Analyzing Vibration with Acoustic–Structural Coupling

FSI techniques using acoustic elements efficiently compute natural frequencies, harmonic response and other vibration effects in structures containing fluids.

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When designing equipment such as vessels, tanks, agitators, hydraulic piping systems, hydraulic turbines, transformers and sensors, engineers often must take into account a contained fluid. Presence of such fluids may add mass, stiffness and damping, which change the structural mechanics of the system. Also, the fluid may act as an excitation mechanism such as occurs in water hammer, which is the shock wave that occurs in a piping system when a water valve is abruptly shut off.

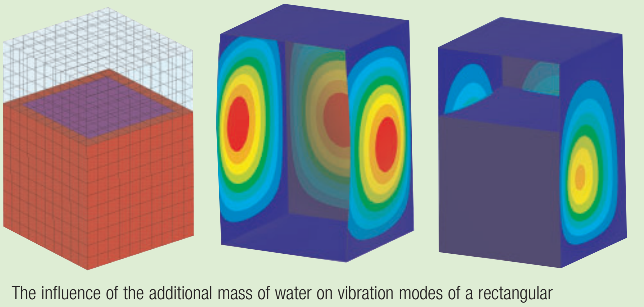
To fully study structural vibration in these types of applications, engineers must model the coupling mechanisms for fluid structure interaction (FSI). For these detailed studies, software from ANSYS has an outstanding breadth and depth of capabilities for structural and fluid analysis. Models are getting more and more realistic, and FSI continues to be one of the largest segments of multiphysics simulation. FSI simulations are usually performed using the ANSYS multi-field solver, which employs implicit sequential coupling to calculate interactions between fluid and structural solutions.

As an alternative to these types of FSI analyses of fluid-filled structures, engineers may want to consider an approach based on the use of ANSYS FLUID30 elements available in the ANSYS Mechanical and ANSYS

How Fluids Influence Structural Vibration

The presence of a fluid can significantly change the vibration characteristics of the containing structure. To determine the extent of this effect, engineers must model all relevant dynamics, especially the fluid–structure coupling that represents the interaction between these two domains. Models based on the ANSYS FLUID30 element must, therefore, account for factors, such as mass, stiffness and damping, that the fluid adds to the overall system.

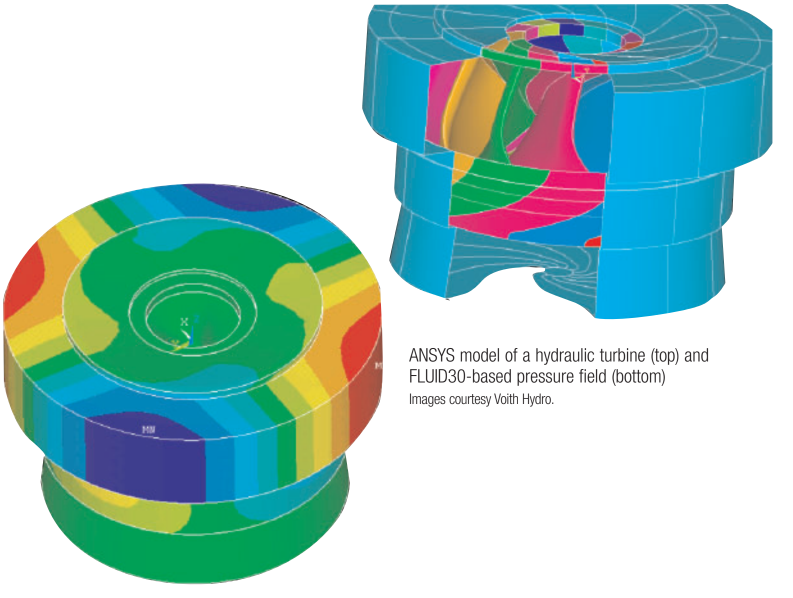
Mass. The additional mass of a heavy, rather incompressible fluid such as water in a vessel usually must be included in the analysis model, such as the thin-walled box in the example. Note that the first vibration mode for the partially filled container is about a third lower than that of the dry container. There is no easy rule of thumb in analytically determining the required added mass because results depend so much on frequency and mode shape. A fully coupled FSI simulation is required to answer this question.



The influence of the additional mass of water on vibration modes of a rectangular tank is shown in models of a partially filled tank (left), an uncoupled structural dry mode of the empty tank at 33 Hz (middle), and a coupled wet mode at 10 Hz taking into account FSI using ANSYS SHELL181/FLUID30 coupling (right).

Multiphysics products. These elements have their origin in acoustic applications; typically, they are used for simulating sound radiation. Their elasto-acoustic and hydro-elastic capabilities, however, are very helpful in solving FSI vibration problems by providing straightforward fluid–structural coupling in a given range of vibration analyses in which:

- The fluid is quiescent or at least moderately slow
- Vibration amplitudes are small (linear theory)
- The influence of fluid viscosity or shear layers is negligible, meaning an ideal gas assumption



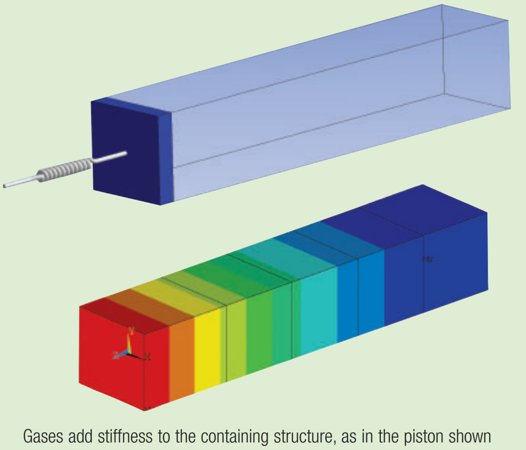
ANSYS model of a hydraulic turbine (top) and FLUID30-based pressure field (bottom)
Images courtesy Voith Hydro.

ANSYS acoustic elements accomplish the required fluid–structural coupling because they have four degrees of freedom (DOF): one for the sound pressure and three optional displacement DOFs. Thus, a consistent matrix coupling is set up between structural and fluid elements in which strongly coupled physics cause no convergence or performance problems. Additionally, in analyzing sensor applications, for example, engineers can use ANSYS FLUID30 elements to attach the piezoelectric part of the multiphysics problem via matrix coupling. In this way, three strongly coupled physical domains can be solved simultaneously: piezoelectric, structural and fluid.

Coupling structural elements to acoustic elements in this manner allows for transient analysis and, even more importantly, for modal and harmonic analysis in the frequency domain. Consequently, for the latter, simulation of the desired stationary peak response within one single frequency step is performed very efficiently. This is conveniently done without having to account for lengthy initial transients (particularly for weakly damped structures) required in most time-domain solutions coupling structural and fluid domains by a load vector.

Stiffness. Light-weight, rather compressible fluids such as gases do not add appreciable mass, but they can add stiffness to a closed air-filled structure. To imagine the “stiffness of air,” think of an air spring (gas shock absorber) or a bicycle air pump that you close with your thumb. In the analysis of a rectangular piston, for example, the added stiffness of air included in the model doubled the natural frequency, from 40 Hz to 80 Hz. Further, instead of one mode, analysis of the air-filled cylinder indicated many resonances from acoustic cavity.

Damping. In an unbounded fluid domain (ANSYS FLUID30 combined with FLUID130 for the external absorbent boundary layer), structural vibration may lead to pressure waves that propagate through the entire fluid system. In these cases, the energy spent on these compressive longitudinal acoustic waves is dissipated in an effect known as “radiation damping.” Particularly large plate-like structures in heavy fluids may encounter considerable added damping that must not be neglected, but no fluid viscosity is required for analyzing such cases.



Gases add stiffness to the containing structure, as in the piston shown here supported by a spring and an attached air enclosure (top) with an uncoupled dry mode at 40 Hz and a coupled wet mode at 80 Hz. Pressure mode of the cavity (bottom) was found using ANSYS FLUID30 elements to analyze the system.

Another advantage of using acoustic elements is their ability to quickly solve for fluid–pressure fluctuations. Since fluid and structural vibration systems have different temporal and spatial scales, properly discretizing wavelengths in time and space for these structural and fluid domains often requires extensive amounts of CPU time and resources. In contrast, acoustic elements account for pressure fluctuations and fluid properties much more efficiently when structural behavior such as resonant frequencies, mode shapes and peak vibration amplitudes must be calculated. Recent ANSYS solver improvements have significantly sped up this task, solving the resulting unsymmetric coupled system of equations in a fraction of time previously required.

The accompanying hydraulic turbine study is an excellent example of a contained fluid application that can be analyzed quickly and easily by a structural engineer using ANSYS acoustic FLUID30 elements. When coupled to the housing and the rotor, the elements include two important features. First, they account for the vibrating mass of water that strongly affects the vibration frequencies and vibration deformation of the structure. Secondly, the elements allow the engineer to easily model the excitation mechanism: the fluctuating pressure field of the water induced by the rotating rotor. Analyzing this coupled system by modal and harmonic response analysis with acoustic elements is considerably easier than with conventional finite element and fluid dynamics FSI methods, which require extensive effort to perform with transient analysis in both domains.

Today, users can complete modal analysis of FLUID30-based coupled systems within hours, even for large assemblies with millions of DOFs that otherwise would take days to perform using conventional FSI methods. Solution speed for huge models can be further improved by using special component mode synthesis (CMS) methods, Krylov subspace-based order reduction methods and symmetric formulations of the originally unsymmetric FSI system matrix. ■

Why Shallow Containers Slosh

To avoid severe load instabilities, engineers often face strict design requirements to control sloshing of liquid in moving containers, such as tanker trucks or rockets. In these applications, designers usually insert interior baffle plates or similar structures to impede the flow of liquid. Other applications include harbor design or study of long-wavelength tsunami waves. In all these cases, simulation plays a key role in predicting sloshing and evaluating ways to solve the problem.

An example of sloshing is the carrying of a dog bowl full of water, where the liquid has the tendency to slop from side to side and often spill. Simulation reveals that this behavior occurs because the first sloshing mode of the bowl is roughly at 2 Hz — the typical human step frequency that excites this undesired resonance. Repeating the analysis for a glass of water reveals a first sloshing mode of 4 Hz, which shows why water glasses are much less prone to spilling than bowls. In these simulations, the structural walls have been assumed to be rigid. Using the hydro-elastic coupling capabilities of software from ANSYS, however, engineers also can study sloshing in elastic vessels such as reactor containment structures. Note that sloshing analysis with ANSYS FLUID30 coupling is restricted to small amplitudes, and that full-fledged finite element and FSI analysis must be applied for simulating very large vibration amplitudes or fluid–surface motion.

Golden retriever Alex assists in a demonstration of sloshing. Analysis indicates the first sloshing mode is 1.6 Hz, the frequency at which the bowl is prone to resonance and spills its contents.