MEMS dynamics: measurements and modeling

Ryszard J. Pryputniewicz, Ryan T. Marinis, Adam R. Klempner, and Peter Hefti
NEST – NanoEngineering, Science, and Technology
CHSLT – Center for Holographic Studies and Laser micro-mechaTronics
Mechanical Engineering Department
Worcester Polytechnic Institute
Worcester, MA 01609

ABSTRACT

Advances in MEMS sensors for diversified applications require use of computational modeling and simulation accompanied by physical measurements. We believe that successful combination of computer aided design (CAD) and multiphysics simulation tools with a state-of-the-art (SOTA) measurement methodology will contribute to reduction of high prototyping costs, long product development cycles, and time-to-market pressures while developing MEMS for a variety of applications. In our approach we combine a unique, fully integrated, software environment for multiscale, multiphysics, high fidelity modeling of MEMS with the SOTA optoelectronic laser interferometric microscope (OELIM) methodology for measurements. The OELIM methodology allows remote, noninvasive, full-field-of-view (FFV) measurements of displacements/deformations with high spatial resolution, nanometer accuracy, and in near real-time. In this paper, both, the modeling environment (including an analytical model used to quantitatively show an influence that various parameters defining a sensor may have on its dynamics - using this model dynamic characteristics of a sensor can be optimized by constraining its nominal dimensions and finding the optimum set of uncertainties/tolerances in these dimensions) and the OELIM methodology are described and their applications are illustrated with representative examples demonstrating viability of the approach, combining measurements and modeling (i.e., M&M), for development of MEMS. Preliminary results demonstrate capability of our M&M approach to quantitatively determine effects of dynamic operational loads on performance of selected MEMS.

Keywords: MEMS, sensors, dynamic loads, multiphysics environment, multiscale analysis, optimization, uncertainty modeling, noninvasive measurements, full-field-of-view

1. INTRODUCTION

Recent and continuing advances of microelectromechanical systems (MEMS), also called microsystems, will continue to dramatically influence consumer, industrial, medical, and defense markets [1]. It is generally recognized that the microsystems technology (MT) will continue to be a focus of intense international competition and exciting new MEMS-based products will drive development of pertinent markets. New generation of MEMS chips will host mechanical devices, fluidic channels, chemical mixers and reactors, bioanalytical laboratories-on-a-chip, photonic devices and circuits, and myriad of others, all integrated with electronics. We believe that success of MEMS industry, to a large extent, will be determined by availability of computer-aided design (CAD) and multiphysics simulation tools, because high prototyping costs, long product development cycles, and time-to-market pressures create acute demands for sophisticated, commercial quality modeling and simulation software.

Analysis of MEMS and MEMS packaging requires a number of special capabilities in modeling/simulation software such as treatment of various operating environments, external fields, and multiphysics solutions addressing coupled fluid-structures-thermal interactions. These capabilities have been made available in new software for development
of MEMS, which has recently been introduced for high-fidelity multiphysics simulations of MEMS [2]. This software package uses the SOTA numerical techniques coupled with user-friendly problem set up, mesh generation, and execution interfaces. With the multiphysics capabilities, ease of use, and rapid turnaround times, such a package can be a great asset in development of MEMS.

Continued demand for flexible and sophisticated, yet lightweight and low power wireless communication and sensor systems, has generated a need for RF MEMS technology that can drastically reduce manufacturing costs, size, and weight while improving performance of the systems they comprise. RF MEMS has a potential to enable wide operational bandwidths, eliminate off-chip passive components, make interconnections losses negligible, and produce almost ideal switches and resonators using micromachining fabrication compatible with existing IC processes [3-6]. More specifically, the objective in developing RF MEMS devices is to achieve fast switching at low actuation voltages for high-performance reconfigurable microwave and millimeter wave circuits [5,6]. Low insertion loss, high isolation, and excellent linearity provided by MEMS switches offer significant improvements over electrical performance provided by conventional PIN diode and MOSFET switching technologies. These superior electrical characteristics permit design of MEMS switched high-frequency circuits not feasible with semiconductor devices, such as high-efficiency broadband amplifiers and quasi-optic beam steering arrays. In addition, operational benefits arise from the RF MEMS switches’ low power consumption, small size and weight, and exceptional capability for integration. To achieve this objective, a number of switches based on different actuation mechanisms and topologies are being developed.

Principles of the MEMS software development environment are presented in Section 2, analytical model for optimization of dynamic characteristics of RF MEMS resistive contact is presented in Section 3, general aspects of computational modeling of physical phenomena are summarized in Section 4, measurements of MEMS are outlined in Section 5, samples used (in this paper) are described in Section 6, while representative examples illustrating (both) selected results of the CFD-ACE+MEMS modeling and the optoelectronic measurements on samples used herein, are presented in Section 7.

### 2. MEMS SOFTWARE DEVELOPMENT ENVIRONMENT

Software development environment, CFD-ACE+MEMS, allows for a number of unique features which enhance design and analysis of MEMS and MEMS packaging [7]. For example, parametric templates, based on Python scripting, can be utilized for in-depth understanding of the designed/desired operation of MEMS. Geometry, material properties, stress fields, contact forces, dynamic response and other parameters, characterizing MEMS, can be investigated using parametric templates to optimize performance of MEMS. Atmospheric conditions (including vacuum and arbitrary pressures), geometry, as well as pull-down voltage profiles can be modeled to understand and optimize dynamic damping conditions of packaged or unpackaged devices.

Coupled electrostatics-structures-flow simulations can also be performed using this development environment. It has the necessary multiphysics capabilities including flow, heat transfer, structured mechanics, and electrostatics. All CFD-ACE+ capabilities are fully coupled for fast and accurate solutions. A brief description of some of the involved codes is given in Sections 2.1 through 2.4.

#### 2.1. Computational design tools

The CFD-ACE+ system, shown in Fig. 1, is a design environment for MEMS, which includes grid generation (CFD-GEOM), data visualization (CFD-VIEW), graphical problem setup (CFD-GUI), and implicit fully coupled fluidic, thermal, mechanical, electrostatic, and magnetic physical model solvers (CFD-ACE). The structural mechanics solutions are handled by FEM-STRESS, a finite-element code, which is coupled implicitly with CFD-ACE+ for predictions of mechanical and thermal stress-strain fields in solid parts.

![Fig. 1. CFD-ACE+ software from CFDRC.](image)
Physical models are solved on 2D, cylindrical, or 3D multi-domain grids. Grids can be structured, unstructured, hybrid, or adaptive Cartesian. There is also a grid capability to track moving and deforming bodies and surfaces. Strong links exist with the data transfer facilities (DTF) for parallel execution on multiple machines. Physical models are implemented in a highly modularized code architecture that facilitates addition of future physical models. CFD-ACE+ is, therefore, well suited for analysis of MEMS and MEMS packaging with implicitly coupled modules that may be activated for analysis of various physical phenomena. Brief overviews of theoretical basis for mechanical and electrostatic physical models in CFD-ACE+ are discussed in Sections 2.2 and 2.3, respectively.

### 2.2. Structural mechanics

Structural mechanics model is used to study stress/deformation of structures using the structural module, which solves for displacements and stresses of device(s) subject to a number of different loads. Both first and second order elements are available to determine an accurate solution even for fairly coarse grids. Contact “regions” can also be analyzed while distinguishing two cases: (1) contact of an elastic body with a rigid body and (2) contact of two elastic bodies. Forces are calculated at regions of contact and, then, resulting stresses in the material(s) are determined. These stresses may be used in a life cycle analysis of a device. The structural solver also contains a calibratable stiction model to analyze effects of fluid damping.

The mechanical model solves structural mechanics equations derived from a principle of virtual work using a finite element method (FEM). In the structure formulation, total strain $\varepsilon$ and total stress $\sigma$ are written as

\[
\varepsilon = D[u] - [\alpha] \Delta T
\]

and

\[
\sigma = M(\varepsilon - \varepsilon_i) + [\sigma_i] ,
\]

respectively, where $D$ is the differential operator matrix, $[u]$ is the displacement vector, $[\alpha]$ is the thermal expansion coefficient vector, $T$ is the temperature, $M$ is the material stiffness matrix, $\varepsilon_i$ is the initial strain, and $\sigma_i$ is the initial stress. If displacements are large, then strains depend nonlinearly on displacements and $D$ becomes a function of $[u]$. Fluid-structure coupling is through boundary conditions. Thermomechanical coupling is facilitated by including thermal expansion in the stress and the strain relationships. As a result, structure equilibrium equation contains additional force term due to thermal expansion. The coupled electrostatic-mechanical model calculates pressure force due to surface charge on a mechanical structure. Additionally, the structural module can model contact forces and stiction.

### 2.3. Electrostatics

Electrostatic model solves for electric potential $\phi$ by a finite volume-based formulation using Poisson’s equation, i.e.,

\[
\nabla \cdot \varepsilon_r \nabla \phi = \frac{\rho}{\varepsilon_0}
\]

or the dc conduction relation, viz.,

\[
\nabla \cdot \sigma_e \nabla \phi = 0
\]

where $\varepsilon_r$ is the relative electric permittivity, $\varepsilon_0$ is the permittivity of free space, $\rho$ is the space charge, and $\sigma_e$ is the electric conductivity.

Based on electric potential, the electric field $E$ ($E = -\nabla \phi$), the pressure force, and the capacitance of the geometry being considered are calculated. If a dc conduction problem is being solved, then the current density, the virtual force, and the Joule heating source are also calculated.
Coupling between the electrostatic model and the structural mechanics model is through pressure forces. The electrostatic model solves Poisson’s equation and uses the electric fields to calculate the pressure force. The stress model uses the pressure forces as boundary conditions. The force \( F \) exerted by a total electric field \( \mathbf{E}_{\text{tot}} \) on a surface \( S \) with a surface charge \( \rho_s \) is given by

\[
F = \int \rho_s \mathbf{E}_{\text{tot}} \, da \quad \text{or} \quad dF = \rho_s \mathbf{E}_{\text{tot}} \, da .
\]  

(5)

Pressure force \( dF/da \) exerted by the total electric field \( \mathbf{E}_{\text{tot}} \) (approximated as an average electric field) on an area element \( da \) with a surface charge \( \rho_s \) separating two regions (indicated in the following equation by subscripts 1 and 2, respectively) is

\[
P = \frac{dF}{da} = -\hat{n}(\varepsilon_1 \mathbf{E}_1 - \varepsilon_2 \mathbf{E}_2)(\mathbf{E}_1 - \mathbf{E}_2) .
\]  

(6)

where the normal is directed toward region 1 and \( \varepsilon \) is the electric permittivity.

### 2.4. Flow and thermal solver

Flow and thermal solver is based on integration of Reynolds Averaged Navier-Stokes equations on an unstructured/hybrid/adaptive mesh system [8]. The flow solver is based on sequential integration of flow and energy using a pressure-based algorithm. Some of the features include time-accurate solutions, implicit links with the structural and the electrostatics solvers for the coupled solutions, and a moving/deforming grid formulation to handle geometry displacements.

### 3. ANALYTICAL MODEL

A cantilever beam of active length \( L \) is fabricated parallel to a substrate in such a way that separation between a pair of electrodes (one electrode is on the bottom of the cantilever and the other is on the top of the substrate) \( d_0 \) is greater than the contact gap distance \( d_g \), Fig 2.

![Fig. 2. RF MEMS switch: cantilever configuration, electrical traces were omitted for simplicity.](image)

The values of \( d_0 \) and \( d_g \) are based on a relationship defining instantaneous distance \((d_0-d)\) between the electrodes, as the switch is being activated, and the corresponding value of the activation voltage, \( V(d) \), which is a function of the cantilever deformation \( d \), i.e.,

\[
V(d) = (d_0 - d) \left( \frac{2kd}{\varepsilon_0 \varepsilon_r A_e} \right) .
\]  

(7)

In Eq. 7, \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r \) is the relative permittivity of the medium between the electrodes, \( A_e \) is the area of the electrodes defined as \( L_e b \), and \( k \) is the spring constant of the cantilever defined as

\[
k = \frac{Ebh^3}{4L^3} ,
\]  

(8)
where $E$ is the modulus of elasticity of the material of the cantilever, while $L$, $h$, and $b$ are its length, thickness, and width, respectively.

Speed of the response of a cantilever contact can be estimated using fundamental undamped resonance frequency, $f_o$, defined as [9,10]

$$f_o = \frac{1}{2\pi} \frac{h}{L^2} \sqrt{\frac{35}{33} \frac{E}{\rho c}}$$  \hspace{1cm} (9)

where $\rho$ is the density of the cantilever material, $g_c$ is the gravitational conversion constant, and other parameters are as previously defined. The phenomenological relationship [11] corresponding to Eq. 9 is

$$f_o = f_o(h, L, E, \rho, g_c)$$  \hspace{1cm} (10)

based on which the partial differential representation of uncertainty, $\delta f_o$, in the resonance frequency can be expressed as [11]

$$\delta f_o = \left[ \left( \frac{\partial f_o}{\partial h} \right) \delta h \right]^2 + \left[ \left( \frac{\partial f_o}{\partial L} \right) \delta L \right]^2 + \left[ \left( \frac{\partial f_o}{\partial E} \right) \delta E \right]^2 + \left[ \left( \frac{\partial f_o}{\partial \rho} \right) \delta \rho \right]^2 + \left[ \left( \frac{\partial f_o}{\partial g_c} \right) \delta g_c \right]^2 \right]^{1/2}$$  \hspace{1cm} (11)

where $\delta$ represents the uncertainties and $\partial$ represents the partial derivatives.

### 4. COMPUTATIONAL MODELING OF PHYSICAL PHENOMENA

The CFD-ACE+ software used in this study provides several fully coupled physical modeling capabilities including:

1) fluid mechanics equations with convection, diffusion, electromigration of mixtures, electrolytes, and biomolecules [12-14];
2) energy equation with conjugate heat transfer in solids, liquids and multiphase flows [15];
3) general multistep chemical kinetics handling stiff reaction mechanisms [16];
4) finite element method stress/deformation and dynamic model [17];
5) electrostatics, electrodynamics, electromagnetics, and solid state electronics;
6) generalized electrokinetics of ionic mixtures for electrophoresis, electroosmosis and bioelectrochemistry [18];
7) free surface flows in 3D using VOF method with surface tension and Marangoni effects for hydrophobic, hydrophilic liquid filling and microdispensing, liquid wicking in membranes and microcapillaries;
8) multiphase flows solved with Eulerian-Eulerian or Eulerian-Lagrangian method to simulate particle, bubble, droplet, micromolecule transport in microchannels;
9) surface chemistry to simulate competitive multi-protein binding, antigen-antibody, receptor-ligand, enzyme-substrate interactions, and non-specific multi-species binding [19]; and
10) mixed-level simulation capability in which 3D device model is connected to circuit models of the remaining parts of the entire microsystem – a link between CFD-ACE+ and SABER is used.

### 5. MEASUREMENTS OF MEMS

Optoelectronic laser interferometric microscope (OELIM) methodology used, in this paper, for measurements of MEMS, is based on recent advances in optoelectronic methods for static and dynamic measurements of shapes and deformations of objects [20-22]. In the configuration of the OELIM system shown in Fig. 3, a beam of collimated coherent light is brought into the system and is directed into a spatial filter (SF) assembly consisting of a microscope objective and a pinhole filter [23]. The resulting, expanded, light field is then collimated by the lens L1, and redirected by the directional beam splitter (DBS) through the long distance microscope objective lens (MO) to illuminate the object. The proximal beam splitter (PBS) is placed close to MEMS. Light reflected from a MEMS being investigated is transmitted back through MO, DBS, and the relay lens to the CCD camera.
Fig. 3. OELIM configuration for study of MEMS gyroscopes: SF is the spatial filter, L1 is the illumination lens, DBS is the directional beam splitter, MO is the long working distance microscope objective, and PBS is the proximal beam splitter.

Images recorded by the camera are processed by a host computer to determine the fringe-locus function, $\Omega$, constant values of which define fringe loci on the surface of object under investigation [24]. The values of $\Omega$ relate to the OELIM system geometry and an unknown vector $L$, defining displacements/deformations, via the relationship

$$\Omega = (K_2 - K_1) \cdot L = K \cdot L \quad , \quad (12)$$

where $K$ is the sensitivity vector defined in terms of vectors $K_1$ and $K_2$ identifying directions of illumination and observation, respectively, in the OELIM system.

Quantitative determination of displacements/deformations of MEMS due to loads they experience during their functional operation can be obtained, by solving a system of equations similar to Eq. 12, to yield [24]

$$L = \left[\widetilde{K}^T \tilde{K}\right]^{-1} \left[\widetilde{K}^T \Omega\right] \quad , \quad (13)$$

where $\widetilde{K}^T$ represents a transpose of the matrix of sensitivity vectors $K$.

Determination of vectors $K$, appearing in Eq. 13, depends on one's ability to establish Cartesian coordinates of points defining path of laser beam in the OELIM system, which is rather straightforward. However, depending on specific application, determination of $\Omega$ may be involved. Therefore, to facilitate determination of $\Omega$ a number of algorithms have been developed [25]. Some of these algorithms require multiple recordings of each of the two states, in the case of a double-exposure method – clearly, other recording methods may require different number(s) of recording depending on the specifics of a given method, of an object being investigated with introduction of a discrete phase step between the recordings [24-27]. For example, intensity patterns of the first and the second exposures, $I_n(x,y)$ and $I'_n(x,y)$, respectively, in the double-exposure sequence, can be represented by the following equations:

$$I_n(x,y) = I_o + I_r + \sqrt{I_o I_r} \cos(\Delta \varphi + \theta_n) \quad , \quad (14)$$

$$I'_n(x,y) = I'_o + I'_r + \sqrt{I'_o I'_r} \cos(\Delta \varphi + \theta_n + \Omega) \quad , \quad (15)$$

where $I_o$ and $I_r$ denote the object and reference beam irradiances, respectively, with $(x,y)$ denoting spatial coordinates, however the term $(x,y)$ was removed from the equations to simplify their representation, $\varphi_n$ denotes random phase of the light reflected from an object, $\varphi_r$ denotes the phase of reference beam, $\theta_n$ denotes the applied
The $n$-th phase step, and $\Omega$ is the fringe-locus function relating to displacements/deformations of the object incurred between the first and the second exposures; $\Omega$ is what we need to determine. When $\Omega$ is known, it is used in Eq. 8 to find $L$ [24].

In the case of a 5-phase-steps algorithm with $\theta_n = 0, \pi/2, \pi, 3\pi/2, \text{and } 2\pi$, the spatial distribution of the values of $\Omega$ can be determined as [25]

$$
\Omega(x, y) = \tan^{-1}\left(\frac{2[I_2(x, y) - I_4(x, y)]}{2[I_2(x, y) - I_4(x, y) - I_6(x, y)]}\right).
$$

(16)

Results produced by Eq. 16 depend on inherent capabilities of the illumination, the imaging, and the processing subsystems of the OELIM system. Developments in laser, fiber optic, CCD camera, and computer technologies have led to advances in the OELIM metrology; in the past, these advances almost paralleled advances in the image recording media [26].

Vector $L$ determined using Eq. 13, for a specific configuration of the OELIM system defined by $K$, subject to the spatial distributions of $\Omega$ resulting from Eq. 16, provides quantitative measurements of displacement/deformation fields of MEMS under static and dynamic loads [23,28-33].

### 6. MEMS SAMPLES USED

Figure 4 shows a representative MEMS gyroscope sample used in this study, indicating a differential configuration consisting of dual proof masses, i.e., shuttles, vibrating in a plane of the masses. Each of the masses is characterized by lateral dimensions of $300 \, \mu m \times 300 \, \mu m$ and is supported by four folded springs, one in each corner of a mass. One end of each of the folded spring(s) is attached to a post fixed on a die/substrate, this end of a spring is stationary and (ideally) does not experience any motions and/or deformations during functional operation of a MEMS gyroscope. The other end of the folded spring(s) is attached to the proof masse(s) and moves as the masses are actuated by the electrostatic comb drives. Each proof mass, in the configuration shown in Fig. 4, is actuated by its own set of comb drives.

![Fig. 4. Microgyro: (a) a representative package, (b) typical MEMS gyroscope with dual proof masses, each $300 \, \mu m \times 300 \, \mu m$.](image)

Based on their topologies, the RF switches can be grouped into two categories [9,34]: (1) membrane type, i.e., capacitive, and (2) cantilever type, i.e., resistive. In this paper, we consider a cantilever type RF MEMS switch configuration, Fig. 2. The samples considered herein were fabricated from Si and had the following dimensions: $160 \leq L \leq 260 \, \mu m$, $L_o = 50 \, \mu m$, $L_e = 100 \, \mu m$, $b = 20 \, \mu m$, $h = 6 \, \mu m$. 

Detail of a single, in this case left, proof mass/shuttle, is displayed in Fig. 5, while an enlarged view of the upper-right section of this mass/shuttle, including its local suspension, is shown in Fig. 6.

![Fig. 5. Detail of a single, in this case left, proof mass/shuttle.](image)
7. REPRESENTATIVE RESULTS

This Section presents representative results on M&M of MEMS gyroscopes and of a RF MEMS contact/resistive switch.

7.1. Representative modeling results

The CFD-ACE+MEMS software was used for predictive modeling and simulation of a number of MEMS configurations [35-39]. Following examples illustrate some of the results relating to development of MEMS gyroscopes.

Figure 7 shows a computational model of a single proof mass. Using this model, structural analysis module of the CFD-ACE+MEMS software computed mode shapes and corresponding frequencies of the proof mass, Fig. 8. Representative deformations of a proof mass/shuttle are shown in Fig. 9.
Computational procedures are also used to model thermomechanical aspects of MEMS devices and microelectronic packages [40-43].

7.2. Representative measurement results

The OELIM methodology was used in a number of applications where accurate measurements of deformations of MEMS, subjected to static and dynamic loads, were needed in FFV [20-23,26-32,42-46]. Figures 10 to 15 illustrate some of the results relating to development of MEMS gyroscopes.

Figures 10 and 11 display representative OELIM fringe patterns, corresponding to displacements/deformations of the left and the right proof masses of the MEMS gyroscope, shown in Figs 4 and 5, vibrating at 10.1 kHz [23]. These fringes clearly indicate not only changes in spatial distributions of deformations of the proof masses as functions of time, but also show differences in the deformations between both masses/shuttles, at the same instant in an actuation cycle.

These results indicate that magnitudes of motions/deformations of the proof masses are about 200 nm and are substantially greater than those that the masses would typically experience when subjected to Coriolis forces caused by angular accelerations [23]. It should be realized, however, that these motions/deformations are while the MEMS gyroscope is placed horizontally on a flat surface and its proof masses are actuated at the design frequency alone. That is, the gyroscope is not subjected to any angular acceleration. Hence, based on the measurements, design of the MEMS gyroscope should be reviewed and modified to assure that the undesired motions/deformations of its proof masses due to an in-plane actuation alone are mitigated.
Figures 12 and 13 display representative deformations of a folded spring supporting the left proof mass of a MEMS gyroscope, as measured using the OELIM methodology. These deformations are up to about 300 nm, over the section of the MEMS gyroscope displayed, corresponding to Fig. 6. More specifically, the folded spring, shown in Figs 12 and 13, deforms approximately 126 nm between the point where it is attached to the post and the point of its attachment to the proof mass. The proof mass itself has the deformation of about 174 nm.

Following procedures used to obtain results presented in this Section, motions/deformations of MEMS other than gyroscopes, subjected to static and dynamic loads, can also be modeled and measured.

Representative results shown in the following paragraphs are based on the RF MEMS switch configured, to satisfy specific design requirements, and characterized by dimensions presented in Section 2.

Activation voltage as a function of cantilever deformation, based on Eq. 7, indicates that a maximum voltage is achieved at an intermediate value of \( d \). This value can be obtained by differentiating Eq. 7 with respect to \( d \) and solved to obtain \( d/d_o = \%d = 0.333 \). In fact, as deformations \( d \) increase from zero to one-third of \( d_o \), the activation voltage, \( V(\%d) \), required to hold a cantilever in its (local) deformed position, increases monotonically with the deformation \( d \). Further increases in the deformation of a cantilever require a monotonically decreasing activation voltage to hold the cantilever in its local equilibrium. As a result, the system is unstable and a cantilever snaps down to close (uncontrollably) the switch at this voltage, which is called a threshold voltage. A relationship for the threshold voltage as a function of the initial separation can be easily obtained from Eq. 7 by substituting \( d = d_o/3 \).

Based on the results obtained, operation of a RF switch is facilitated by providing a protruding “contact-tip” beneath the free end of a cantilever, which limits the deflection of the cantilever to such an extent that it becomes stable and no longer snaps down.

Switching time depends on a fundamental resonance frequency. Using Eq. 9, \( f_o \) can be computed as a function of \( L \) [10]; the corresponding percentage overall uncertainty, based on Eq. 11, is displayed in Fig. 14. Effective reduction of the overall uncertainty can be performed by examination of Fig. 15, which shows contributions of individual uncertainties to the value of \( \%\sigma_{f_o} \). Clearly, the greatest contribution, some 60%, to the overall uncertainty in \( f_o \) is due to the uncertainty in \( L \). Therefore, reducing \( \sigma_L \) will reduce \( \sigma_{f_o} \) and subsequently the uncertainty in the switching time.

However, changing the uncertainty in one variable changes the contributions that uncertainties in other variables have on \( \sigma_{f_o} \) and the individual contributions must be reevaluated before subsequent changes in the uncertainties are made, if needed.
Effective computational simulation of a RF switch must simultaneously combine different loads including, but not limited to, the following: electromagnetic, electrostatic, thermal, mechanical, and aeroelastic. A representative result of such computational multiphysics modeling is shown in Fig. 16, which indicates damping effects of air surrounding a cantilever switch. In some applications, these damping effects help control switch dynamics and enhance tribological characteristics of the contacts. In other applications, they adversely affect dynamic characteristics of RF MEMS switches.

Computational simulation of RF MEMS switch packaging has also been initiated and representative results will be presented in a forthcoming publication.

Prototype cantilever beams were fabricated and their dynamic characteristics were determined in real-time using optoelectronic metrology [47-52]. Figure 17 shows representative results obtained for a 225 µm long Si cantilever. These results indicate that as actuation conditions change the operational response of the switch also changes. For example, the cantilever vibrating at 160 kHz reaches a maximum amplitude of 500 nm while the same cantilever vibrating at 1 MHz has an amplitude of a mere 4 nm, Fig. 17.
8. CONCLUSIONS

This paper describes modeling and measurements (M&M) of MEMS gyroscopes and contacts of resistive RF MEMS switches.

Modeling is accomplished using CFD-ACE+MEMS software, which provides a fully integrated environment for multiscale, multiphysics, high fidelity analysis of MEMS and MEMS packaging. Also analytical modeling is used to optimize uncertainties/tolerances on nominal values of parameters/variables controlling dynamic characteristics of RF MEMS cantilever contacts. The multiphysics simulations allow for a streamlined parametric analysis of coupled effects, while multiscale simulations allow for full analysis of the entire device as well as detailed analysis of specific components of a given device or a package.

Measurements are accomplished using optoelectronic laser interferometric microscope (OELIM) methodology, which provides remote, noninvasive, FFV, high spatial resolution results with nanometer accuracy and in near real-time.

Comparison of the modeling results with the results of measurements shows good correlation, subject to the bounds determined by uncertainty analysis, in accordance with ACES methodology.

Results obtained in this study show that nanoscale displacements/deformations can be readily measured and displayed in near real-time over the entire surface of investigated MEMS [52]. These displacements/deformations were due to static and dynamic load conditions. Magnitude of the deformations, discussed in Section 7, was on the order of 200 nm.

Although the specific case shown in this paper considers MEMS dual proof mass gyroscopes vibrating at 10.1 kHz, MEMS operating at other frequencies can also be readily characterized. For example, dynamics of microengines, developed to operate at 1,000,000 (yes, one-million!) rpm, were also studied using the OELIM methodology [53].

In addition, a cantilever-type resistive contact for RF MEMS switches was considered by employing the hybrid methodology. Advanced multiphysics computational modeling and simulation were used to analyze effects of contact design on performance of the switches. Computational analysis combined the electromagnetic properties of the RF MEMS with their electrostatic, thermal, and mechanical properties. Making such analysis changes in design were evaluated to see their effects on dynamic performance of the device. In particular, electromagnetic simulations of a cantilever-type contact switch were performed for a frequency spectrum ranging from 1 to 100 GHz and resulted in full 3D electric fields and magnetic flux densities based on which dynamic operational characteristics of the switch were determined. Some of the parameters considered in this determination were switch resonant frequency, displacement versus actuation voltage, and switch speed. More specifically, the switch speed was estimated to be about 3 µsec and \( d_g < d_o/3 \).

Effective development of RF MEMS switches, in addition to a good knowledge of signal propagation, also requires a good knowledge of switch dynamics. Preliminary results, presented in this paper, characterize dynamics of a cantilever-type microswitch. These results are based on analytical and computational modeling and simulation, to determine effects that contact design has on performance of the switch, and on noninvasive optoelectronic measurements of contact deformations, which provide FFV quantitative display of mode shapes of contacts. These mode shapes are measured with submicron spatial resolution and nanometer measuring accuracy.

All in all, results presented herein demonstrate that the hybrid approach, combining modeling and measurements, is a viable approach for development of MEMS.

More results based on use of the M&M approach will be presented in the future as the work on software development, its implementation, and modeling/simulation applications, as well as development, implementation, and measurement applications of the OELIM methodology, will continue.

7. REFERENCES


