

Multiphysics Modeling of MEMS Devices

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Multiphysics Modeling of MEMS Devices.*

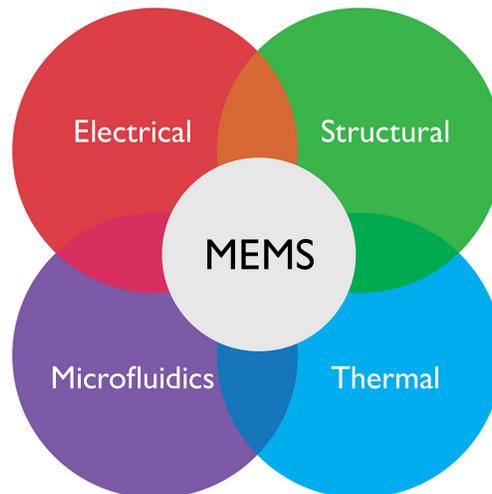
Introduction

There are many excellent reasons to simulate microelectromechanical system (MEMS) devices. For example, if you're going to create a new product or process, such as a capacitive pressure sensor, you'll first want to get the concepts right. The most important decisions are often made early in the product development cycle when multiphysics simulation can give you the valuable insight you need. The benefits of multiphysics simulation can also extend easily to the design and optimization of a product by reducing the time and money spent on prototypes. And, if you integrate multiphysics simulation with manufacturing and quality assurance, you'll end up with a product that's much better understood and better characterized.

Technical Overview

MEMS devices are incorporated in equipment that we use on a day-to-day basis. The MEMS market is already more than a \$10 billion market, and projected to become double of that in the next five years. This rapid growth in the MEMS market is being driven by a variety of applications catering to a host of industries.

For example, inkjet printer heads consist of microactuators. MEMS RF filters are used in wireless devices including phones and GPS to isolate communication signals within the desired operational frequency band from signals outside that band. Digital projection systems use a large array of MEMS micromirrors. In recent times, one of the biggest drivers of the MEMS industry has been smartphones. In most smartphones, when the orientation of the phone is changed, the video or picture changes from portrait to landscape mode. Operations such as these require information from a MEMS gyroscope. Home entertainment and gaming products that rely on the movement of our arms or body posture use a combination of MEMS accelerometers and gyroscopes to convert the human motion into electrical signals that are then used to represent the movement of our virtual self on-screen.

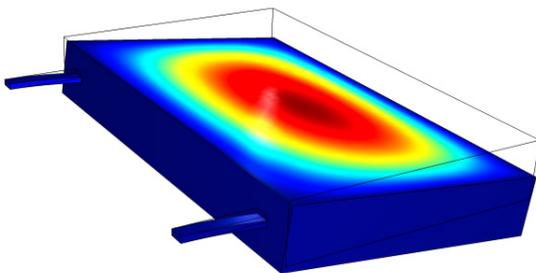


The design and simulation of microelectromechanical systems (MEMS) is a unique engineering discipline covering a variety of coupled physics, including electromagnetic-structure, thermal-structure, or fluid-structure interactions.

MEMS devices can be categorized based on their functionality and application area. Many of these devices are being used either as actuators or sensors. Many actuators and sensors are also integrated into microfluidic systems used in biomedical and chemical applications. Switches and resonators are used in RF MEMS applications. MEMS speakers and microphones are becoming increasingly prevalent in smartphones and tablets. Small devices also require small power generation and power storage mechanisms. This is where energy harvesting transducers and microfuel cells fit in. With so many types of MEMS devices that fit like a jigsaw puzzle to make a bigger device work, it is really important to design a MEMS device in a way that would help increase its efficiency and at the same time, optimize its physical size and cost of production.

Simulation Solves MEMS Design Challenges

So how can simulation help make better MEMS devices? MEMS is inherently a multidisciplinary field combining the knowledge of different physics such as electromagnetics, structural analysis, heat transfer, and fluid dynamics to design and fabricate devices that



Squeezed-film gas damping is a critical aspect of many MEMS transducers and actuators. In accelerometers, for example, inertia produces a motion that the device detects. A typical structure connects a large proof mass to surrounding structures with elastic beams, which forms a mechanical oscillator with a specific resonance frequency. However, in accurate motion-detection applications these resonances are unwanted, and the device should dampen the movements to produce smooth time-step and frequency responses.

vary in size from a few hundred nanometers to a few hundred microns. Simulation could be used during the different stages of the product cycle such as prototype design, processing, and virtual performance testing. Simulation also can be used for better design of processing equipment including, for example, simulating the fluid dynamics in an ultrahigh vacuum system such as an ion implanter or modeling the plasma chemistry inside a CVD chamber.

There are a few basic design challenges, and a good simulation tool should help address and overcome these challenges. While designing MEMS devices, we work across different length scales where different forces dominate. So we should have the option to choose the effect of the appropriate forces in our simulations. Another inherent challenge is working with high-aspect-ratio structures that not only are difficult to deal with during fabrication, but also in simulation. MEMS devices use a variety of materials such as metals, polymers, and semiconductor materials, so we should have access to a mechanism to incorporate realistic material behavior into the simulation. Furthermore, we should be able to incorporate the different physics involved in the operation of a device and be able to capture any interactions between these different physics.

For example, modeling an accelerometer would include taking into account the inertial force on the structure. If the accelerometer works based on the principle of changes in capacitance, one would also need to include the effect of electrostatic force on the structure. This would involve modeling the dielectric properties as well as structural stiffness of the materials used in fabricating the accelerometer. All these can be easily done in COMSOL Multiphysics®, a general-purpose software environment for modeling and simulating physics-based problems.

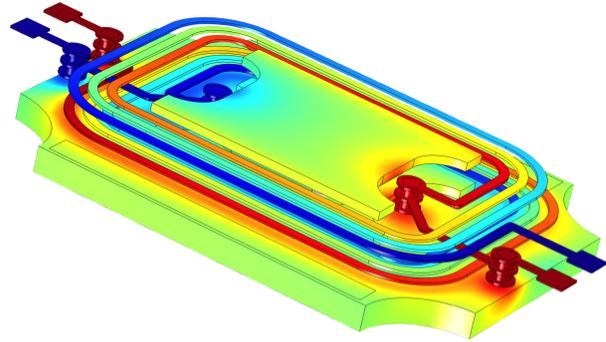
COMSOL Multiphysics includes a set of core physics interfaces covering application areas such as electrical, mechanical, fluid flow, and chemical. By adding application-specific modules, the modeling

power is increased with dedicated tools. In the COMSOL Multiphysics software any number of physics can be combined in one and the same simulation. Moreover, it can interface with different CAD formats and programs for data organization and visualization. The MEMS Module offers specialized features for simulating most MEMS devices. These features could also be combined with advanced features available in other products such as the Microfluidics Module or Acoustics Module if you need to simulate additional effects involved in the operation of a MEMS device.

A Framework for Simulating Coupled Physics

The COMSOL Desktop® is an integrated environment with a unified workflow, regardless of the application area. The add-on modules work seamlessly with COMSOL Multiphysics, and the workflow remains the same no matter which add-on products are used. Through the COMSOL Desktop you have a full overview of the model and access to all functionality from geometry, mesh, physics settings, and boundary conditions, to studies, solvers, postprocessing, and visualizations. With COMSOL Multiphysics you can easily extend your models for one type of physics to a multiphysics model including coupled physics phenomena. A Model Library contains many helpful example models that are relevant for several applications, including MEMS devices.

COMSOL Multiphysics provides several options to work with high-aspect-ratio geometry that is inherent in MEMS design. Its built-in geometry modeling tools let you create your design completely within the software. There are also options to import solid CAD geometry and electronic CAD (ECAD) formats, which can be used to create the modeling geometry. There are features to clean up complex geometric details that are not needed for the simulation. Similarly, there are built-in meshing



The picture shows the electric potential on the surface of a planar transformer. The layout is imported from an ODB++(X) file using the ECAD Import Module and is automatically converted to a 3D geometry model. The AC/DC Module is used to compute the capacitance and inductance parameters of the device.

methods available to efficiently set up structured volumetric mesh in high-aspect-ratio geometries. All these can greatly contribute to making MEMS simulations easier to set up and more computationally efficient.

A MEMS device typically has several layers, some of which could be a few microns thick, while some could be only a few nanometers thick. One of the greatest challenges in accurate simulation is to account for physical effects from layers that are three (or more) orders of magnitude thinner than the thickest layer. For example, there could be a very thin adhesion layer whose structural stiffness or electrical conductivity may not be negligible. Such scenarios can be modeled in COMSOL using several advanced boundary conditions and a combination of solid and shell modeling techniques. These techniques allow you to represent very thin layers as zero-thickness geometry. Their physical effects can be computed using information about their physical thickness and material properties.

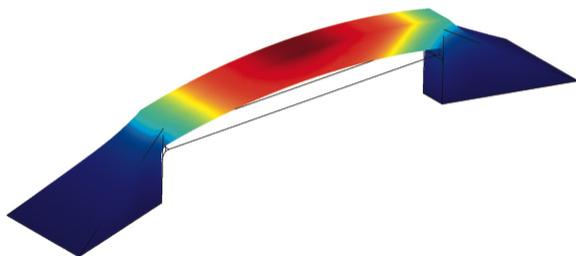
In some cases, you may also need to resolve the effect of thin regions that may not necessarily be part of the device. For example, a thin air gap between a cantilever and the substrate would create a squeeze film damping effect on the vibrating cantilever. The Thin Film Damping feature in COMSOL can model the

desired physical effect without drawing or meshing the thin air gap, and even without solving the detailed fluid dynamics in the air gap.

MEMS devices use different types of materials such as metals, dielectrics and semiconductors. In COMSOL, you can easily incorporate both isotropic and anisotropic materials properties. This is of utmost importance for modeling single crystals, and also the piezoelectric and piezoresistive effects. It is also possible to create user-defined coordinate systems and define material properties in those coordinate systems to represent different crystalline orientation. You can even incorporate experimental data to represent the variability in any material properties as a result of any change in temperature, electric field, magnetic field, chemical concentration, pressure, or any physical quantity. There are also easy-to-use options available to include structural nonlinearities such as thermal creep and viscoplasticity that are useful to model mechanical response of metals when they are exposed to a combination of prolonged mechanical stress and elevated temperature. Similarly, one could choose from a host of hyperelastic material models to simulate the mechanical response of polymers such as polydimethylsiloxane (PDMS).

Multiphysics Critical to MEMS

Almost all MEMS devices need to be represented by modeling more than one type of physics. The multiple physics governing the operation of a device



Current is often used as a way of heating and thus thermally expanding microstructures. This model is a study of the resistive heating and thermal expansion of a micro beam, as a current is conducted through it.

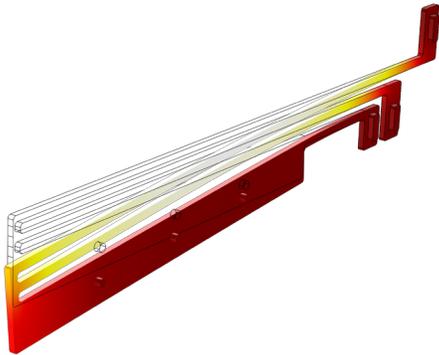
could be coupled in different ways. For example, piezoelectric and piezoresistive devices both work based on electromechanical coupling. However, the nature of multiphysics coupling is different for these two phenomena. So it is not only important to identify the relevant physics that are taking place in the operation of the device, but also it is important to understand how these physics are connected. In COMSOL, there are several ready-to-use multiphysics modeling interfaces to choose from, which provide a great starting point for simulations.

Electro-Thermal Interaction

Joule heating is one of the most common working principles for MEMS devices that rely on heat generation due to electric current conduction. In COMSOL, you can perform Joule heating simulations to obtain detailed information about spatial distribution of voltage, electric field, and temperature to determine how much voltage is required to produce the desired temperature, and whether any part of the device is getting hotter than desired. A natural extension of the simulation could be to consider temperature-dependent resistivity of the conductor, which is the working principle behind thermoresistive sensors. The thermoelectric effect is another type of electrothermal coupling used to design heat pumps that could remove heat from microprocessors to heat sinks. COMSOL provides a dedicated physics interface for modeling such effects.

Thermal-Structure Interaction

There are different types of thermomechanical effects that you may want to account for in MEMS devices. Actuators and switches that operate based on thermal expansion are quite common. In such devices, it could be important to model how much deformation and stress you get in a structure due to thermal expansion. You may also want to find out if the stresses in any region are too high to cause



A basic electro-thermal beam flexure actuator uses the principle of Joule heating for thermal expansion and movement.

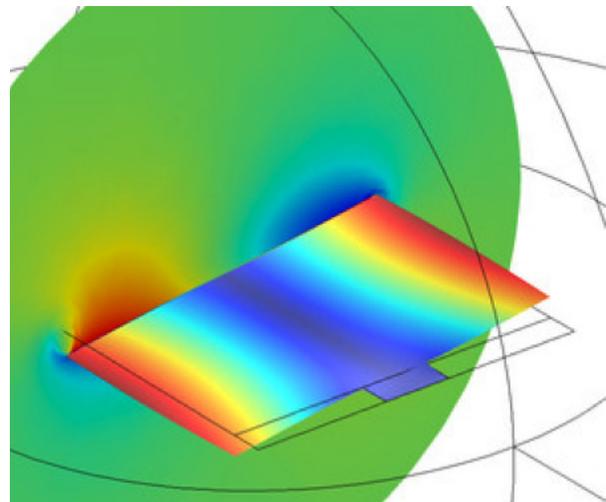
mechanical failure. You can also use COMSOL to account for more advanced thermomechanical effects. For example, a vibrating structure would produce heat as a result of structural damping. Also, if the vibration time scale is smaller than the thermal relaxation time scale, the structure would experience thermoelastic damping. All these factors can contribute to resonance shift and a change in the Q-factor of the device. Incorporating such multiphysics effects in your simulation could be crucial in the design of narrow-band filters and timing devices.

Acoustic and Thermoacoustic Effect

Vibrating structures produce sound by creating pressure waves in the surrounding fluid media. In return, the fluid media contributes to damping the structural vibration. Such acoustic-structure interaction can be crucial to account for in your simulations to get a measure of the effect of fluid damping on the resonance characteristics. This is also a critical multiphysics interaction for MEMS speakers and microphones. An associated analysis is looking into thermoacoustic effects that account for small temperature variation and viscous damping in fluid.

Piezoresistive Devices

The piezoresistive effect exhibited by semiconductors is a type of electromechanical



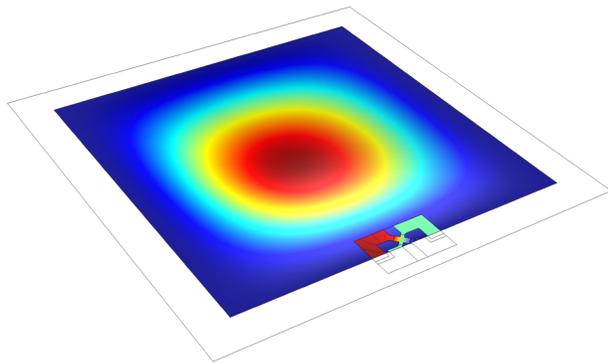
This model of a vibrating micromirror surrounded by air uses the Thermoacoustic-Shell Interaction user interface to model the fluid-solid interaction, and it thus includes the correct viscous and thermal damping of the mirror from the surrounding air. The resonance frequency of the mirror when under a torquing load is studied in the frequency domain by means of both frequency-response and eigenfrequency analyses.

coupling that results in producing a significant change in the electrical resistivity as a function of mechanical stress. Hence, this phenomenon is used commonly in MEMS pressure sensors. In simulating a piezoresistive sensor attached to a thin diaphragm, any force acting on the diaphragm will alter the current through the sensor, which could be measured and correlated with the applied force. The piezoresistive effect is anisotropic and also shows a nonlinear dependency on the doping concentration. These things are easily accommodated in the modeling framework offered by COMSOL. A library of piezoresistive material properties for lightly doped single-crystal and polycrystalline n- and p-type silicon can be used in your models.

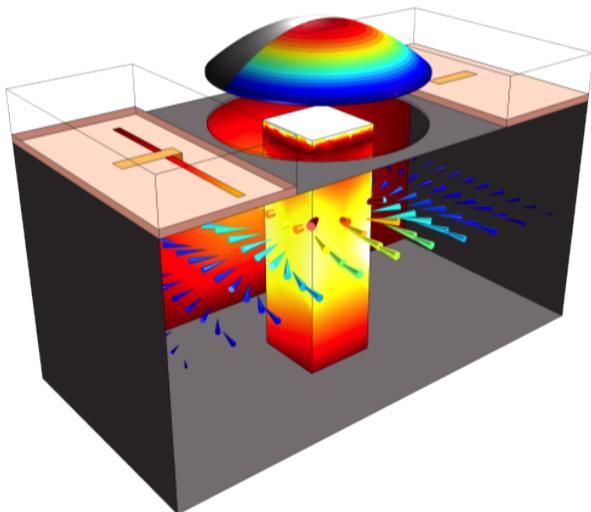
Piezoelectric Devices

COMSOL also provides a dedicated modeling interface for simulating piezoelectric actuators, sensors, and resonators. The piezoelectric effect is a bidirectionally coupled electromechanical effect where an electric field can produce strain in the

material, and a mechanical force can generate a voltage difference across the material. With COMSOL Multiphysics' modeling framework, you can extend a piezoelectric simulation by adding any other physics involved in the operation of the MEMS device. For example, a piezoelectric actuator can be used to control the air gap between the walls of a resonant



Piezoresistive pressure sensors were some of the first MEMS devices to be commercialized. Compared to capacitive pressure sensors, they are simpler to integrate with electronics, their response is more linear and they are inherently shielded from RF noise. They do, however, usually require more power during operation and the fundamental noise limits of the sensor are higher than their capacitive counterparts.

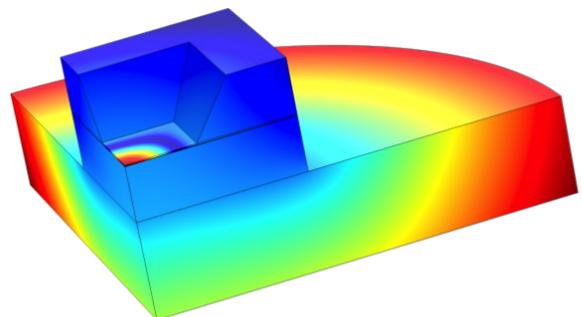


A piezo actuator is used to tune the resonant frequency of a cavity filter used in a miniaturized satellite. Other applications include broadcasting and wireless communication.

cavity and a metallic post inside the cavity, thereby enabling us to design a tunable resonant cavity. In order to simulate such a device, the piezoelectric model can be combined with a full-wave Maxwell's equation to resolve the EM waves inside the cavity. This is a demonstration of how multiphysics simulation can help in more accurate device-level modeling.

Electrostatic Devices

Last, but not least, there are MEMS devices that work based on the use of electrostatic force. The building block in such devices is essentially a parallel plate capacitor. An increase in the potential difference across these plates enhances the electrostatic force between them, thereby physically drawing the plates closer to each other. This effect can be used in comb-drive actuators and microgrippers. Also, there is a critical pull-in voltage at which the metallic plates snap, resulting in an electrical connection that allows current conduction. The pull-in effect is used in MEMS switches. The same building block can also be used to design sensors. If a force acts on one of the two parallel plates, decreasing the gap between them, it will result in a change in the capacitance. This change is correlated to the applied force in capacitive pressure sensors. Electrostatic devices are also used as tunable



In this multiphysics model, capacitance is related to the deformation of the structure, which depends on pressure, temperature, materials used, and initial stresses.

resonators. These resonators are biased with a DC voltage, and an additional AC signal is used to harmonically oscillate them. The DC bias is used to tune the resonance characteristics.

Summary

COMSOL Multiphysics provides a great framework for solving the combined effects of electrical, thermal, structural, and other physics essential for simulating MEMS devices. COMSOL provides flexibility in terms of handling modeling geometry, mesh, and physical effects of thin layers, which are some of the key challenges involved in simulating MEMS devices. COMSOL also offers several ready-to-use physics interfaces that are tailored to serve as platforms for addressing different types of electromechanical,

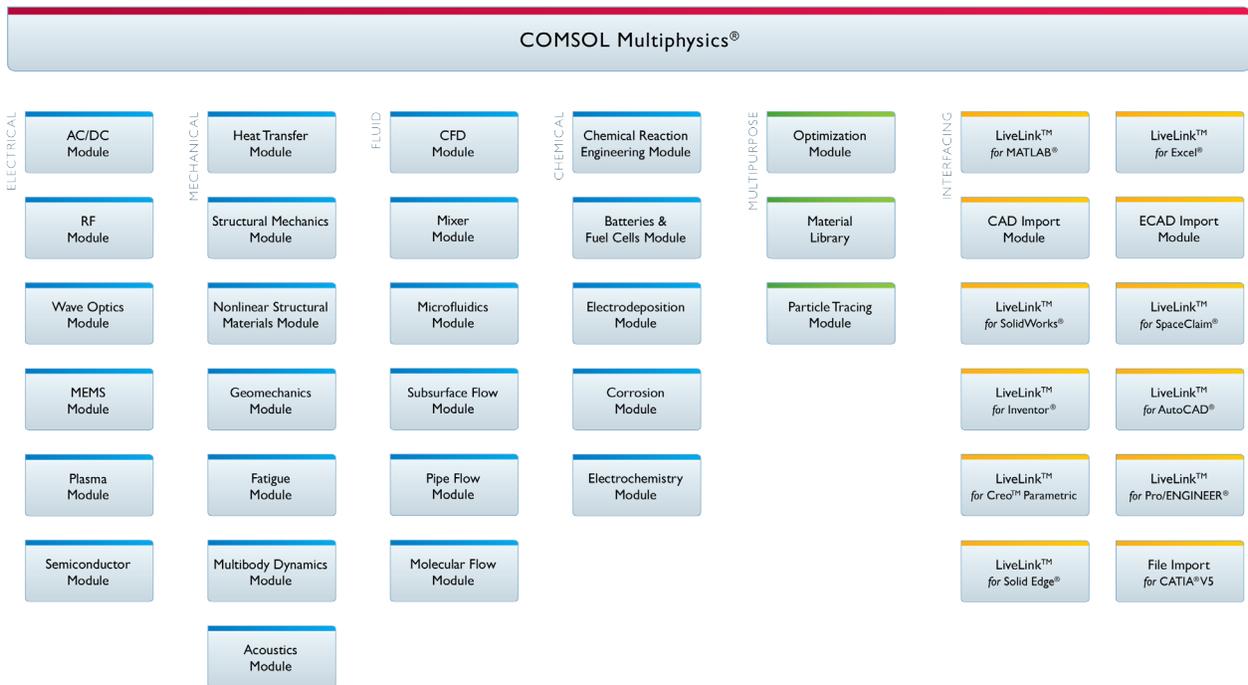
electrothermal, and thermomechanical effects that are widely encountered in MEMS devices.

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View the original webcast at
www.comsol.com/video/modeling-mems-devices-multiphysics-simulation-software.



COMSOL Multiphysics includes a user interface and a set of predefined physics and associated modeling tools for simulating your applications. A suite of add-on products expands this multiphysics simulation platform for modeling specific application areas as well as interfacing to third-party software.