Coupled Electrostatic-Structures-Fluidic Analysis of a Micromirror

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ABSTRACT

For micromirrors used in optical MEMS, in addition to the static displacement-voltage characteristics, the accurate transient characterization of these devices is becoming increasingly important. The latter one is strongly affected by the viscous damping of the surrounding air. A complete analysis of the dynamic behavior should consist of coupled transient simulations including electrostatics, stress, deformation, and fluidics of the air. This paper presents for the first time results of such fully coupled 3D simulations. CFD-ACE+ multi-physics simulator from CFDRC was used for both the static and transient analysis of an electrostatically actuated micromirror. The pull-down voltage was calculated very accurately. The micromirror dynamic response to step voltage varies for different ambient pressures. Air damping is clearly visible in the higher pressure, and it can be optimized in a real design to minimize the settling time of the optical switch.

Keywords: MEMS, optical switches, micromirrors, 3D simulations, fluid-structure interaction.

1 INTRODUCTION

Microelectromechanical system (MEMS) devices are finding increasing use in the field of optical communications [1]-[3] and displays [4]. In wavelength-division-mulitplexing (WDM) transport networks, optical MEMS are key components in modulators, variable attenuators, add-drop multiplexers, and optical crossconnects. A MEMS two-axis mirror used in an optical crossconnect is shown in Figure 1. MEMS are particularly well suited for optical applications because these devices are well matched to optical wavelengths, and can be manufactured in high volume and in high-density arrays in semiconductor manufacturing processes.

In addition to the static displacement-voltage characteristics, the accurate transient characterization of these devices is becoming increasingly important as these devices are being driven at higher speeds. In contrast to the more widely used MEMS devices such as accelerometers and pressure sensors, optical MEMS devices tend to be large angle or large displacement actuators. As such, the accurate transient characterization of these devices presents a challenge to simulations tools. Damping coefficients calculated for small displacements are not valid for large displacements [5]. Analytic calculations for large displacement actuators only work well for devices that are engineered to have well-defined damping or acoustic characteristics and boundary conditions [6].

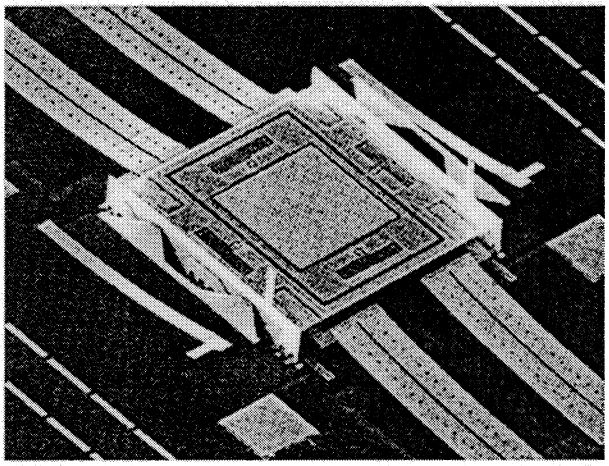


Figure 1: Two-axis micromirror used in an all-optical crossconnect system [1].

Therefore, there is a growing need for a general simulation tool to characterize the transient response of optical MEMS devices which tends to be dominated by air damping. The first characteristic of interest is switching speed. A designer would like to optimize design parameters such as mirror size, gap size, and drive signal to minimize the rise times and settling times. For example, the digital-micromirror display (DMD) is driven with a complex waveform that depends critically on the dynamics of the micromirror [4]. The simulation and optimization is currently done with an in-house simulation tool that is customized to the particulars of the DMD [7]. Transient inertial effects can also inadvertently push a device into the electromechanically-unstable regime (dynamic pull-in) and must be avoided by careful drive-pulse shaping.

Sensitivity to vibration is another parameter that is of great interest for telecommunications equipment that might have to be installed in remote locations and exposed to an environment that is not well controlled. It is important to understand the amplitude and duration of the perturbation of a mirror position due to external vibrations or shocks. An accurate damping model is needed in addition to an accurate characterization of the mechanical housing of the MEMS device.

As devices are being packed more closely together, issues of crosstalk arise due not only to electrostatic fringing fields but also to air flow. The faster a device is switched, the larger the air flow effect. A designer therefore needs to the understand the air flow patterns of a given device in order to minimize disturbing neighboring devices. A general 3D simulation tool allows the designer to optimize the overall shape of the movable parts, the location of etch holes, and the design of channels to control the movement of air.

This paper presents for the first time results of such fully coupled 3D simulations including interactions between electrostatics, stress, deformation, and fluidic behavior of the surrounding air. The following sections present a brief description of the model and numerical methods as well as example results of both static and dynamic behavior of a two-axis micromirror used in optical MEMS.

2 MICROMIRROR MODEL

As a test device for our coupled electrostatic-structural-fluidic simulations we chose an electrostatically actuated micromirror, similar to one fabricated at Lucent Technologies (Figure 1, [1]). Three-dimensional computational models were built at CFDRC, in collaboration with Lucent, using both CFD-GEOM (structured mesh) and CFD-Micromesh [4] (unstructured mesh) – see Figure 2.

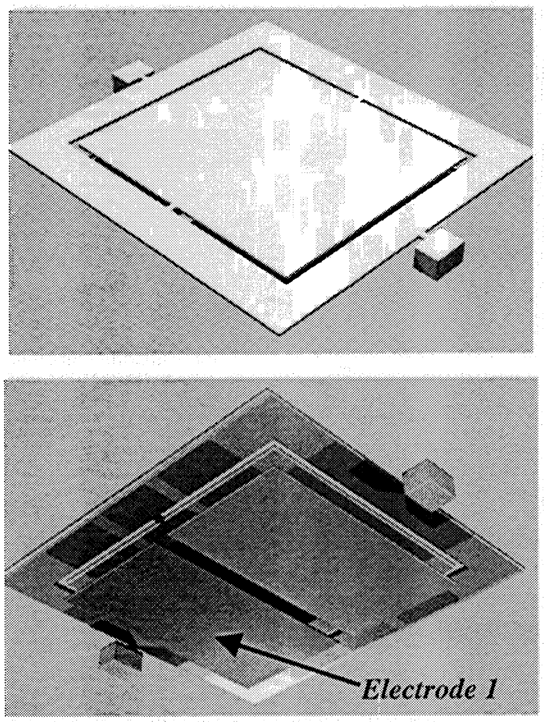


Figure 2: Micromirror 3D model built automatically from layout, using CFD-Micromesh.

The CFD-ACE+ multi-physics simulator [9] from CFD Research Corporation (CFDRC) was used to run 3D transient simulations of the electrostatically actuated micromirror. A series of coupled electrostatic-stress computations was performed, to determine static behavior of this two-axis tilting mirror, in particular pull-down voltage values for different electrodes activated. Transient simulations, including coupled electrostatics-stress-air damping, were also performed to analyze the speed of mirror response to step voltage applied to one of the electrodes. Example results are shown in Section 4.

3 NUMERICAL METHODS AND TOOLS

The coupled electrostatics-structures-flow simulations were performed using CFD-ACE+ [9, 10]. It has the necessary multiphysics capabilities including flow, heat-transfer, structured mechanics and electrostatics. In the present problem linking between electrostatics, structural mechanics, and the flow is of interest. A brief description of the involved codes is given below.

Flow and Thermal Solver: The flow and thermal solver is based on integration of Reynolds Averaged Navier-Stokes equations on unstructured/hybrid/adaptive mesh system. The flow solver is based on sequential integration of the flow and energy using a pressure-based SIMPLE-C algorithm. Some of the features needed in the present analysis include: time-accurate solutions, implicit links with a structures and electrostatics solver for the coupled solutions and a moving/deforming grid formulation to handle the micromirror displacements.

Structures Solver: The deformation/displacement of the micromirror was simulated using a finite-element solver module FEMSTRESS being part of CFD-ACE+ package. The relevant capabilities needed here include implicit links with other solvers, shell elements for efficient representation of the thin diaphragm, high spatial accuracy via second-order elements and large deformation analysis (if needed), steady and transient solutions and fast matrix solvers for quick turnaround. An efficient contact model, using non-linear springs is also available for simulations of the micromirror contact with electrodes or supports.

Electrostatics Solver: Solves a Poisson's equation for the potential using a finite volume-based formulation. Variable medium permittivity can be handled. The electrostatic pressures at various boundaries are calculated and imposed at boundaries for structures calculations.

Interdisciplinary Coupling: Refers to the link between electrostatic, structures, and flow solver. The electrostatic and fluid pressures are imposed on the deformable structures. The flow equations are written in terms of the grid velocities, which in turn are tied to the velocities from the structures solver. The structures solver uses the electrostatic and fluid pressures to evaluate the velocities at the fluid-solid interfaces. A remeshing tool is used to map the boundary velocities over the entire flow domain. A predictor-corrector method is then used to link the flow and structures velocities for fluid-structures interaction, where the local deformation is successively corrected using a second-order algorithm. This algorithm provides the degree of implicit coupling between the flow and structures needed for robust convergence behavior.

4 EXAMPLE RESULTS

In this section we present examples of results obtained from the coupled 3D simulations using the model and numerical tools described above. To determine static behavior of the two-axis tilting square micromirror, in particular pull-down voltage values for different electrodes activated, we performed several coupled electrostatic-stress steady-state computations. Results for one particular applied voltage are shown in Figure 3 where the local displacement of the structure is represented in the form of color map. Figure 4 shows the local stress (Von Mises) distribution in the supporting beam at the calculated deformation/ displacement of the mirror. As shown in Figure 5, the maximum displacement of the micromirror before pull-down was calculated very accurately by CFD-ACE+, close to the theoretical limit for electrostatically actuated torsional structures. Thus, the tool can help in designing micromirrors with the large tilt angles required for large port count optical crossconnects.

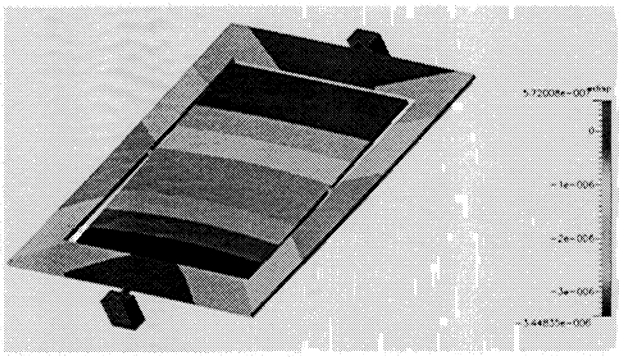


Figure 3: Example of steady-state results of 3D electrostatic simulation with CFD-ACE+. The color map shows local vertical displacement.

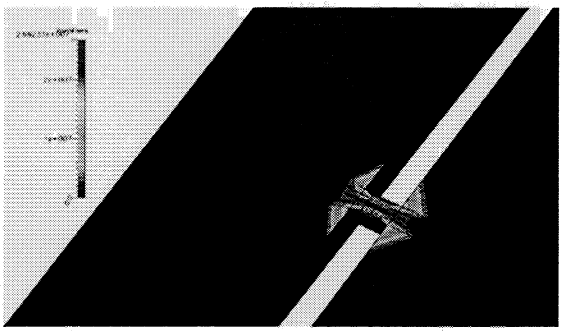
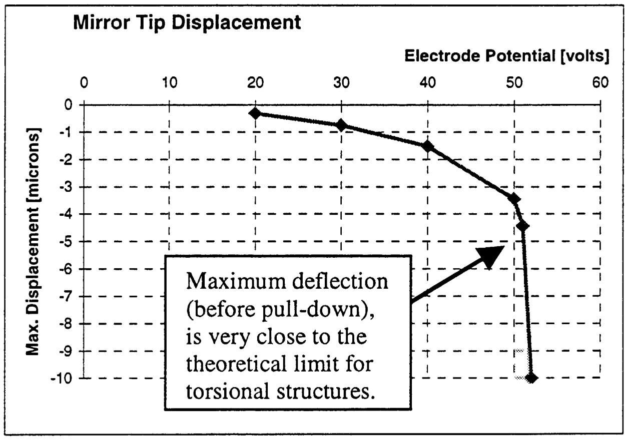


Figure 4: Stress distribution in the supporting beam.



Maximum deflection (before pull-down), is very close to the theoretical limit for torsional structures.

Figure 5: Static characteristic of the micromirror deflection, calculated with CFD-ACE+, with the voltage applied to Electrode 1 (cf. Fig. 2).

Transient 3D simulations including coupled electrostatics, structural stress, and air flow were performed to analyze the speed of mirror response to step voltage applied to one of the electrodes (Figure 6).

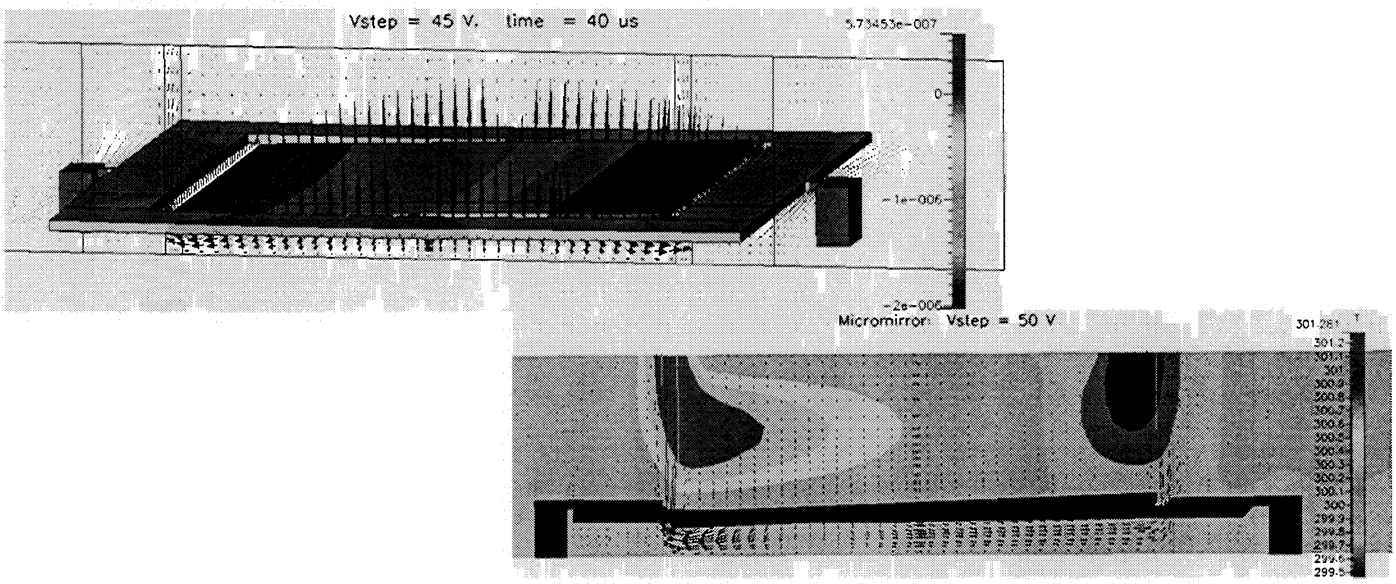


Figure 6: Examples of transient results of 3D fully coupled electrostatics-stress-flow simulation: the arrows represent the air flow vectors, the color maps – local deformation (top) or local temperature change (bottom).

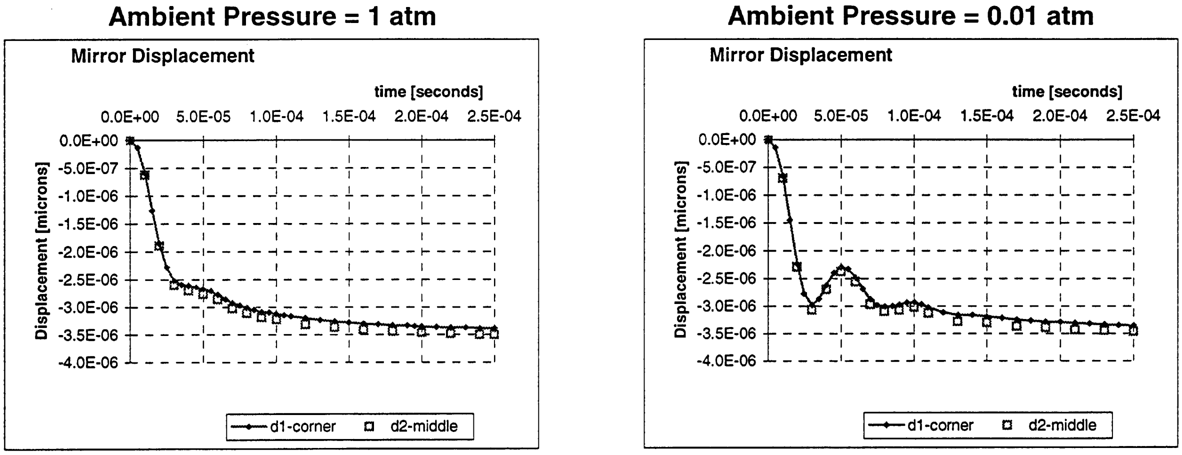


Figure 7: Transient responses of the micromirror to step voltage of 50V applied to Electrode 1, calculated with CFD-ACE+ for different ambient pressure values.

Figure 7 shows the transient behavior of the micromirror edge points, in response to a step voltage of 50V applied to Electrode 1. The first calculation is for standard atmospheric pressure P = 1 atm, and the second calculation is for P = 0.01 atm. Air damping is clearly visible for the higher pressure simulation and can be optimized in a real design to minimize the settling time of the optical switch.

6 CONCLUSIONS

In this paper, we presented for the first time results of fully coupled 3D simulations including complete physical interaction between electrostatics, stress, deformation, and fluidics of the air. CFD-ACE+ multi-physics simulator from CFDRC was used for both the static and transient analyses of an electrostatically actuated micromirror. The pull-down voltage was calculated very accurately according to analytically defined expected values. The micromirror dynamic response to quickly varying control voltage depends on ambient pressure value due to air damping phenomena. The damping is clearly visible in the higher (atmospheric) pressure, and it can be optimized in a real design to minimize the settling time of the optical switch.

The general 3D multi-physics simulation tool allows the designer to optimize the overall shape of the movable parts, the location of etch holes, and the design of channels to control the movement of air and overall dynamic behavior of the fast moving MEMS devices.

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