Appendix W: Acoustic Volume Element and Spectral Element Solvers

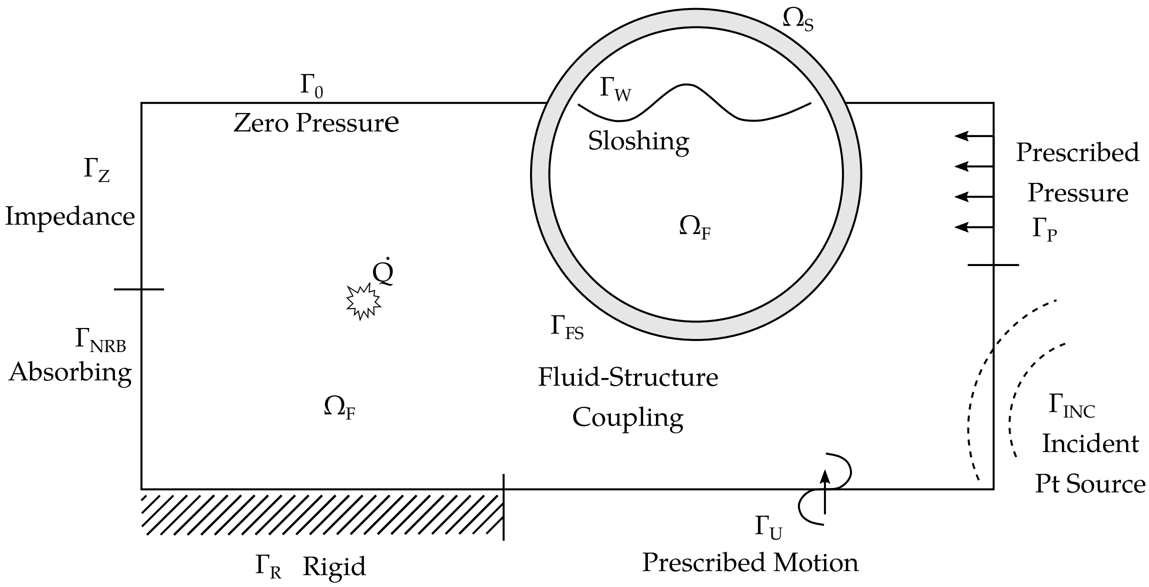

Figure 74-1. Sketch of the structural-acoustic system

Explicit Transient Acoustic Iso-parametric Element Solutions

The longstanding and default solution path for transient acoustic solutions in LS-DYNA uses low-order iso-parametric finite elements. It is capable of treating shock-induced cavitation and uses the displacement potential as the fundamental nodal unknown. This is the approach used if neither *CONTROL_IMPLICIT_SSD_DIRECT nor *CONTROL_ACOUSTIC_SPECTRAL is used.

Boundary condition treatment is summarized in Table 74-1. This solution path uses an inverted boundary condition strategy that may be confusing to analysts familiar with potential formulations. Kinematic boundary conditions are interpreted as if the formulation were a Lagrangian, displacement-based model like *MAT_ELASTIC. Thus, fluid faces that are constrained with nodal displacement constraints are rigid, sliding faces. Fluid faces that are left free are pressure release or zero pressure faces. And fluid faces that are merged with structural nodes are coupled faces. Structural coupling when there is fluid on both sides of a shell element requires *BOUNDARY_ACOUSTIC_COUPLING or *BOUNDARY_ACOUSTIC_COUPLING_MISMATCH. Non-reflecting and absorbing boundaries use either *BOUNDARY_NON_REFLECTING or the perfectly matched layer of *MAT_PML_ACOUSTIC.

Model Parameters	Keywords
Material Properties, Ω_F	*MAT_ACOUSTIC
Structural Coupling, Γ_{FS}	Merge fluid and structural nodes on one side *BOUNDARY_ACOUSTIC_COUPLING *BOUNDARY_ACOUSTIC_COUPLING_-MISMATCH
Prescribed Boundary Motion, Γ_U	No support
Prescribed Boundary Pressure, Γ_P	*LOAD_SEGMENT_SET
Rigid Boundary, Γ_R	*BOUNDARY_SPC
Impedance Boundary, Γ_Z	*BOUNDARY_ACOUSTIC_IMPEDANCE
Absorbing Boundary, Γ_{NRB}	*BOUNDARY_NON_REFLECTING *MAT_PML_ACOUSTIC
Zero Pressure Boudnary, Γ_{NRB}	Leave these nodes unconstrained
Small Amplitude Wave Boundary, Γ_W	No support
Internal Point Source, $\dot{Q}$	No support

Table 74-1. Keywords for explicit transient acoustic iso-parametric finite element solutions

Explicit Transient Acoustic Spectral Element Solutions

The spectral acoustic elements in LS-DYNA invoked with *CONTROL_ACOUSTIC_SPECTRAL use higher-order interpolants based on Legendre polynomials. The elements converge exponentially and support integration orders from 2 to 15. They are especially recommended for ultrasonic wave propagation. These elements have internal degrees-of-freedom (invisible to users). These degrees-of-freedom are generated automatically based on the integration order chosen. You may change the integration order and accuracy of the solution without remeshing.

For the explicit solution to the transient, fluid-structure interaction problem with acoustic spectral elements, the following nonsymmetric system is solved at every time step:

$$\begin{bmatrix} M_{ss} & 0 \\ -\rho c^2 T_{fs}^T & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{u} \\ \ddot{p} \end{bmatrix} + \begin{bmatrix} W_{ss} & 0 \\ 0 & W_{ff} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{p} \end{bmatrix} + \begin{bmatrix} K_{ss} & T_{fs} \\ 0 & K_{ff} \end{bmatrix} \begin{bmatrix} u \\ p \end{bmatrix} = \begin{bmatrix} r_s \\ r_f \end{bmatrix}$$

Here M_{ss}, W_{ss}, and K_{ss} are the structural mass, damping and stiffness. M_{ff}, W_{ff}, and K_{ff} are the equivalent matrices for the fluid. T_{fs} is the fluid-structure coupling matrix. Vector u is the structural displacements, and p is the pressure. The time step used is the smallest stable time step in either of the acoustic or structural domains. The applicable keywords are summarized by Table 74-2.

Model Parameters	Keywords
Material Properties, Ω_F	*MAT_ACOUSTIC *MAT_ACOUSTIC_DAMP
Structural Coupling, Γ_{FS}	*BOUNDARY_ACOUSTIC_COUPLING_-SPECTRAL
Weak Structural Coupling, Γ_{FS}	*INTERFACE_ACOUSTIC *BOUNDARY_ACOUSTIC_INTERFACE
Prescribed Boundary Motion, Γ_U	*BOUNDARY_ACOUSTIC_PRESCRIBED_-MOTION
Prescribed Boundary Pressure, Γ_P	*BOUNDARY_ACOUSTIC_PRESSURE_-SPECTRAL
Rigid Boundary, Γ_R	This is a natural condition
Impedance Boundary, Γ_Z	*BOUNDARY_ACOUSTIC_IMPEDANCE
Absorbing Boundary, Γ_{NRB}	*BOUNDARY_ACOUSTIC_NON_RE-FLECTING
Zero Pressure Boudnary, Γ_{NRB}	*BOUNDARY_ACOUSTIC_FREE_SURFACE
Small Amplitude Wave Boundary, Γ_W	*BOUNDARY_ACOUSTIC_FREE_SURFACE
Internal Point Source, $\dot{Q}$	*LOAD_ACOUSTIC_SOURCE

Table 74-2. Keywords for explicit transient acoustic spectral element solutions

The perfectly matched layer of *MAT_ACOUSTIC_PML is not currently supported in spectral acoustic element solutions.

For post-processing, pressure-time histories are written with *DATABASE_ACE-OUT and *DATABASE_HISTORY_ACOUSTIC. Plot states for the user's mesh are written to the D3PLOT file. The integration point used for those plot states is derived from the closest spectral pressure degree-of-freedom.

Implicit Direct Steady State Acoustic FE Solutions

For the direct solution to the forced vibration problem with acoustic fluid coupling, a complex symmetric system of equations is solved. This starts with

$$\begin{bmatrix} M_{ss} & 0 \\ 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{u} \\ \ddot{q} \end{bmatrix} + \begin{bmatrix} W_{ss} & T_{fs} \\ T_{fs}^T & W_{ff} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{q} \end{bmatrix} + \begin{bmatrix} K_{ss} & 0 \\ 0 & K_{ff} \end{bmatrix} \begin{bmatrix} u \\ q \end{bmatrix} = \begin{bmatrix} r_s \\ r_f \end{bmatrix}$$

Here M_{ss}, W_{ss}, and K_{ss} are the structural mass, damping and stiffness. M_{ff}, W_{ff}, and K_{ff} are the equivalent matrices for the fluid. T_{fs} is the fluid-structure coupling matrix. Vector u contains the displacements of structural nodes. Vector q contains the integral of the pressure, that is, the fluid nodal pressure equals $\dot{q}$.

Assuming $u = \overline{U_s} e^{i\omega t}$, $q = \overline{\Phi_f} e^{i\omega t}$, and $r_{f/s} = \overline{F_{f/s}} e^{i\omega t}$, the assembled system of equations becomes complex

$$\begin{bmatrix} -\omega^2 M_{ss} + i\omega W_{ss} + \overline{K_{ss}} & i\omega T_{fs} \\ i\omega T_{fs}^T & -\omega^2 \overline{M_{ff}} + i\omega \overline{W_{ff}} + \overline{K_{ff}} \end{bmatrix} \begin{bmatrix} \overline{U_s} \\ \overline{\Phi_f} \end{bmatrix} = \begin{bmatrix} \overline{F_s} \\ F_f \end{bmatrix}$$

Submatrices K_{ss}, M_{ff}, W_{ff}, and K_{ff} may also be complex and may be frequency dependent. This is the system that is solved for every forcing frequency with *CONTROL_IMPLICIT_SSD_DIRECT.

Model Parameters	Keywords
Material Properties, Ω_F	*MAT_ACOUSTIC *MAT_ACOUSTIC_DAMP *MAT_ACOUSTIC_COMPLEX *MAT_ACOUSTIC_POROUS_DB
Structural Coupling, Γ_{FS}	*BOUNDARY_ACOUSTIC_COUPLING_-MISMATCH
Weak Structural Coupling, Γ_{FS}	*INTERFACE_ACOUSTIC *BOUNDARY_ACOUSTIC_INTERFACE
Prescribed Boundary Motion, Γ_U	*BOUNDARY_ACOUSTIC_PRESCRIBED_-MOTION
Rigid Boundary, Γ_R	This is a natural condition
Impedance Boundary, Γ_Z	*BOUNDARY_ACOUSTIC_IMPEDANCE *BOUNDARY_ACOUSTIC_COMPLEX

Model Parameters	Keywords
	*BOUNDARY_ACOUSTIC_MECHANICAL
Absorbing Boundary, Γ_{NRB}	*BOUNDARY_ACOUSTIC_NON_REFLECTING
Zero Pressure Boundary, Γ_{NRB}	*BOUNDARY_ACOUSTIC_FREE_SURFACE
Small Amplitude Wave Boundary, Γ_W	*BOUNDARY_ACOUSTIC_FREE_SURFACE
Internal Point Source, $\dot{Q}$	*LOAD_ACOUSTIC_SOURCE
Incident Wave Point Source, Γ_{INC}	*LOAD_ACOUSTIC_SOURCE

Table 74-3. Keywords for implicit, direct steady state acoustic finite element solutions

For post-processing, real and imaginary nodal response is written with *DATABASE_ACEOUT and *DATABASE_HISTORY_ACOUSTIC.