Extraction of Damping Coefficients of Comb Drive by Partitioning

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ABSTRACT

The interaction between MEMS devices and their environmental fluid is a major design consideration. An efficient macro-model technique is developed in this work to study the impact of fluid damping coefficients for moving parts of MEMS. A comb-based accelerometer has been analyzed to demonstrate the methodology. A system-level model is created to analyze the device. Damping templates are exported and incorporated into the system-level model. Small signal and transient simulations are run to examine the impact of damping coefficients on device performance. The technique has been applied successfully to extract the damping coefficients of a comb-drive based tunneling accelerometer. The method is simple and fast for damping analysis. It can be applied to accelerometer of other shapes and under large deflections as well.

Keywords: MEMS modeling, damping coefficient extraction, squeeze film damping

1 INTRODUCTION

The interaction between MEMS devices and their environmental fluid liquid needs to be considered in many applications of MEMS [1]. The effect of squeezed film damping is important in the design of MEMS devices, such as sensors [8, 10], RF switches [12], and MOEMS [13]. Comb-driven electrostatic actuation has been widely used in micro devices, for example, micro-scanner [14, 15], mechanical filters [16], and optical switches [17]. Comb structures enhance the net capacitance variation and, as a result high-actuation forces can be reached with relatively low drive voltages. In-plane motion of a comb drive is governed by a second-order differential equation, and the whole system is a simple harmonic oscillator. [14]

Veijola et. al. [3] in 1995 developed a numerical model for the squeezed film damping between moving rigid, rectangular surfaces. Lewis et. al. [4] in1995 established a detailed squeeze film damping model of a micromachined accelerometer and implemented system-level simulation using a commercial SPICE package. Turowski et. al [5] in 1999 present simulations of air damping in MEMS for large displacements, including squeeze-film damping for plates and mirrors, as well as viscous dissipation for laterally oscillating microstructures. Vemuri et. al. [6] in 2000 studied low-order behavioral squeeze film model of oscillating planar microstructures with critical dimensions in the range of a few microns. Keating et. al. [1] in 2000 offered a new squeezed film damping analysis method, including the governing equations and the required assumptions. The governing equations were presented for both compressible and incompressible fluids. Yang et. al. [7] in 2001 presented a fast macromodel extraction technique for gas damping and spring effects for arbitrarily shaped MEMS devices. The technique used an Arnoldi-based model-order-reduction algorithm to generate low-order models from an FEM approximation of the linearized Reynolds equation. Chang et. al. [8] in 2002 discussed the dynamical characteristics of a torsion mirror in MEMS systems.

Accurate prediction of the dynamic behavior of comb-driven MEMS device is important to optimize the structure design. Viscous damping in the surrounding air determines the dynamic response of movable structures close to resonance. Viscose damping of a structure vibrating in a fluid is the integral effect of dynamic force components reacting from the fluid back to the structure. Damping analysis of comb drive was seldom studied due to its complex structure, and there is little report about the damping behavior of the whole comb structure. Due to low-cost packaging requirement, a large class of MEMS devices, such as comb-driven accelerometer, must operate at ambient gas pressures. The air molecules underneath the moving structure alter or even downgrade the device performance significantly. Comb devices require an understanding of gas damping and spring effects for accurate modeling. [7] An efficient methodology is developed in this study to consider fluid damping on MEMS devices e.g. comb-based accelerometers.

2 MODELING

Damping is a consequence of the boundary condition at the surface, which states that sum of the surface stresses must be equal and opposite to the sum of the viscous stresses. Models used to simulate fluid damping and spring effects are: Squeeze Film, Couette Flow and Steady Stokes Flow [9].

2.1 Squeeze Film Model

Squeeze Film is a lubrication theory model for the case of a thin film of fluid between parallel surfaces with a motion normal to the gap. It also includes compressibility effects. The solution is computed by a 2-D finite element model. Squeezed film damping is a term used to describe one of the more common fluid-structure interactions that impacts the performance of MEMS devices [1]. The analytic solution to the compressible Navier-Stokes equation gives a damping coefficient based on an infinite plate moving in an infinite medium and results in the following expression [9].

$$C_d = P_0 \sqrt{\frac{\gamma}{RT}} A \tag{1}$$

Where P_0 is the ambient pressure, $\gamma = \frac{C_P}{C_v}$ and $R = \frac{R_{univ}}{m}$ where C_p and C_v are the specific heat with constant pressure and constant volume, respectively, A is the plate area, T is the temperature in Kelvin, and R is the gas constant, where R_{univ} is the universal gas constant and m is the molecular weight. Figure 1 and 2 show schematic of squeeze film damping analysis module.

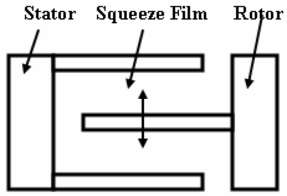

Figure 1: Squeeze film between comb fingers.

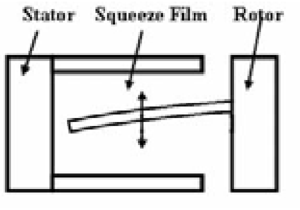

Figure 2: Mode shape squeeze film between comb fingers.

2.2 Stroke Flow Model

The Stokes Flow model is intended for use where there may be small gaps, but geometry and motion are more general. The only restriction is that Reynolds number be small. For large gaps, a Stokes flow oscillating plate model (infinite “gap” shear) is more appropriate and is given by [9].

$$C_d = \sqrt{\frac{\omega \rho \mu_{eff}}{2}} A \tag{2}$$

Where $\omega = 2\pi$ stands for frequency, ρ is the density, μ_{eff} is shown as effective viscosity, and A is the plate area.

3 DAMPING COEFFICIENTS EXTRACTION

Complex mechanical devices can be modeled with the finite element approach using commercially available FEM tools. Comb drive is too complicate to be analyzed using one damping model for the whole device due to computational constraints. The device is divided into sub sections. Now each individual section is analyzed separately. This partition and analyzed methodology is efficient and fast to study the impact of damping on device behavior.

3.1 Extraction Methodology

The extraction methodology is based on following steps:

a. Identify the sections of a device experiencing damping. Each section is an independent partition to be analyzed. Solid models are built for FEM simulations.

b. Appropriate simulation model is selected for each partition based on behavior of the sub-section.

c. Numerical simulations are run with FEM based tool.

d. Damping templates are exported to be used in system level simulation.

First, critical areas of a device being impacted by damping are identified. Fig 3 shows a comb drive structure to be analyzed. The comb driver is a complicate device; it is difficult to analyze the whole device by using only one damping analysis model constraint by computational complexity. The areas that experience damping are marked 1 through 7 in the Fig. It divides the device into subsections to be analyzed separately. Sub-sections 1 and 4 are comb structures. Subsections 2, 3, 5 are like parallel plate surfaces. Partitions 6 and 7 are special cases of parallel plate surfaces.

Second, suitable simulations models are to be selected for each sub-section. Three models are available in simulation tool Squeeze Film, Couette Flow and steady Stroke Flow. A key assumption in using Squeeze Film solver is that the gap is small compared to the plate dimensions. Thus it is useful for gaps on the order of microns being squeezed by plates that are tens to hundreds of microns in size. So it is not applicable for the ends of comb fingers whose “plate” is about the size of the gap. The sub-sections 2 and 5 will experience this type of damping.

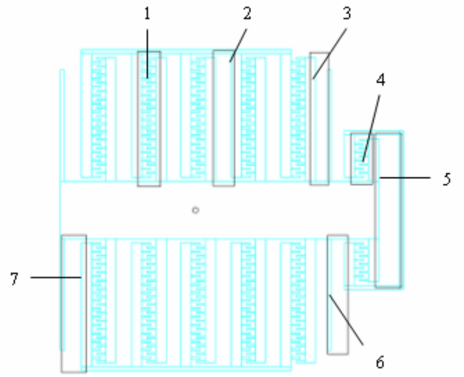

Figure 3: Locations for damping analysis.

Generally, in squeeze film the two plates approach directly with stable parallel plane. But if the squeeze film is not uniform during the motion as in case of subsections 6 and 7 A special case called mode shape squeeze film damping is used. In this case, one of the plates is distorted caused by combination of fixed end and motion of proof mass. See Fig. 2(c). After calculating track of the moving plate, the damping coefficient can be gained by finite element model.

Steady Stokes Flow is a model for fluid damping due to general, unrestricted geometries and general body motions. Theoretically, the Stokes Flow model matches the requirement of computation for comb drive. However, this general model has considerably more computational cost than the Squeeze Film or Couette models.

Couette flow model is applied if there is flow between parallel plates, one of which is moving parallel to the other. In the present case this damping is not seen. It is important when device is packaged. The Couette damping between package and device become significant.

Third, export individual macro model templates to be used in system level model. Macromodel creation is supported for Squeeze Film and Stokes Flow models. Squeeze Film models are created by Arnoldi model-order reduction, and complex, frequency-domain coefficients are reported for an input set of frequencies. For Squeeze Film models, a symbol and two templates (one for a finite gap solution and on for an infinite gap solution) are created for a full system level simulation. Stokes Flow models are created from parametric study runs that produce real damping coefficients that vary by translational or rotational position. For a Stokes Flow model, a single symbol is generated, which incorporates position and damping coefficient data in two vectors. A pre-defined fluid library template accepts these vectors, providing full system level simulation support.

3.2 System Level Damping Analysis

An ideal damper exerts a force proportional to the velocity: $F = cv = c\dot{x}$ where c is the damping coefficient. These extracted parameters can be grouped to form template. The system analysis is done with model built in Saber including exported damping templates.

System level model is built for analysis. The schematics are shown in Figs. 4 and 5. The small signal analysis for resonance frequency with damping components were compared with the case without damping components, as shown in Fig. 6. Transient analysis is shown in Fig. 7. The simulation shows the impact of damping along X direction. The oscillation tends to be steady after 0.022 seconds. The simulation shows the impact of damping coefficients on the device performance. The amplitude of the resonance frequency is reduced (damped). The dynamic response is impacted as well and reduced the oscillating amplitude in transient simulation.

4 CONCLUSION

Fluidic damping significantly affects the dynamic characteristics of MEMS's device. Damping behavior greatly dependents on the structure of the device of interest. In this paper, partitioning method is adopted to analyze simple damping performance at different locations. Stroke Flow, Squeeze Flow and Model shape squeeze film are used to extract damping co-efficient of a comb drive. A criterion has been developed to apply at any device of any shape. Damping templates are extracted using FEM and included in the system level simulations. Transient and small signal simulations are run to study the impact of the damping on device characteristics.

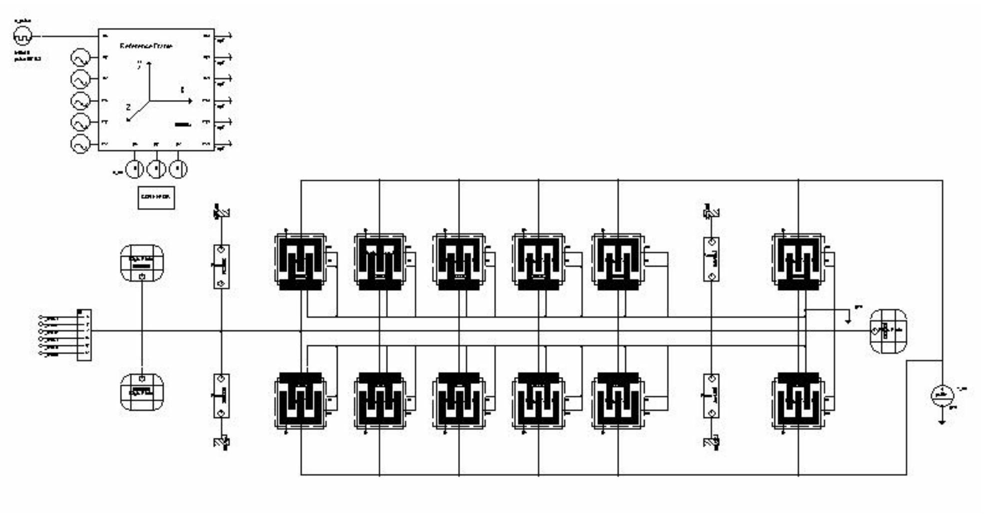

Figure 4: System level model without damping.

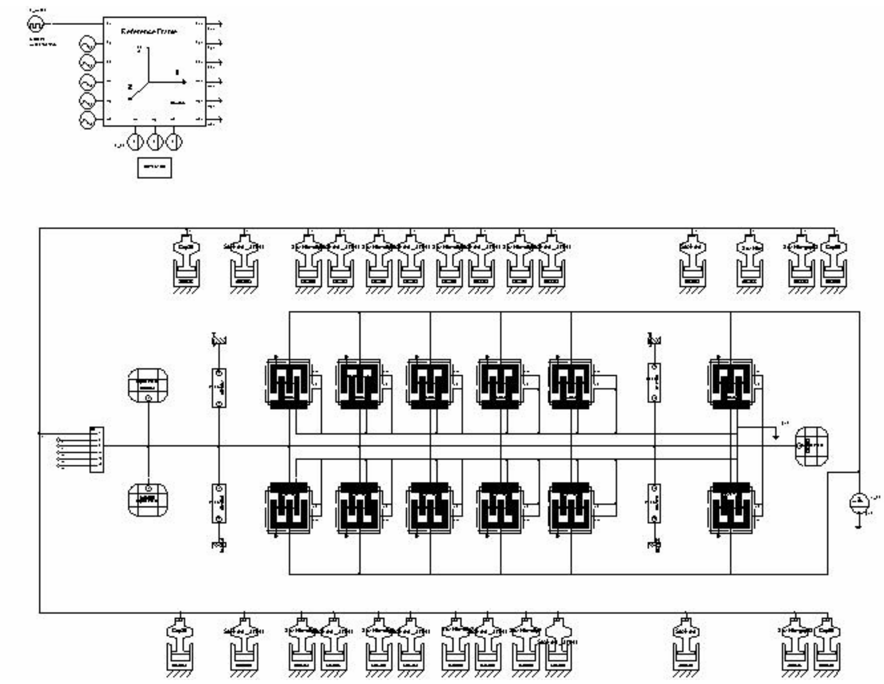

Figure 5: System level model with damping.

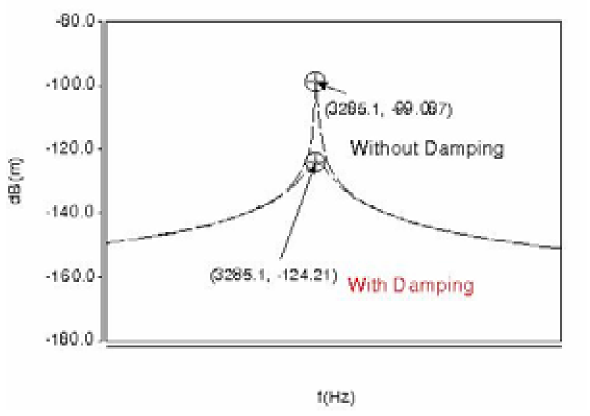

Figure 6: Resonance frequency plot.

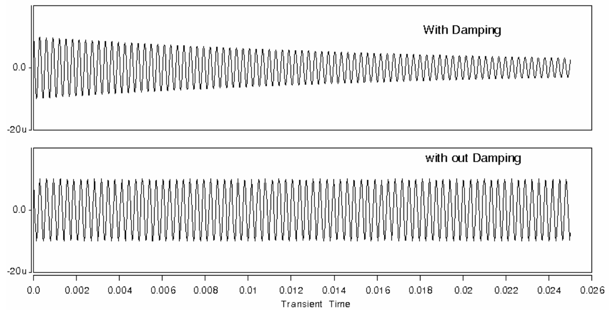

Figure 7: Transient Analysis.

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