Aerostructural developments in FAST-OAD

Summary

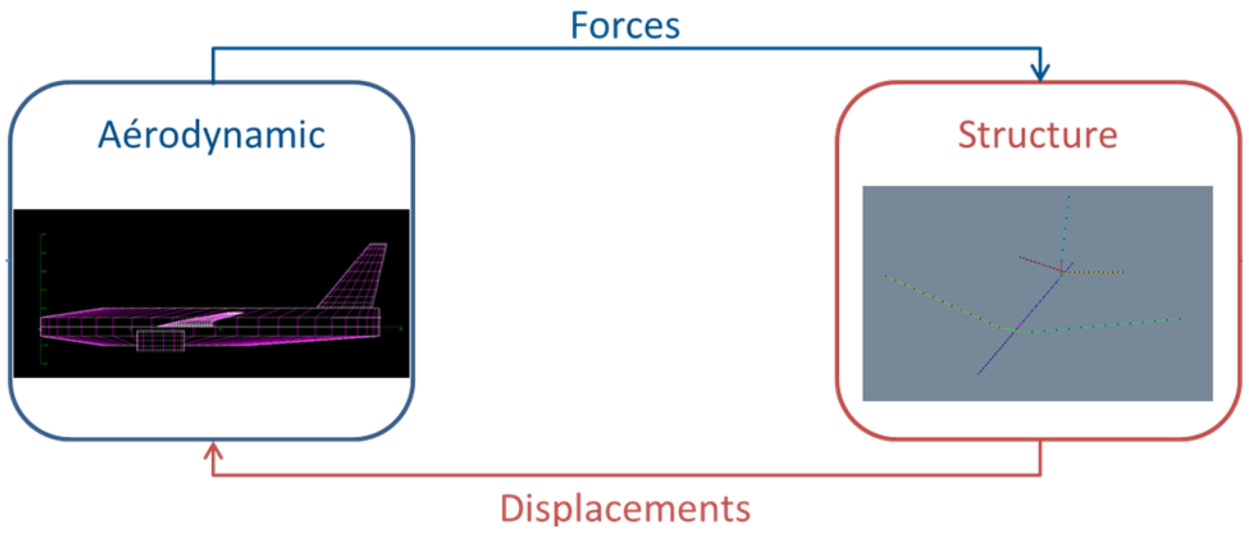
- Method & tools
  - Aerostructure loop
  - Mystran
  - AVL
  - PyNastran
- Implementation in FAST-OAD
  - Structure mesh
  - Structure weight
  - Aerodynamic mesh
  - Transfer matrix
  - Aerodynamic solver
  - Structural solver

Method & Tools

- Aerostructural loop

The principle of aerostructural coupling is to size the structural components taking into account of aerodynamic loading variation due to structural deformations.

The loop occurs as structural deformation depends on aerodynamic loading and aerodynamic loading depends on structural deformation (mainly wing twist deformation).



The interest to take into account this interaction early in the preliminary design stages may allow to better estimate (wing) primary structure weight and aerodynamic performances (induced drag)

Method & Tools: MYSTRAN

- General introduction

To compute structural deformations and stresses Mystran open-source software is used. It is a lighten version of well-know finite element solver NASTRAN. Code and executable can be found in https://www.mystran.com/. Documentation comes with the downloadable content.

This solver relies on the same approach as NASTRAN:

- A unique input text file .bdf or .dat (that can calls include files) that define the problem.
- The input file is composed of 3 main sections: Executive control section, Control case section, Bulk data section these section are shortly describes in the following pages.
- Ouput files in different format: the f04 and f06 text files, op2 or xdb binary files + other optional outputs.
- Structural nodes, properties, loading, materials, constraints… are defined using the same formalism as NASTRAN. This will be recall in the following pages.

This solver comes also with some limitations:

- BEAM elements are not supported,
- SOL 144 and SOL 145 for aeroelasticity are not implemented.

Method & Tools: MYSTRAN

- Input file description:

Executive control section:

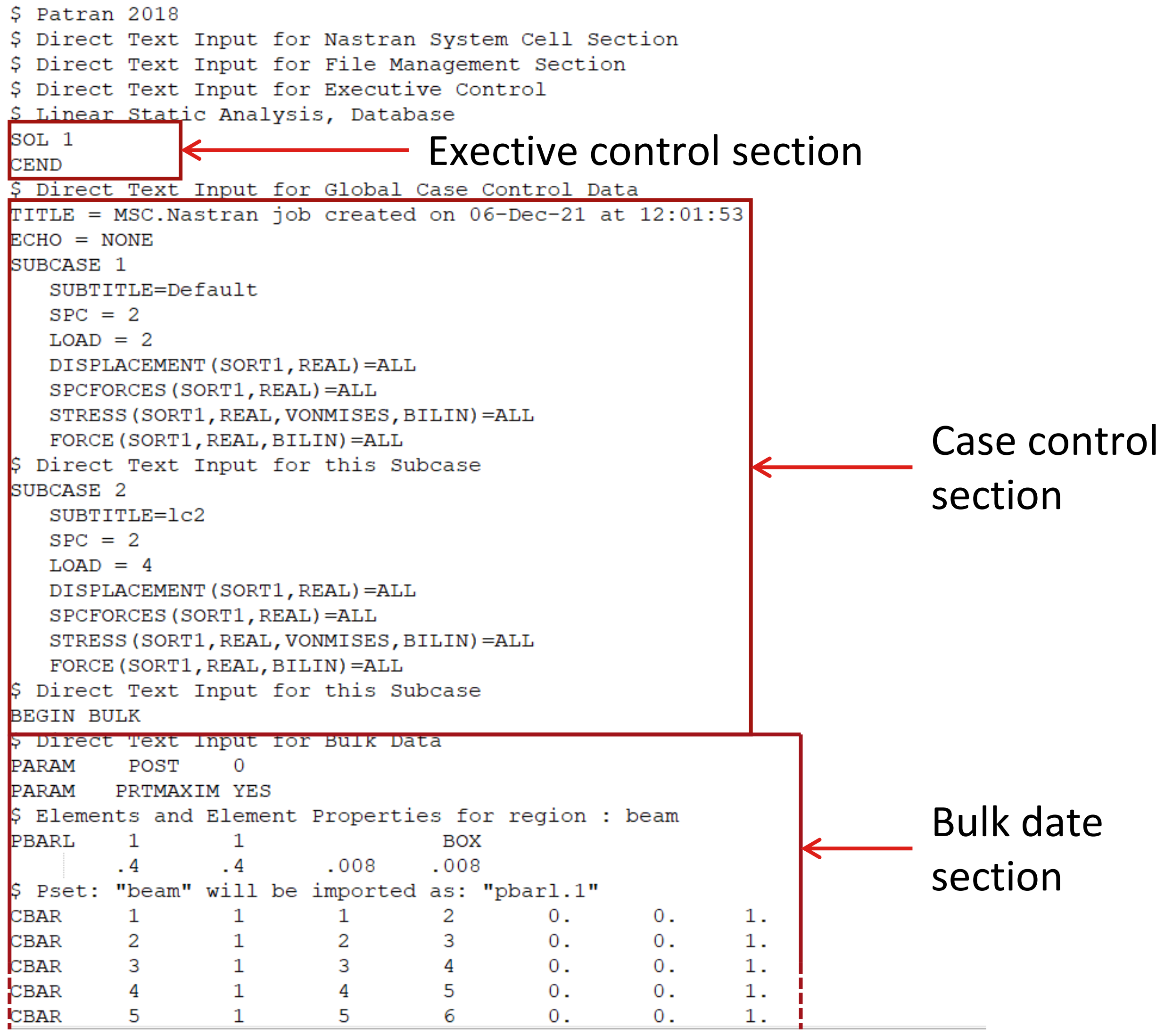
- Description of the solution selected: SOL 1 (101) for linear static, SOL 3 (103) for modal analysis
- Ends with « CEND » keyword.

Case control section

- Defines the Title of the analysis,
- Defines the subcases with:
  - Name
  - Boundary conditions (SPC, MPC)
  - Loading
  - Requested outputs (Displacements, stressess, Forces…)
- Ends with BEGIN BULK keyword

Bulk data section:

- Decribes the finite element model : Nodes locations, Elements nodes & properties, material properties, loads, constraints …. Throught dedicated cards.



```
$ Patran 2018
$ Direct Text Input for Nastran System Cell Section
$ Direct Text Input for File Management Section
$ Direct Text Input for Executive Control
$ Linear Static Analysis, Database
SOL 1
CEND
$ Direct Text Input for Global Case Control Data
TITLE = MSC.Nastran job created on 06-Dec-21 at 12:01:53
ECHO = NONE
SUBCASE 1
   SUBTITLE=Default
   SPC = 2
   LOAD = 2
   DISPLACEMENT(SORT1,REAL)=ALL
   SPCFORCES(SORT1,REAL)=ALL
   STRESS(SORT1,REAL,VONMISES,BILIN)=ALL
   FORCE(SORT1,REAL,BILIN)=ALL
$ Direct Text Input for this Subcase
SUBCASE 2
   SUBTITLE=lc2
   SPC = 2
   LOAD = 4
   DISPLACEMENT(SORT1,REAL)=ALL
   SPCFORCES(SORT1,REAL)=ALL
   STRESS(SORT1,REAL,VONMISES,BILIN)=ALL
   FORCE(SORT1,REAL,BILIN)=ALL
$ Direct Text Input for this Subcase
BEGIN BULK
$ Direct Text Input for Bulk Data
PARAM    POST    0
PARAM   PRTMAXIM YES
$ Elements and Element Properties for region : beam
PBARL    1       1               BOX
        .4      .4      .008    .008
$ Pset: "beam" will be imported as: "pbarl.1"
CBAR     1       1       1       2       0.      0.      1.
CBAR     2       1       2       3       0.      0.      1.
CBAR     3       1       3       4       0.      0.      1.
CBAR     4       1       4       5       0.      0.      1.
CBAR     5       1       5       6       0.      0.      1.
```

Method & Tools: MYSTRAN

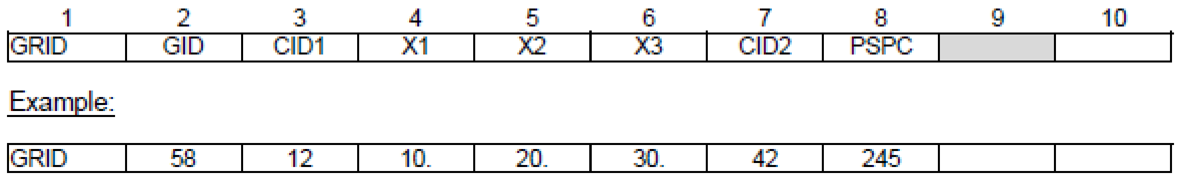
• Focus on cards formalism

The base principle is that a card that will define either a node, a property, a load, … is made of 10 horizontal field of 8 digit width each. The width cannot be less or greater than 8 digit i.e. if an entry is less than 8 characters spaces must be used. An example for grid is provided.

The card can be compressed using coma to separate colums. Here, the constraint on maximum width remains but the lower bound constraints vanishes:

GRID, GID, CID1, X1, X2, X3, CID2, PSPC

Each card has its specific entries details must be checked in the documentation.



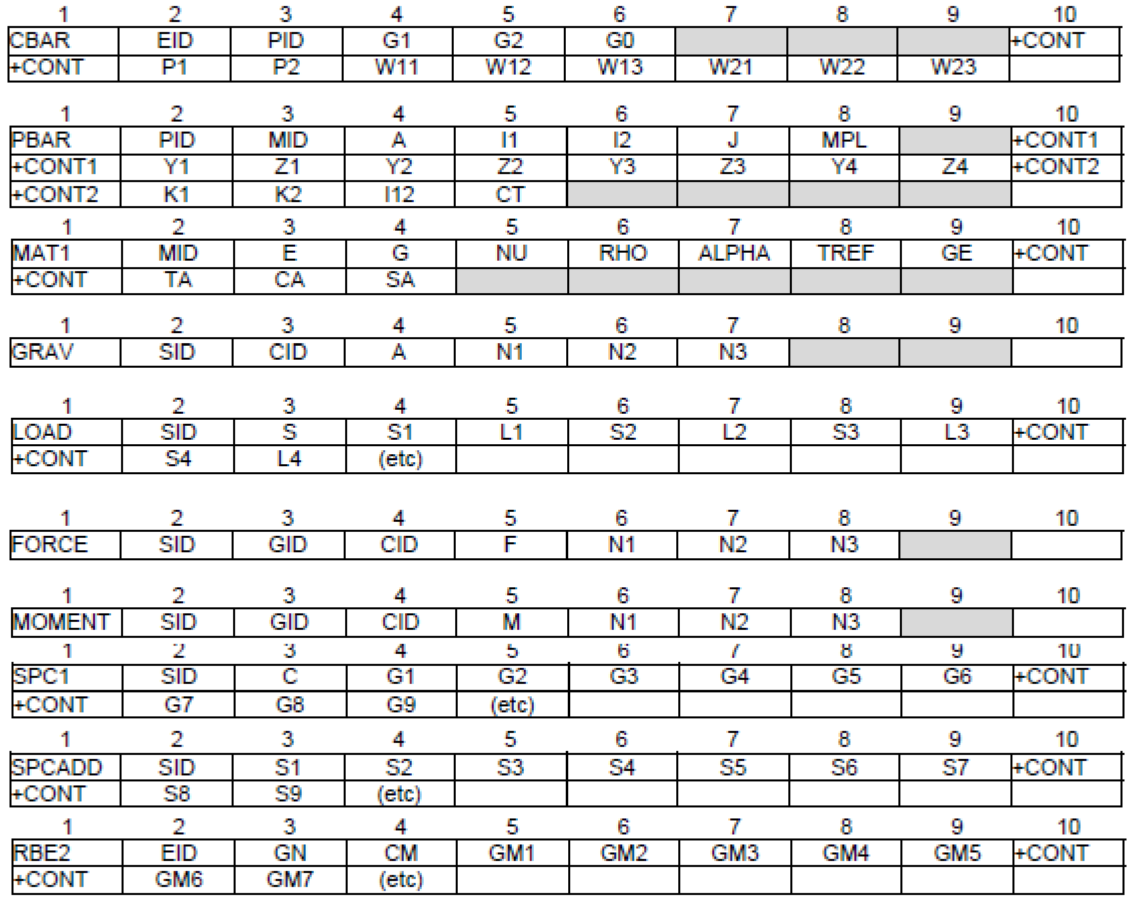
1	2	3	4	5	6	7	8	9	10
GRID	GID	CID1	X1	X2	X3	CID2	PSPC	▨	

Example:

GRID	58	12	10.	20.	30.	42	245		

Method & Tools: MYSTRAN

- Cards mainly used:
  - GRID
  - CBAR
  - PBAR
  - MAT1
  - GRAV
  - LOAD
  - FORCE
  - MOMENT
  - SPC1
  - SPCADD
  - RBE2



1	2	3	4	5	6	7	8	9	10
CBAR	EID	PID	G1	G2	G0				+CONT
+CONT	P1	P2	W11	W12	W13	W21	W22	W23	

1	2	3	4	5	6	7	8	9	10
PBAR	PID	MID	A	I1	I2	J	MPL		+CONT1
+CONT1	Y1	Z1	Y2	Z2	Y3	Z3	Y4	Z4	+CONT2
+CONT2	K1	K2	I12	CT					

1	2	3	4	5	6	7	8	9	10
MAT1	MID	E	G	NU	RHO	ALPHA	TREF	GE	+CONT
+CONT	TA	CA	SA						

1	2	3	4	5	6	7	8	9	10
GRAV	SID	CID	A	N1	N2	N3			

1	2	3	4	5	6	7	8	9	10
LOAD	SID	S	S1	L1	S2	L2	S3	L3	+CONT
+CONT	S4	L4	(etc)						

1	2	3	4	5	6	7	8	9	10
FORCE	SID	GID	CID	F	N1	N2	N3		

1	2	3	4	5	6	7	8	9	10
MOMENT	SID	GID	CID	M	N1	N2	N3		

1	2	3	4	5	6	7	8	9	10
SPC1	SID	C	G1	G2	G3	G4	G5	G6	+CONT
+CONT	G7	G8	G9	(etc)					

1	2	3	4	5	6	7	8	9	10
SPCADD	SID	S1	S2	S3	S4	S5	S6	S7	+CONT
+CONT	S8	S9	(etc)						

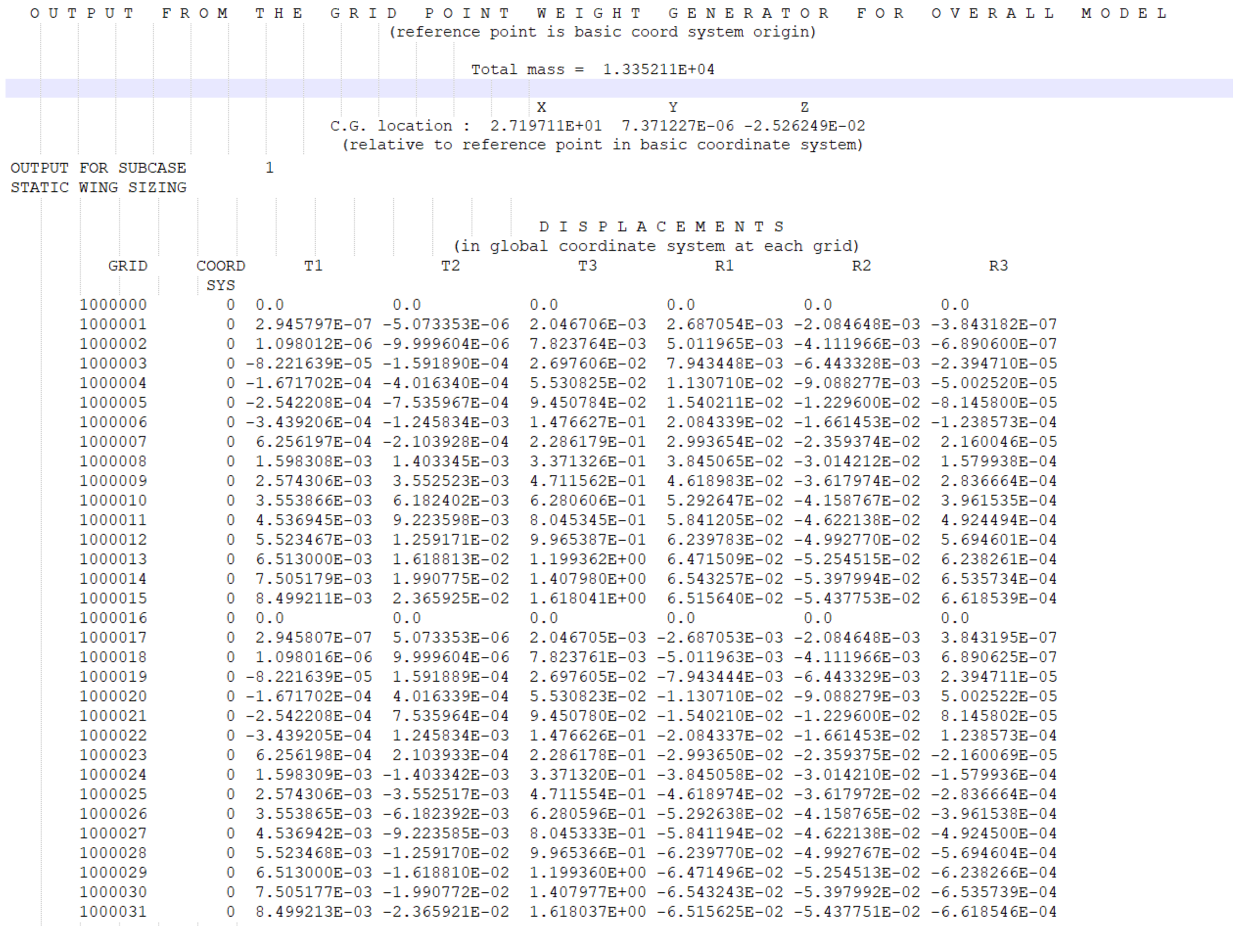
1	2	3	4	5	6	7	8	9	10
RBE2	EID	GN	CM	GM1	GM2	GM3	GM4	GM5	+CONT
+CONT	GM6	GM7	(etc)						

Method & Tools: MYSTRAN

- Output file focus on .f06

The .f06 is a text file that provides with de requested ouputs in the .bdf. For exemple:

- Displacements and stresses for static analysis
- Modes and eigenvector for modal analysis. It provides also with the masses and center of gravity location.



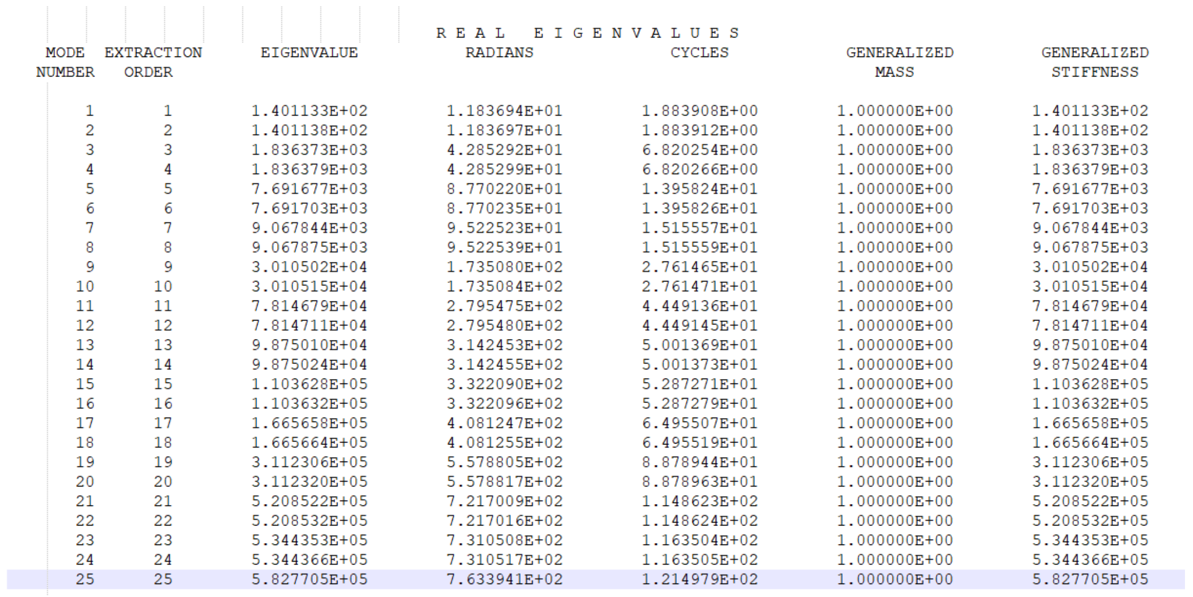
```
 O U T P U T   F R O M   T H E   G R I D   P O I N T   W E I G H T   G E N E R A T O R   F O R   O V E R A L L   M O D E L
                                          (reference point is basic coord system origin)

                                                    Total mass =  1.335211E+04

                                                          X                 Y                 Z
                                     C.G. location :  2.719711E+01  7.371227E-06 -2.526249E-02
                                      (relative to reference point in basic coordinate system)
OUTPUT FOR SUBCASE        1
STATIC WING SIZING

                                                    D I S P L A C E M E N T S
                                            (in global coordinate system at each grid)
      GRID      COORD      T1            T2            T3            R1            R2            R3
                 SYS
    1000000        0  0.0           0.0           0.0           0.0           0.0           0.0
    1000001        0  2.945797E-07 -5.073353E-06  2.046706E-03  2.687054E-03 -2.084648E-03 -3.843182E-07
    1000002        0  1.098012E-06 -9.999604E-06  7.823764E-03  5.011965E-03 -4.111966E-03 -6.890600E-07
    1000003        0 -8.221639E-05 -1.591890E-04  2.697606E-02  7.943448E-03 -6.443328E-03 -2.394710E-05
    1000004        0 -1.671702E-04 -4.016340E-04  5.530825E-02  1.130710E-02 -9.088277E-03 -5.002520E-05
    1000005        0 -2.542208E-04 -7.535967E-04  9.450784E-02  1.540211E-02 -1.229600E-02 -8.145800E-05
    1000006        0 -3.439206E-04 -1.245834E-03  1.476627E-01  2.084339E-02 -1.661453E-02 -1.238573E-04
    1000007        0  6.256197E-04 -2.103928E-04  2.286179E-01  2.993654E-02 -2.359374E-02  2.160046E-05
    1000008        0  1.598308E-03  1.403345E-03  3.371326E-01  3.845065E-02 -3.014212E-02  1.579938E-04
    1000009        0  2.574306E-03  3.552523E-03  4.711562E-01  4.618983E-02 -3.617974E-02  2.836664E-04
    1000010        0  3.553866E-03  6.182402E-03  6.280606E-01  5.292647E-02 -4.158767E-02  3.961535E-04
    1000011        0  4.536945E-03  9.223598E-03  8.045345E-01  5.841205E-02 -4.622138E-02  4.924494E-04
    1000012        0  5.523467E-03  1.259171E-02  9.965387E-01  6.239783E-02 -4.992770E-02  5.694601E-04
    1000013        0  6.513000E-03  1.618813E-02  1.199362E+00  6.471509E-02 -5.254515E-02  6.238261E-04
    1000014        0  7.505179E-03  1.990775E-02  1.407980E+00  6.543257E-02 -5.397994E-02  6.535734E-04
    1000015        0  8.499211E-03  2.365925E-02  1.618041E+00  6.515640E-02 -5.437753E-02  6.618539E-04
    1000016        0  0.0           0.0           0.0           0.0           0.0           0.0
    1000017        0  2.945807E-07  5.073353E-06  2.046705E-03 -2.687053E-03 -2.084648E-03  3.843195E-07
    1000018        0  1.098016E-06  9.999604E-06  7.823761E-03 -5.011963E-03 -4.111966E-03  6.890625E-07
    1000019        0 -8.221639E-05  1.591889E-04  2.697605E-02 -7.943444E-03 -6.443329E-03  2.394711E-05
    1000020        0 -1.671702E-04  4.016339E-04  5.530823E-02 -1.130710E-02 -9.088279E-03  5.002522E-05
    1000021        0 -2.542208E-04  7.535964E-04  9.450780E-02 -1.540210E-02 -1.229600E-02  8.145802E-05
    1000022        0 -3.439205E-04  1.245834E-03  1.476626E-01 -2.084337E-02 -1.661453E-02  1.238573E-04
    1000023        0  6.256198E-04  2.103933E-04  2.286178E-01 -2.993650E-02 -2.359375E-02 -2.160069E-05
    1000024        0  1.598309E-03 -1.403342E-03  3.371320E-01 -3.845058E-02 -3.014210E-02 -1.579936E-04
    1000025        0  2.574306E-03 -3.552517E-03  4.711554E-01 -4.618974E-02 -3.617972E-02 -2.836664E-04
    1000026        0  3.553865E-03 -6.182392E-03  6.280596E-01 -5.292638E-02 -4.158765E-02 -3.961538E-04
    1000027        0  4.536942E-03 -9.223585E-03  8.045333E-01 -5.841194E-02 -4.622138E-02 -4.924500E-04
    1000028        0  5.523468E-03 -1.259170E-02  9.965366E-01 -6.239770E-02 -4.992767E-02 -5.694604E-04
    1000029        0  6.513000E-03 -1.618810E-02  1.199360E+00 -6.471496E-02 -5.254513E-02 -6.238266E-04
    1000030        0  7.505177E-03 -1.990772E-02  1.407977E+00 -6.543243E-02 -5.397992E-02 -6.535739E-04
    1000031        0  8.499213E-03 -2.365921E-02  1.618037E+00 -6.515625E-02 -5.437751E-02 -6.618546E-04
```

Method & Tools: MYSTRAN

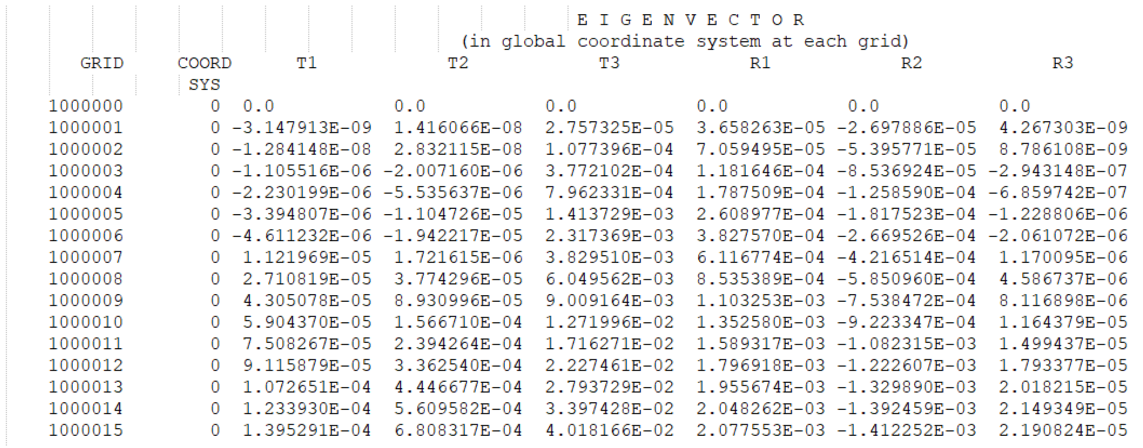
- Output file focus on .f06

The .f06 is a text file that provides with de requested ouputs in the .bdf. For exemple:

- Displacements and stresses for static analysis
- Modes frequencies and eigenvector for modal analysis. It provides also with the masses and center of gravity location.



```
                                              R E A L   E I G E N V A L U E S
MODE  EXTRACTION      EIGENVALUE          RADIANS             CYCLES          GENERALIZED         GENERALIZED
NUMBER   ORDER                                                                    MASS             STIFFNESS

    1        1      1.401133E+02       1.183694E+01       1.883908E+00       1.000000E+00       1.401133E+02
    2        2      1.401138E+02       1.183697E+01       1.883912E+00       1.000000E+00       1.401138E+02
    3        3      1.836373E+03       4.285292E+01       6.820254E+00       1.000000E+00       1.836373E+03
    4        4      1.836379E+03       4.285299E+01       6.820266E+00       1.000000E+00       1.836379E+03
    5        5      7.691677E+03       8.770220E+01       1.395824E+01       1.000000E+00       7.691677E+03
    6        6      7.691703E+03       8.770235E+01       1.395826E+01       1.000000E+00       7.691703E+03
    7        7      9.067844E+03       9.522523E+01       1.515557E+01       1.000000E+00       9.067844E+03
    8        8      9.067875E+03       9.522539E+01       1.515559E+01       1.000000E+00       9.067875E+03
    9        9      3.010502E+04       1.735080E+02       2.761465E+01       1.000000E+00       3.010502E+04
   10       10      3.010515E+04       1.735084E+02       2.761471E+01       1.000000E+00       3.010515E+04
   11       11      7.814679E+04       2.795475E+02       4.449136E+01       1.000000E+00       7.814679E+04
   12       12      7.814711E+04       2.795480E+02       4.449145E+01       1.000000E+00       7.814711E+04
   13       13      9.875010E+04       3.142453E+02       5.001369E+01       1.000000E+00       9.875010E+04
   14       14      9.875024E+04       3.142455E+02       5.001373E+01       1.000000E+00       9.875024E+04
   15       15      1.103628E+05       3.322090E+02       5.287271E+01       1.000000E+00       1.103628E+05
   16       16      1.103632E+05       3.322096E+02       5.287279E+01       1.000000E+00       1.103632E+05
   17       17      1.665658E+05       4.081247E+02       6.495507E+01       1.000000E+00       1.665658E+05
   18       18      1.665664E+05       4.081255E+02       6.495519E+01       1.000000E+00       1.665664E+05
   19       19      3.112306E+05       5.578805E+02       8.878944E+01       1.000000E+00       3.112306E+05
   20       20      3.112320E+05       5.578817E+02       8.878963E+01       1.000000E+00       3.112320E+05
   21       21      5.208522E+05       7.217009E+02       1.148623E+02       1.000000E+00       5.208522E+05
   22       22      5.208532E+05       7.217016E+02       1.148624E+02       1.000000E+00       5.208532E+05
   23       23      5.344353E+05       7.310508E+02       1.163504E+02       1.000000E+00       5.344353E+05
   24       24      5.344366E+05       7.310517E+02       1.163505E+02       1.000000E+00       5.344366E+05
   25       25      5.827705E+05       7.633941E+02       1.214979E+02       1.000000E+00       5.827705E+05
```



```
                                                        E I G E N V E C T O R
                                               (in global coordinate system at each grid)
     GRID      COORD      T1            T2            T3            R1            R2            R3
                SYS
   1000000       0   0.0           0.0           0.0           0.0           0.0           0.0
   1000001       0 -3.147913E-09  1.416066E-08  2.757325E-05  3.658263E-05 -2.697886E-05  4.267303E-09
   1000002       0 -1.284148E-08  2.832115E-08  1.077396E-04  7.059495E-05 -5.395771E-05  8.786108E-09
   1000003       0 -1.105516E-06 -2.007160E-06  3.772102E-04  1.181646E-04 -8.536924E-05 -2.943148E-07
   1000004       0 -2.230199E-06 -5.535637E-06  7.962331E-04  1.787509E-04 -1.258590E-04 -6.859742E-07
   1000005       0 -3.394807E-06 -1.104726E-05  1.413729E-03  2.608977E-04 -1.817523E-04 -1.228806E-06
   1000006       0 -4.611232E-06 -1.942217E-05  2.317369E-03  3.827570E-04 -2.669526E-04 -2.061072E-06
   1000007       0  1.121969E-05  1.721615E-06  3.829510E-03  6.116774E-04 -4.216514E-04  1.170095E-06
   1000008       0  2.710819E-05  3.774296E-05  6.049562E-03  8.535389E-04 -5.850960E-04  4.586737E-06
   1000009       0  4.305078E-05  8.930996E-05  9.009164E-03  1.103253E-03 -7.538472E-04  8.116898E-06
   1000010       0  5.904370E-05  1.566710E-04  1.271996E-02  1.352580E-03 -9.223347E-04  1.164379E-05
   1000011       0  7.508267E-05  2.394264E-04  1.716271E-02  1.589317E-03 -1.082315E-03  1.499437E-05
   1000012       0  9.115879E-05  3.362540E-04  2.227461E-02  1.796918E-03 -1.222607E-03  1.793377E-05
   1000013       0  1.072651E-04  4.446677E-04  2.793729E-02  1.955674E-03 -1.329890E-03  2.018215E-05
   1000014       0  1.233930E-04  5.609582E-04  3.397428E-02  2.048262E-03 -1.392459E-03  2.149349E-05
   1000015       0  1.395291E-04  6.808317E-04  4.018166E-02  2.077553E-03 -1.412252E-03  2.190824E-05
```

Method & Tools: AVL

- General introduction:

To compute aerodynamic forces and moments, open-source vortex lattice method tool AVL is used. The executable and source code may be found in: http://web.mit.edu/drela/Public/web/avl/.

AVL software works with a geometry *.avl input file that describes the different aerodynamic surfaces and their characteristics as it will be seen in the next page and a run case *.run file that defines the parameters of the computation.

The sofware delivers aerodynamic forces by surface, strip and/or element as well as global drag and lift coefficients, induced drag coefficient and Oswald factor.

AVL offers the possibility to perform trimmed computations e.g. it adjusts the angle of attack to meet a given lift coefficient. If a tail and a stabilizer is defined a given pitching moment can also be target for example.

This software has the same limitations any VLM code i.e. it is only valid for incompressible, inviscid and linear flows. A Prandtl-Glauert correction for subsonic compressibility is implemented.

Method & Tools: AVL

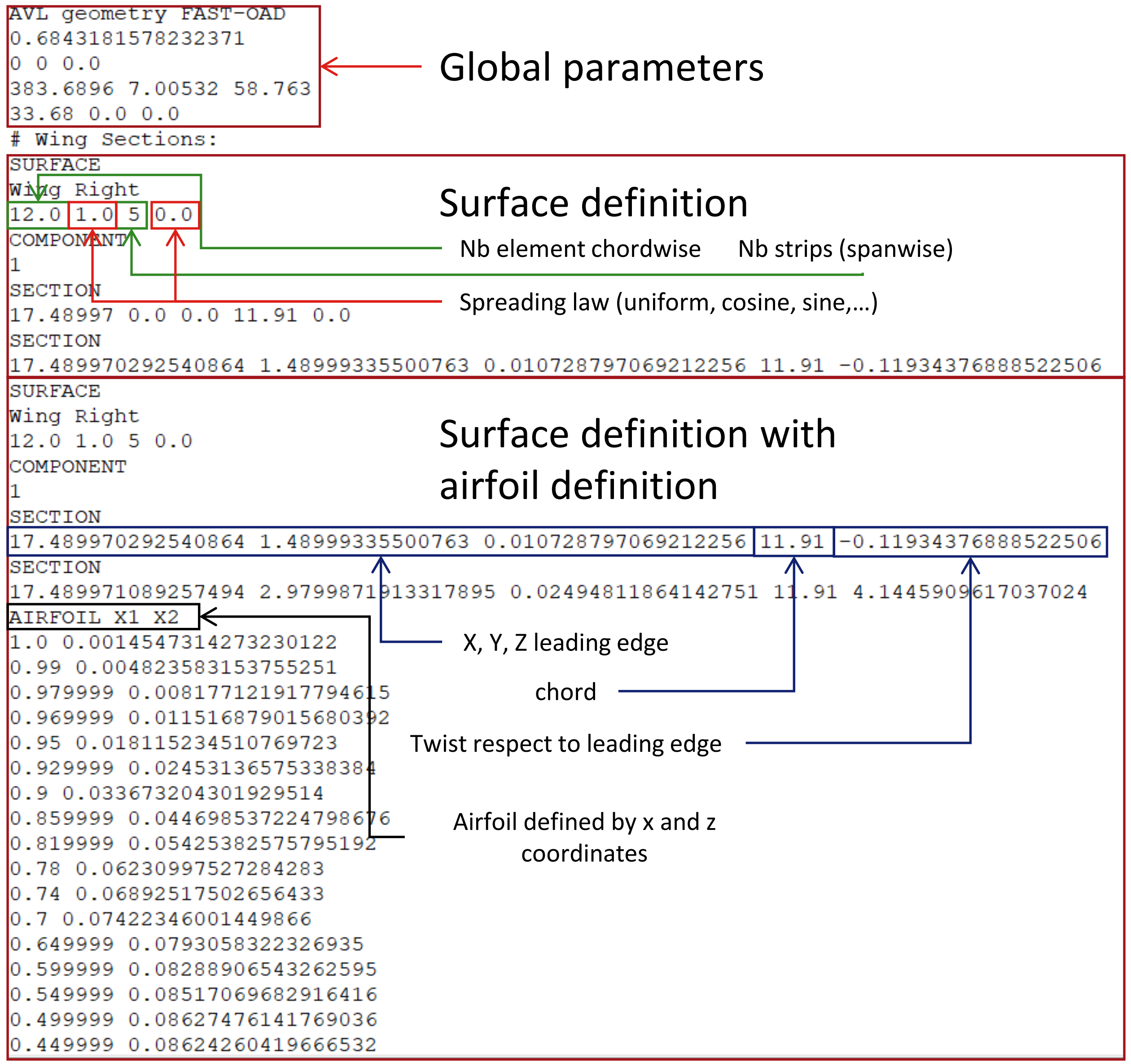
- Input file description:

Global parameters description:

- Mach number to be considered for PG correction
- Symmetry consideration about Y=0 and Z=Zsym
- Reference surface, chord and span
- Reference point for moments computation
- Profile drag to be added to total drag.

Surface definition:

- Name
- Chordwise and spanwise (=nb of strips) vortices layout.
- Component the surface belongs to
- Definition of sections that characterise the geometry of the surface (X, Y, Z location of leading edge point, chord and twist)
- Airfoil (optional)



```
AVL geometry FAST-OAD
0.6843181578232371
0 0 0.0
383.6896 7.00532 58.763
33.68 0.0 0.0
# Wing Sections:
SURFACE
Wing Right
12.0 1.0 5 0.0
COMPONENT
1
SECTION
17.48997 0.0 0.0 11.91 0.0
SECTION
17.489970292540864 1.48999335500763 0.010728797069212256 11.91 -0.11934376888522506
SURFACE
Wing Right
12.0 1.0 5 0.0
COMPONENT
1
SECTION
17.489970292540864 1.48999335500763 0.010728797069212256 11.91 -0.11934376888522506
SECTION
17.489971089257494 2.979987191317895 0.02494811864142751 11.91 4.144590961703702 4
AIRFOIL X1 X2
1.0 0.0014547314273230122
0.99 0.004823583153755251
0.979999 0.008177121917794615
0.969999 0.011516879015680392
0.95 0.018115234510769723
0.929999 0.024531365753383 84
0.9 0.03367320430192 9514
0.859999 0.044698537224798676
0.819999 0.05425382575795192
0.78 0.0623099752728 4283
0.74 0.068925175026 56433
0.7 0.074223460014 49866
0.649999 0.07930583223 26935
0.599999 0.08288906543262595
0.549999 0.08517069682916416
0.499999 0.08627476141769036
0.449999 0.08624260419666532
```

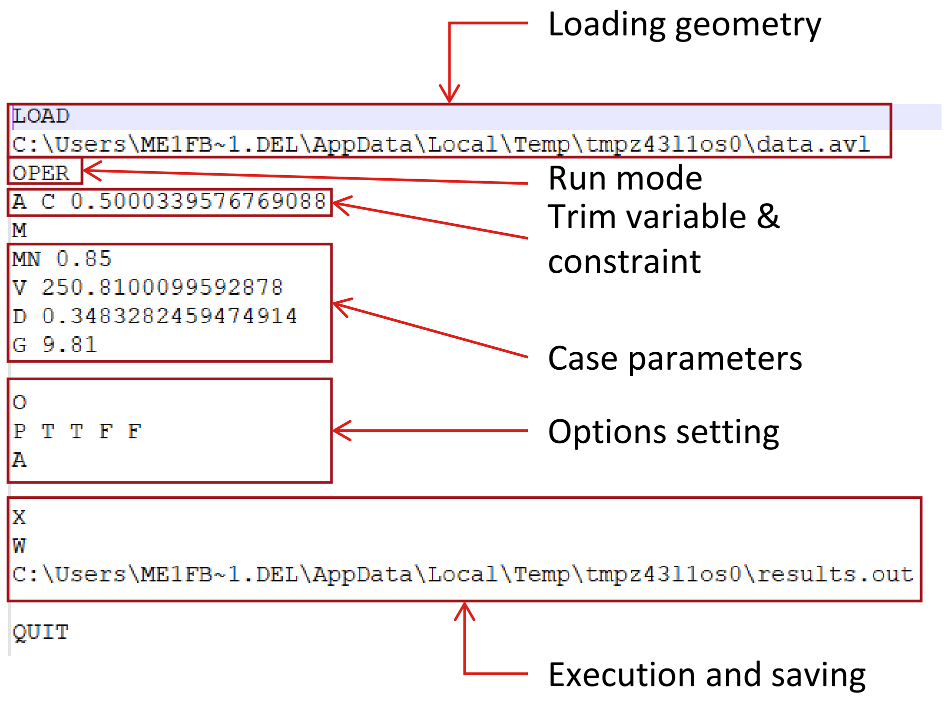
Global parameters
Surface definition
Nb element chordwise
Nb strips (spanwise)
Spreading law (uniform, cosine, sine,…)
Surface definition with airfoil definition
X, Y, Z leading edge
chord
Twist respect to leading edge
Airfoil defined by x and z coordinates

Method & Tools: AVL

- Run case file description:

This file describes the operation to be performed in AVL it can be edited manually or using graphic interface of AVL on a reference case. For example:

- Loading of avl input geometry file : LOAD + file name
- OPER to enter in « operating point » run mode
- A and C define the constraint on C(L) and the adjusted variable A(oA) for trim
- M to define case parameters : MN for Mach number V for airspeed, D for density and G for gravity acceleration
- O to define options and P for printing outputs T T F F means (total and surface forces On strips and elements forces Off) A to change axis orientation to Z upward (Default downward)
- X to execute and W + file name to save printing results



```
LOAD
C:\Users\ME1FB~1.DEL\AppData\Local\Temp\tmpz43l1os0\data.avl
OPER
A C 0.5000339576769088
M
MN 0.85
V 250.8100099592878
D 0.3483282459474914
G 9.81

O
P T T F F
A

X
W
C:\Users\ME1FB~1.DEL\AppData\Local\Temp\tmpz43l1os0\results.out

QUIT
```

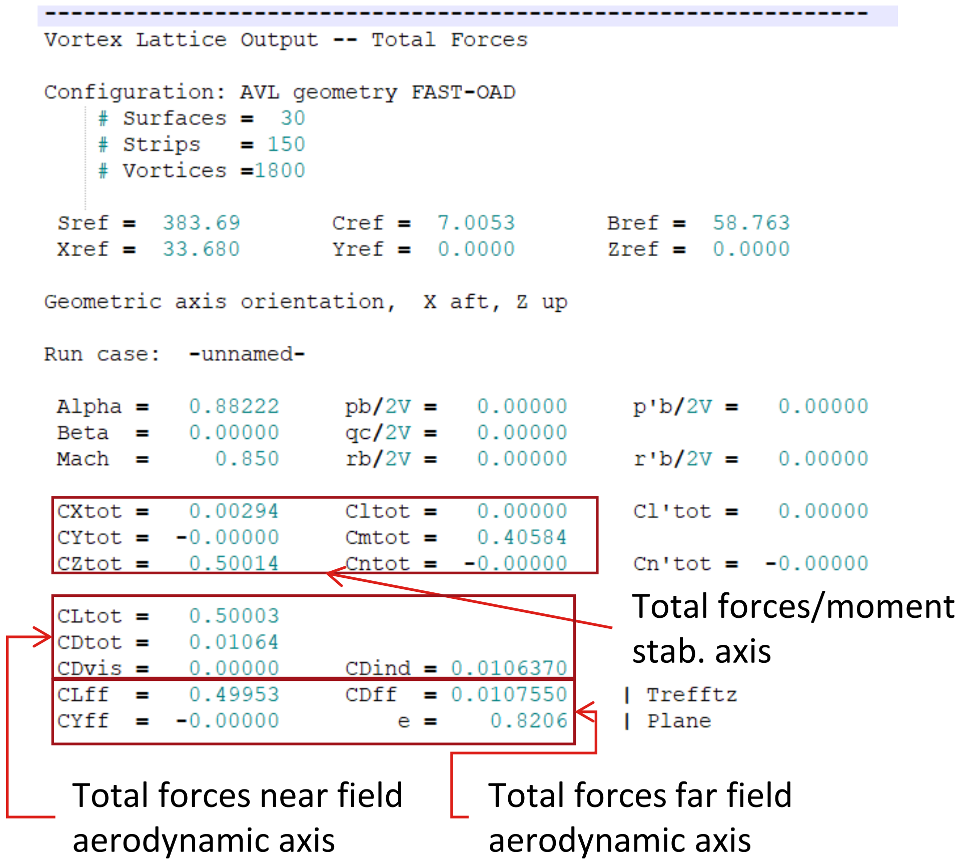
Method & Tools: AVL

• Output file description:

Depending on the outputs requested through the graphic interface or run case file the output file will look differently. However, in this document we are mainly interested in two outputs which are the total forces and the surface forces:

Total force:

- For trimmed computation gives the converged AoA
- Total lift and drag coefficients are provided (aerodynamic axis).
- Induced drag from near field pressure integration and from Trefftz Plane integration are delivered.
- Total moment and forces in stability axis are also provided.



```
 ---------------------------------------------------------------
 Vortex Lattice Output -- Total Forces

 Configuration: AVL geometry FAST-OAD
     # Surfaces =  30
     # Strips   = 150
     # Vortices =1800

  Sref =  383.69       Cref =  7.0053       Bref =  58.763
  Xref =  33.680       Yref =  0.0000       Zref =  0.0000

 Geometric axis orientation,  X aft, Z up

 Run case:  -unnamed-

  Alpha =   0.88222     pb/2V =   0.00000     p'b/2V =   0.00000
  Beta  =   0.00000     qc/2V =   0.00000
  Mach  =     0.850     rb/2V =   0.00000     r'b/2V =   0.00000

  CXtot =   0.00294     Cltot =   0.00000     Cl'tot =   0.00000
  CYtot =  -0.00000     Cmtot =   0.40584
  CZtot =   0.50014     Cntot =  -0.00000     Cn'tot =  -0.00000

  CLtot =   0.50003
  CDtot =   0.01064
  CDvis =   0.00000     CDind = 0.0106370
  CLff  =   0.49953     CDff  = 0.0107550    | Trefftz
  CYff  =  -0.00000         e =    0.8206    | Plane
```

Total forces/moment stab. axis
Total forces near field aerodynamic axis
Total forces far field aerodynamic axis

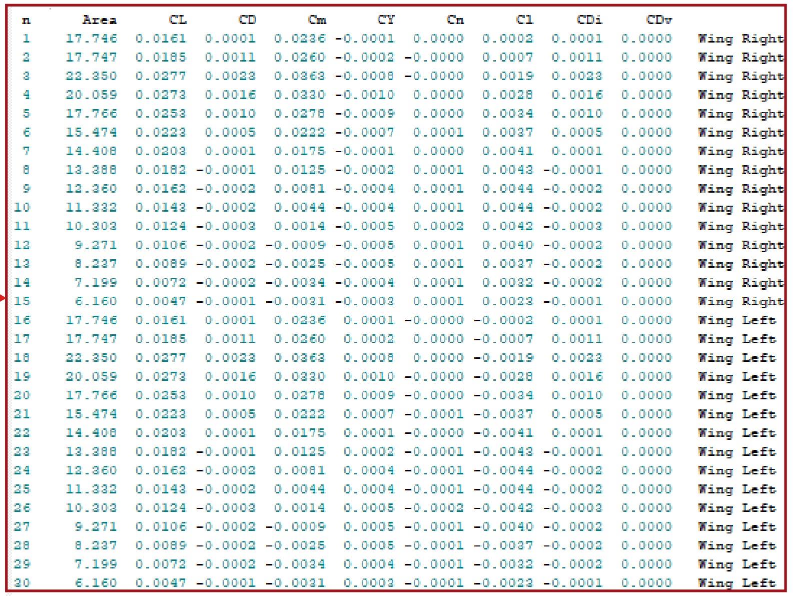
Method & Tools: AVL

- Output file description:

Surface force:

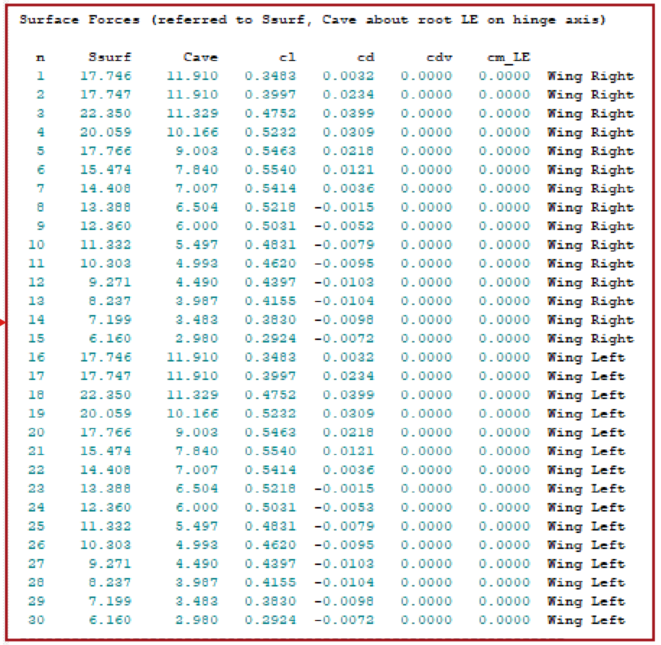
- Provides with Lift, drag and lateral force coefficient for each surface referred to Sref, Cref and Bref.
- Provides with Pitching, rolling and yawing moment coefficient for each surface about Xref, Yref, Zref.
- Provides also coefficients with respect to Ssurf and average chord.

Surface forces / moment respect to reference values



```
n      Area     CL      CD      Cm      CY      Cn      Cl     CDi     CDv
1    17.746  0.0161  0.0001  0.0236 -0.0001  0.0000  0.0002  0.0001  0.0000   Wing Right
2    17.747  0.0185  0.0011  0.0260 -0.0002 -0.0000  0.0007  0.0011  0.0000   Wing Right
3    22.350  0.0277  0.0023  0.0363 -0.0008 -0.0000  0.0019  0.0023  0.0000   Wing Right
4    20.059  0.0273  0.0016  0.0330 -0.0010  0.0000  0.0028  0.0016  0.0000   Wing Right
5    17.766  0.0253  0.0010  0.0278 -0.0009  0.0000  0.0034  0.0010  0.0000   Wing Right
6    15.474  0.0223  0.0005  0.0222 -0.0007  0.0001  0.0037  0.0005  0.0000   Wing Right
7    14.408  0.0203  0.0001  0.0175 -0.0001  0.0000  0.0041  0.0001  0.0000   Wing Right
8    13.388  0.0182 -0.0001  0.0125 -0.0002  0.0001  0.0043 -0.0001  0.0000   Wing Right
9    12.360  0.0162 -0.0002  0.0081 -0.0004  0.0001  0.0044 -0.0002  0.0000   Wing Right
10   11.332  0.0143 -0.0002  0.0044 -0.0004  0.0001  0.0044 -0.0002  0.0000   Wing Right
11   10.303  0.0124 -0.0003  0.0014 -0.0005  0.0002  0.0042 -0.0003  0.0000   Wing Right
12    9.271  0.0106 -0.0002 -0.0009 -0.0005  0.0001  0.0040 -0.0002  0.0000   Wing Right
13    8.237  0.0089 -0.0002 -0.0025 -0.0005  0.0001  0.0037 -0.0002  0.0000   Wing Right
14    7.199  0.0072 -0.0002 -0.0034 -0.0004  0.0001  0.0032 -0.0002  0.0000   Wing Right
15    6.160  0.0047 -0.0001 -0.0031 -0.0003  0.0001  0.0023 -0.0001  0.0000   Wing Right
16   17.746  0.0161  0.0001  0.0236  0.0001 -0.0000 -0.0002  0.0001  0.0000   Wing Left
17   17.747  0.0185  0.0011  0.0260  0.0002  0.0000 -0.0007  0.0011  0.0000   Wing Left
18   22.350  0.0277  0.0023  0.0363  0.0008  0.0000 -0.0019  0.0023  0.0000   Wing Left
19   20.059  0.0273  0.0016  0.0330  0.0010 -0.0000 -0.0028  0.0016  0.0000   Wing Left
20   17.766  0.0253  0.0010  0.0278  0.0009 -0.0000 -0.0034  0.0010  0.0000   Wing Left
21   15.474  0.0223  0.0005  0.0222  0.0007 -0.0001 -0.0037  0.0005  0.0000   Wing Left
22   14.408  0.0203  0.0001  0.0175  0.0001 -0.0000 -0.0041  0.0001  0.0000   Wing Left
23   13.388  0.0182 -0.0001  0.0125  0.0002 -0.0001 -0.0043 -0.0001  0.0000   Wing Left
24   12.360  0.0162 -0.0002  0.0081  0.0004 -0.0001 -0.0044 -0.0002  0.0000   Wing Left
25   11.332  0.0143 -0.0002  0.0044  0.0004 -0.0001 -0.0044 -0.0002  0.0000   Wing Left
26   10.303  0.0124 -0.0003  0.0014  0.0005 -0.0002 -0.0042 -0.0003  0.0000   Wing Left
27    9.271  0.0106 -0.0002 -0.0009  0.0005 -0.0001 -0.0040 -0.0002  0.0000   Wing Left
28    8.237  0.0089 -0.0002 -0.0025  0.0005 -0.0001 -0.0037 -0.0002  0.0000   Wing Left
29    7.199  0.0072 -0.0002 -0.0034  0.0004 -0.0001 -0.0032 -0.0002  0.0000   Wing Left
30    6.160  0.0047 -0.0001 -0.0031  0.0003 -0.0001 -0.0023 -0.0001  0.0000   Wing Left
```

Surface forces / moment respect to local values



```
Surface Forces (referred to Ssurf, Cave about root LE on hinge axis)

  n     Ssurf      Cave        cl        cd       cdv     cm_LE
  1    17.746    11.910    0.3483    0.0032    0.0000    0.0000  Wing Right
  2    17.747    11.910    0.3997    0.0234    0.0000    0.0000  Wing Right
  3    22.350    11.329    0.4752    0.0399    0.0000    0.0000  Wing Right
  4    20.059    10.166    0.5232    0.0309    0.0000    0.0000  Wing Right
  5    17.766     9.003    0.5463    0.0218    0.0000    0.0000  Wing Right
  6    15.474     7.840    0.5540    0.0121    0.0000    0.0000  Wing Right
  7    14.408     7.007    0.5414    0.0036    0.0000    0.0000  Wing Right
  8    13.388     6.504    0.5218   -0.0015    0.0000    0.0000  Wing Right
  9    12.360     6.000    0.5031   -0.0052    0.0000    0.0000  Wing Right
 10    11.332     5.497    0.4831   -0.0079    0.0000    0.0000  Wing Right
 11    10.303     4.993    0.4620   -0.0095    0.0000    0.0000  Wing Right
 12     9.271     4.490    0.4397   -0.0103    0.0000    0.0000  Wing Right
 13     8.237     3.987    0.4155   -0.0104    0.0000    0.0000  Wing Right
 14     7.199     3.483    0.3830   -0.0098    0.0000    0.0000  Wing Right
 15     6.160     2.980    0.2924   -0.0072    0.0000    0.0000  Wing Right
 16    17.746    11.910    0.3483    0.0032    0.0000    0.0000  Wing Left
 17    17.747    11.910    0.3997    0.0234    0.0000    0.0000  Wing Left
 18    22.350    11.329    0.4752    0.0399    0.0000    0.0000  Wing Left
 19    20.059    10.166    0.5232    0.0309    0.0000    0.0000  Wing Left
 20    17.766     9.003    0.5463    0.0218    0.0000    0.0000  Wing Left
 21    15.474     7.840    0.5540    0.0121    0.0000    0.0000  Wing Left
 22    14.408     7.007    0.5414    0.0036    0.0000    0.0000  Wing Left
 23    13.388     6.504    0.5218   -0.0015    0.0000    0.0000  Wing Left
 24    12.360     6.000    0.5031   -0.0053    0.0000    0.0000  Wing Left
 25    11.332     5.497    0.4831   -0.0079    0.0000    0.0000  Wing Left
 26    10.303     4.993    0.4620   -0.0095    0.0000    0.0000  Wing Left
 27     9.271     4.490    0.4397   -0.0103    0.0000    0.0000  Wing Left
 28     8.237     3.987    0.4155   -0.0104    0.0000    0.0000  Wing Left
 29     7.199     3.483    0.3830   -0.0098    0.0000    0.0000  Wing Left
 30     6.160     2.980    0.2924   -0.0072    0.0000    0.0000  Wing Left
```

Method & Tools: PyNastran

• General introduction

PyNastran is a Python package that provides with a GUI do manage FEM models with Nastran but also functions to read and write input .bdf files. These latter functionalities are the focus of this document. Some documentation can be found here: https://pynastran-git.readthedocs.io/en/latest/installation/index.html.

• BDF generation:

Here some more details are provided regarding the BDF file generation using pyNastran.

First, import pyNastran.bdf.bdf.BDF and pyNastran.bdf.bdf.CaseControlDesck classes.

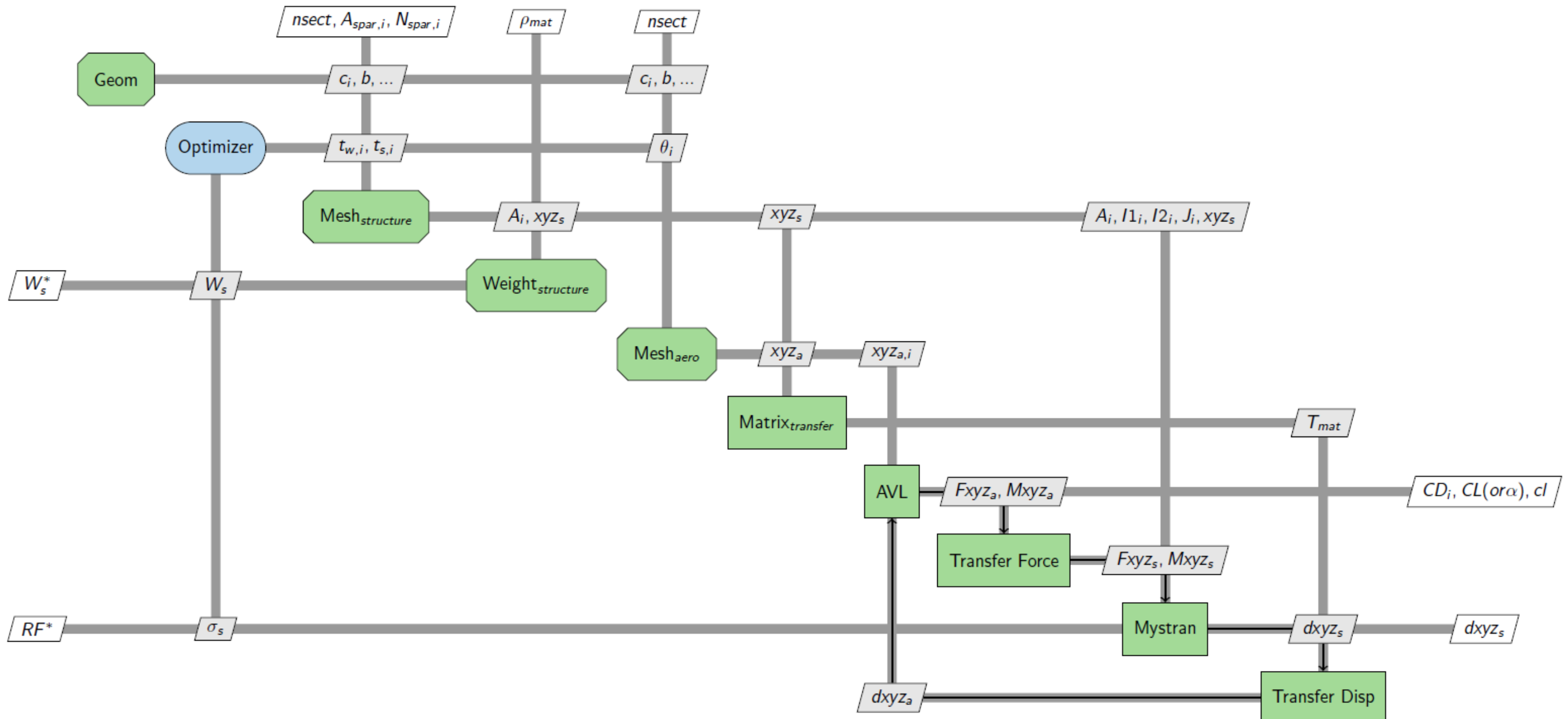
Then for an given instance "bdf" we are able to:

- Define the solution bdf.sol = (10)1, (10)3 …
- Add a case control section bdf.case_control_deck = CaseControlDeck([*list of case controle section entries*])
- Add cards bdf.add_*card_name*(*args, **kargs)
- Write the bdf bdf.write_bdf(*file_name*, enddata=True).

pyNastran also proivde with a functionality to run equivalence routine on nodes (i.e. merge nodes within a given tolerance) it can be found in pyNastran.bdf.mesh_utils.bdf_equivalence.bdf_equivalence_nodes.

Implementation in FAST-OAD: Presentation

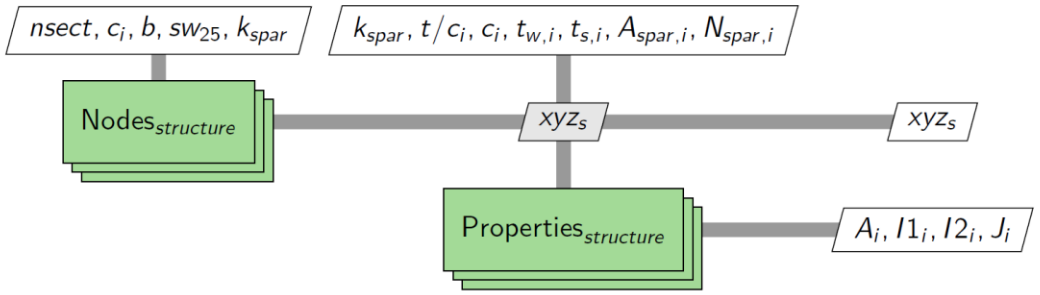
As it can be seen from the XDSM plot presented below, the implementation of aerostructural sizing in FAST-OAD involves several new groups and components. The geometry part is not addressed here as it is already existing in the current version of FAST-OAD. We will focus on structural and aerodynamic discretization and coupled computation procedure.



Implementation in FAST-OAD: Structure mesh

• General presentation

The structure mesh group aims to compute structural nodes location as well as finite elements properties. As illustrated on the XDSM graph:



$nsect, c_i, b, sw_{25}, k_{spar}$
$k_{spar}, t/c_i, c_i, t_{w,i}, t_{s,i}, A_{spar,i}, N_{spar,i}$
$\text{Nodes}_{structure}$
xyz_s
xyz_s
$\text{Properties}_{structure}$
$A_i, I1_i, I2_i, J_i$

For each structural part (wing, vertival tail, horizontal tail, …) a component that compute nodes location is created. These component are active or not depending on « structural_components » option value (list). This option gather too upper level options which are “coupled_components” and “additional_structural_components” that are list of structural part coupled to be considered in the coupling with aerodynamic solver and structural parts only consider for structural computation.

Another option “structural_components_sections” correspond to the number of elements (spanwise for the wing) wished by the user for each part, it is used to set the output vectors size. It is a list of integer.

Implementation in FAST-OAD: Structure mesh

• Node component example for wing part

Let’s consider the example of the wing.

The *StructureNodesWing* component take as inputs:

- characteristic chords (root, kink, tip),
- wing box spars ratios (root, kink, tip)
- wing sweep
- Characteristic sections spanwise locations (root, kink, tip).

And returns the nodes locations as a [(2 + number_of_sections)*2, 3] matrix (left and right wings considered). The nodes components also return what has been called “aeroelastic nodes” that are nodes located at the leading and trailing edges of each section to generate a “fishbone” structural representation useful for aeroelastic considerations.

The component take as option “number_of_sections” that correspond to the number of section desired for a given structural part and read from “structural_components_sections”.

Remark: the matrix is currently build from center node (y=0) to right tip and symmetrized, that means that 2 nodes are collocated at the center and “glued” together in the FEM. Another, maybe more relevant procedure would have been to build matrix from left to right – or opposite – to have only one node at the center.

Implementation in FAST-OAD: Structure mesh

• Properties component example for wing part

If we now look at the properties components, here again a component is created for each structural part and is activated by the active parts specified through the option “structural_components”. Elements properties currently implemented refer only to beam properties i.e. only 1D model are used so far. The method could be extended to more than 1D models adding shell properties for example.

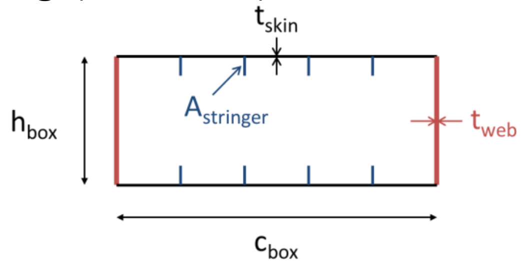
For the wing example, the property component *WingBeamProps* computes beam section characteristics at each structural nodes location. Linear interpolations are used to interpolate values between nodes. The wing (also tails) cross section is represented below with main parameters.

This component takes as inputs:

- Aerodynamic section characteristics: chord, t/c for characteristic sections (root, kink, tip)
- Wing box spars ratios (root, kink, tip)
- Box skin and web thickness for characteristic sections (root, kink, tip)
- The area and number of spars per side (upper/lower) [optional, by defauld nspar = 0].

The component returns sections characteristics:

- Inertias, Ixx, Iyy, J
- Area
- Stress recovery point coordinates in section local axis (4 corners for a box)



Wing box cross-section

$$I_1 = 2t_w\frac{h^3}{12} + c\left(t_{s,u} + t_{s,l}\right)\frac{h^2}{4} + NA_S\frac{h^2}{4} + 4A_{SC}\frac{h^2}{4},$$

$$I_2 = 2\left(ht_w\frac{c^2}{4} + t_s\frac{c^3}{12} + NA_S\sum_{i=1}^{N}\left(x_{1,i} - x_{1,\text{ref}}\right)^2\right),$$

$$J = \frac{4c^2h^2}{2\left(h/t_w\right) + c\left(1/t_{s,u} + 1/t_{s,l}\right)}.$$

Inertias computation from [1]

[1] https://doi.org/10.1155/2016/4805817

Implementation in FAST-OAD: Structure mesh

- Properties component example for wing part

Important remark: The wing section properties have been computed from local aerodynamic chord value but the projection on elastic axis has been forgotten. Therefore, a slight over estimation of the wing box chords is expected. This should be corrected in future version even if the error should be limited for the wings currently under study with sweep around 25°-30°.

Implementation in FAST-OAD: Structure weight

• General presentation

The *StructuralWeight* group is composed currently of only one component for wing weight estimate. But, this is subject to change is we want to consider other structural parts.

The wing weight component (*WingStructuralWeight*) computes primary structure weight considering the following inputs:

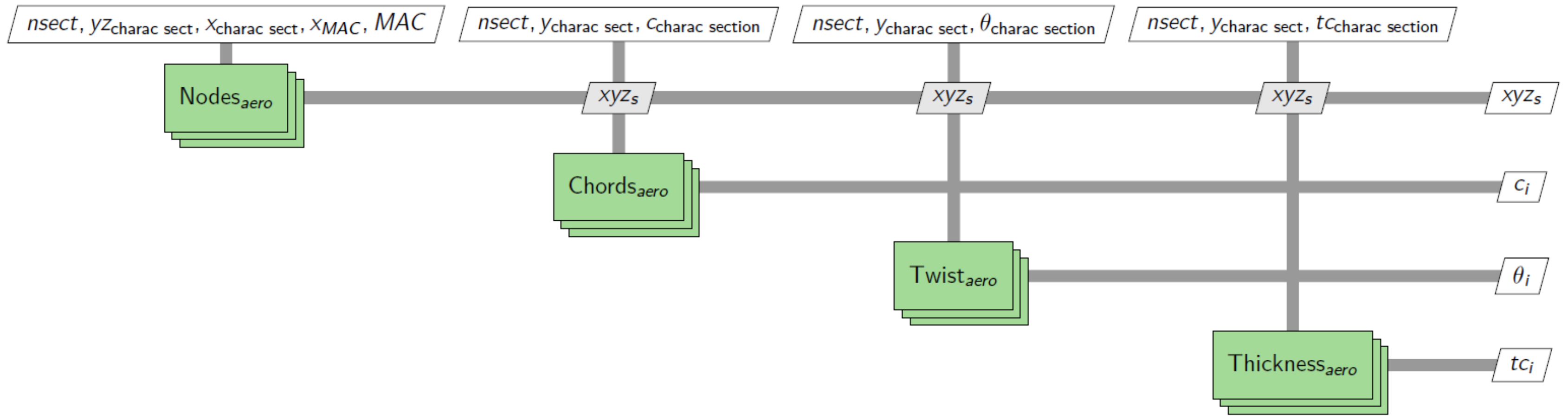
- Structural nodes location
- Beam areas for each structural section
- Material density

It returns the primary structure weight for the wing as the sum of elements weight. Similar approach can be extended to other structural parts such as tails.

Implementation in FAST-OAD: Aero mesh

• General presentation:

The aerodynamic mesh group (*AerodynamicMesh*) aims to compute aerodynamic nodes location, chords and optionally twist and thickness ratios to be inputted directly in AVL geometry file or to compute profiles coordinates.


$nsect, yz_{\text{charac sect}}, x_{\text{charac sect}}, x_{MAC}, MAC$
$nsect, y_{\text{charac sect}}, c_{\text{charac section}}$
$nsect, y_{\text{charac sect}}, \theta_{\text{charac section}}$
$nsect, y_{\text{charac sect}}, tc_{\text{charac section}}$
Nodes_{aero}
xyz_s
xyz_s
xyz_s
xyz_s
Chords_{aero}
c_i
Twist_{aero}
θ_i
Thickness_{aero}
tc_i

In that purpose, components are created for each aerodynamic parts (wing, tails, …) to computes nodes locations (leading edge) depending on the number of sections desired and indicated through “aerodynamic_components_sections” option. As for structural mesh, the components of aerodynamc mesh are activated depending on the aerodynamic part listed in the option “aerodynamic_components” that gathers the upper level options “coupled_components” and “additional_aerodynamic_components” that correspond to parts to be coupled with structure or to be considered only for aerodynamic computation, respectively.

Implementation in FAST-OAD: Aero mesh

- Node component example for wing part

Let’s consider the example of the wing.

The *AerodynamicNodesWing* component take as inputs:

- characteristic section leading edge location in wing local axis (root, kink, tip),
- wing MAC length, quarter chord location, leading edge location in wing local axis (i.e. w.r.t. root)
- Characteristic sections spanwise and vertical [new w.r.t. current FAST-OAD version, manually computed and input right now but should be computed from dihedral angle in future versions] locations (root, kink, tip).

And returns the nodes locations as a [(1 + number_of_sections)*2, 3] matrix (left and right wings considered).

The component take as option “number_of_sections” that correspond to the number of section desired for a given aerodynamic part and read from “aerodynamic_components_sections”.

Implementation in FAST-OAD: Aero mesh

- Chord component example for wing part

Let’s consider the example of the wing.

The *AerodynamicChordsWing* component take as inputs:

- Characteristic sections chords (root, kink, tip)
- Characteristic sections spanwise (root, kink, tip)
- Aerodynamic wing nodes previously computed.

And returns local chords values at aerodynamic nodes locations using linear interpolation between characteristic sections (root, kink, tip).

The component take as option “number_of_sections” that correspond to the number of section desired for a given aerodynamic part and read from “aerodynamic_components_sections”. It is only to control output vector size.

Implementation in FAST-OAD: Aero mesh

• Twist component example for wing part

Let’s consider the example of the wing.

The *AerodynamicTwistWing* component take as inputs:

- Characteristic sections twist (root, kink, tip) [new geometric parameter w.r.t current FAST-OAD version, are inputs and potential design variables]
- Characteristic sections spanwise (root, kink, tip)
- Aerodynamic wing nodes previously computed.

And returns local geometric twist values at aerodynamic nodes locations using linear interpolation between characteristic sections (root, kink, tip).

The component take as option “number_of_sections” that correspond to the number of section desired for a given aerodynamic part and read from “aerodynamic_components_sections”. It is only to control output vector size.

<u>Remark</u>: The twist values returned by the component correspond to local geometric twists and not, as it could be thought from the name of the class, aerodynamic twists.

Implementation in FAST-OAD: Aero mesh

• Thickness ratios component example for wing part

Let's consider the example of the wing.

The *AerodynamicThicknessRatiosWing* component take as inputs:

- Characteristic sections thicknes ratios (root, kink, tip)
- Characteristic sections spanwise (root, kink, tip)
- Aerodynamic wing nodes previously computed.

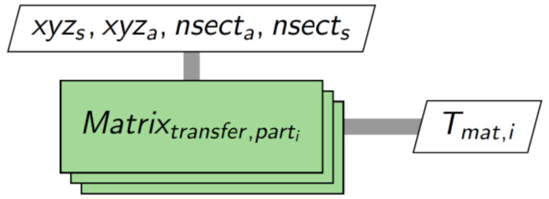
And returns local thickness ratio values at aerodynamic nodes locations using linear interpolation between characteristic sections (root, kink, tip).

The component take as option "number_of_sections" that correspond to the number of section desired for a given aerodynamic part and read from "aerodynamic_components_sections". It is only to control output vector size.

Implementation in FAST-OAD: Transfer matrix

- General presentation

The *TransferMatrices* group is made of components that compute displacements transfer matrix for each coupled parts defines in the option “coupled_components” (list of str), the number of section for aerodynamic and structural models (listed in the options “aerodynamic_components_sections” and “structural_components_sections”) and interpolation method (only linear method implemented so far).



Implementation in FAST-OAD: Transfer matrix

- ComponentMatrix example:

The component takes as input:

- Structure nodes coordinates
- Aerodynamic nodes coordinates

And return a displacements transfer matrix for the coupled part considered (wing, tails, …)

The component take as options “component” that is the name of the part under consideration from “coupled_components” upper level option, “number_of_aerodynamic_sections”, “number_of_structural_sections” and “interpolation_method”

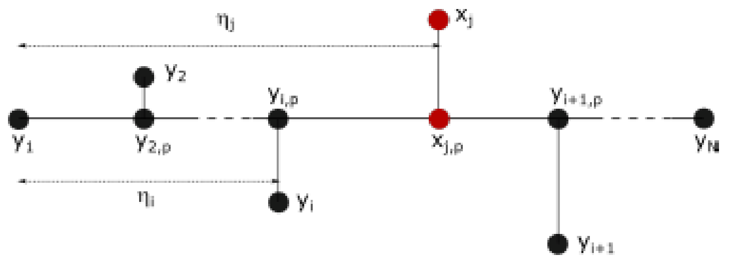
At the moment only linear interpolation is used: The displacements of aerodynamic nodes are computed from those of their projection on the beam formed by structural nodes. The projected node displacements are linearly interpolated from displacement of the two closest structural nodes. Then displacement of the aerodynamic nodes are computed using rigid displacement and rotation matrix. Graphical explanation is provided on next page.

Implementation in FAST-OAD: Transfer matrix

- ComponentMatrix example:

Let’s denote aerodynamic nodes as x_i and structural ones as y_i the subscript “p” stands for projection.

Structural and aerodynamic nodes are projectted on beam formed by extreme structural nodes. Structural displacements of projections (t_1, t_2, t_3) are computed from translation and rotation (t_4, t_5, t_6) :



$$[t_{1y_{i,p}}, t_{2y_{i,p}}, t_{3y_{i,p}}, t_{4y_{i,p}}, t_{5y_{i,p}}, t_{6y_{i,p}}] = \begin{bmatrix} 1 & 0 & 0 & 0 & d_{3_i} & -d_{2_i} \\ 0 & 1 & 0 & -d_{3_i} & 0 & d_{1_i} \\ 0 & 0 & 1 & d_{2_i} & -d_{1_i} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} t_{1y_i} \\ t_{2y_i} \\ t_{3y_i} \\ t_{4y_i} \\ t_{5y_i} \\ t_{6y_i} \end{bmatrix}$$

Then aerodynamic nodes projection displacement are linearly interpolated:

$$t_{kx_{j,p}} = t_{ky_{i,p}} + \frac{t_{ky_{i+1,p}} - t_{ky_{i,p}}}{\eta_{y_{i+1}} - \eta_{y_i}} \cdot (\eta_{x_j} - \eta_{y_i})$$

Then aerodynamic nodes displacement are computed with rigid rotations matrix:

$$[t_{1x_j}, t_{2x_j}, t_{3x_j}] = \begin{bmatrix} 1 & 0 & 0 & 0 & d_{3_j} & -d_{2_j} \\ 0 & 1 & 0 & -d_{3_j} & 0 & d_{1_j} \\ 0 & 0 & 1 & d_{2_j} & -d_{1_j} & 0 \end{bmatrix} \begin{bmatrix} t_{1y} \\ t_{2y} \\ t_{3y} \\ t_{4y} \\ t_{5y} \\ t_{6y} \end{bmatrix}$$

The $d_{k,i}$ terms represents the projected distances on axis k between 2 nodes.

Implementation in FAST-OAD: Aero solver

- General presentation

The aerodynamic solver AVL is called through an ExternalComponent that take as inputs:

- Wing span, leading edge sweep and area
- MAC length, quarter chord longitudinal location
- Load case: nz, altitude, weight, mach
- Aerodynamic nodes, displacements rotations
- Local chords and twist (for wing only)
- Local thickness ratio (for wing only)

It returns aerodynamic forces and moments at aerodynamic nodes locations. And optionally, lift, induced drag, Oswald coefficients, AoA.

The AVL run case file is generated using the parser provided by OpenMDAO. Particularly computation are performed at constant CL computed from nz, weight, altitude and wing area.

The AVL geometry file is generated with a dedicated function. Here, we decided to define an AVL surface per aerodynamic section to be able to retrieve local force and moments directly for ouputs. But, we still performed a spanwise discretization and each surface is made of 5 strip. This is hardcoded while number of chordwise panels is a tuning parameter.

Implementation in FAST-OAD: Aero solver

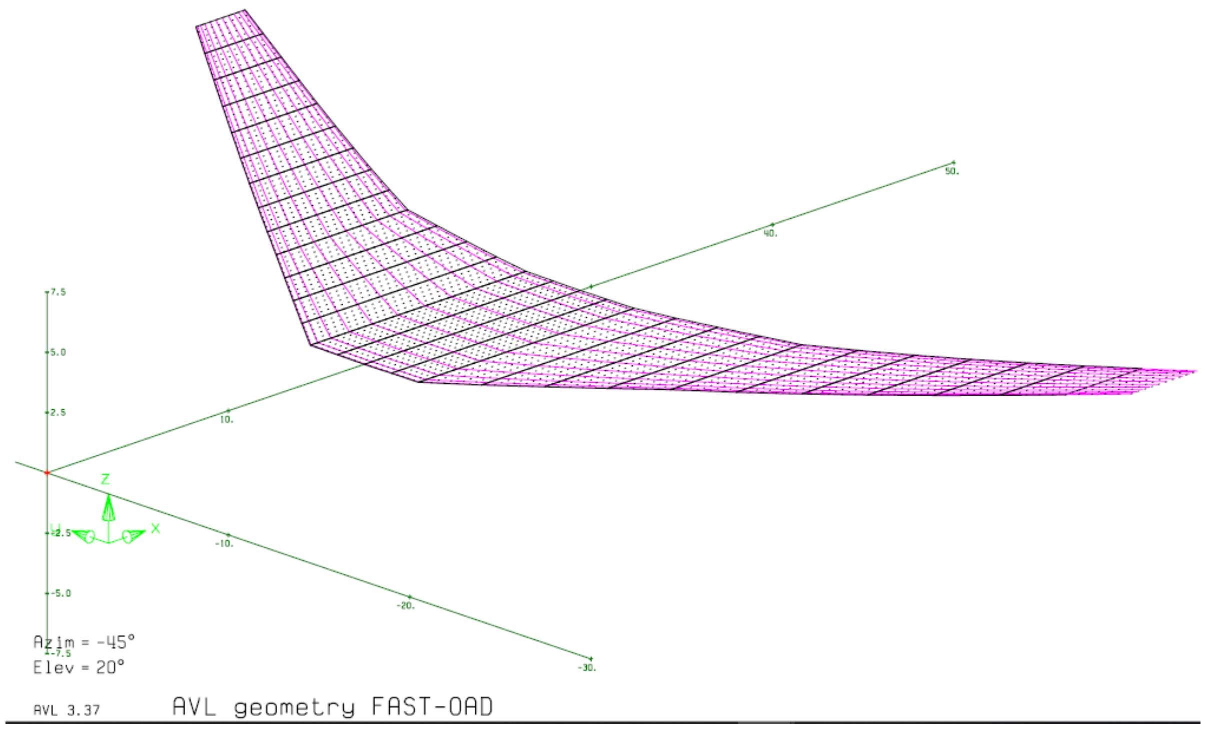
- General presentation

Each surface generated is part of a component that correspond to the aerodynamic part it belongs to. In other words, all the surfaces of a given part belongs to the same component to have a proper consideration of interaction between panels.

A distinction is made however between symmetric components (wing) for what regards surface names such that no symmetry is considered in AVL. It allow to deal with none symmetric loading resulting from lateral load cases (not yet implemented).

An example of AVL geometry for CRM test case is represented opposite:

Surfaces are delimited by black lines, dashed line represent the additional spanwise discretization



Implementation in FAST-OAD: Strucutre solver

• General presentation

The finite element solver MYSTRAN is called through an ExternalComponent that takes as inputs:

- The structure nodes
- The local beam properties
- The material properties (Young's modulus, density, Poisson's modulus, minimal thickness)
- The nodal forces and moment at structure nodes locations.

It returns the nodes displacements and the maximum stress within the structure.

The MYSTRAN input bdf file is generated with a dedicated static method using pyNastran package.

The model is only 1D. With every part (wing, tails, …) clamped at symmetry plan location. For the wing, strut and horizontal tail with 2 collocated nodes lying on symmetry plane, those nodes are « glued » with RBE2 element and one of them is clamped.

If a strut is present, it is linked to the wing node with an RBE2.

Remark: For the moment, only linear static solver is considered but to solve modal analysis is straightforward. However, one must pay attention on the fact that MYSTRAN only accept BAR elements and to take into account torsional inertia in dynamic computation for those element one must use NASTRAN with "NASTRAN   BARMASS=1" in the FMS section (top of the bdf file).

Implementation in FAST-OAD: Strucutre solver

- General presentation

The force and moment transfer is insured using nearest neighbor approach. For each structural nodes, the set of aerodynamic nodes for which the given node is the closest transfer there force to this node. The moments are computed w.r.t. lever arms from aero nodes to the considered node.

- Important remark

An uncorrect mistake appears in the wing weight computation that has not been corrected so far for lack of time. The error comme from the fact that the wing weigh is computed using distance between to adjacent node BUT when we change of wing (right to left) we have to jump an indice because of the double node at the center. Therefore in the current approach we take the section characteristic of the root section of the left wing multiplied by the distance between right wing tip and center node which highly incorrect. We should have for right wing Dist(node[i+1] to node[i]) for left wing dist (node[i+1] to node[i+2]).

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