Fluid-structure interactions

The fully coupled solution of fluid flows with structural interactions, a rapidly evolving discipline, represents the natural next step in simulating mechanical systems. **By Klaus-Jürgen Bathe**

FINITE-ELEMENT METHODS are now widely used in the analysis of solids and structures, and they provide great benefits in product design. In fact, with today's highly competitive design and manufacturing markets, it is nearly impossible to ignore the advances that have been made in the computer analysis of structures without losing an edge in innovation and productivity. Various commercial finite-element programs are widely used and have proven to be indispensable in designing safer, more-economical products.

In the analysis of fluids, significant advances also have been made during recent decades. A number of commercial programs have been developed, and applications in product design are increasing rapidly.

At present, there are in essence two large application areas of fluid-flow analysis. In one, aerodynamic compressible-flow analyses are conducted in the course of airplane design; in the other, incompressible- and compressible-flow analyses are performed on mechanical and civil engineering designs.

Numerical simulations have been used for quite some time in aeronautics, but their application in mechanical engineering is more recent. The total annual expenditure for flow simulations in mechanical engineering is still much smaller than for structural analysis, but the number of applications in fluid-flow analysis is growing. This is largely due to valuable analysis capabilities that are now available for many practical cases of fluid flow in mechanical engineering—and the trend will undoubtedly grow stronger, thanks to a newly emerging field of analysis.

This new field of analysis is the fully coupled solution of fluid flows with structural interactions, commonly referred to as fluid-structure interaction (FSI). It is the natural next step to take in the simulation of mechanical systems.

The mechanical principles governing fluids and solids are the same. Indeed, only in the human mind are fluids separated from solids, largely because the response characteristics are quite different for the two media. These different characteristics result in different solution difficulties in numerical simulations of fluids and structures. Now that these difficulties, for structures and fluids, have been largely overcome, the complex response of various combined fluid and solid media can be analyzed effectively. Exciting developments and applications are now on the horizon for FSI.

Fluids in FSIs can be classified into three distinct categories: the acoustic fluid, the incompressible Navier-Stokes
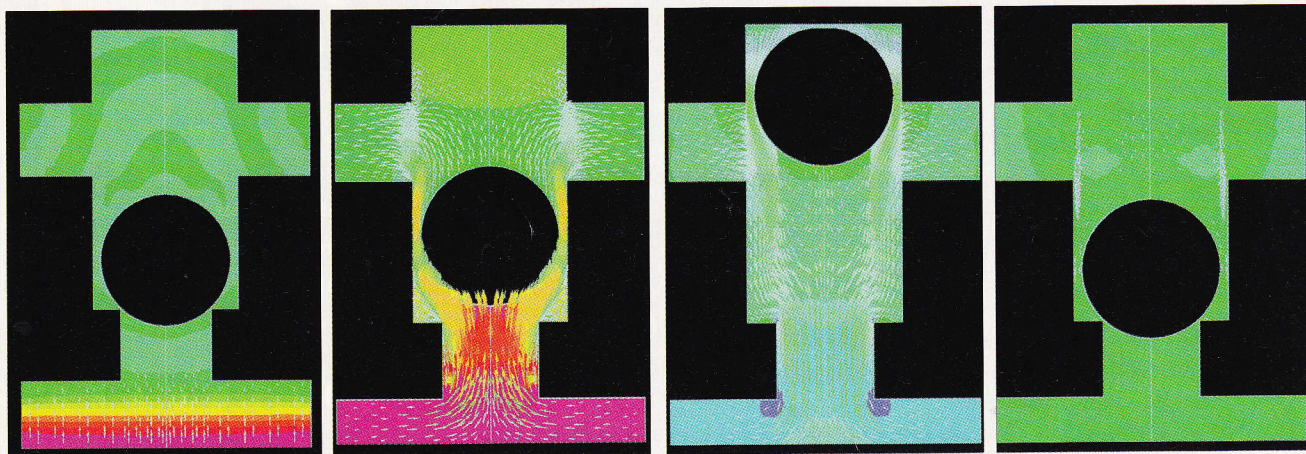
As the piston rises in this braking-system model created with the ADINA FEA system, the ball is pushed by the fluid to allow flow until the opening is closed.
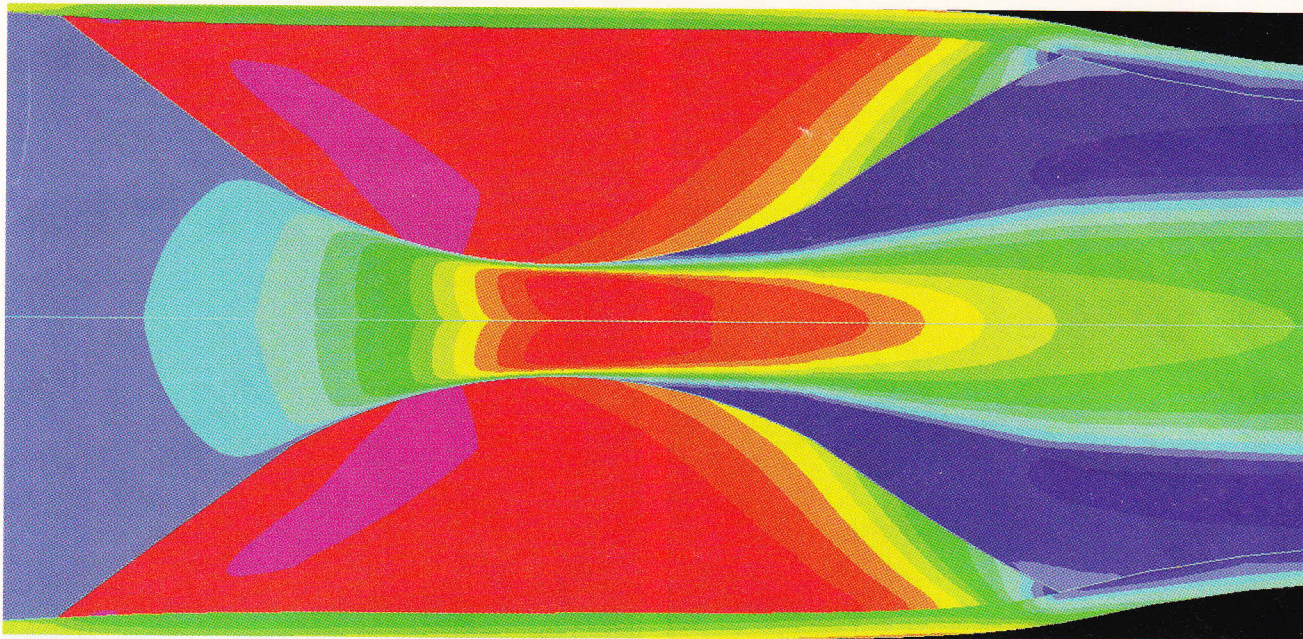
In a fluid-flow/structural interaction analysis of a compliant stenotic artery with the ADINA system, principal stresses are shown in the artery (the outer thin shell) and in the stenosis (the material deposited on the artery and carrying low stresses). The longitudinal velocity of the blood is also depicted.

fluid, and the compressible Navier-Stokes fluid.

The acoustic-fluid model is in many ways the simplest model to deal with, because the fluid is assumed to be inviscid and not to flow; i.e., the fluid-particle motions are small. Therefore, the fluid only transmits pressure waves. The finite-element analysis of acoustic-fluid/structure interactions using potential- or displacement-based Lagrangian formulations is now well established.

The primary advantage of a potential-based analysis is that only one degree of freedom (the potential) needs to be calculated at each finite-element node. The result is that considerably fewer degrees of freedom are used than in displacement- (or velocity-) based formulations, in which two and three nodal degrees of freedom for two- and three-dimensional analyses are employed. In each approach, only symmetrical coefficient matrices need be established.

The coupling between the structure and the fluid is simpler using the displacement-based formulations, as are the solution procedures for frequencies and dynamic response. In general, however, potential-based finite-element formulations are used because of the much smaller number of unknowns to be solved. Both internal and external fluid regions can be modeled; infinite elements or boundary-element techniques are used in modeling external regions as well.

Applications of acoustic-fluid/structure interactions are found whenever the fluid can be modeled to be inviscid and to undergo only relatively small particle motions. Some examples are the analysis of pressure waves in a piping system, a fluid sloshing in a tank, and sound waves traveling through fluid-solid media. Since the matrices are
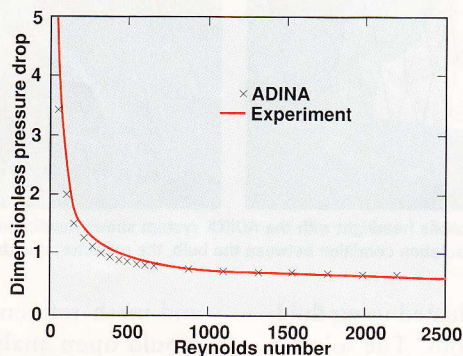
Comparison of the dimensionless pressure drop shows a high correlation between FEA and experimental results.

symmetrical, fine finite-element meshes can be used, allowing detailed effects to be simulated.

Considering actual fluid flows, the Euler equations are solved when assuming an inviscid compressible fluid, and the full Navier-Stokes equations are solved for general incompressible or compressible flows. In each case, the fluid flow is fully coupled to the structure. The solution schemes used for these analyses are based on Lagrangian formulations for the structural parts and arbitrary Lagrangian-Eulerian formulations for the fluid regions.

Generally, an important ingredient of the fully coupled analysis is that the fluid domain can be meshed with a much finer discretization than the structure. Completely different meshes are thus usually employed for the fluid and the structure, and they must adjoin each other in a compatible manner. Furthermore, the fluid mesh must be able to slide over the structural mesh, since the length of an FSI interface may change during the analysis.

Using these techniques, internal and external flows can be analyzed, just as in the case of an acoustic fluid. In addition to the coupled fluid-structure interaction, free surfaces can be solved.

Applications of these analysis techniques already abound, and they should increase rapidly due to the enormous benefits obtained from their use. Companies already using FSI can be found in the automotive, aircraft, biomedical, and civil engineering industries.

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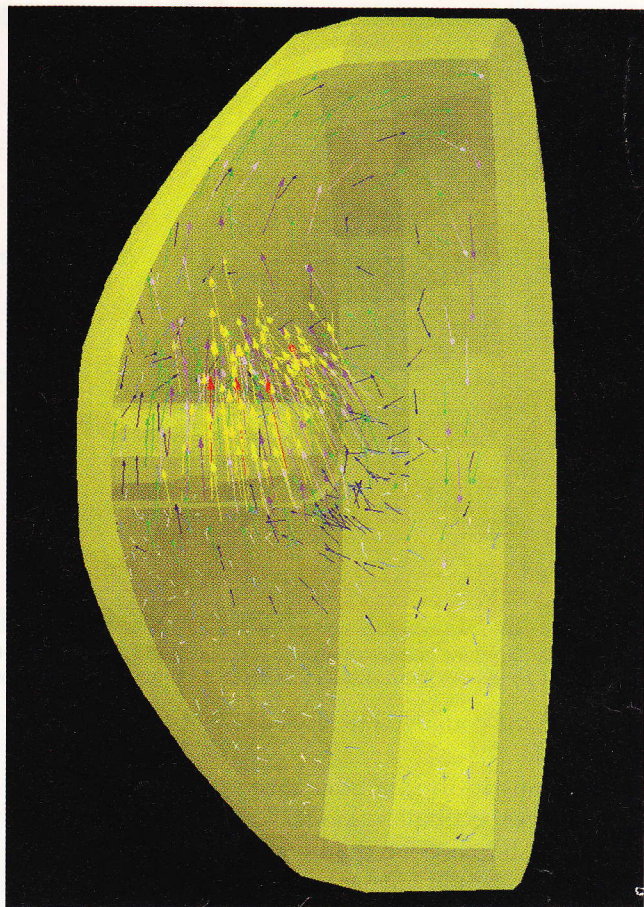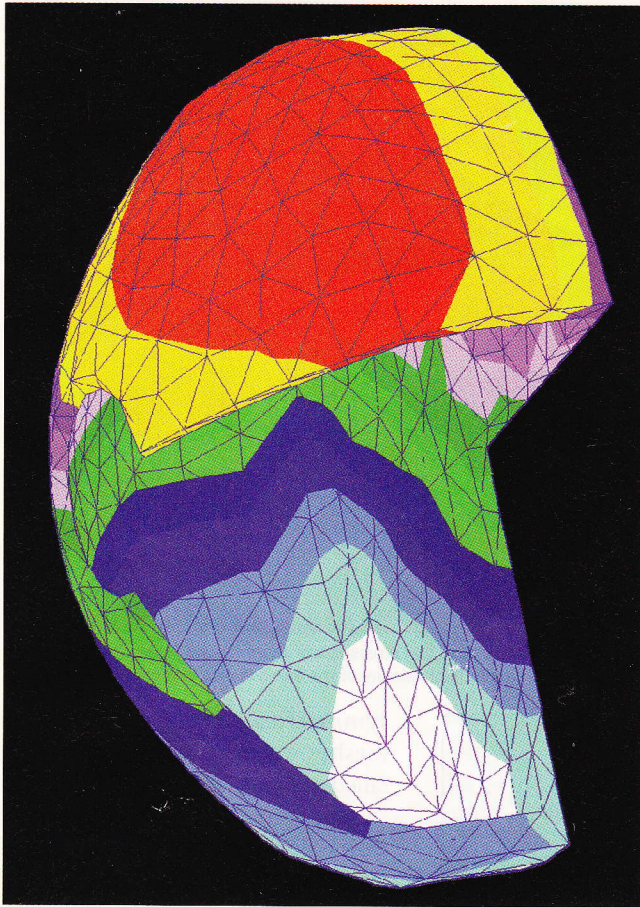
A fluid-flow and heat-transfer analysis of an automobile headlight with the ADINA system shows nondimensionalized temperature and velocity distributions. An important feature in the model is the specular radiation condition between the bulb, the reflector, and the lens.

A wide variety of systems can be evaluated using fluid-flow analyses with structural interactions. The solution of an antilock-braking-system model, for example, shows that in an FSI analysis, the structure can undergo very large displacements within the fluid flow. Here, the interest lies in identifying the transient velocity and pressure distributions in the fluid as well as the resulting stresses in the structure.

The analysis of blood flow in a diseased artery is a biomechanical application of great interest. The objective is to better understand the effects of a stenosis in the failure of a major artery, which can lead to a heart attack.

Finally, the coupled thermal and fluid-flow analysis of automobile headlights is of interest in the design process. The use of new geometries and more-economical materials in headlight design must be tested by analyzing the temperature distribution in the lamp and the resulting stresses. These analyses will identify situations that may lead to failure.

With these impressive FSI applications now possible, where is further development needed, and what are the current limits of analysis? These primarily pertain to limitations we currently see in modeling structures and fluids, whether coupled or not. For fluid-flow analyses, large systems of equations need to be solved. Therefore, more-effective discretization schemes and solution procedures that exploit parallel processing capabilities are in great demand. In addition, effective self-adaptive mesh-repair

and mesh-refinement methods based on error criteria would open analysis possibilities further. Similar advances to increase the capabilities available for structural analysis are also much desired.

Finally, of course, the limits to modeling physical phenomena for fluid and structural domains must be advanced—for instance, by improving the ability to model turbulence in fluids and contact conditions in structures.

Very interesting FSI applications, for which the numerical methods and the modeling of physical phenomena are clearly at their present limits, are found in the analysis of biomechanical problems. Researchers have expressed a keen interest in modeling various organs and organ subsystems in the human body, not only to understand their functions better but also to understand the effects that disabilities, surgical procedures, and other physical changes have on them. Such state-of-the-art applications of finite-element methods are now being conducted, but with many limitations on what physical phenomena can actually be modeled.

Considering what is yet to be achieved, the interplay between finite-element modeling and analysis with the recognition and understanding of new physical phenomena will advance our understanding of physical processes. This will lead to increasingly better simulations. Based on current technology and realistic expectations of further hardware and software developments, a tremendous future for FSI applications lies ahead. ▪