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Fluid-Structure Interaction of MEMS Resonators

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Summary:

The modelling of the fluid-structure interaction of MEMS resonators with a surrounding fluid is a formidable challenge. Only for resonators with slender beam geometries reliable methods are available. Here, we present a novel modelling approach that overcomes the geometry restrictions of beam-based methods while still being computationally efficient. We use this method to study the spectral response of a MEMS resonator immersed in a liquid. The results give insights into the fluid-structure interaction of MEMS resonators that could not have been achieved with established methods.

Keywords: MEMS resonators, fluid sensors, fluid-structure interaction, plate models, finite element methods

Introduction

Resonators based on microelectromechanical systems (MEMS) play a key role in numerous sensing applications. This prominent role is not only due to the small size and low cost of MEMS resonators. MEMS resonators also establish a gateway between the physical world and the digital domain. An important aspect of this gateway is that MEMS resonators comprise mechanically moveable parts that interact with their environment. Different types of interactions can be utilized to measure various physical quantities. One particular important interaction is the fluid-structure interaction (FSI) of a MEMS resonator with a surrounding fluid [1]. This fluid can either be a gas or a liquid and for practically every MEMS resonator outside vacuum or near-vacuum FSI is the dominant interaction with the environment. Despite this prominent role of FSI and the long history of MEMS development, the FSI of MEMS resonators is well understood only for a few limiting cases. Especially for resonators with beam geometries, various methods are available for determining the FSI. However, these models are only valid for resonators with slender beam geometries which severely limits their applicability. Moreover, only vibrational modes that can be found in beam geometries can be investigated with beam-based methods. These methods fall short of explaining the FSI of MEMS resonators vibrating in non-beam modes as the mode shown in fig. 1 [2]. Here, we present a novel method to investigate the FSI of MEMS resonators with non-beam geometries and demonstrate how these methods can be used for predicting the spectral response of MEMS resonators in fluids.

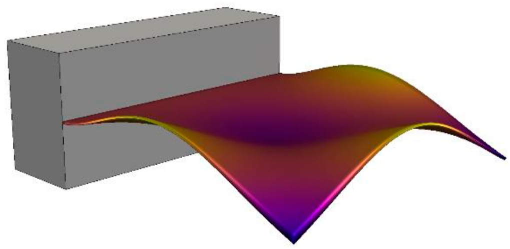

Fig. 1. Non-beam vibrational mode of a cantilevered MEMS resonator. Such modes are present in every MEMS resonator. However, they appear at frequencies of lower-order beam modes only if the width of the resonator is comparable to the resonator's length.

Description of the Method

A difficult challenge in the modelling of MEMS resonators is posed by the mismatch of scales between large resonator geometries and small fluid displacements. This scale mismatch prevents the use of conventional computational fluid dynamics (CFD) methods. We address this challenge by modelling the fluid flow with a boundary integral representation. The pressure p exerted by a fluid flow field $\boldsymbol{u}$ on the resonator surface is then determined by inverting an integral equation over the resonator surface A,

$$u(\boldsymbol{x}) = \int_A p(\boldsymbol{x}')\psi(\boldsymbol{x},\boldsymbol{x}')d\boldsymbol{x}', \quad (1)$$

where ψ is a geometry-dependent Green's function. In doing so, we avoid a computationally costly discretization of the full fluid domain.

We assume that the resonator exhibits a thin geometry, i.e. its thickness is much smaller than the resonator's width and length, which allows for using the Kirchhoff plate equation,

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$$D\,\nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} = p, \qquad (2)$$

for modelling the solid mechanics of the resonator. Here, w is the transversal displacement of the resonator, D is its flexural rigidity, ρ its density and t is the time. This approach allows for going beyond beam models while circumventing the complexity of three-dimensional continuum mechanics models. We combine equation (1) and (2) and solve the resulting equation using a non-conformal finite element method [3]. This method does not suffer from the limitations of beam-based models but avoids high computational costs.

Results

Using the method presented above, we can investigate how the FSI of a MEMS resonator changes as the geometry deviates from an ideal beam geometry [4]. As an example, we compute the spectral response of a cantilevered MEMS resonator as a function of its anchor width shown in fig. 2.

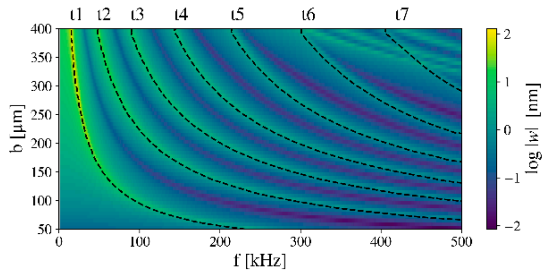

Fig. 2. Deflection spectrum as a function of resonator width for a cantilevered rectangular silicon MEMS resonator with a length of 800 µm and a thickness of 5 µm. The resonator is immersed in water and symmetrically driven at both of its free corners. The resonances of the first nine beam vibrational modes are marked by dashed lines.

At a width of 50 µm, the resonator is well approximated as a beam and only beam vibrational modes can be found in the frequency interval up to 500 kHz. These beam modes shift towards lower frequencies as the resonator width increases indicating an increased fluid-added mass. Above a width of 200 µm, additional resonances are visible in the spectral response which correspond to non-beam modes like the mode shown in fig 1. These modes experience a larger increase of the fluid-added mass than classical beam modes which results in a lager decrease of their resonance frequency as the resonator width increases.

The resonance frequency is not the only quantity that depends on the resonator width. The quality factor of all vibrational modes also changes for different resonator widths. The resonance frequencies and quality factors for different beam modes and resonator widths are shown in fig. 3. Generally, it can be observed that the quality factor increases as the width of the resonator increases.

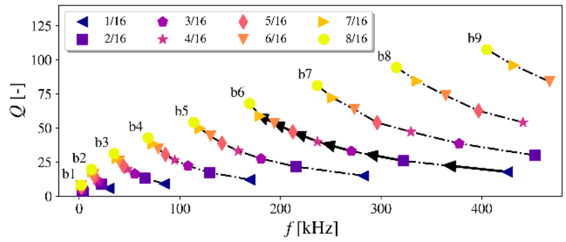

Fig. 3. Quality factors of the beam vibrational modes of the spectrum in fig. 2. The aspect ratio of the resonator is indicated by different marker symbols shown in the legend.

A similar analysis can be performed for non-beam modes. A comparison of the results reveals that the quality factor of any vibrational mode is well predicted by

$$Q = 0.23\,\beta^{0.45}, \qquad (3)$$

where β is a generalized Reynolds number.

Conclusion

We have presented a modelling approach for the FSI of MEMS resonators with non-beam geometries. The method mitigates scale mismatches that are inherent in the modelling of MEMS-FSI by combining a boundary integral fluid flow representation with plate solid mechanics. We use this approach to study the spectral response of non-slender resonators in water. The results show that the quality factor of different modes can be predicted by a generalized Reynolds number. We anticipate that the presented methods and results will play a vital role in the development of novel MEMS resonators with non-conventional geometries.

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