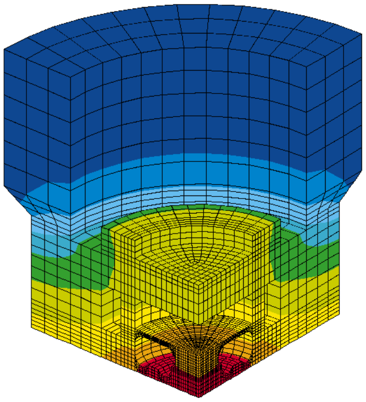


PUTTING ANALYSIS TO WORK:
MULTIPHYSICS TOOLS FOR MEMS

Putting Analysis to Work: Multiphysics Tools for MEMS

One of the hottest technology growth areas is microelectromechanical systems (MEMS), which also is called micromachines and microsystems in Asia and Europe. Made with semiconductor construction techniques, these devices have tiny parts measured in microns (millionths of a meter) and are frequently combined with integrated circuits on a single chip to provide built-in intelligence and signal processing.

These small, intricate devices must perform accurately and reliably, often in the hostile environments of vehicles and industrial machines. As a result, engineers developing MEMS must rely on finite element analysis (FEA) software to study these microstructures in determining stress, deformation, resonance, temperature distribution, electromagnetic interference, and electrical properties.

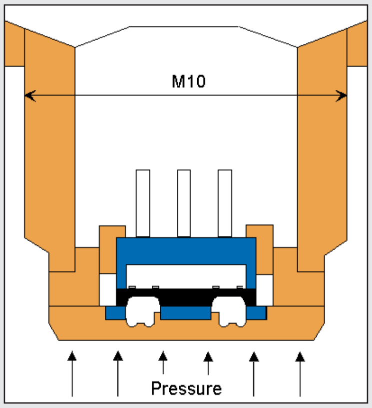
Leading organizations which use FEA technology in the development of MEMS devices include Analog Devices Inc. (Norwood, MA), Lucas NovaSensor (Fremont, CA), and the engineering consulting firm, Colibri Pro Development AB (Stockholm, Sweden). Extensive research activities also are underway at educational institutions around the world such as the Technical University of Berlin's Microsensor and Actuator Technology Center (Berlin, Germany).

Rapidly Growing Market

According to the market research firm Frost & Sullivan (Mountain View, CA), MEMS is one of a handful of new technologies that could revolutionize the 21st century. They estimate that the total MEMS market, now at $1.4 billion, will increase at a compound annual growth rate averaging 17 percent through the year 2004, when the market is expected to exceed $3.6 billion. Revenues are predicted to grow exponentially several years into the new millennium.

Emerging from research and development (R&D) labs in the 1970s, commercially available MEMS were first applied in automotive systems as manifold absolute pressure (MAP) sensors. According to Frost & Sullivan, automotive applications comprise one third of the total market, the largest proportion of any industry using MEMS. The medical market is another large segment, using MEMS in disposable blood pressure sensors and other applications. MEMS technology also is used for ink-jet printer nozzles, display devices, and other electronic equipment applications.

Analysts at the market research firm System Planning Corp. (Arlington, VA) see pressure sensors having an especially large potential, particularly in automotive applications such as MAP devices. They anticipate a need for MEMS pressure sensors increasing dramatically in the coming years as more engine and passenger functions are automated. According to the firm, ten or more MEMS sensors could be used, in tomorrow's new cars, for measuring values such as fuel level, tire inflation, hydraulics, oil pressure, and airflow.



The Technical University of Berlin used ANSYS® software to develop a MEMS sensor for measuring cylinder pressure in combustion engines. Above is a schematic of the sensor with the package membrane-based piezoresistive sensor chip.

System Planning Corp. also recognizes inertial sensors as a sizable portion of the MEMS market, with current automotive applications such as accelerometers in air bag deployment systems, as well as electronic vehicle suspension systems and antilock braking systems. Other promising inertial sensor applications include smart munitions that can alter their paths after firing, pacemakers with accelerometers to monitor patient activity, sensors to measure the vibration of industrial machines, and a range of motion control applications for robots and disk drive arms.

Economy and Simplicity

The advantage of MEMS for these applications is the relatively low cost and simplicity of the devices. Produced through the same semiconductor fabrication methods as integrated circuits (IC), thousands of MEMS can be mass produced on a single silicon wafer along with the associated electronic circuits. The devices can be easily produced using older IC fabrication equipment that otherwise would have to be retired, since the dimensions of MEMS devices are much coarser than those of state-of-the-art semiconductors.

Using this well-proven fabrication technology which includes bulk micromachining or surface deposition, MEMS can be produced and sold for a fraction of the cost of conventional sensing devices. Conventional blood pressure transducers costing $600, for example, can be replaced by MEMS intravenous sensors selling for about $10.

MEMS devices not only cost less, but their one-piece construction also is more economical and reliable than larger electromechanical systems with multiple parts. A single-point MEMS accelerometer, for example, can replace entire sets of electromechanical crash sensors mounted around the front of a car and connected to a microcomputer with complicated wiring harnesses.

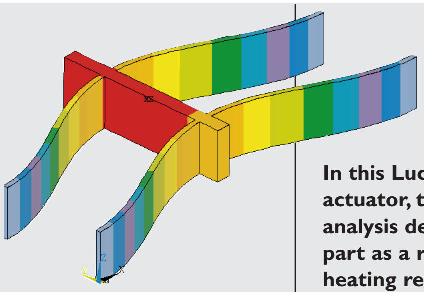
Design Challenges

One of the most formidable tasks in the development of MEMS devices is designing these miniscule parts (some thinner than a human hair) and determining how they best fit together and operate properly. These parts often perform in vehicles and machinery where the environment is less than hospitable to delicate mechanical components and sensitive electronic circuitry.

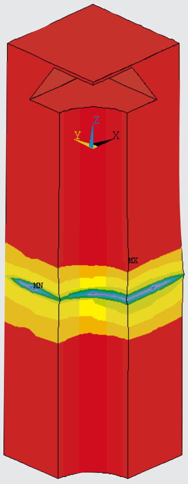
Developing the internal components for these devices, as well as associated packaging so MEMS operate flawlessly for years in these demanding applications, is an engineering challenge. They must resist damaging internal heat build-up while withstanding a wide variety of structural loads and ambient temperature swings. Parts such as diaphragms, valves, membranes, beams, and other microstructures on the same silicon chip also must survive severe shock and vibration to adequately perform their mechanical functions.

Ordinary-sized electromechanical products traditionally have these same requirements. However, designing MEMS is particularly challenging because of the tremendous size differences, component movements, and overall sensitivity of the device's internal components compared to its surroundings.

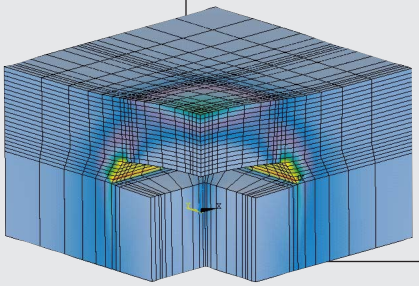
A MEMS sensor that measures gas pressures in the



In this Lucas NovaSensor lateral thermal actuator, thermal/electric coupled-field analysis determined the displacement of the part as a result of feeding current through a heating resistor.



Stresses caused by differences in thermal coefficients of expansion for silicon, Pyrex, solder, and Kovar were determined from this analysis of a Lucas NovaSensor pressure sensor.



Displacement and stress produced by fluid pressure are represented on this model of a micromachined silicon diaphragm made by Lucas NovaSensor.

range of 0.15 psi by detecting a few microns deflection of a microbeam, for example, often must undergo shock and vibration as it is knocked, jarred, and otherwise shaken on a piece of factory-floor equipment. “Imagine trying to detect a sneeze in the middle of an earthquake,” said one Lucas NovaSensor MEMS designer. “That's the scale of the task for MEMS.”

Another complication in MEMS design is that many physical phenomena interact and affect the operation of the devices including mechanical driving forces as well as resonant behavior, thermal levels, piezoelectric effects, and electromagnetic interference. The way in which MEMS units are packaged also can affect the operation, reliability, and accuracy of the units, further compounding the difficulty of MEMS design. Because many of these effects are interdependent, predicting output and performance of MEMS devices is a complex problem that often defies intuitive approaches used in the development of larger assemblies.

Developers of MEMS also have greater obstacles to overcome in the area of prototype testing. Whereas physical mock-ups of conventional electromechanical devices may undergo several test and redesign cycles in which parts are modified and switched around, the initial semiconductor fabrication setup for MEMS is so time-intensive that prototype testing is almost always done to verify the design rather than to find bugs.

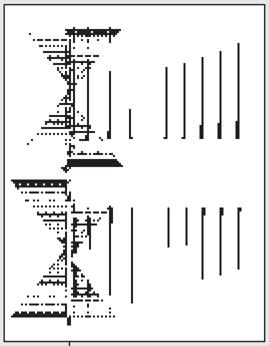
“The device has to work right the first time,” explains Steve Lewis, Design Engineering Manager at Analog Devices. “The design has to be refined up front in development so the unit operates as intended when we validate with a single round of physical testing.”

The Analysis Solution

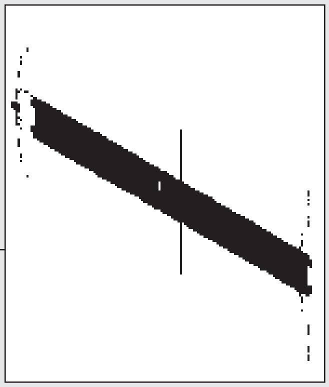
To meet these challenges, MEMS engineers almost universally rely on FEA in the mechanical design of the devices. One leading package proven to be particularly well-suited to MEMS development is ANSYS software from ANSYS, Inc. (Canonsburg, PA). The program is used in a wide range of MEMS applications, primarily because of its capabilities in the areas of multiphysics, coupled-field analysis, submodeling, and optimization.

Multiphysics features handle many different physical effects with different element types, each with its unique attributes such as material properties, boundary conditions, analysis options, loadings, couplings, constraints, and solver requirements. Available types of analysis include structural, thermal, electrical, acoustics, fluid flow, and electromagnetics.

Structural analyses determine parameters such as stress, strain, displacement, and natural frequency vibrations in mechanical parts as a result of applied loads. Available computational fluid dynamics (CFD) capabilities handle problems ranging from laminar, turbulent, and compressible flow to the simulation and analysis of characteristics such as pressure drops, velocities, and thermal distributions. Heat transfer problems involving both solids and fluids are common in MEMS, since heat buildup is so destructive to electronic circuits. Electromagnetic analyses are used in cases of devices with electrically or magnetically activated forces to calculate force, torque, inductance, impedance, Joule losses, field leakage, and field saturation.



Analysis of an accelerometer from Analog Devices shows displacement of the sensor mass.



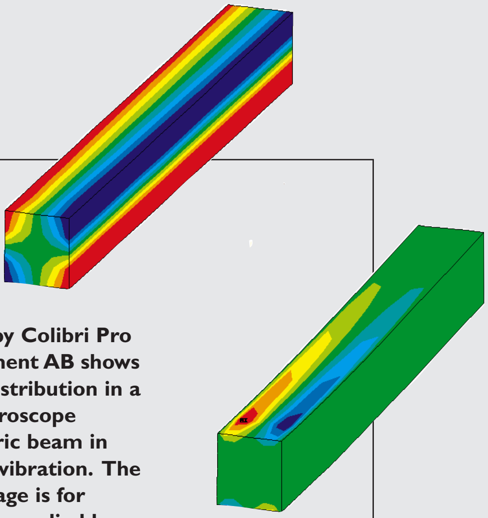
Stress in the associated tethers resulting from a 100-G acceleration.

Coupled-field analysis allows users to determine the combined effects of interacting variables, and is particularly helpful in MEMS design because so many disciplines must be considered. For many of these variables, multi-field elements are available in ANSYS software to directly solve coupled-field interaction in a single analysis. For example, thermal and electrical effects can be combined to study Joule heating, the effect of an electrical current passing through a resistive part which produces a temperature increase in the part. In MEMS, piezoelectric direct coupling of electrical and mechanical elements also is useful in determining both the amount of part deformation resulting from a given current flow, and vice versa. In ANSYS software, acoustical and structural elements also may be tightly coupled to account for fluid vibrations and the way they are transferred to physical parts, an important consideration in MEMS pressure transducers and fluid flow devices.

Another popular approach for many MEMS problems is sequential coupling, in which the standard element analysis output from one discipline is fed into a subsequent analysis of another standard element. Sequential coupling is effective for analyzing interactions that are not highly nonlinear. In fact, problems such as thermal-stress are among the simplest to address because the simulation requires only a single pass. On the other hand, many sequential coupled analyses require multiple passes (recursive coupling) for problems such as fluid-structure iteration in which structural deformation can affect the flow results. Multiple passes are required until the flow field and the deformation are in equilibrium.

Submodeling features allow users to apply an analysis output from an entire structure to a selected portion of the model, which is remeshed and analyzed in greater detail. In MEMS, this scaling capability is particularly useful in representing intricate details of small microstructure parts measured in microns in a comparatively large macrostructure assembly where dimensions often are measured in millimeters. In going from a macro- to microanalysis, users are relieved of the burden of rewriting the problem, transitioning complicated meshes from coarse to fine regions, and translating results from one analysis to another. In ANSYS software, users only specify the required region and the software automatically superimposes the proper boundary conditions (displacements, temperatures, voltages, etc.) This allows engineers to obtain more accurate information about the tiny parts of a MEMS device without representing the entire structure with a fine mesh.

Optimization routines determine the optimal design to meet all specified capacities while minimizing specified factors such as shape, weight, temperature, surface area, volume, stress, vibration, and cost. Using a design-of-experiments (DOE) approach, users define a range of values for selected parameters and the software iterates through multiple analyses, feeding results from each into the next simulation until converging on a satisfactory result.



Analysis by Colibri Pro Development AB shows voltage distribution in a MEMS gyroscope piezolectric beam in resonant vibration. The above image is for maximum applied harmonic voltage. Results for voltage passing through zero are on the right.

FEA in Action

Engineers at leading-edge organizations are employing the functionality provided by ANSYS software to develop a wide range of advanced MEMS devices.

At consulting firm Colibri Pro Development AB, Dr. Jan Soderkvist uses ANSYS software extensively in the development of MEMS gyroscopes for high-end automotive applications such as suspension control, rollover sensors, and navigation systems. Currently, the hottest application for the gyro is in electronic stabilization systems for cars. In these units, orientation is sensed by measuring the vibration amplitude of a tiny tuning fork.

“The vibration amplitude we are sensing in these devices is only one-tenth of an atomic radius,” says Soderkvist. “With such a sensitive system, every possible physical effect must be considered, so we use coupled-field analysis and multiphysics capabilities extensively. The piezoelectric effect changes with the frequency. Thermal and electromagnetic fields interact with the tines. Therefore, the entire system has to be tuned to optimize resonance and minimize error sources from outside shock and vibration. Mechanical deformation of the tines must also be studied to determine stresses and the resulting piezoelectric interaction at the surface-deposited electrodes. This experience is of great importance to us in other MEMS development projects we are involved in.”

At Analog Devices Inc., analyst Don Carow uses ANSYS software as the primary tool in the design process for the company’s line of MEMS accelerometers. His company designs crash sensors for air bag deployment, two-axis units for front/side impacts, and a new low-G sensitivity model used recently for sensing head movement in virtual-reality headsets.

The accelerometers are only about nine square millimeters in size, with all parts made of thin, micromachined silicon. A small central mass (800 microns square and 2 microns thick) is suspended by an array of spring-like tethers only 2 microns wide, spread around its perimeter. As the unit accelerates, the mass moves and forces the tethers closer to a stationary set of fingers. The resulting change in capacitance between the tethers and fingers is proportional to acceleration and is registered on built-in signal-conditioning circuitry that provides the unit’s electrical output.

Carow says submodeling is essential in representing the small tethers in context with the rest of the structure. This feature is particularly useful in performing stress analysis on the tethers to ensure that they can withstand forces as they hold the central mass in place. Also, modal analysis capabilities predict mode shapes and resonant frequencies, so designs can be tuned to vibrations most often encountered in automobile crashes, for example. In these calculations, ANSYS/FLOTRAN™ is useful in predicting damping effects as the components press against air when they move.

According to Carow, coupled-field analysis involving different effects was particularly useful in a study to solve a production problem with silicon wafers curling excessively during deposition and etching, due to differences in coefficients of expansion between layers. "By coupling a thermal analysis with mechanical stress, we were quickly able to determine the resulting deformation and curvature using a single ANSYS model," explains Carow. "Otherwise, manual calculations and trial-and-error changes would have held up production."

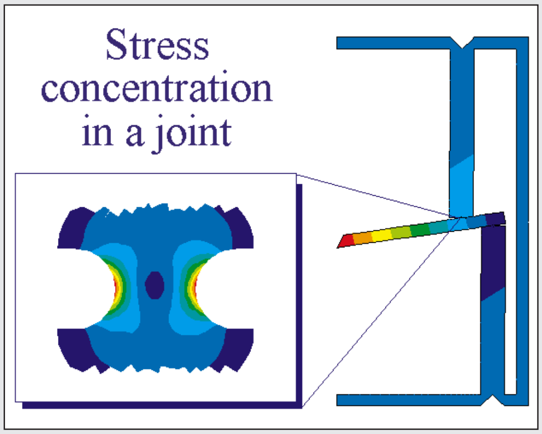
ANSYS tools also are used to handle a wide range of MEMS applications in many disciplines at Lucas NovaSensor. Their main product line is pressure sensors, in which a tiny silicon diaphragm deflects under pressure to change the device's resistance, and produce an electrical signal. Considerable research and development efforts also are going into the design of MEMS valves, nozzles, and orifices for advanced microfluidic systems, as well as accelerometers and inertial sensors.

Gertjan van Sprakelaar, Senior Design Engineer at Lucas, explains that fluid flow features are used most often in their work. Also, multiphysics and coupled-field analysis are indispensable tools in work such as self-heating studies of thermal-actuated MEMS devices, in which an electrical current passing through a resistive structure heats the part to deform it and close a tiny electrical circuit. "In these studies, a direct coupled analysis with one solution accounts for electrical, thermal, and mechanical effects," says Sprakelaar.

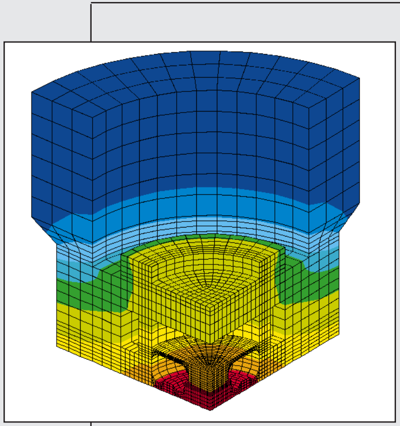
ANSYS multiphysics capabilities also are useful in packaging studies, where different types of material must be represented including silicon microstructures and the surrounding metal leads, plastic frames, and ceramic enclosures. "In devices with parts so small and sensitive packaging can significantly alter measurement accuracy," explains Sprakelaar. "We use FEA in studying these packaging effects, because the problem is far too complex for manual calculations, and trial-and-error prototype testing would take too long."

In an effort to increase product development efficiency further, Lucas also has developed customized templates that enable ANSYS output files to be fed directly into a semiconductor layout system. "We use FEA analysis throughout the design process," says Sprakelaar. "We just can't afford the time and expense of developing MEMS any other way."

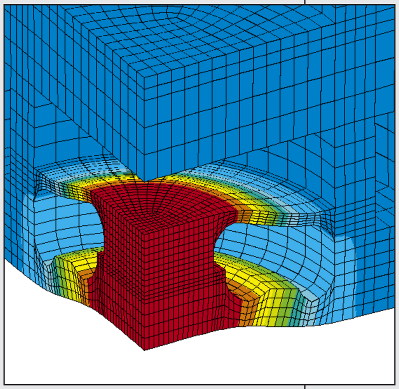
Like most of the organizations developing MEMS, Lucas views FEA as a critical tool in the product development process, not only for its specialized analysis capabilities, but for its power in communicating design ideas and facilitating cooperation among members of the development team. According to Sprakelaar, analysis software serves as a bridge enabling mechanical engineers, circuit designers, packaging engineers, and chip fabrication personnel to understand the behavior of the product and to cooperate in solving multidisciplinary problems and developing optimal designs.



Analysts at Colibri Pro Development AB used ANSYS submodeling to study stress concentrations in a 4-micron wide joint of a MEMS test structure used for evaluating the quality of a 10-micron thick polysilicon film. Design of the joint was optimized to be sufficiently flexible yet withstand buckling and fracture forces.



Automotive MAP sensors work on principles of piezoresistivity while sensing the pressure in the manifold. The sensitivity of the device is measured with ANSYS software.



Temperature also influences the performance of the automotive MAP sensor.

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