ANSYS Multiphysics Capabilities for MEMS Modeling and Simulation

Part 2 of 3: Analyzing fluid-structural interactions

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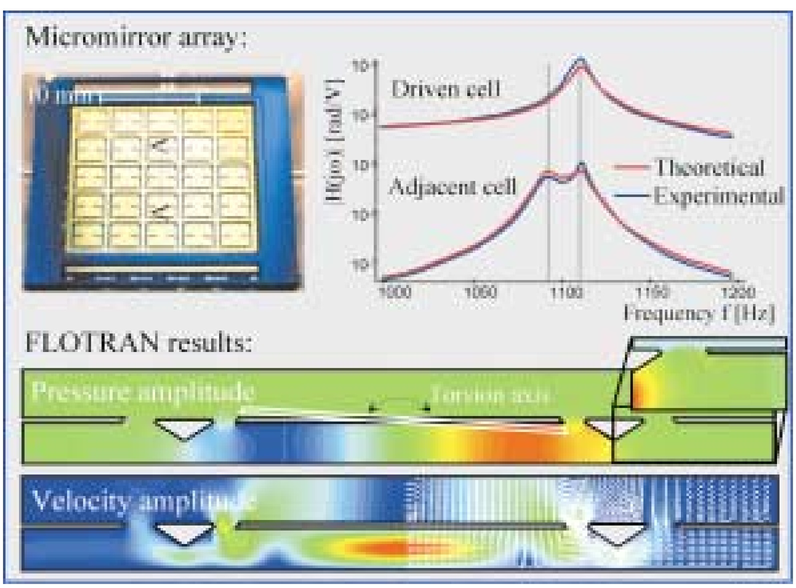
The response functions of dynamically operated micromechanical devices are decisively shaped by dissipative effects. In order to find and optimize performance parameters like Q-factor, transient overshoot, and settling time, proper damping models are essential.

Damping has a variety of sources of which viscose damping in the surrounding fluid (generally air) is clearly dominant at atmospheric pressure. Only in high vacuum, solid material loss, thermoelastic loss and electromagnetic dissipative effects are of growing importance. This article emphasizes preferred methods in MEMS design to compute fluidic damping parameters for movable microstructures operating at atmospheric pressure or in partially evacuated environments.

Figure 1: CFD of electrostatic micromirror arrays. (Courtesy of Chemnitz Center of Microtechnologies.)



Micron Scale Fluidics

Viscose damping of a structure vibrating in a fluid is the integral effect of dynamic force components reacting from the fluid back to the structure. According to the excitation, pressure and fluidic shear stress near the fluid-structure interface are understood as oscillating quantities. They are governed by the Navier-Stokes equation, which is solved in ANSYS/FLOTRAN using FLUID141/142 elements for 2-D and 3-D space, respectively. With ANSYS 5.7 (November 2000), the ANSYS/FLOTRAN elements offer Arbitrary Lagrangian-Eularian as an alternative to the traditional Eularian formulation. ALE accepts mesh distortion in the fluidic domain and is thereby particularly capable of handling large amplitude motion of the mechanical parts against the fluid.

Many MEMS devices with narrow part gaps below 7 µm and/or operating under reduced pressure enter the transition range from viscose (continuum) to molecular flow. Though molecular flow differs in its physical nature, substitute descriptions are available to still apply the continuum theory implemented in FLUID141/142 elements for the transition flow range.

Figure 1 shows the ANSYS/FLOTRAN analysis of a micromirror array used for a voltage-controlled laser scanner. The array mirrors are synchronously driven in resonance where the phase shift of each mirror is very sensitive to its damping coefficient. The analysis task is to relate dimension tolerances, damping coefficients to the resulting statistical range of phase shift. Moreover, the design engineer has to study fluidic cross-talk between adjacent mirrors due to the displaced airflow underneath the array.

Energy dissipation is not the only fluidic phenomenon effective in MEMS. The compressibility of gas causes spring-type behavior, which adds to structural elasticity. While dissipation creates in-phase force components with respect to a sinusoidal structure velocity (i.e., real parts), gas compression creates out-of-phase components (i.e., imaginary parts). The phenomenon is exclusively relevant for squeeze film problems at high frequency. Published by Griffin, a cut-off frequency is defined where real and imaginary force components are identical. It separates a lower frequency range of dominant dissipation from a higher frequency range of dominant compression.

Modal Damping

Similar to the transient analysis of coupled electrostatic-structural problems reported in the first article of this series, fluidic interactions can be treated in a sequential iteration scheme where plate velocities and fluidic forces are exchanged in each time step. This method is preferred for highly nonlinear vibrations but is far-fetched for quasilinear systems.

A significant acceleration of dynamic analysis procedures for quasilinear systems is achieved by the modal superposition method. Computational Fluid Dynamics analysis is now exploited to extract proper damping parameters for the most significant eigenmodes. In a subsequent transient or harmonic structural analysis, the obtained parameters are applied to the mechanical system via alpha-beta or modal damping. The modal decomposition method for automatic generation of reduced-order macromodels relies on modal damping parameters as well. This topic will be covered in our final article in the next issue.

The extraction procedure for modal damping ratios is straightforward and begins with a modal analysis in the structural domain. In subsequent transient CFD analyses, one needed for each derived eigenmode, the eigenvectors are successively imposed onto the fluid domain model as sinusoidal displacement loads with their associated eigenfrequencies. Mapping reaction force distribution to the eigenmodes retrieves damping ratios. The unidirectional algorithm without fluid-to-structural reaction feedback takes advantage of the fact that fluidic reaction forces leave shapes of eigenmodes unchanged although they attenuate amplitudes.

Heat Flow Analogy

CFD is commonly one of the most demanding tasks for finite element solvers. Heat flow analogy can be substituted for true CFD for a majority of MEMS analysis that allow approximation to 2-D models. The analyst benefits from a severe decrease of model size, first by model size reduction into 2-D and second by reduction of the large degree of freedom set to a single DOF "TEMP." Despite simplifications inherent to the method, it provides quick access to satisfying damping data. The following two examples are calculated using this analogy.

Squeeze Film Models

For squeezed gas films, the Navier-Stokes equation can be simplified to Reynold's squeeze film equation known from lubrication theory—a 2-D partial differential equation describing in-plane pressure distribution between plates. Arbitrary plate shapes, including perforation holes, flexible membrane-type structures and tilting motion, are accepted. The application of Reynold's equation is constrained to small vibration amplitudes compared to the gap and zero pressure am-

Figure 2: Squeeze film damping of a tilting micromirror.

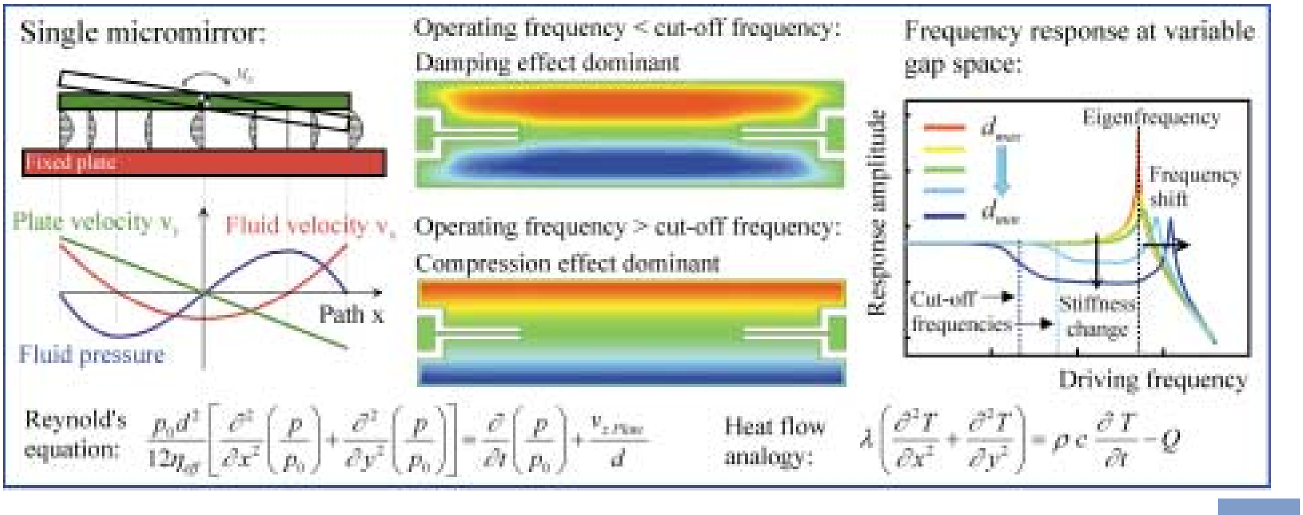
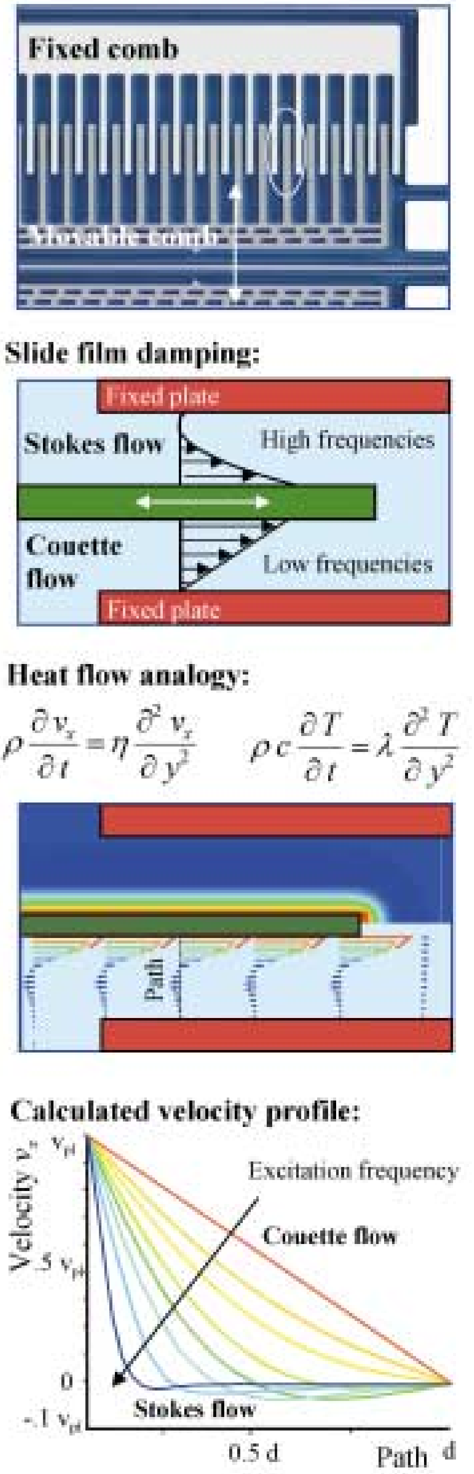


Figure 3: Slide film damping of a comb drive/capacitor.



plitude at all plate edges. When solved with heat flow analogy, heat generation rate substitutes local plate normal velocity, and temperature is interpreted as pressure.

Squeeze film damping has considerable impact on microstructures and may totally suppress the resonance peak in some cases. It is heavily dependent on the ratio of lateral dimensions and gap distance. The transition from dissipative lateral flow to compression in high-frequency devices leads to completely different pressure images, as illustrated in Figure 2. It is relevant for devices with gaps lower than 5 µm and operating frequencies of several 10 kHz and more. Very close gaps may even cause the cut-off frequency to drop below the natural frequency of a structure. Since the damping effect turns into spring effect above the cut-off frequency, sensitivity changes and resonance shift in the response function are common in such cases.

Slide Film Models

Slide film damping is present in structures such as surface micromachined comb devices where the fingers of the comb "slide" tangentially along the gaps (Figure 3). Its effect is usually lower than squeeze film damping for comparable dimensions. In contrast to squeezed films, pressure is constant across the sliding surfaces. Energy dissipation results completely from viscose shear motion near the surface.

At low operating frequencies, a linear velocity profile is established (Couette flow). With growing frequency, inertial effects in the gas cause rapid reduction of the adhering layer thickness (Stokes flow), and dissipation is concentrated within this layer. Damping coefficients are frequency-dependent for Stokes flow, due to the increased velocity-gradient near the surface.

Heat flow analogy is capable of solving the Stokes problem numerically. While for squeeze film damping, a 2-D thermal model is reproduced from the top view onto the surface, it now represents a cross-section through the gap. Instead of pressure, fluid velocity is directly related to temperature.

Conclusion

Demands not only determine the specification of details and mesh density in the model, but the method to use. By exploiting shape and behavioral specifics of MEMS devices, methods with less computational effort become available in addition to classical CFD. The trend toward automatic macromodel generation from FEA results of the MEMS component assigns increasing importance to modal damping parameter extraction from CFD rather than expensive transient coupled-field algorithms.

For further information on fluid-structural interactions, read "A Study of Squeeze-Film Damping" *by Griffin et al in the* Journal of Basic Engineering, *1966, pp. 451-456, and* "Simulation of Gas Film Damping on Microstructures with Nontrivial Geometries" *by Mehner et al from the 11th International Workshop on MEMS, Heidelberg, Germany, 1998, pp. 172-177.*