenever either of the following criteria is satisfied

$$\|r^k\|_2 = 0 \qquad \text{or} \qquad \|r^k\|_2 \leq \textit{epsrelres-real} \; \|r^0\|_2$$

or

$$k > 0 \quad \text{and} \quad \|r^k\|_2 \leq \textit{epsabsres-real} \quad \text{and} \quad \|x^k - x^{k-1}\|_2 \leq \textit{epsabsinc-real}$$

where r^0 is the initial nonlinear residual, x^k and r^k are the iterate solution at the k -th Newton iteration and its corresponding residual, respectively, *epsrelres-real* is defined above, and *epsabsinc-real* is defined below. The default value for *epsabsres-real* is the machine precision for double precision arithmetics (the difference between 1 and the smallest representable value that is greater than 1) which is typically of the order of 1e-16. Hence, it is sufficiently small so that by default, the convergence criterion of the Newton process is in principle based on the Eucledian norm of the relative value of the nonlinear residual r^k .

epsabsinc-real [`MachinePrecision`]:

Tolerance for monitoring at each k -th Newton iteration the Eucledian norm of the incremental solution of the nonlinear problem being solved. Convergence of the Newton process is declared whenever either of the following criteria is satisfied

$$\|r^k\|_2 = 0 \qquad \text{or} \qquad \|r^k\|_2 \leq \textit{epsrelres-real} \; \|r^0\|_2$$

or

$$k > 0 \quad \text{and} \quad \|r^k\|_2 \leq \textit{epsabsres-real} \quad \text{and} \quad \|x^k - x^{k-1}\|_2 \leq \textit{epsabsinc-real}$$

where r^0 is the initial nonlinear residual, and x^k and r^k are the iterate solution at the k -th Newton iteration and its corresponding residual, respectively, and *epsrelres-real* and *epsabsres-real* are defined above. The default value of *epsabsinc-real* is the machine precision for double precision arithmetics (the difference between 1 and the smallest representable value that is greater than 1) which is typically of the order of 1e-16. Hence, it is sufficiently small so that by default, the convergence criterion of the Newton process is in principle based on the Eucledian norm of the relative value of the nonlinear residual r^k .

`LinearSolver`:

Specifies the linear equation solver (and its parameters) to be used at each Newton iteration.

Note:

1. when *failsafe-str* is set to `On` or `AlwaysOn` and a negative pressure and/or density is encountered during a Newton iteration, no information is recorded in the restart file about the whereabout of that negative pressure and/or density. As a result, the first residual obtained after a restart operation may differ from the last residual computed in the previous run.

- LinearSolver

Up: Newton

4.15.1 SOLVING A SYSTEM OF LINEAR EQUATIONS

Object:	**LinearSolver**

The object `LinearSolver` specifies how a linearized system of equations is solved at each Newton iteration, or during a sensitivity analysis (see SensitivityAnalysis and Sensitivities). Its syntax is:

```
under LinearSolver {
  under NavierStokes (or TurbulenceModel or LevelSet){
  Type = type-id;
  Output = output-str;
  MaxIts = maxits-int;
  KrylovVectors = krylov-int;
  Eps = eps-real;
  under Preconditioner { ... }
  }
}
```

with

type-id [`Gmres`]:

`Gmres`
: Generalized minimum residual algorithm.

`Richardson`
: Richardson's algorithm.

`Cg`
: Conjugate gradient algorithm. This linear equation solver is applicable only to the system of equations associated with mesh motion (see MeshMotion).

`Gcr`
: Generalized conjugate residual algorithm.

output-str [`""`]:

Name of the ASCII file that contains the sequence of linear residuals. If *output-str* is set to `"stdout"` (`"stderr"`) the linear residuals are printed on the standard I/O stream stdout (stderr).

maxits-int [`30`]:

Maximum number of linear iterations.

krylov-int [`30`]:

Number of search directions (only for the GMRES algorithm).

eps-real [`0.01`]:

Relative decrease of the linear residual.

`Preconditioner`:

Specifies the preconditioner to be used with the linear equation solver.

Notes:

1. when `Implicit.TurbulenceModelCoupling` is set to `Weak` — that is, the contributions of the linearizations of the mean flow and turbulence model equations to the Jacobian of the implicit problem are decoupled (see Implicit) — or the "ghost fluid method of the poor" for which the level set and flow equations are also decoupled is specified (see MultiPhase) for the solution of a multi-phase problem, the parameters of the linear equation solver should be specified separately for each independent system of equations. In such cases, the definition of the `LinearSolver` object within the `Newton` object (see Newton) becomes

```
          under LinearSolver {
            under NavierStokes { ... }
            under TurbulenceModel { ... }
            under LevelSet { ... }
          }
```

   with

   `NavierStokes`:

   Specifies the linear solver for the Euler or averaged Navier-Stokes equations by specifying all parameters described at the beginning of this section under this object.

   `TurbulenceModel`:

   Specifies the linear solver for the turbulence model equation(s) by specifying all parameters described at the beginning of this section under this object.

   `LevelSet`:

   Specifies the linear solver for the level set equation(s) by specifying all parameters described at the beginning of this section under this object.
2. when `Implicit.TurbulenceModelCoupling` is set to `Strong` — that is, the contributions of the linearizations of the mean flow and turbulence model equations to the Jacobian of the implicit problem are coupled (see Implicit) — the parameters of the linear equation solver should be specified for the `NavierStokes` object only because a single set of coupled equations is solved in terms of both the flow and turbulence model variables. In this case, the definition of the object `LinearSolver` within the object `Newton` (see Newton) becomes

```
          under LinearSolver {
            under NavierStokes { ... }
          }
```

- SolverPreconditioner

Up: LinearSolver

4.15.1.1 ACCELERATING A LINEAR SOLVER

Object:	**Preconditioner**

To increase the efficiency of the linear solver, it can be preconditioned. The preconditioners currently available are described within the `Preconditioner` object. Its syntax is:

```
under Preconditioner {
  Type = type-id;
  Fill = fill-int;
}
```

with

type-id [`Ras`]:

`Identity`
: No preconditioner.

`Jacobi`
: Jacobi preconditioner.

`Ras`
: Restricted additive Schwarz algorithm.

fill-int [`0`]:

Level of fill for the incomplete LU factorization used in the restricted additive Schwarz algorithm.

Next: Accelerated, Previous: Newton, Up: Objects

4.16 IMPOSING FORCED OSCILLATIONS

Object:	**Forced**

The `Forced` object enables the simulation of flow problems on dynamic meshes set in a prescribed oscillatory motion, if the problem type (*type-id*) is set to `Forced` (see Problem). This motion can be associated with the prescribed heaving or pitching of a rigid obstacle, or the prescribed deformation of a flexible obstacle. The syntax of the `Forced` object is:

```
under Forced {
  Type = type-str;
  Frequency = frequency-real;
  TimeStep = timestep-real;
  under Heaving{ ... }
  under Pitching{ ... }
  under Deforming{ ... }
}
```

with

type-str [Deforming]:

Specifies a heaving, pitching, or deforming type of forced oscillations of the obstacle.

frequency-int [—]:

Frequency of the prescribed oscillatory motion.

timestep-real [—]:

Computational time-step for sampling the prescribed oscillatory motion.

`Heaving`:

Prescribes a rigid heaving motion.

`Pitching`:

Prescribes a rigid pitching motion.

`Deforming`:

Prescribes a motion associated with a flexible obstacle.

- Heaving
- Pitching
- Deforming

Next: Pitching, Up: Forced

4.16.1 DESCRIBING A PRESCRIBED HEAVING MOTION

Object:	**Heaving**

This object can be used to specify the following heaving motion of a rigid obstacle

$$x = x_0 + a(1 - \cos(2\pi f t))$$

and move the fluid mesh accordingly. In the above equation, x_0 denotes the initial position of the fluid mesh (or its surfacic component), a denotes the vector amplitude of the displacement of the fluid mesh (or the obstacle), f its frequency specified in *frequency-int* of object `Forced` (see Forced), and x denotes either the position of the entire fluid mesh or that of the surfacic fluid mesh. In the latter case, the motion of the remaining fluid grid points is computed using a mesh updating algorithm to be specified (see MeshMotion). The syntax of the `Heaving` object is:

```
under Heaving{
  Domain = domain-id;
  AX   =  ax-real;
  AY   =  ay-real;
  AZ   =  az-real;
}
```

with

domain-id [`Volume`];

`Volume`
: In this case, the entire fluid mesh is set into the specified heaving motion.

`Surface`
: In this case, only the surfacic mesh is set into the specified heaving motion and the position of the remaining fluid grid points is computed by one of AERO-F's mesh motion algorithms to be specified (see MeshMotion).

ax-real [`0.0`]:

x component of the vector amplitude of the motion.

ay-real [`0.0`]:

y component of the vector amplitude of the motion.

az-real [`0.0`]:

z component of the vector amplitude of the motion.

Next: Deforming, Previous: Heaving, Up: Forced

4.16.2 DESCRIBING A PRESCRIBED PITCHING MOTION

Object:	**Pitching**

This object can be used to specify the following pitching motion of a rigid obstacle

$$\tilde{x} = x_0 + [\mathbf{R_1}(\alpha_0 + \alpha_{max}\sin(2\pi ft)) - \mathbf{I}]x_0$$
$$x = \tilde{x} + [\mathbf{R_2}(\beta_0 + \beta_{max}\sin(2\pi ft)) - \mathbf{I}]\tilde{x}$$

where x_0 denotes the initial position of the fluid mesh (or its surfacic component), $\mathbf{R_1}$ and $\mathbf{R_2}$ denote two rotation matrices around two specified pitching axes, α_0 denotes the angle about which the instantaneous pitch angle around the first axis is to oscillate, α_{max} the desired amplitude of the oscillatory pitching motion of the obstacle around the first axis, β_0 the angle about which the instantaneous pitch angle around the second axis is to oscillate, β_{max} the desired amplitude of the oscillatory pitching motion of the obstacle around the second axis, f the frequency of the oscillations specified in *frequency-int* of the object Forced, $\mathbf{I}$ denotes the identity matrix, and x denotes either the position of the entire fluid mesh or that of the surfacic fluid mesh. In the latter case, the motion of the remaining fluid grid points is computed using a mesh updating algorithm to be specified (see MeshMotion).

The syntax of the `Pitching` object is:

```
under Pitching{
  Domain   = domain-id;
  Alpha0   = alpha0-real;
  AlphaMax = alphamax-real;
```

```
    Beta0     = beta0-real;
    BetaMax   = alphamax-real;
    X11       = x11-real;
    Y11       = y11-real;
    Z11       = z11-real;
    X21       = x21-real;
    Y21       = y21-real;
    Z21       = z21-real;
    X12       = x12-real;
    Y12       = y12-real;
    Z12       = z12-real;
    X22       = x22-real;
    Y22       = y22-real;
    Z22       = z22-real;
  }
```

with

domain-id [`Volume`];

`Volume`
: In this case, the entire fluid mesh is set into the specified pitching motion.

`Surface`
: In this case, only the surfacic mesh is set into the specified pitching motion and the position of the remaining fluid grid points is computed by one of **AERO-F**'s mesh motion algorithms to be specified (see MeshMotion).

alpha0-real [`0.0`]:

Angle about which the instantaneous pitch angle around the first axis is to oscillate. A positive value rotates the obstacle around the first axis of rotation specified below in the clockwise direction. If *alpha0-real* is non zero, **AERO-F** will first get the obstacle and surrounding mesh to the position implied by this rotation.

alphamax-real [`0.0`]:

Amplitude of the oscillatory pitching motion of the obstacle around the first axis. A positive value rotates the obstacle around this axis of rotation specified below in the clockwise direction.

beta0-real [`0.0`]:

Angle about which the instantaneous pitch angle around the second axis is to oscillate. A positive value rotates the obstacle around the second axis of rotation specified below in the clockwise direction. If *beta0-real* is non zero, AERO-F will first get the obstacle and surrounding mesh to the position implied by this rotation.

betamax-real [`0.0`]:

Amplitude of the oscillatory pitching motion of the obstacle around the second axis. A positive value rotates the obstacle around this axis of rotation specified below in the clockwise direction.

x11-real [`0.0`]:

x-component of the first point defining the first axis of pitching.

y11-real [`-1.0`]:

y-component of the first point defining the first axis of pitching.

z11-real [`0.0`]:

z-component of the first point defining the first axis of pitching.

x21-real [`0.0`]:

x-component of the second point defining the first axis of pitching.

y21-real [`1.0`]:

y-component of the second point defining the first axis of pitching.

z21-real [`0.0`]:

z-component of the second point defining the first axis of pitching.

x12-real [`-1.0`]:

x-component of the first point defining the second axis of pitching.

y12-real [`0.0`]:

y-component of the first point defining the second axis of pitching.

z12-real [`0.0`]:

z-component of the first point defining the second axis of pitching.

x22-real [`1.0`]:

x-component of the second point defining the second axis of pitching.

y22-real [`0.0`]:

y-component of the second point defining the second axis of pitching.

z22-real [`0.0`]:

z-component of the second point defining the second axis of pitching.

Note:

1. as implied by the sequencing of $\tilde{x}$ and x given above, the position of the second axis of pitching is continuously updated by the pitching motion around the first axis of pitching.

Previous: Pitching, Up: Forced

4.16.3 DESCRIBING A PRESCRIBED MOTION ASSOCIATED WITH A FLEXIBLE OBSTACLE

Object:	**Deforming**

This object can be used to specify the following motion associated with a flexible obstacle

$$x = x_0 + \alpha(x_f - x_0)\sin(2\pi f t)$$

where

x_0 and x_f denote the initial and final mesh positions, α is an amplification factor, and f is the frequency of the oscillations.

The syntax of the `Deforming` object is:

```
under Deforming {
  Domain = domain-id;
  Position = position-str;
  Amplification = amplification-real;
}
```

with

domain-id [`Volume`];

`Volume`
: In this case, the entire fluid mesh is set into the specified deforming motion.

`Surface`
: In this case, only the surfacic mesh is set into the specified deforming motion and the position of the remaining fluid grid points is computed by one of AERO-F's mesh motion algorithms to be specified (see MeshMotion).

position-str [`""`]:

Name of the binary file containing the final mesh position. See Hints and tips for an explanation regarding how to obtain that file.

amplification-real [`1.0`]:

Amplification factor.

Next: Aeroelastic, Previous: Forced, Up: Objects

4.17 ACCELERATING THE MESH

Object:	**Accelerated**

AERO-F can be used to compute a flow around a rigid or flexible obstacle set in accelerated motion. In this case, the “hybrid wind tunnel” framework of computation (see Figure HWT) is adopted — that is, an increase of the free-stream velocity associated with an acceleration of the obstacle is accounted for by accelerating accordingly the ALE mesh. In other words, the motion of the obstacle, which is initially at the free-stream velocity then accelerated, is represented in a frame moving at the free-stream velocity with respect to the ground. The accelerated motion can be characterized either by a constant acceleration field, or deduced from a piecewise linear velocity time-profile that is specified in the `TimeVelocity` object. For an obstacle moving with a piecewise linear velocity, a set of time-velocity pairs are specified. In this case, the velocity is linearly interpolated and the acceleration is approximated by a corresponding piecewise constant field.

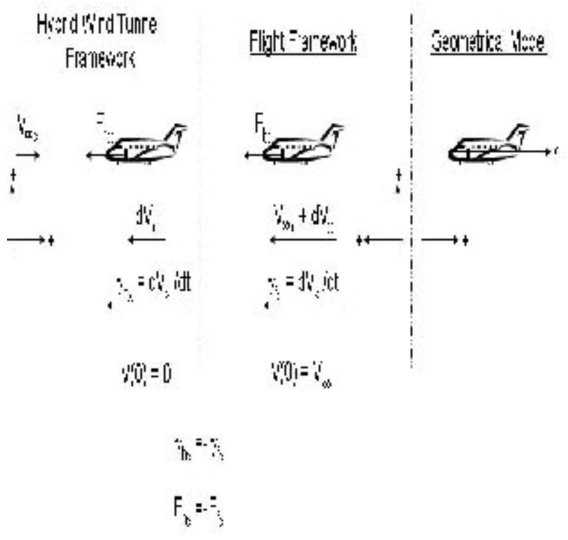


Figure HWT: the hybrid wind tunnel computational framework

The syntax of the `Accelerated` object is:

```
under Accelerated {
  Tag = tag-id;
  LawType = lawtype-id;
  AccelerationX = acc-x-real;
  AccelerationY = acc-y-real;
  AccelerationZ = acc-z-real;
  TimeStep = timestep-real;
  under TimeVelocity1 { ... }
}
```

with

tag-id [`Mach`]:

`Mach`
: The value associated with the sequence of outputed nodal values (see Postpro) is the free-stream Mach number.

`Velocity`
: The value associated with the sequence of outputed nodal values (see Postpro) is the free-stream velocity magnitude.

`Time`
: The value associated with the sequence of outputed nodal values (see Postpro) is the time.

lawtype-id [`ConstantAcceleration`]:

`ConstantAcceleration`
The obstacle has a constant acceleration given by `AccelerationX`, `AccelerationY`, and `AccelerationZ`. The sign convention is that of the hybrid wind tunnel computational framework graphically depicted in Figure HWT. For example, a positive acceleration in the x direction corresponds to a physical deceleration.
`VelocityLaw`
The obstacle has a piecewise linear in time velocity specified by the `TimeVelocity` objects.

acc-x-real [`0.0`]:

Constant acceleration of the obstacle in the x-direction. The sign convention is that of the hybrid wind tunnel computational framework graphically depicted in Figure HWT.

acc-y-real [`0.0`]:

Constant acceleration of the obstacle in the y-direction. The sign convention is that of the hybrid wind tunnel computational framework graphically depicted in Figure HWT.

acc-z-real [`0.0`]:

Constant acceleration of the obstacle in the z-direction. The sign convention is that of the hybrid wind tunnel computational framework graphically depicted in Figure HWT.

timestep-real [—]:

Time-step. If this specified time-step is larger than the specified or CFL-induced time-step of the flow-solver, the flow-solver will subcycle.

`TimeVelocity1`:

Defines the velocity at a specified time. Its syntax is defined by the object `TimeVelocity`.

Note:

1. acceleration can affect the angle of attack. For example, the acceleration along the x-axis shown in Figure Acceleration causes the angle of attack to decrease in time. On the other hand, for this example, an acceleration along both x- and z-axes with the ratio *acc-z-real*/*acc-x-real* equal to the tangent of the angle of attack will maintain the angle of attack constant in time.

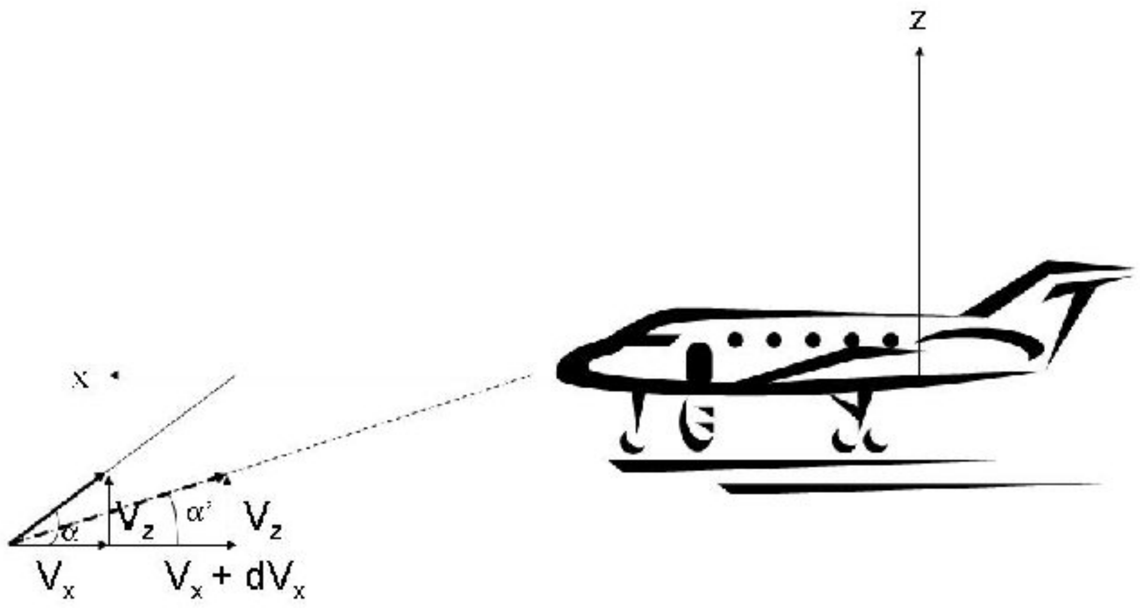


Figure Acceleration: example of the effect of acceleration on the angle of attack

- TimeVelocity

Up: Accelerated

4.17.1 SPECIFYING A VELOCITY AT A GIVEN TIME

Object:	**TimeVelocity**

The `TimeVelocity` object specifies the velocity of an obstacle at a certain time.

```
under TimeVelocity1 {
  Time = time-real;
  VelocityX = v-x-real;
  VelocityY = v-y-real;
  VelocityZ = v-z-real;
}
```

with

time-real [—]

Specified time.

v-x-real [`0.0`]

Velocity of the obstacle in the x-direction at the specified time.

v-y-real [`0.0`]

Velocity of the obstacle in the y-direction at the specified time.

v-z-real [`0.0`]

Velocity of the obstacle in the z-direction at the specified time.

Notes:

1. currently, only 10 time-velocity pairs can be specified.
2. it is implied that the first time-velocity pair is not specified by any `TimeVelocity` object. It is rather automatically generated using zero for the initial time and the free-stream flow conditions for the initial velocity (Mach number and angles of attack). It is also assumed that the `TimeVelocity` objects are ordered with increasing time;
3. from the above, it follows that the first specified time must be different from zero;
4. when the time is greater than the time specified in the last `TimeVelocity` object, the velocity is assumed to be constant and set to the value specified by the last `TimeVelocity` object.

Next: MeshMotion, Previous: Accelerated, Up: Objects

4.18 SPECIFYING AEROELASTIC PARAMETERS

Object:	**Aeroelastic**

Aeroelastic parameters are specified within the `Aeroelastic` object. Its syntax is:

```
under Aeroelastic {
  Force = force-id;
  InternalPressure = pressure-real;
}
```

force-id [`Last`]:

`Last`
: The local aerodynamic forces exchanged with the structure code are based on the last computed pressure field within a cycle of the staggered solution procedure.

`Averaged`
: The local aerodynamic forces exchanged with the structure code are based on the time-averaged pressure field within a cycle of the staggered solution procedure.

pressure-real [0.0]:

When computing the generalized local aerodynamic forces exerted on the surface of an obstacle, **AERO-F** always assumes the presence of a uniform pressure field within (or from the dry side of) the obstacle; therefore, it computes the net generalized forces due to both the external and internal (or dry side) pressure fields. The *pressure-real* parameter specifies the value of the uniform pressure field within (or from the dry side of) the obstacle (the default value is 0). The reader should note that for an obstacle with a closed surface, this feature, which is very convenient for aeroelastic computations, has no effect on the values of the global generalized aerodynamic forces. It affects however the resulting displacements and stresses of the obstacle.

Next: EmbeddedFramework, Previous: Aeroelastic, Up: Objects

4.19 MOVING THE MESH

Object:	**MeshMotion**

For a simulation on a moving grid, the `MeshMotion` object constructs a strategy and specifies an algorithm for updating the position of the grid points of the CFD mesh. In general, the motion of the interior grid points is driven by that of the points lying on the surfaces of the CFD mesh (see the **CD2TET** user manual for the mesh motion attributes of the various types of surfaces recognized by **AERO-F**). Therefore, the mesh motion conventions of three important types of surfaces are first discussed below.

The mesh motion of the nodes on a moving wall can be either prescribed (see Forced), or obtained via communication with **AERO-S** during a fluid-structure simulation.

The nodes on a sliding plane (see SurfaceData) slide in this plane — that is, the component of their displacement field along the specified normal to the sliding plane is constrained to zero.

By default, the nodes of a symmetry plane are fully restrained — that is, their motion is set to zero. However, there is one exception to this rule. If *type-id* of this `MeshMotion` object is set to *Corotational*, **AERO-F** does not necessarily fully restrain (set to zero) the motion of the nodes of a symmetry plane (see Symmetry). Furthermore, if desired — for example, to prevent mesh crossovers near a moving wall — the nodes of a symmetry plane can be forced to slide within this plane if it is also explicitly declared as a sliding plane (see SurfaceData). In this case, if *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion), it is strongly recommended to specify the `Symmetry` object within the `MeshMotion` object (see Symmetry).

The syntax of the `MeshMotion` is:

```
under MeshMotion {
  Type = type-id;
  Element = element-id;
  VolumeStiffness = stiffness-factor;
  Mode = mode;
  NumIncrements = numincrements;
  FeedBack = feedback-frequency;
  under Symmetry { ... }
  under Newton { ... }
}
```

with

type-id [`Basic`]:

`Basic`
: In this case, no special treatment is applied to potentially large displacements and/or deformations.

`Corotational`
: In this case, potentially large displacements and/or deformations are handled by the corotational method, which is applied in addition to the chosen mesh motion algorithm. The corotational method separates the motion of the moving walls into two components: a rigid one that is trivially transmitted to the interior mesh points, and a deformational one that is treated by the chosen mesh motion algorithm.

element-id [`BallVertexSprings`]:

`FiniteElement`
: Specifies the mesh motion method based on the linear finite element structural analogy.

`NonLinearFiniteElement`
: Specifies the mesh motion method based on the nonlinear finite element structural analogy. This method can be equipped with a safeguard against mesh instabilities (not to be confused with mesh crossovers, see *stiffness-factor* below). It does not suffer from the hysterisis phenomenon and therefore is suitable for long cyclic problems.

`TorsionalSprings`
: Specifies the mesh motion method based on the linear torsional springs analogy. This method can also be equipped with a safequard against mesh instabilities (not to be confused with mesh crossovers, see *stiffness-factor* below). It is a good candidate for problems with large-amplitude mesh deformations.

`BallVertexSprings`
: Specifies the mesh motion method based on the linear ball vertex springs analogy. This method can also be equipped with a safeguard against mesh instabilities (not to be confused with mesh crossovers, see *stiffness-factor* below). It is a good candidate for problems with large-amplitude mesh deformations and is more economical than the torsional springs method.

`NonlinearBallVertexSprings`
: Specifies the nonlinear version of the ball vertex springs method. This method can also be equipped with a safeguard against mesh instabilities (not to be confused with mesh crossovers, see *stiffness-factor* below). It does not suffer from the hysterisis phenomenon and therefore is a good candidate for long cyclic problems with large-amplitude mesh deformations.

stiffness-factor [`0.0`]:

This parameter is active for all mesh motion algorithms except that based on the linear finite element method (*element-id* = `FiniteElement`). When **positive**, it adds to the basic pseudo-stiffness of an element — which is usually inversely proportional to its volume in order to prevent mesh crossovers — a positive term that is proportional to its volume and multiplied by *stiffness-factor*, thereby preventing this element from becoming increasingly flexible when stretched and causing a mesh instability. By default, the value of this parameter is zero, which does not provide additional stiffening during stretching. The higher the value of this parameter is, the stiffer the pseudo-structure becomes when stretched and the less likely to induce a mesh instability. However, as the value of this parameter is increased, the conditioning of the corresponding pseudo-stiffness matrix becomes worse, and more iterations may become necessary for updating the position of the mesh.

mode [`NonRecursive`]:

The prescribed boundary displacement field can be applied in multiple increments (or fractions) to minimize the likelyhood of crossovers during the mesh motion. The number of increments can be specified is *numincrements* (see below).

`NonRecursive`
: If *mode* is set to `NonRecursive` (which is the default value), then the prescribed boundary displacement field is applied in *numincrements* equal increments and the stiffness of the mesh is updated at each step.

`Recursive`
: If *mode* is set to `Recursive`, the prescribed boundary displacement field is recursively applied in fractions computed so that, in principle, the motion of the moving surface does not exceed, for a given fraction (except possibly the last one), the thickness of the first layer of elements above this surface. In this case, the stiffness of the mesh is also updated at each step and *numincrements* defines the maximum number of allowable increments.

numincrements [`1`]:

This parameter defines either the number of increments in which to apply the prescribed boundary displacement field when *mode* is set to `NonRecursive`, or the maximum number of allowable fractions of this displacement when *mode* is set to `Recursive`. The default value is 1.

feedback-frequency [`0`]:

> Feedback on the performance of the choice made in *mode* is available in the form of output to the screen of the minimum and maximum applied fractions of a prescribed wall-boundary displacement. The feedback is printed every *feedback-frequency* iterations/time-steps of a steady/unsteady computation. It is useful for checking, when *mode* is set to `Recursive`, whether a large discrepancy occurs between the minimum and maximum applied fractions of the prescribed wall-boundary displacement, in which case setting *mode* to `NonRecursive` would produce a better performance of the chosen mesh motion algorithm. Setting *feedback-frequency* to zero (default) results in turning off this option.

`Newton`:

> Specifies the parameters of the Newton method for solving the nonlinear system of discrete equations.

`Symmetry`:

> Acknowledges the presence of a symmetry plane in the mesh so that the mesh motion solver can constrain the solution of the mesh motion equations appropriately.

Note:

1. the default value for `Newton.LinearSolver.Type` is `Cg` while the default value for `Newton.LinearSolver.Preconditioner.Type` is `Jacobi`;

- BoundaryLayer
- Symmetry
- Newton

Up: MeshMotion

4.19.1 MESH MOTION IN THE PRESENCE OF A PLANE OF SYMMETRY

Object:	**Symmetry**

For a simulation on a moving grid, this object should be specified within the mesh motion object (see MeshMotion) when *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion), the computational domain contains a symmetry plane, and it is desired to fully restrain the nodes of this symmetry plane or constrain their motion to sliding within the symmetry plane.

The syntax of the `Symmetry` object is:

```
under Symmetry {
  Nx = Nx-real;
  Ny = Ny-real;
  Nz = Nz-real;
}
```

with

Nx-real [`0.0`]:

The x-component of the normal to the symmetry plane.

Ny-real [`0.0`]:

The y-component of the normal to the symmetry plane.

Nz-real [`0.0`]:

The z-component of the normal to the symmetry plane.

Notes:

1. currently, **AERO-F** allows only one plane of symmetry if the simulation involves a moving grid and requires this plane of symmetry to be parallel to one of the three canonical planes;
2. if *type-id* of the `MeshMotion` object is set to *Corotational* (see MeshMotion) and the `Symmetry` object is specified, the nodes of a symmetry plane will “rigidly” slide within this plane. To have them slide while allowing deformation of the elements they are attached to, the user must also declare the symmetry plane a sliding plane (see SurfaceData).

Next: Linearized, Previous: MeshMotion, Up: Objects

4.20 SPECIFYING THE EMBEDDED BOUNDARY METHOD FOR CFD

Object:	**EmbeddedFramework**

The object `EmbeddedFramework` is primarily used to specify **AERO-F**'s embedded boundary method for CFD. This method is activated however only if `Problem.Type` is set to `Embedded` (see Problem). Its parameters are: (a) the specific intersector which tracks the position (and shape) of an embedded discrete surface (which can be the union of multiple disconnected embedded surfaces) representing the wet surface of an obstacle (which can be the union of multiple disconnected obstacles); and (b) the specific energy conserving algorithm for computing the flow-induced forces and moments on this embedded surface and enforcing the equilibrium transmission condition in the case of a fluid-structure simulation.

In the case of a closed embedded discrete surface, the object `EmbeddedFramework` is also used to specifiy the initial state of the fluid medium occupying the region of the computational domain enclosed by this surface.

The syntax of this object is:

```
under EmbeddedFramework {
  Intersector      = intersector-id;
  SurrogateSurface = surrogatesurface-id;
  RiemannNormal    = rnormal-id;
  under InitialConditions { ... }
}
```

with

intersector-id [`FRG`]:

Specifies a computational approach for computing the intersection of an embedded discrete surface with the embedding CFD grid in order to track in time the position and shape of this embedded surface.

`FRG`

In this case, a fast, projection-based approach is used for tracking the fluid-structure interface. This approach requires that the embedded surface be closed and remain closed throughout the entire simulation. Furthermore, it is accurate only if the region enclosed by the embedded surface is resolved by the embedding CFD grid.

`PhysBAM`

In this case, a slower but more general geometric-based approach is used for tracking the fluid-structure interface. This approach is equally applicable to open and closed embedded surfaces. Furthermore, it is accurate even when the embedded discrete surface is closed and the region enclosed by this surface is not resolved by the embedding CFD grid.

surrogatesurface-id [`ReconstructedSurface`]:

Specifies a surrogate surface on which to compute the flow-induced forces and moments and a corresponding conservative algorithm for performing this computation and that of the load transferred to the real structure in the case of a fluid-structure simulation.

`ReconstructedSurface`

In this case, the surrogate surface is reconstructed within **AERO-F** based on the computed intersection between the embedded discrete surface and embedding fluid mesh.

`ControlVolumeFace`

In this case, the surrogate surface is defined as the assembly of the control volume faces that are the closest to the computed intersection between the embedded discrete surface and embedding fluid mesh.

rnormal-id [`Structure`]:

Specifies the normal to be used in the solution of the one-dimensional fluid-structure Riemann problem along an edge of the fluid mesh which intersects the structure.

`Structure`

In this case, the aforementioned normal is set to that of the structure at the point of intersection of the structure and the relevant edge of the fluid mesh. This is the default setup as it offers better accuracy.

`Fluid`

In this case, the aforementioned normal is set to that of the control volume face of the fluid mesh associated with the intersecting edge. This option trades optimal accuracy for better numerical stability by introducing dissipation indirectly in the semi-discretization process.

`InitialConditions`:

In the case of a closed embedded discrete surface, this object allows a convenient initialization of the state (or states) of the fluid medium (or media) occupying the region (or regions) enclosed by this surface.

- InitialConditionsEmbedded

Up: EmbeddedFramework

4.20.1 SPECIFYING THE INITIAL CONDITIONS IN A REGION DELIMITED BY A CLOSED EMBEDDED SURFACE

Object:	**InitialConditions**

This object provides a convenient way for initializing to a uniform condition the state of a fluid medium in a region of the computational fluid domain delimited by a closed embedded discrete surface. Because a closed surface can consist of multiple disconnected closed surfaces, the aforementioned region of interest is identified here by specifying a point it contains (this point does not need to be a CFD grid point). Because the initialization procedure depends on the EOS of the fluid medium of interest, the integer identification number of this fluid medium is also specified in Point. Finally, the initial state itself is specified in InitialState.

The syntax of this object is:

```
under InitialConditions {
  under Point[point-id-int] { ... }
  ...
}
```

with

point-id-int[—]

> Integer identification number of a point located in a region of the computational fluid domain delimited by a closed embedded discrete surface. This point does not need to be a CFD grid point.

`Point`:

> Specifies the coordinates of a point in space identified by *point-id-int* and the integer identification number of the fluid medium that contains it.

- Point

Up: InitialConditionsEmbedded

4.20.1.1 SPECIFYING A POINT AND THE FLUID MEDIUM CONTAINING IT

Object:	**Point**

This object specifies the coordinates of a point (which is not necessarily a CFD grid point) identified by *point-id-int* for the purpose of identifying the region of the computational fluid domain containing this point and delimited by an embedded discrete and closed surface. It also identifies the fluid medium occupying this region by specifying its integer identification number, and initializes its state to that of a uniform condition specified in InitialState.

The syntax of this object is:

```
under Point {
  FluidID = fluid-id-int;
  X = x-real;
  Y = y-real;
  Z = z-real;
  under InitialState{ ... }
}
```

with

fluid-id-int [—]:

> Integer number identifying the fluid medium containing the point identified by *point-id-int*.

x-real [0.0]:

Coordinate of the point identified by *point-id-int* along the x axis.

y-real [0.0]:

Coordinate of the point identified by *point-id-int* along the y axis.

z-real [0.0]:

Coordinate of the point identified by *point-id-int* along the z axis.

`InitialState`:

Specified the initial conditions to be applied in the region of the computational fluid domain containing the point identified by *point-id-int* and delimited by an embedded discrete and closed surface.

- InitialState

Next: SensitivityAnalysis, Previous: EmbeddedFramework, Up: Objects

4.21 DEFINING THE PARAMETERS OF THE LINEARIZED MODULE AERO-FL

Object:	**Linearized**

AERO-F can also be used to solve a set of linearized flow equations around a given (equilibrium) configuration when the considered fluid is a perfect gas. The module within AERO-F that performs this task is referred to as AERO-FL. This module also offers a dimensional POD-based ROM capability trained for obstacle vibrations. Currently, AERO-FL supports only the linearized Euler equations in descriptor form and for a perfect gas. It can be used to perform (see Problem):

1. an unsteady linearized Euler flow perturbation computation in the time-domain;
2. an unsteady linearized Euler-based aeroelastic computation in which the structure is represented by a truncated set of its natural modes (dimensional);
3. a construction of a time- or frequency-domain POD basis (dimensional);
4. a construction of a time- or frequency-domain POD basis by linear interpolation between several sets of POD basis vectors (dimensional);
5. a construction of a fluid ROM trained for obstacle vibrations (dimensional);
6. a construction of an aeroelastic ROM trained for structural vibrations (dimensional);
7. a time-domain ROM fluid computation (dimensional);
8. a time-domain ROM aeroelastic computation in which the flow is expressed in a POD basis and the structure is represented by a truncated set of its natural modes (dimensional).

The linearized Euler flow simulations are initialized by a perturbation of the steady-state flow solution around which the linearized flow was computed. This is performed by: a) perturbing a flow parameter such as the angle of attack, Mach number, altitude, or shape of the obstacle and computing a new steady-state solution, then b) specifying the obtained perturbed flow solution in `Input.Perturbed` (see Input). A noteworthy initialization is that in which the perturbed flow corresponds to a shape perturbation induced by a modal displacement of the structure (communicated to the fluid by a ping-pong step). In this case, and in the event of a linearized aeroelastic computation, the structure can be conveniently initialized by the same modal displacement using `Linearized.ExcMode` as explained below.

Currently, a linearized Euler-based aeroelastic simulation can be driven only by a modal source term associated with the structure. For this reason, such a simulation can be performed only in dimensional mode. See Problem.

The syntax of the `Linearized` object is:

```
under Linearized{
  StrModes    =  strmodes-str;
  NumStrModes =  numberstructuralmodes-int;
  ExcMode     =  idmodetobeexcited-int;
  Domain = domain-id;
  InitialCondition = ic-id;
  Amplification = amplitude-real;
  FreqStep    =  frequencystep-real;
  Eps            =  finitedifferenceepsilon-real;
  Tolerance   =  eigensolvertolerance-real;
  NumPOD      =  numberPODmodes-int;
  under Pade { ... }
}
```

with

strmodes-str [`""`]:

Name of the binary file containing the initial mesh position, a set of natural structural frequencies, and the set of fluid mesh positions that are compatible with the corresponding set of natural structural modes. This information is needed to construct a fluid POD basis, a fluid ROM, or an aeroelastic ROM. It can also be used to create a source term to drive a (full-order or reduced-order) linearized unsteady flow simulation. Even when specified, this file is not exploited unless the corresponding entry `NumStrModes` is set to a non-zero positive value.

numberstructuralmodes-int [`0`]:

Specifies the first so-many structural modes to be exploited among those speficied in `StrModes`. If this parameter is set to 0, the `StrMode` file is not exploited even if specified.

idmodetobeexcited-int [`1`]:

This information is processed only when performing a linearized Euler-based aeroelastic simulation to be driven by a source term constructed from a modal input to the underlying structure. It identifies the structural mode to be excited by its relative position in the `StrModes` file. Again, this parameter has no effect if `NumStrModes` is set to 0.

domain-id [`Time`]:

`Time`
: Specifies time-domain integration of the linearized fluid equations when generating snapshots — that is, when `Problem.Type` is set to `PODConstruction` (see Problem).

`Frequency`
: Specifies the solution of the linearized Euler equations in the frequency-domain.

ic-id [`Displacement`]:

`Displacement`
: Specifies that the initial disturbance (excitation) originates from a structural displacement mode. Not needed when *type-id* is set to `PODConstruction` or to `PODInterpolation`. See Problem.

`Velocity`
: Specifies that the initial disturbance (excitation) originates from a structural velocity mode. Not needed

when *type-id* is set to `PODConstruction` or to `PODInterpolation`. See Problem.

amplitude-real [`1.0`]:

Amplification factor for the time-domain initial excitation specified by `ExcMode`.

frequencystep-real [`0`]:

This variable specifies the reduced frequency stepping for the snapshots when constructing a POD basis in the frequency-domain. The first considered reduced frequency is always set to zero. The total number of considered reduced frequencies is given by `MaxIts` of the `Time` object (see Time).

finitedifferenceepsilon-real [`1e-4`]:

Perturbation parameter used for generating by finite-differencing some of the terms governing the linearized fluid equations.

eigensolvertolerance-real [`1e-8`]:

Tolerance for convergence criterion used in the solution of eigen problems associated with the generation of a POD basis.

numberPODmodes-int [`0`]:

When constructing a POD basis directly or by interpolation, this parameter specifies the number of POD modes to be constructed or interpolated between two POD basis vectors. See Problem. In direct mode, `NumPOD` must be smaller than `StrModes`*(2*`MaxIts` + 1). In interpolation mode, `NumPOD` must be smaller or equal to the common size of the two existing POD basis vectors input in `PODData` (see Input). When constructing a ROM, this parameter specifies the first so-many POD basis vectors to use among those specified in `PODData` (see Input).

`Pade`:

Sets the parameters of the Pade-based reconstruction strategy for accelerating the computation of the snapshots during the construction of a POD basis in the frequency domain.

Notes:

1. currently, AERO-FL performs space-discretization using only the second-order MUSCL scheme;
2. currently, AERO-FL computes the gradient of the flux vector with respect to the fluid state vector using only the exact method, and all gradients with respect to mesh motion using finite differencing;
3. currently, AERO-FL performs time-discretization using only the implicit three-point backward difference scheme for the fluid, the implicit midpoint rule for the structure, the A6 staggered procedure for their coupling (see the **AERO-S** user manual), and a constant global time-step. The implicit three-point backward difference scheme for the fluid is initialized in this case using the explicit `RungeKutta2` scheme. As far as time-stepping is concerned, only `TimeStep` and `MaxIts` need be set in the `Time` object (see Time) when running AERO-FL. In this case, the first parameter specifies the time-step — which in this case is held constant because the system is linear — and the second one specifies the number of steps to be performed or half the number of snapshots per modal impulse to be generated. However, all other commands such as the `Newton` command which contains the `LinearSolver` object (see Newton, see LinearSolver) must be specified by the user;
4. currently, AERO-FL saves a constructed POD but not a constructed ROM. The reason is that constructing a POD is computationally far more expensive than constructing a ROM. Starting from a saved POD basis,

AERO-FL builds a ROM on the fly and uses it to perform a time-domain simulation. However, if the user is interested in outputting a ROM for usage by another code such as, for example, MATLAB, the user can request a ROM simulation, set `MaxIts` to zero, and specify a filename in `Postpro.ROM`. In this case, the ROM is built but no time-domain simulation is performed, and the ROM is outputted in the specified output file;

5. AERO-FL's POD construction capability can also be used to construct a POD basis from snapshots collected during previous dimensional or non-dimensional nonlinear simulations and saved in `Postpro.StateVector` (see Postpro);
6. if `Problem.Type` = `PODConstruction` and `Time.Form` = `Descriptor`, the computed POD basis is orthonormal with respect to the matrix of cell volumes A (see Time);
7. if `Problem.Type` = `PODConstruction` and `Time.Form` = `NonDescriptor`, the snapshot computations are performed using the descriptor form of the governing linearized fluid equations (see Time), but the computed POD basis is orthonormal with respect to the identity matrix;
8. if `Problem.Type` = `ROM` or `Problem.Type` = `ROMAeroelastic`, and `Time.Form` = `Descriptor`, the descriptor form of the governing linearized fluid equations is reduced by the specified POD basis, which leads to a ROM that does not suffer from the potential ill-conditioning of the matrix of cell volumes A (see Time);
9. if `Problem.Type` = `ROM` or `Problem.Type` = `ROMAeroelastic`, and `Time.Form` = `NonDescriptor`, the non descriptor form of the governing linearized fluid equations is reduced by the specified POD basis, which leads to a ROM that may suffer from the potential ill-conditioning of the matrix of cell volumes A (see Time) and become unstable. Therefore, it is currently recommended to always use the descriptor form of the equations to be reduced when constructing a POD basis or a ROM.

- Pade

Up: Linearized

4.21.1 PADE-BASED RECONSTRUCTION OF SNAPSHOTS

Object:	**Pade**

When constructing a POD basis in the frequency domain, snapshots are computed by sweeping over a set of reduced frequencies and solving for each one of them a system of equations with multiple right-sides (one right-side per applied structural vibration mode). These frequencies, which are determined by the parameters `Linearized.FreqStep` and `Time.MaxIts`, are referred to here as the "fine reduced frequency points" by analogy with a "fine grid". The snapshot computation can be expedited by a reconstruction strategy that can be described as follows. The user can specify up to 11 coarse reduced frequency points referred to here as the "coarse reduced frequency points", by analogy with a "coarse grid". Then, the snapshots and their successive reduced frequency derivatives are computed at these coarse reduced frequency points only, for all specified structural vibration modes, and reconstructed on the fine reduced frequency points using a multi-point Pade approximation scheme. For each coarse reduced frequency point, the successive reduced frequency derivatives of the snapshots can be obtained by solving the same system of equations governing the snapshot itself but with a different right-side. Hence, the reconstruction strategy described here is most effective when the chosen iterative solver is tailored for systems of equations with multiple right-sides. For this reason, this Pade-based frequency sweep strategy can be activated only when the linear, Krylov-based, iterative solver is Gcr (see LinearSolver).

Furthermore, the polynomial degrees *L* and *M* of the numerator and denominator of the Pade approximation, respectively, must be chosen so that L+M+1 is a multiple of the number of coarse reduced frequency points used at one-time, in order to have a constant number of right-sides per coarse reduced frequency point.

The syntax of the `Pade` object is :

```
under Pade {
Freq1 = freq1-real;
Freq2 = freq2-real;
Freq3 = freq3-real;
Freq4 = freq4-real;
.;
.;
.;
Freq11 = freq11-real;
L = numeratordegree-int;
M = denominatordegree-int;
NumPoints = nptspade-int;
}
```

with

freq1-real [`-1`]:

Value for the first coarse reduced frequency point.

numeratordegree-int [`3`]:

Degree of the polynomial in the numerator of the Pade approximation.

denominatordegree-int [`4`]:

Degree of the polynomial in the denominator of the Pade approximation.

nptspade-int [`0`]:

Number of coarse frequency points exploited at one-time in each Pade approximation.

Note:

1. the coarse reduced frequency points must be specified in ascending order.

Previous: Linearized, Up: Objects

4.22 SENSITIVITY ANALYSIS

Object:	**SensitivityAnalysis**

When `Problem.Type` is set to `SteadySensitivityAnalysis`, the user can request in the object Postpro the computation and output of sensitivities (gradients) of aerodynamic-related quantities q_i with respect to a speficied set of flow and shape parameters s_j , at a steady-state fluid solution specified in `Input.Solution` (see Sensitivities). The object SensitivityAnalysis is used to set the parameters of the underlying sensitivity analysis.

The aerodynamic quantities q_i for which **AERO-F** can evaluate sensitivities $\frac{dq_i}{ds_j}$ at a specified steady-state flow solution are (see Postpro):

1. The aerodynamic forces and moments.

2. The nodal density values.
3. The nodal velocity values.
4. The nodal Mach number values.
5. The nodal temperature values.
6. The nodal pressure values.
7. The nodal total pressure values.
8. The nodal fluid state-vector (conservative variables) values.
9. The nodal mesh displacement values.

The parameters s_j with respect to which **AERO-F** can compute sensitivities $\frac{dq_i}{ds_j}$ at a specified steady-state flow solution are:

1. The free-stream Mach number.
2. The free-stream angle of attack.
3. The free-stream sideslip angle.
4. One or several shape parameters (of the obstacle).

Notes:

1. currently, sensitivities can be computed only when the computational fluid domain is discretized by a tetrahedral mesh, the fluid is modeled as a perfect gas, and turbulence modeling — if any — is performed using the modified form of the Spalart-Allmaras turbulence model, the Detached Eddy Simulation (DES) model, or the k - ϵ turbulence model (see TurbulenceModel); however for the first two turbulence models, the effect of the parameter distance to the wall is not accounted for and therefore the sensitivities may not be accurate when this effect is significant;
2. for a sensitivity analysis, `Problem.Type` must be set to `SteadySensitivityAnalysis`, `Problem.Mode` must be set to `Dimensional`, `FarField.Type` must be set to `StegerWarming`, and `MeshMotion.Type` must be set to `Basic`;
3. performing a sensitivity analysis requires specifying a mesh motion algorithm in MeshMotion in order to determine the interior components of the mesh shape gradients (see Sensitivities);
4. for a sensitivity analysis, the linearized fluid system of equations and the mesh motion equation must be solved very precisely (see Sensitivities);
5. in the presence of a low-mach preconditioner, **AERO-F** automatically sets `Implicit.MatrixVectorProduct` and `Implicit.FiniteDifferenceOrder` to `FiniteDifference` and 2, respectively, for the purpose of sensitivity analysis;
6. in the presence of turbulence modeling, **AERO-F** automatically sets `Implicit.TurbulenceModelCoupling` to `Strong` and `Implicit.MatrixVectorProduct` to `FiniteDifference` for the purpose of sensitivity analysis;
7. when `Implicit.MatrixVectorProduct` is set to `Approximate`, **AERO-F** automatically changes this setting to `FiniteDifference` for the purpose of sensitivity analysis.

The syntax of the object `SensitivityAnalysis` is:

```
under SensitivityAnalysis{
  SensitivityComputation = sensitivitycomputation-id;
  SensitivityMesh        = sensitivitymesh-flag;
  SensitivityMach        = sensitivityMach-flag;
  SensitivityAlpha       = sensitivityalpha-falg;
  SensitivityBeta        = sensitivitybeta-flag;
  EpsFD                  = epsfd-real;
  under LinearSolver{ ... }
}
```

with

sensitivitycomputation-id [`Analytical`]

`Analytical`
: Requests the analytical computation of the derivatives appearing in the right-hand side of the linearized fluid system of equations and of the gradients of the aerodynamic forces and moments with respect to the specified flow and shape parameters (see Sensitivities). This option is not supported for turbulent flows modeled using the Spalart-Allmaras or DES model.

`SemiAnalytical`
: Requests the approximation by the second-order central finite difference method of the derivatives appearing in the right-hand side of the linearized fluid system of equations, and the analytical computation of the gradients of the aerodynamic forces and moments with respect to the specified flow and shape parameters (see Sensitivities). This option is not supported for turbulent flows modeled using the Spalart-Allmaras or DES model.

`FiniteDifference`
: Requests the approximation by the second-order central finite difference method of the derivatives appearing in the right-hand side of the linearized fluid system of equations and of the gradients of the aerodynamic forces and moments with respect to the specified flow and shape parameters (see Sensitivities).

sensitivitymesh-flag [`Off`]

`On`
: This flag setting specifies that the computation of the sensitivities requested in Postpro be (also) performed with respect to shape parameters s_j . The user does not need to specifiy these shape parameters directly.

  Instead, the user should specify in this case the wall boundary components of the mesh shape gradients in the binary file inputted in `Input.ShapeDerivative` (see Sensitivities). Failure to input this binary file results in skipping the computation of the sensitivities requested in Postpro with respect to any shape parameter.

`Off`
: In this case, no sensitivity requested in Postpro is computed with respect to a shape parameter.

sensitivityMach-flag [`Off`]

`On`
: This flag setting specifies that the computation of the sensitivities requested in Postpro be (also) performed with respect to the free-stream Mach number.

`Off`
: In this case, no sensitivity requested in Postpro is computed with respect to the free-stream Mach number.

sensitivityalpha-flag [`Off`]

`On`
: This flag setting specifies that the computation of the sensitivities requested in Postpro be (also) performed with respect to the free-stream angle of attack.

`Off`
: In this case, no sensitivity requested in Postpro is computed with respect to the free-stream angle of attack.

sensitivitybeta-flag [`Off`]

`On`

This flag setting specifies that the computation of the sensitivities requested in Postpro be (also) performed with respect to the free-stream sideslip angle.

`Off`

In this case, no sensitivity requested in Postpro is computed with respect to the free-stream sideslip angle.

epsfd-real [`1e-5`]

Scalar defining the magnitude of the perturbation performed when approximating a derivative by the second-order central finite difference method.

`LinearSolver`:

Specifies the linear equation solver (and its parameters) to be used for solving the

- LinearSolver

Next: Running Aero-F, Previous: Objects

5 EXAMPLES

- Steady flow computation
- Unsteady aeroelastic computation
- Full order linearized
- POD basis
- ROM simulation

Next: Unsteady aeroelastic computation, Up: Examples

5.1 STEADY FLOW COMPUTATION

First, the computation of a steady-state inviscid flow around a three-dimensional wing is examplified.

```
/* ----------------------------
   File ``wing.steady''
---------------------------- */

under Problem {
  Type = Steady;
  Mode = NonDimensional;
}

under Input {
  Prefix = "data/";
  Connectivity = "wing.con";
  Geometry = "wing.msh";
  Decomposition = "wing.dec";
  CpuMap = "wing.4cpu";
}

under Output {
  under Postpro {
    Prefix = "result/";
    Residual = "wing.res";
    Force = "wing.lift";
    Mach = "wing.mach";
    Frequency = 0;
  }
  under Restart {
    Prefix = "result/";
    Solution = "wing.sol";
    RestartData = "wing.rst";
    Frequency = 0;
  }
}

Equations.Type = Euler;

under BoundaryConditions {
  under Inlet {
    Mach = 0.5;
    Alpha = 0.0;
    Beta = 0.0;
  }
}

under Space {
  under NavierStokes {
    Reconstruction = Linear;
    Gradient = Galerkin;
  }
}

under Time {
  MaxIts = 10;
  Eps = 1.e-6;
  Cfl0 = 10.0;
  CflMax = 1.e99;
  Ser = 1.0;
  under Implicit {
    MatrixVectorProduct = FiniteDifference;
    under Newton {
      MaxIts = 1;
      under LinearSolver {
        under NavierStokes {
          Type = Gmres;
          MaxIts = 30;
          KrylovVectors = 30;
          Eps = 0.05;
          Preconditioner.Type = Ras;
        }
      }
    }
  }
}
```

Next: Full order linearized, Previous: Steady flow computation, Up: Examples

5.2 UNSTEADY AEROELASTIC COMPUTATION

Next, the aeroelastic computation of an inviscid flow around a three-dimensional wing is examplified.

```
/* ----------------------------
   File ``wing.aero''
---------------------------- */

Problem.Type = UnsteadyAeroelastic;
```

```
under Input {
  Prefix = "data/";
  Connectivity = "wing.con";
  Geometry = "wing.msh";
  Decomposition = "wing.dec";
  CpuMap = "wing.4cpu";
  Matcher = "wing.match";
  Solution = "pingpong/wing.sol";
  Position = "pingpong/wing.pos";
}

under Output {
  under Postpro {
    Prefix = "result/";
    Force = "wing.lift";
    Mach = "wing.mach";
    Displacement = "wing.disp";
    Frequency = 10;
  }
  under Restart {
    Prefix = "result/";
    Solution = "wing.sol";
    Position = "wing.pos";
    RestartData = "wing.rst";
  }
}

Equations.Type = Euler;

under BoundaryConditions {
  under Inlet {
    Mach = 0.901;
    Alpha = 0.0;
    Beta = 0.0;
    Density = 1.117e-7;
    Pressure = 11.0;
  }
}

under Space {
  under NavierStokes {
    Reconstruction = Linear;
    Limiter = VanAlbada;
    Gradient = Galerkin;
    Beta = 0.3333333;
  }
}

under Time {
  Cfl0 = 1.e5;
  CflMax = 1.e5;
  under Implicit {
    Type = ThreePointBackwardDifference;
    MatrixVectorProduct = Approximate;
    under Newton {
      MaxIts = 2;
      Eps = 0.01;
      under LinearSolver {
        under NavierStokes {
          Type = Gmres;
          MaxIts = 30;
          KrylovVectors = 30;
          Eps = 0.01;
          Preconditioner.Type = Ras;
        }
      }
    }
  }
}

under MeshMotion {
  Type = Basic;
  Element = TorsionalSprings;
  under Newton {
    MaxIts = 1;
    under LinearSolver {
      Type = Cg;
      MaxIts = 50;
      Eps = 0.001;
      Preconditioner.Type = Jacobi;
    }
  }
}
```

Next: POD basis, Previous: Unsteady aeroelastic computation, Up: Examples

5.3 FULL-ORDER LINEARIZED AEROELASTIC COMPUTATION

Next, the full-order linearized aeroelastic computation of an inviscid flow around a three-dimensional wing is examplified.

```
/* ----------------------------
   File ``wing.full''
---------------------------- */
under Problem {
  Type = UnsteadyLinearized;
  Mode = Dimensional;
}

under Input {
  Prefix = "InputFiles.d/";
  Connectivity = "pp.con";
  Geometry = "pp.msh";
  Decomposition = "pp.dec";
  CpuMap = "pp.4cpu";

  Perturbed = "agard.m0.678.deformed.lsq.steady.sol";
  Solution = "agard.m0.678.nodisp.lsq.steady.sol";
  Position = "agard.undisp.pp.pos";
}

under Output {
  under Postpro {
    Prefix = "";
    Force = "liftfull4.m0.678.p34_5";
    Frequency = 1;
  }
}

under Linearized{
  StrModes = "modes1.pp";
  NumStrModes = 4;
  ExcMode = 1;
  Domain = Time;
  Amplification = 0.1;
  Eps = 1e-4;
}
```

```
under Equations {
  Type = Euler;
}

under BoundaryConditions {
  under Inlet {
    Mach = 0.678;
    Density = 2.338e-7;
    Pressure = 34.5;
    Alpha = 0.0;
    Beta = 0.0;
  }
}

under Space  {
  under NavierStokes {
    Reconstruction = Linear;
    Limiter = VanAlbada;
    Gradient = LeastSquares;
    Beta = 0.33333333;
  }
}

under Time {
  Type = Implicit;
  TypeTimeStep = Global;
  TimeStep = .001;
  MaxIts = 200;
  Eps = 1.e-8;
  under Implicit {
    MatrixVectorProduct = Exact;

    under Newton {
      MaxIts = 1;
      Eps = 0.0001;
      under LinearSolver {
        under NavierStokes {
          Type = Gmres;
          MaxIts = 100;
          KrylovVectors = 100;
          Eps = 0.0001;
          Output = "stdout";
          under Preconditioner { Type = Ras; Fill = 0; }
        }
      }
    }
  }
}
```

Next: ROM simulation, Previous: Full order linearized, Up: Examples

5.4 CONSTRUCTING A POD BASIS

Next, the construction of a POD basis in the frequency-domain for a three-dimensional wing operating at M = 0.901 is examplified.

```
/* -----------------------------
   File ``wing.pod''
----------------------------- */
under Problem {
  Type = PODConstruction;
  Mode = Dimensional;
}

under Input {
  Prefix = "InputFiles.d/";
  Connectivity = "pp.con";
  Geometry = "pp.msh";
  Decomposition = "pp.dec";
  CpuMap = "pp.4cpu";

  Solution = "agard.m0.901.nodisp.lsq.steady.sol";
  Position = "agard.undisp.pp.pos";
}

under Output {
  under Postpro {
    Prefix = "";
    Frequency = 0;
    PodData = "PodData.d/podVecs4.freq0.901.df5e3.150snap.400pod";
  }
}

under Linearized{
  StrModes = "modes1.pp";
  NumStrModes = 4;
  Domain = Frequency;
  FreqStep = 0.005;
  Eps = 1e-5;
  NumPOD = 400;
}

under Equations {
  Type = Euler;
}

under BoundaryConditions {
  under Inlet {
    Mach = 0.901;
    Density = 1.117e-7;
    Pressure = 5.0;
    Alpha = 0.0;
    Beta = 0.0;
  }
}

under Space  {
  under NavierStokes {
    Reconstruction = Linear;
    Gradient = LeastSquares;
    Beta = 0.33333333;
  }
}

under Time  {
  Type = Implicit;
  TypeTimeStep = Global;
  TimeStep = 4.0e-5;
  MaxIts = 151;
  Eps = 1.e-8;
  under Implicit {
    MatrixVectorProduct = Exact;

    under Newton {
      MaxIts = 1;
      Eps = 1e-8;
      under LinearSolver {
        under NavierStokes {
          Type = Gmres;
          MaxIts = 100;
          KrylovVectors = 100;
          Eps = 0.0001;
          Output = "stdout";
          under Preconditioner { Type = Ras; Fill = 0; }
        }
      }
    }
  }
}
```

Previous: POD basis, Up: Examples

5.5 REDUCED-ORDER AEROELASTIC COMPUTATION

Next, a ROM aeroelastic computation of a wing operating at M = 0.800 is examplified.

```
/* ----------------------------
   File ``wing.rom''
---------------------------- */
under Problem {
  Type = ROMAeroelastic;
  Mode = Dimensional;
}

under Input {
  Prefix = "InputFiles.d/";
  Connectivity = "pp.con";
  Geometry = "pp.msh";
  Decomposition = "pp.dec";
  CpuMap = "pp.4cpu";

  Perturbed = "agard.m0.800.deformed.lsq.steady.sol";
  Solution = "agard.m0.800.nodisp.lsq.steady.sol";
  Position = "agard.undisp.pp.pos";

  PodData = "../PodData.d/podVecs4.m0.800.dt4e5.225snap.300pod";
}

under Output {
  under Postpro {
    Prefix = "";
    Force = "liftrom.freq800.30snap.50of100pod.p7";
    Frequency = 1;
  }
}

under Linearized{
  StrModes = "modes1.pp";
  NumStrModes = 4;
  ExcMode = 1;
  Amplification = 0.1;
  Eps = 1e-4;
  NumPOD = 300;
}

under Equations {
  Type = Euler;
}
```

```
under BoundaryConditions {
  under Inlet {
    Mach = 0.800;
    Density = 1.117e-7;
    Pressure = 10.0;
    Alpha = 0.0;
    Beta = 0.0;
  }
}

under Space  {
  under NavierStokes {
    Flux = Roe;
    Reconstruction = Linear;
    Gradient = LeastSquares;
    Beta = 0.33333333;
  }
}

under Time  {
  Type = Implicit;
  TypeTimeStep = Global;
  TimeStep = .001;
  MaxIts = 500;
  Eps = 1.e-8;
  under Implicit {
    MatrixVectorProduct = Exact;

    under Newton {
      MaxIts = 1;
      Eps = 1e-8;
      under LinearSolver {
        under NavierStokes {
          Type = Gmres;
          MaxIts = 100;
          KrylovVectors = 100;
          Eps = 0.0001;
          under Preconditioner { Type = Ras; Fill = 0; }
        }
      }
    }
  }
}
```

Next: Running AERO-FL, Previous: Examples

6 RUNNING AEROF

AERO-F has no graphical interface. It is a command-line driven program that reads a problem definition file once at the beginning of the processing. This problem definition file is a regular ASCII text file (see Object oriented input).

Calls for simulations involving only AERO-F look like

```
mpirun [host_name] nb_cpus aerof filename
```

where *host_name* is the (optional) name of the computer on which the job is executed, *number_cpus* is the number of processes allocated for the job, and *filename* is the ASCII file containing the problem definition.

Aeroelastic and aerothermal simulations require the interaction of AERO-F with a structural code. If AERO-S or AERO-H is used for that purpose, aeroelastic and aerothermal calls look like

```
mpirun [fluid_host_name] fluid_nb_cpus aerof fluid_filename :
[struct_host_name] struct_nb_cpus aeros struct_filename
```

If the above syntax is not supported by your MPI implementation, the same simulation can be started with

```
mpirun [host_name] total_nb_cpus loader fluid_nb_cpus aerof.so fluid_filename ,
struct_nb_cpus aeros.so struct_filename
```

Aerothermoelastic simulations require the interaction of AERO-F with a structural code and a heat transfer code. If AERO-S and AERO-H are used for that purpose, aerothermoelastic calls look like

```
mpirun [fluid_host_name] fluid_nb_cpus aerof fluid_filename :
[struct_host_name] struct_nb_cpus aeros struct_filename :
[heat_host_name] heat_nb_cpus aeros heat_filename
```

If the above syntax is not supported by your MPI implementation, the same simulation can be started with

```
mpirun [host_name] total_nb_cpus loader fluid_nb_cpus aerof.so fluid_filename ,
struct_nb_cpus aeros.so struct_filename , heat_nb_cpus aeros.so heat_filename
```

- ExampleSteadyFlowComputation
- ExampleUnsteadyFlowComputation
- ExampleForcedOscillationsComputation
- ExampleUnsteadyAeroelasticComputation

Next: ExampleUnsteadyFlowComputation, Up: Running Aero-F

6.1 STEADY FLOW COMPUTATION

A steady-state flow computation is selected by setting `Problem.Type = Steady`. By default, the computation starts from a uniform flowfield around the undeformed configuration. To modify this behavior, `Input.Solution` and `Input.Position` must be set to some appropriate values. The other critical variables to watch for are the total number of time-steps (`Time.MaxIts`), the spatial residual relative decrease (`Time.Eps`), and the inital and maximum CFL numbers (`Time.Cfl0` and `Time.CflMax`). As a first-order time-integrator is always selected for steady-state computations, only one Newton iteration (`Time.Implicit.Newton.MaxIts`) should be performed at every time-step.

Next: ExampleForcedOscillationsComputation, Previous: ExampleSteadyFlowComputation, Up: Running Aero-F

6.2 UNSTEADY FLOW COMPUTATION

An unsteady flow computation is selected by setting `Problem.Type = Unsteady`. By default, the computation starts from a uniform flowfield around the undeformed configuration. To modify this behavior, `Input.Solution` and `Input.Position` must be set to some appropriate values. The other critical variables to watch for are the time-step (`Time.TimeStep`) or alternatively the CFL strategy, the maximum number of time-steps and the maximum time (`Time.MaxIts` and `Time.MaxTime`), and the type of time-integrator (`Time.Implicit.Type`). At least two Newton iterations (`Time.Implicit.Newton.MaxIts`) should be performed at every time-step to preserve the accuracy of the time-integrator.

Next: ExampleUnsteadyAeroelasticComputation, Previous: ExampleUnsteadyFlowComputation, Up: Running

Aero-F

6.3 FORCED OSCILLATIONS COMPUTATION

A forced oscillations computation is selected by setting `Problem.Type = Forced`. In addition to what applies to an unsteady flow computation (see ExampleUnsteadyFlowComputation), the critical variables to watch for are the forced oscillations parameters (`Forced`) and the mesh motion algorithm (`MeshMotion`). During such a flow computation, the shape of the obstacle shape is varied between the final shape (`Forced.Position`) and its symmetric position with respect to the original shape. Note that the computation starts from the original shape. The latter that can be generated by a “ping-pong” step (see ExampleUnsteadyAeroelasticComputation).

Previous: ExampleForcedOscillationsComputation, Up: Running Aero-F

6.4 UNSTEADY AEROELASTIC COMPUTATION

Aeroelastic computations using AERO-F require the additional usage of a structure solver that is equipped to communicate with this flow solver, and a fluid-structure preprocessor that is capable of generating the data structures necessary for exchanging aeroelastic data between the fluid and structural codes. If AERO-S and MATCHER are used for that purpose, an aeroelastic simulation is usually (but not necessarily) carried out in the following three steps:

1. a “ping-pong” step to transmit to AERO-F the initial deformation of the flexible obstacle. This step is performed like a true aeroelastic computation (see below) and is requested by setting the AERO command in the AERO-S input file to PP. The critical variables to watch for are the mesh motion algorithm (`MeshMotion`) and the position of the deformed obstacle (`Output.Restart.Position`) that will be needed for the next two steps;
2. a steady-state flow computation around the deformed obstacle configuration (see ExampleSteadyFlowComputation). This is a recommended but not mandatory step of an aeroelastic simulation;
3. an unsteady flow computation around the moving and deforming obstacle. Such a computation is performed by setting `Problem.Type` to `UnsteadyAeroelastic`. The critical variables to watch for are the initial flow solution and node position (`Input.Solution` and `Input.Position`) obtained from the two previous steps, the time-step (`Time.TimeStep`) or alternatively the CFL strategy, the type of time-integrator (`Time.Implicit.Type`), and the mesh motion algorithm (`MeshMotion`). Note that to avoid subcycling (i.e. performing several fluid time-steps during one structural time-step), the CFL number (`Time.Cfl0` and `Time.CflMax`) needs to be set to a large value (e.g. `1.e5`);

Next: Restarting AERO-F, Previous: Running Aero-F

7 RUNNING AEROFL

The linearized fluid code may be used for a variety of purposes including the following:

1. conducting a time-domain linearized flow simulation possibly coupled to a (currently modalized) vibrating structure;
2. constructing a time- or frequency-domain POD basis;
3. interpolating a POD basis from previously computed ones;
4. constructing an aeroelastic ROM in the frequency domain;
5. conducting a time-domain aeroelastic ROM simulation in which the structure is modalized;

All of the above running modes require performing first one or several simulations aimed at generating a reference equilibrium solution. Next, in order to perform any of the computations listed above, the following parameters must be specified under `Problem` (see Problem) and `Linearized` (see Linearized).

1. To conduct full-order linearized simulations, set `Type` in `Problem` to `UnsteadyLinearized` or `UnsteadyLinearizedAeroelastic`. In the latter case, represent the structure by a set of modes (currently) by setting appropriately `Linearized.StrModes` and `Linearized.NumStrModes`, and excite it by setting appropriately `Linearized.ExcMode` and `Linearized.Amplification`. Do not forget to input the information needed for initializing the flow perturbation by specifying `Input.Perturbed`.
2. To construct a POD basis, set `Type` in `Problem` to `PODConstruction`. The construction process requires sources of excitation. Currently, these sources are modal impulses of the structure. For this reason, set appropriately `Linearized.StrModes`, `Linearized.NumStrModes`, `Linearized.Amplification`, and `Time.MaxIts`. The latter parameter specifies half the number of snapshots per modal impulse. The POD basis may be constructed in either the time- or frequency-domain; this is specified in `Domain` (see Linearized). To accelerate the construction of a POD basis in the frequency-domain, consider the Pade reconstruction strategy defined under the `Pade` object. Do not forget to specify in `NumPOD`, the number of desired POD basis vectors. To interpolate a POD basis, set `Type` in `Problem` to `PODInterpolation`. Use `Input.PODData` to specify the two sets of POD basis vectors and their respective Mach numbers to be used in the interpolation process (see Input); also, input the desired Mach interpolation point. Specify the desired POD output file in `Postpro.PODData`.
3. To construct a fluid ROM, set `Type` in `Problem` to `ROM` and `Domain` in `Linearized` to `Time`, and set `Input.PODData` and `Linearized.NumPOD` appropriately. Set `Time.MaxIts` to zero if you want AERO-FL to exit after constructing the ROM, or to a non zero value if you desire a time-domain simulation using this ROM. Do not forget to specify the desired output file in `Postpro.ROM`.
4. To construct an aeroelastic ROM, set `Type` in `Problem` to `ROMAeroelastic` and `Domain` in `Linearized` to `Time`, and set `Input.PODData` and `Linearized.NumPOD` appropriately. Represent the structure by a set of modes by specifying also appropriately `Linearized.StrModes` and `Linearized.NumStrModes`. Set `Time.MaxIts` to zero if you want AERO-FL to exit after constructing the aeroelastic ROM, or to a non zero value if you desire a time-domain simulation using this aeroelastic ROM. Do not forget to specify the desired output file in `Postpro.ROM`.
5. To conduct a fluid ROM simulation, set `Type` in `Problem` to `ROM`. Also, specify the POD basis using `Input.PODData` and `Linearized.NumPOD`. Do not forget to input the information needed for initializing the flow perturbation by specifying `Input.Perturbed`.
6. To conduct aeroelastic ROM simulations, set `Type` in `Problem` to `ROMAeroelastic`. Specify the POD basis using `Input.PODData` and `Linearized.NumPOD`. Do not forget to input the information needed for initializing the flow perturbation by specifying `Input.Perturbed`. Represent the structure by a set of modes (currently) by setting appropriately `Linearized.StrModes` and `Linearized.NumStrModes`, and excite it by setting appropriately `Linearized.ExcMode` and `Linearized.Amplification`.

Next: Restarting Aero-FL, Previous: Running AERO-FL

8 RESTARTING AEROF

For all flow simulations, AERO-F can restart from a previous run that was successfully completed. AERO-F can also restart from a previous run that was for some reason interrupted (i.e. computer crash) if the value of `Output.Restart.Frequency` was different from zero. In both cases, in order to restart AERO-F, the variables `Input.Solution`, `Input.Position` (if applicable) and `Input.RestartData` need to be set to their appropriate values (i.e. the ones used in the object `Output.Restart` of the previously completed or interrupted run). For example, an initial input file used for an aeroelastic simulation should contain

```
under Output {
  under Restart {
    Solution = "wing.sol";
    Position = "wing.pos";
    RestartData = "wing.rst";
  }
}
```

To restart the aeroelastic simulation, the second input file should contain

```
under Input {
  Solution = "wing.sol";
  Position = "wing.pos";
  RestartData = "wing.rst";
}
```

and can also contain in `Output.Restart` the information necessary to save future restart data.

Notes:

1. there is no need to copy any of the output files (specified in `Output.Postpro`) since the restart appends the data to the original (ASCII and binary) files;
2. it is currently not allowed to change the output frequency `Output.Postpro.Frequency` nor to change the name of the output files nor to add other output files (in `Output.Postpro`) when restarting a simulation. This restriction does not exist if the variable `Input.RestartData` is not set. In that case, the run restarts from a previous solution `Input.Solution` and a previous position `Input.Position` (if applicable) but the time-step number and the physical time are reset to zero;
3. as mentioned in Restart, the value of the restart frequency `Output.Restart.Frequency` must be specified in the AERO-S input file in the case of an aerothermal, aeroelastic, or aerothermoelastic simulation with the AERO-S code;
4. the variable `Input.RestartData` should not be used when starting an aeroelastic simulation from a pre-computed steady-state of the flow-field because it de-synchronizes in this case AERO-F and the structural solver.

Next: Hints and tips, Previous: Restarting AERO-F

9 RESTARTING AEROFL

Currently, AERO-FL cannot run in restart mode.

Next: ROM, Previous: Restarting Aero-FL

Appendix A HINTS AND TIPS

- Decompose the mesh in many subdomains to be able to run a simulation with the same input files but with a different number of processors.
- Terminate the execution of AERO-F with

  ```
  kill -USR1 pid
  ```

  where *pid* is the process identification number of one of the AERO-F processes. Once the kill signal is sent to AERO-F, it exits at the next time-iteration.

- Create binary files from ASCII **XPost** files by using the SOWER program:

```
sower -fluid -split -con <connectivity file>
-mesh <mesh file prefix> -result <ASCII file> -ascii
-output <binary file prefix>
```

- Install the info version of this user's guide. On your (Unix) system, this can be achieved by 1) copying the aerof.info file to the place where your info files live (usually /usr/local/info), and 2) issuing the command install-info /usr/local/info/aerof.info /usr/local/info/dir. You will then be able to access the documentation with the command info aerof. Note that particular sections ("nodes") can be accessed directly. For example, info aerof Problem will take you directly to the definition of the `Problem` object.

Next: DESMESH, Previous: Hints_and_tips

Appendix B ROM OUTPUT FORMAT

AERO-FL can output in ASCII format either a fluid ROM, or an aeroelastic ROM. This appendix characterizes the ROM in each case and describes the format of the corresponding output.

- Fluid ROM
- Aeroelastic ROM

Next: Aeroelastic ROM, Up: ROM

B.1 FLUID ROM

In this case, the outputted ROM matrix is an $n_f \times n_f$ POD-based, real, full matrix $\tilde{\mathbf{H}}$ whose exploitation may require first its dimensionalization as follows

$$\mathbf{H}(p_\infty, \rho_\infty) = \sqrt{\frac{p_\infty}{\rho_\infty}}\ \tilde{\mathbf{H}}$$

where p_∞ and ρ_∞ denote the free-stream pressure and density, respectively. In other words, $\tilde{\mathbf{H}}$ does not contain information about the altitude whereas $\mathbf{H}$ does.

The adjusted ROM matrix $\mathbf{H}$ governs the reduced perturbed equations of equilibrium

$$(\mathbf{w})_{,t} + \mathbf{H}\mathbf{w} = 0$$

where $\mathbf{w}$ denotes the perturbation of the reduced-order fluid state vector about a steady-state operating point and $_{,t}$ denotes a time-derivative. Note that whether the descriptor or non descriptor form of the governing higher-dimensional (“full order”) fluid equations have been reduced (see Time and Linearized), the adjusted ROM matrix $\mathbf{H}$ governs in both cases the non descriptor form of the reduced order fluid equations.

The matrices $\mathbf{H}$ and $\tilde{\mathbf{H}}$ can be exploited at least in the following ways:

- In principle, $\mathbf{H}$ can be used for a time-domain simulation assuming that an appropritate initial condition is specified. However, providing an initial condition for the above equation is not an intuitive task (unlike a modal coordinate system in the case of a structure). A straightforward approach for constructing a meaningful initial condition consists of gaining access to the POD basis that was used for computing $\mathbf{H}$ and projecting a meaningful full order initial condition onto this reduced basis.

- Alternatively, $\tilde{\mathbf{H}}$ can be used to investigate the stability of the fluid system. If all the real parts of its eigenvalues are positive, the fluid system is stable for all free-stream densities and pressures.

The output format of $\tilde{\mathbf{H}}$ is as follows:

- n_f 0 (line 1)
- Row 1 of $\tilde{\mathbf{H}}$ (line 2)
- Row 2 of $\tilde{\mathbf{H}}$ (line 3)
- $\vdots$
- Row n_f of $\tilde{\mathbf{H}}$ (line n_f + 1)

For example, the following MATLAB code can read in this case the ROM output file:

```
M=readRom('filename');
function [N] = readRom(fn)
line1 = dlmread(fn,' ',[0 0 0 1]);
N=dlmread(fn, ' ', [1 0 line1(1)+2*line1(2) line1(1)+2*line1(2)-1]);
```

Previous: Fluid ROM, Up: ROM

B.2 AEROELASTIC ROM

In this case, the outputted ROM consists of the following 3×3 block, real matrix $\tilde{\mathbf{N}}$

$$\tilde{\mathbf{N}} = \left| \begin{array}{ccc} -\tilde{\mathbf{H}} & -\mathbf{B_m} & -\tilde{\mathbf{C}}_\mathbf{m} \\ \tilde{\mathbf{P}}_\mathbf{m} & 0 & -\mathbf{\Omega}^2 \\ 0 & \mathbf{I}_s & 0 \end{array} \right|$$

which does not depend on the free-stream pressure and density — and therefore on altitude — and whose exploitation may first require its dimensionalization as follows

$$\mathbf{N}(p_\infty, \rho_\infty) = \left| \begin{array}{ccc} -\sqrt{\frac{p_\infty}{\rho_\infty}}\,\tilde{\mathbf{H}} & -\mathbf{B_m} & -\sqrt{\frac{p_\infty}{\rho_\infty}}\,\tilde{\mathbf{C}}_\mathbf{m} \\ p_\infty\,\tilde{\mathbf{P}}_\mathbf{m} & 0 & -\mathbf{\Omega}^2 \end{array} \right|$$

$$\Big| \qquad \mathbf{0} \qquad \mathbf{I}_s \qquad \mathbf{0} \qquad \Big|$$

where p_∞ and ρ_∞ denote the free-stream pressure and density at the desired altitude, respectively,

$$\mathbf{P_m} = p_\infty \tilde{\mathbf{P}}_\mathbf{m} = \mathbf{X^T}(\partial \mathbf{f^{ext}}/\partial \mathbf{w})$$

and

- $\tilde{\mathbf{H}}$ is as in the previous case the $n_f \times n_f$, real fluid ROM matrix
- $\mathbf{H}(p_\infty, \rho_\infty) = \sqrt{p_\infty/\rho_\infty}\tilde{\mathbf{H}}$ is the corresponding $n_f \times n_f$, real, dimensional, adjusted fluid ROM matrix
- $\mathbf{B_m}$ and $\mathbf{C_m} = \sqrt{p_\infty/\rho_\infty}\tilde{\mathbf{C}}_m$ are two $n_f \times n_s$ fluid/structure coupling matrices
- $\mathbf{X}$ is the matrix of natural mode shapes of the dry structure (in this case, without the rotational degrees of freedom), $\mathbf{f^{ext}}$ is the vector of aerodynamic loads and $\mathbf{w}$ is the state vector of the fluid system
- $\mathbf{P_m} = p_\infty \tilde{\mathbf{P}}_\mathbf{m}$ is an $n_s \times n_f$ load transfer matrix
- $\mathbf{\Omega}^2$ is an $n_s \times n_s$ diagonal matrix storing the squares of the structural natural circular frequencies
- $\mathbf{I}_s$ is the $n_s \times n_s$ identity matrix

The adjusted ROM matrix $\mathbf{N}$ governs the non descriptor form of the perturbed dimensional equations of equilibrium

$$\dot{\mathbf{q}} = \mathbf{Nq}$$

where

$$\mathbf{q} = [\qquad \mathbf{w} \qquad \dot{\mathbf{u}}_\mathbf{m} \qquad \mathbf{u_m} \qquad]^T$$

is the aeroelastic state vector consisting of the perturbation of the reduced-order fluid state vector about an operating point, the structural modal displacements, and structural modal velocities.

The blocks of $\mathbf{N}$ govern the following system of coupled, fluid/structure equations

$$(\mathbf{w})_{,t} + \mathbf{Hw} + \mathbf{B_m}\dot{\mathbf{u}}_\mathbf{m} + \mathbf{C_m u_m} = 0$$
$$\mathbf{I}_s \ddot{\mathbf{u}}_\mathbf{m} + \mathbf{\Omega}^2 \mathbf{u_m} = \mathbf{P_m w}$$

where the dot and the $_{,t}$ represent both a derivative with respect to time.

The matrix $\mathbf{N}$ can be exploited at least in the following ways:

- The eigenvalue analysis of $\mathbf{N}$ determines the stability of the aeroelastic system for the flight conditions defined by p_∞ and ρ_∞ . Altitude sweeps are simply performed by changing appropriately the values of the free-stream pressure and density in $\mathbf{N}$.
- The matrix blocks of $\mathbf{N}$ may be used to form the above system of equations. The aeroelastic ROM can then be used for time-domain simulations provided that initial conditions are specified for $\mathbf{u_m}$ and $\mathbf{w}$ (see related comment in section describing the fluid ROM output).

The output format of $\tilde{\mathbf{N}}$ is as follows:

- n_f n_s (line 1)
- Row 1 of $\tilde{\mathbf{N}}$ (line 2)
- Row 2 of $\tilde{\mathbf{N}}$ (line 3)
- $\vdots$
- Row n_f of $\tilde{\mathbf{N}}$ (line $n_f + 2n_s + 1$)

For example, the following MATLAB code can read in this case the ROM output file — that is, the matrix $\tilde{\mathbf{N}}$:

```
[N,nf,ns]=readRom('filename');

function [N,nf,ns] = readRom(fn)
line1 = dlmread(fn,' ',[0 0 0 1]);
endOfN = line1(1)+2*line1(2);
endCol = line1(1)+2*line1(2)-1;
N=dlmread(fn, ' ', [1 0 endOfN endCol]);
nf = line1(1);
ns = line1(2);
```

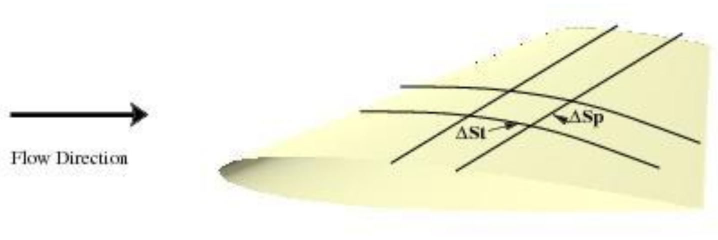
Furthermore, the following MATLAB code can read the ROM output file and output the dimensionalized matrix $\mathbf{N}$ for specified values of p_∞ and ρ_∞ :

```
[N,nf,ns] = readRom('filename',p_inf,rho_inf)

function [N,nf,ns] = readRom(fn,p_inf,rho_inf)
line1 = dlmread(fn,' ',[0 0 0 1]);
endOfN = line1(1)+2*line1(2);
endCol = line1(1)+2*line1(2)-1;
Ntilde = dlmread(fn, ' ', [1 0 endOfN endCol]);
nf = line1(1);
ns = line1(2);


N(1:nf,1:nf)                = sqrt(p_inf/rho_inf) ...
                                  *Ntilde(1:nf,1:nf);
N(1:nf,nf+1:nf+ns)          = Ntilde(1:nf,nf+1:nf+ns);
N(1:nf,nf+ns+1:nf+2*ns)     = sqrt(p_inf/rho_inf) ...
                                  *Ntilde(1:nf,nf+ns+1:nf+2*ns);
N(nf+1:nf+ns,1:nf)          = p_inf*Ntilde(nf+1:nf+ns,1:nf);
N(nf+1:nf+ns,nf+1:nf+2*ns) = Ntilde(nf+1:nf+ns,nf+1:nf+2*ns);
N(nf+ns+1:nf+2*ns,:)        = Ntilde(nf+ns+1:nf+2*ns,:);
```

Next: TAB, Previous: ROM

Appendix C DETACHED EDDY SIMULATIONS (DES): MESH REQUIREMENTS

Detached Eddy Simulation (DES) is a hybrid (zonal) turbulence model that employs a RANS type closure close to the wall (in the boundary-layer) and a LES type closure in the detached shear layer. This approach surmounts the expensive problem of having to resolve the thin boundary-layer by traditional LES means. Hence, DES aims at achieving best of both worlds, by making use of the reliability of the RANS model in predicting boundary-layer separation points and by resolving the effect of the separated shear layers using a subgrid scale LES model.



In AERO-F, a DES procedure based on the the Spalart-Allmaras (SA) one-equation model is implemented. DES uses a mesh dependent length scale to switch between the RANS and LES domains. More specifically, the length scale (l_{DES}) of the DES model is computed in each tetrahedron T_I as

$$l_{DES}(T_I) = \min\left(d_{wall}(T_I), C_{DES}\Delta(T_I)\right)$$

with

$$\Delta = \max_{e \in T_I}\left(meas(e)\right)$$

where, d_{wall} is the shortest distance to the wall from the centroid of tetrahedron T_I , C_{DES} is the DES model constant and e is an edge of tetrahedron T_I . The value of the model constant is set to $C_{DES} = 0.65$ after calibration with homogeneous isotropic turbulence. If $l_{DES} = d_{wall}$ then the RANS model is active and if

$l_{DES} = C_{DES}\Delta$ then the LES model is active.

Hence, when creating a mesh for DES simulations, one has to adhere to the following details:

1. Create a surface mesh such that its streamwise (ΔSt) and spanwise (ΔSp) lengths are of the order of the boundary-layer thickness so that l_{DES} always switches to d_{wall} in the boundary-layer. For unstructured meshes, this means that one has to choose a surface mesh size of at least the boundary-layer thickness. For the leading edge, one has usually to choose a smaller mesh size to capture the geometry accurately but this size has to be at least the boundary-layer thickness at the leading edge. Again, this would ensure that $l_{DES} = d_{wall}$ in the leading edge boundary-layer. At the trailing edge, one again has to use smaller mesh sizes to correctly capture the geometry, but in this case one does not need to worry about the mesh requirements of DES. This is because, once the flow has separated, the RANS model does not help in modeling the physics of the detached boundary layer any longer.
2. Introduce (extrude) prism layers to fill up the boundary-layer thickness. The vertical spacing of each prism layer can be based on any mesh growth scheme chosen by the user. This is because the vertical spacing of each prism layer is always smaller than the boundary-layer thickness and hence the switch always selects $l_{DES} = d_{wall}$ in the boundary-layer.
3. Outside the prism layers, in the expected shear layers, create isotropic LES meshes with characteristic mesh sizes of the order of the Taylor microscale $\lambda_T \approx \sqrt{15} {Re_L}^{-1/2} L$, where, *L* is the integral length scale (usually the body length) and Re_L is the Reynolds number based on *L*. It is a good practice to use a mesh size of around $5\lambda_T$ near the wall and gradually increase the size to about $10\lambda_T$ in the far-field.

Next: Sensitivities, Previous: DESMESH

Appendix D SPARSE GRID TABULATION OF RIEMANN INVARIANTS AND SOLUTIONS

Sparse grid tabulations are used in **AERO-F** to accelerate the solution of multi-phase flow problems involving a medium modeled by a complex and computationally intensive Equation Of State (EOS), such as the JWL EOS, using the `FiniteVolumeWithExactTwoPhaseRiemann` method which requires the computation of the solutions of local, one-dimensional two-phase Riemann problems (see MultiPhase). The tabulation of certain quantities related to this computation allows to bypass some of the more costly computational steps. While such tabulations may not be readily available to the user, they can be generated in a sparse grid format using **AERO-F**. This appendix provides instructions to set up the input file needed by **AERO-F** to generate these tabulations, as well as guidelines for how to choose their appropriate parameters.

General Settings

In order to tabulate some data in sparse grid format, the user must specify

```
Problem.Type = SparseGridGeneration;
```

as well as the name *filename-str* of the output file(s) that will contain the tabulated data

```
Output.PostPro.SparseGrid = filename-str;
```

(see Problem and PostPro).

Data to Tabulate

Currently, **AERO-F** can tabulate quantities related to the computation of the solution of a one-dimensional two-phase Riemann problem between a JWL EOS and a perfect or stiffened gas EOS only. These quantities are the Riemann invariants of the JWL EOS, and the solutions of one-dimensional, two-phase Riemann problems. The first option (Riemann invariants) is recommended because it is fast, easy, and has demonstrated superior potential for accelerating the computation of two-phase flow problems involving the JWL EOS using the numerical method `FiniteVolumeWithExactTwoPhaseRiemann`.

In order to tabulate the Riemann invariants of the JWL EOS, the user must specify in the **AERO-F** ASCII input file:

```
under Equations {
  under FluidModel[0] {
    Fluid = JWL;
    under JWLModel { ...  }
  }
}

under MultiPhase{
  RiemannComputation = TabulationRiemannInvariant;
}
```

where JWLModel specifies the parameters of the considered JWL EOS.

In order to tabulate the solutions of one-dimensional two-phase Riemann problems between a JWL EOS and a perfect or stiffened gas EOS, the user must specify in the **AERO-F** ASCII input file:

```
under Equations {
  under FluidModel[0] {
    Fluid = StiffenedGas;
    under GasModel { ...  }
  }
  under FluidModel[1] {
    Fluid = JWL;
    under JWLModel { ...  }
  }
}

under MultiPhase{
  RiemannComputation = TabulationRiemannProblem;
}
```

where GasModel and JWLModel specify the parameters of the two considered EOSs.

How to Tabulate Riemann Invariants of the JWL EOS

The Riemann invariant of the JWL EOS is the scalar quantity

$$I(\rho, s) = \int \frac{c(\rho,s)}{\rho} d\rho$$

which depends on two variables:

the density ρ , and the mathematical entropy

$$s = \frac{p - A_1 e^{-\frac{R_1 \rho_0}{\rho}} - A_2 e^{-\frac{R_2 \rho_0}{\rho}}}{\rho^{\omega+1}}$$

where p is pressure and the other parameters of the JWL EOS are user-specified in `FluidModel`[0].

Therefore, in this case the user must specify in the object SparseGrid: (a) that the sparse grid will have two input variables and one output variable, and (b) the lower and upper bounds of each input variable as follows:

```
NumberOfInputs  = 2;
NumberOfOutputs = 1;
Input1Minimum   = in1min-real;
Input1Maximum   = in1max-real;
Input2Minimum   = in2min-real;
Input2Maximum   = in2max-real;
```

The first input variable is the density and the second one is the entropy. Determining the optimal choices of the bounds of the input variables requires predicting accurately the ranges of these variables spanned during the exploitation of the tabulation and therefore is a difficult task. For this reason, these bounds can be only estimated. The density of a highly explosive gas modeled by the JWL EOS usually has a maximum value given by the initial conditions of the application problems and a minimum value that is several orders of magnitude lower. For example, in SI units, the density can easily vary between 1 and 1630 $Kg.m^{-3}$. Estimates of the bounds for entropy are not straightforward to obtain. With pressure values varying in a typical application problem between an initial value often of the order of several $10^9 Pa$ s and a value that is several orders of magnitude lower than that of the surrounding fluid, the computed entropies associated with such density and pressure values can span several orders of magnitude. Instead, it is easier to compute the value of the entropy corresponding to the values of the density and pressure of the JWL fluid associated with typical initial conditions of application problems of interest and tabulate around this value. This is generally sufficient as a highly explosive gas usually undergoes an expansion during which the entropy does not vary significantly.

The choice of the numerical parameters for the construction of a sparse grid depends on several factors such as the data to be tabulated, the user-desired accuracy, and the maximum size of the grid (which can determine how long it takes to generate and exploit a sparse grid). As such, several tabulation iterations may be needed to obtain the desired result.

AERO-F refines a sparse grid tabulation until one of three stopping criteria is reached: the desired relative accuracy is satisfied, the desired absolute accuracy is satisfied, or the maximum number of points in the tabulation is exceeded. For the tabulation of Riemann invariants of the JWL EOS, the user can start with

```
MaximumNumberOfPoints = 10000;
RelativeAccuracy      = 1.0e-3;
AbsoluteAccuracy      = 0.1;
```

The errors are estimated a posteriori at the last created points of the sparse grid. The relative errors are computed with respect to the difference between the largest and smallest computed values of the data to be tabulated. A minimum number of points for the tabulation can also be specified. For example,

```
MinimumNumberOfPoints = 100;
```

Since the data to be tabulated may not exhibit the same variations for different input variables, the user is given the possibility to refine the sparse grid along the input variable for which the errors decrease the most. This is done by specifying the degree of dimensional adaptivity which can take any real value between 0 and 1. A degree of 0 corresponds to a uniform refinement in each input variable, while a degree of 1 corresponds to a refinement based solely on the errors. For the tabulation of Riemann invariants of the JWL EOS, the user is advised to use values above 0.7 but below 1.0:

```
     DegreeDimAdapt = 0.7;
```

To enable parallel processing during the tabulation and accelerate the exploitation of this tabulation during subsequent **AERO-F** computations, the user can request the tabulation of a single domain in several complementary sparse grids characterized by the same numerical parameters. For this purpose, the user can specify a uniform splitting of the domain of each input variable in a number of subdomains that depends directly on its range (the larger is the range, the more attractive it becomes to decompose it). For example, the user can specify:

```
     NumberOfDomains1 = 3;
     NumberOfDomains2 = 2;
```

which leads to six complementary sparse grids characterized by the same numerical parameters.

How to Tabulate Solutions of One-Dimensional Two-Thase JWL-Gas Riemann Problems

The solution of a one-dimensional, two-phase Riemann problem at the interface between two initial states depends on the initial values of the density and pressure, and the jump in the initial velocities. This solution can be reconstructed from the knowledge of the constant density states on both sides of the material interface. Therefore, in this case the user must specify in the object `SparseGrid`: (a) that the sparse grid will have five input and two output variables (which are the constant density states at the left and right of the material interface), and (b) the lower and upper bounds of each input variable as follows:

```
     NumberOfInputs  = 5;
     NumberOfOutputs = 2;
     Input1Minimum   = in1min-real;
     Input1Maximum   = in1max-real;
     Input2Minimum   = in2min-real;
     Input2Maximum   = in2max-real;
     Input3Minimum   = in3min-real;
     Input3Maximum   = in3max-real;
     Input4Minimum   = in4min-real;
     Input4Maximum   = in4max-real;
     Input5Minimum   = in5min-real;
     Input5Maximum   = in5max-real;
```

The first and second input variables are the density and pressure in the perfect or stiffened gas, the third and fourth are the density and pressure in the medium modeled by the JWL EOS, and the fifth input variable is the difference between the velocity of the perfect/stiffened gas and that of the JWL medium. Specifying the bounds of each input variable is not easy, especially since some initial states lead to vacuum state solutions. For this purpose, the user needs to estimate a priori these bounds. To this effect, it is useful to note that the velocity jump at the material interface can be either positive or negative, and that in general it is not very large unless the jump of the initial velocities is large, or a strong shock wave interacts with the material interface.

The choice of the numerical parameters characterizing the sparse grid are specified in the same manner as in the previous case. In particular, the same values as before can be used for the minimum number of points and desired accuracies:

```
     MinimumNumberOfPoints = 100;
```

```
    RelativeAccuracy      = 1.0e-3;
    AbsoluteAccuracy      = 0.1;
```

It is recommended to choose a maximum number of points of at least 100,000 and a degree of dimensional adaptivity of 0.9. It is also particularly useful to consider splitting the domain of each input variable. It is strongly advised to split the domain of the velocity difference input variable so that a sparse grid avoids as much as possible tabulating both vacuum state and non-vacuum state solutions. Therefore, even if the values of the velocity difference do not span several orders of magnitude, it is still recommended to split the domain of this input variable.

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Appendix E COMPUTATION OF SENSITIVITIES

The derivative at a fluid equilibrium point — that is, a steady-state fluid sate vector $\mathbf{W}_o$ — of an aerodynamic-related quantity $q_i = q_i\left(\mathbf{W}(s_j)\right)$ with respect to a flow or shape parameter s_j can be written as

$$\frac{dq_i}{ds_j}|_{\mathbf{W}_o} = \frac{dq_i}{d\mathbf{W}}|_{\mathbf{W}_o}\frac{d\mathbf{W}}{ds_j}|_{\mathbf{W}_o}$$

where:

- $\frac{dq_i}{d\mathbf{W}}|_{\mathbf{W}_o}$ can be computed analytically or by finite differencing, depending on the complexity of the dependence of q_i on $\mathbf{W}$.
- $\frac{d\mathbf{W}}{ds_j}|_{\mathbf{W}_o}$ can be determined from the stationarity at $\mathbf{W}_o$ of the equation of dynamic equilibrium of the fluid

  $$\mathbf{F}\left(\mathbf{W}(s_j), \mathbf{X}(s_j), s_j\right) = \mathbf{0}$$

  where $\mathbf{F}$ denotes the system of nonlinear equations governing the steady-state fluid sate vector $\mathbf{W}_o$, and $\mathbf{X}$ denotes the vector of nodal positions of the fluid mesh. The differentiation of the above equation at $\mathbf{W}_o$ leads to the characterization of the gradient $\frac{d\mathbf{W}}{ds_j}|_{\mathbf{W}_o}$ as the solution of the linearized system of equations

  $$\left[\frac{\partial \mathbf{F}}{\partial \mathbf{W}}|_{\mathbf{W}_o}\right]\frac{d\mathbf{W}}{ds_j}|_{\mathbf{W}_o} = -\frac{\partial \mathbf{F}}{\partial s_j}|_{\mathbf{W}_o} - \frac{\partial \mathbf{F}}{\partial \mathbf{X}}|_{\mathbf{W}_o}\frac{d\mathbf{X}}{ds_j}$$

  where:

- $\frac{\partial \mathbf{F}}{\partial s_j}|_{\mathbf{W}_o}$ can be computed analytically or by finite differencing.
- $\frac{d\mathbf{X}}{ds_j}$ is non zero only when s_j is a shape parameter; for this reason, $\frac{d\mathbf{X}}{ds_j}$ is referred to here as the "shape gradient" of the fluid mesh position vector, or simply as the mesh shape gradient.

The mesh shape gradient can be divided into two components:

- The wall boundary component $\frac{d\mathbf{X}_\Gamma}{ds_j}$ which is associated with the grid points of the CFD mesh lying on the wall boundary Γ. This component is *user-specified* in `Input.ShapeDerivative` as it pertains directly to the shape of the obstacle around/within which a flow is computed.
- The interior component $\frac{d\mathbf{X}_\Omega}{ds_j}$ which is associated with the grid points located in the interior Ω of the computational fluid domain. Using for the CFD mesh a deformation model based on a structural analogy (see MeshMotion), this component is determined by solving the usual boundary-driven mesh deformation problem to obtain

$$\frac{d\mathbf{X}_\Omega}{ds_j} = -\left[\tilde{\mathbf{K}}_{\Omega\Omega}^{-1}\tilde{\mathbf{K}}_{\Omega\Gamma}\right]\frac{d\mathbf{X}_\Gamma}{ds_j}$$

where $\tilde{\mathbf{K}}$ is the pseudo stiffness matrix of the CFD mesh generated by the chosen of **AERO-F** mesh motion algorithm (see MeshMotion).

In summary, given a *user-specified* wall-boundary shape derivative $\frac{d\mathbf{X}_\Gamma}{ds_j}$, **AERO-F** computes the gradient at a fluid equilibrium point $\mathbf{W}_o$ of an aerodynamic-related quantity q_i with respect to a flow or shape parameter s_j as follows

$$\frac{dq_i}{ds_j}|_{\mathbf{W}_o} = -\frac{dq_i}{d\mathbf{W}}|_{\mathbf{W}_o}\left[\frac{\partial \mathbf{F}}{\partial \mathbf{W}}|_{\mathbf{W}_o}\right]^{-1}\left(\frac{\partial \mathbf{F}}{\partial s_j}|_{\mathbf{W}_o} + \left[\begin{array}{cc}\frac{\partial \mathbf{F}}{\partial \mathbf{X}_\Omega}|_{\mathbf{W}_o} & \frac{\partial \mathbf{F}}{\partial \mathbf{X}_\Gamma}|_{\mathbf{W}_o}\end{array}\right]\left[\begin{array}{c}-\tilde{\mathbf{K}}_{\Omega\Omega}^{-1}\tilde{\mathbf{K}}_{\Omega\Gamma}\\ \mathbf{I}\end{array}\right]\frac{d\mathbf{X}_\Gamma}{ds_j}\right)$$