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On the response of a resonating plate in a liquid near a solid wall

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Abstract

We investigate the effect of a nearby solid wall on a microfabricated resonating plate immersed in a fluid. This phenomenon, known as squeeze film damping, has long been studied with microfabricated devices in gases but only recently with incompressible liquids. Here, we make measurements with a rectangular plate operating in its fundamental resonance mode in close proximity to a solid wall in a wide range of fluid viscosities (1–50 cP). For the plate oriented parallel to the wall, we measure power law-like behavior for the dependence of both the effective mass and the drag experienced by the sensor as a function of wall distance (−1/2 and −1, respectively). For the plate oriented perpendicular to the wall, we discover the surprising result that each viscosity has a unique distance of maximum damping.

Keywords: Resonance; Fluids; Cantilever; Drag; AFM; Viscosity

1. Introduction

The ever-increasing demand for technology based on microfabrication, especially those consisting of Micro-ElectroMechanical Systems (MEMS), has driven forward a great amount of applied and fundamental research [1]. An especially pertinent issue with devices that sense or produce motion is that of squeeze film damping, an effect that results from the compression of air or liquid between structures. Perhaps the simplest example would be that of a cantilever vibrating above a surface, where the entire system is immersed in a liquid or gas. Each oscillation of the beam requires that the fluid be squeezed from between the beam and surface, creating an additional drag or dampening. Such phenomena greatly affect the resonance frequency, quality-factor and amplitude of motion. Accelerometers, pressure sensors and actuators often take advantage of these effects to optimize their designs [1].

Our interest in this topic comes from our development of a miniaturized sensor to measure the physical properties of fluids, such as their density or viscosity. This sensor, consisting of an actuated cantilever with a built-in strain gauge, must operate in confined environments, such as in the small diameter flow lines of an oil-services tool used downhole. Hence, it was of great interest to characterize and understand how the damped resonance of a cantilever in a fluid would be influenced by a nearby wall. For example, it may be necessary to compensate for the presence of a wall or flow line diameter in the working equations of the sensor.

The preponderance of investigations into squeeze film damping with MEMS or small devices has focused on compressible fluids, such as gases [1–3]. Only recently have investigators examined this phenomenon with small devices in liquids, one example being that of Naik et al. [4], who examined a high aspect-ratio beam, characterizing the effect of a nearby wall on the resonance. While conventional models suggest that the viscous damping should scale inversely as the third power of the gap height, these researchers found a highly disparate behavior [5]. Theoreticians are beginning to investigate this phenomenon more closely, especially as liquid-immersion atomic

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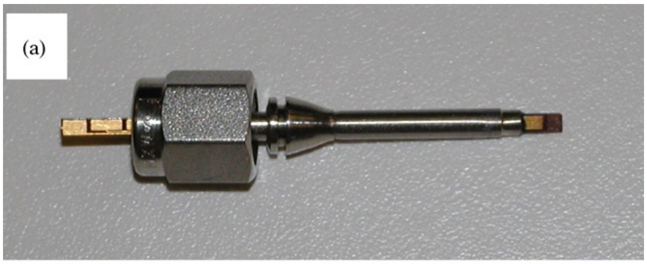

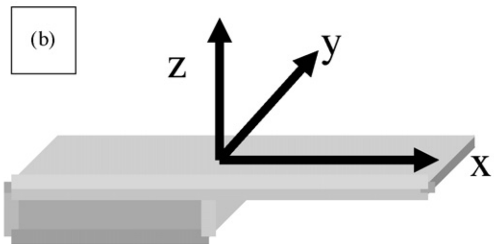

Fig. 1. (a) Bulkhead consisting of a swagelok nut and glue-filled tube; electrical connections that pass through the tube can be observed on left-hand side. Vibrating plate can be seen as the rectangular shape at the end of tube on the right-hand side of photo. (b) Schematic of vibrating plate with coordinate system illustrated. The plate oscillates in the $\hat{z}$ direction much like a diving board.

force microscopy has gained in popularity [6–10]. While it is generally agreed that the viscous damping should scale as the inverse cube of the gap height as an asymptote, it is interesting to note that this has not yet been observed experimentally with MEMS devices [5].

In this article, we will study the afore-mentioned effects with a millimetre-scale microfabricated cantilever-style plate. After describing its fabrication process (Section 2), the methodology and theory for extracting the added mass and damping terms will be described (Section 3). Vibrometer measurements will next be presented to establish that we are exciting the plate in its fundamental mode (Section 4). The resonance will be extensively characterized under vacuum as a function of temperature to measure the internal damping and effective mass (Section 5). We will then measure the effects of squeeze film damping with three liquids and compare our results with recent theoretical and experimental studies (Section 6).

2. Experimental

2.1. Device fabrication

The vibrating MEMS plate is fabricated via a multi-layer lithography process that starts with a ⟨1 0 0⟩ silicon on insulator (SOI) wafer with a 20 μm thick device layer [11]. The thickness of this device layer determines the thickness of the plate, though there is an increase of a couple of additional microns from the fabricated circuitry. Several hundred plates (1.45 mm long × 1.8 mm wide) are fabricated per wafer, with an integrated strain gauge consisting of a polysilicon Wheatstone bridge, a coil for actuation and a resistance based thermometer. The chip is mounted and packaged such that it can be operated in a high pressure, high temperature environment (Fig. 1a). A permanent magnet consisting of samarium cobalt (SmCo) is placed such that the magnetic field is parallel to the x axis (Fig. 1b). At the typical plate-to-magnet distance, we measured a magnetic field of 0.1 T, which is largely temperature insensitive. Current passing (ca. 1 mA) through the chip's coil experiences a Lorentz force in the presence of an external magnetic field, deflecting the plate with an out-of-plane motion, which is then detected by the strain gauge.

2.2. Interrogation methods

The motion of the plate creates an imbalance in the piezoresistant arms of the polysilicon Wheatstone bridge. It is biased across one diagonal with 1.0 V and the amplitude of the motion is detected by measuring the oscillatory output on the opposite diagonal. The output of the Wheatstone bridge is amplified with a Stanford Research System pre-amplifier (SRS 560) typically operated at a gain of 10^3. The excitation and measurement process is carried out with a Agilent 35670A digital signal analyzer (DSA) operated in burst chirp (1.0 V) mode with a Hanning window with an average of 15 spectras. The DSA records the complex ratio of the excitation and bridge voltages. Both the in-phase and quadrature components of the spectra are transferred to a personal computer where regression is performed.

2.3. Regression methodology

Regression is performed by algorithms written in MatLab, which implement the ideas of Mehl [12] and Ewing and Trusler [13]. The regression employed here measures the background-subtracted peak amplitude, frequency, width and quality factor (q-factor).

The output spectra from the strain gauge are fit with the following complex function where u refers to the in-phase component, v the quadrature component and $\mathrm{i} = \sqrt{-1}$.

$$u(f) + \mathrm{i}v(f) = \frac{Af}{f^2 - F^2} + B + C(f - f_0) \quad (1)$$

The following four complex parameters are determined by regression and defined as indicated below:

$$A = a_\mathrm{r} + \mathrm{i}a_i \quad (2)$$

$$B = b_\mathrm{r} + \mathrm{i}b_i \quad (3)$$

$$C = c_\mathrm{r} + \mathrm{i}c_i \quad (4)$$

$$F = f_0 + \mathrm{i}g_0 \quad (5)$$

f_0 and g_0 correspond to the resonance frequency (frequency of maximum amplitude) and half peak width of the square of the amplitude, respectively. The constants A, B and C are used to isolate the resonant signal. For example, A is a scaling factor for the peak height, B accounts for a background offset and C for a background slope. An example of the effectiveness of this function is shown in Fig. 2.