Sensors and Actuators A 238 (2016) 299–306

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Hydrodynamic analysis of piezoelectric microcantilevers vibrating in viscous compressible gases

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ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form
14 November 2015
Accepted 20 December 2015
Available online 28 December 2015

Keywords:
Microcantilever
Resonant mode
Viscosity density sensing
Compressibility

ABSTRACT

The dynamics of microcantilever beams can be profoundly affected by immersion in fluids. While viscous effects are widely acknowledged to have a strong influence on these dynamics, the influence of fluid compressibility is commonly neglected. Here we experimentally study the hydrodynamic loading effect on a flexural vibrating microcantilever, which is immersed in six different viscous compressible gases. We find that the quality factor prediction from a viscous model shows good agreement with experimental result in the low resonance frequency/mode regime, while the influence of fluid compressibility becomes increasingly important with rising mode number and frequency. In contrast, it is found in all cases that the resonance frequency is independent of the fluid compressibility, which is consistent with the inviscid fluid model's prediction.

1. Introduction

Oscillating micro structures can be profoundly influenced by the fluid that surrounds them, thus promising to have great potential for microscale sensing of fluid properties. The peak resonance response frequency f_r and the quality factor Q of a microcantilever are the two main dynamic characteristics that are very sensitive to the density and viscosity of the surrounding fluid. Therefore, the viscosity and density of a fluid can be determined by analyzing the frequency response of a cantilever immersed in the fluid. Both theoretical and experimental work suggest that the resonance frequency shift Δf depends mainly on the fluid density [1], while the Q factor relates to both the viscosity and density of the fluid [2]. By analyzing the frequency response of a micro resonator in a fluid, the viscosity and density of the fluid can be determined. Only fluids with identical density and viscosity will give the same resonance frequency and Q factor. Fluids that have similar viscosities or densities can be easily distinguished with this technique. Most previous researches have been focused on the viscous drag effect on microcantilevers vibrating in the first few harmonic modes. The fluid flow is expected to be incompressible and viscous drag is typically the dominant fluid damping mechanism. Viscous drag models require a solution of the Navier-Stokes equations for unsteady, incompressible flow. Typically some simple geometry like a sphere [2] or a cylinder [3,4] is taken as an approximation of the actual geometry, besides [4] also modified the function for a cylinder to account for a thin rectangular beam. Furthermore, former investigations, e.g. [5–8], pointed out that the Q factor of a resonator in a higher order flexural mode is larger than that of a lower one. However, recent papers [9,10] detailed a model for a cantilever beam oscillating in a compressible fluid. They predict that, as the mode number increases and passes a “coincidence point”, the Q factor will finally start to decrease. This is further confirmed by Weiss et al. [11] who compared the compressible and incompressible fluid simulation results using a numerical method. Jensen and Hegner [12] carried out measurements in atmospheric air and found qualitative agreement between experimental results and calculations based on the compressible fluid model of Van Eysden and Sader [9,10].

This work aims at evaluating and comparing the effects of higher flexural mode operation, ambient pressure and the nature of the surrounding fluid on the resonance behavior. The experiments are carried out by using aluminum nitride (AlN) based piezoelectric microcantilevers, which were tested in a chamber filled with different specific gases under controlled pressure. Several typical modes of the cantilever have been detected and characterized. In the following an analysis about the fluid loading characteristics of the flexural vibrating modes of the cantilever is carried out. Further-

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http://dx.doi.org/10.1016/j.sna.2015.12.024
0924-4247/

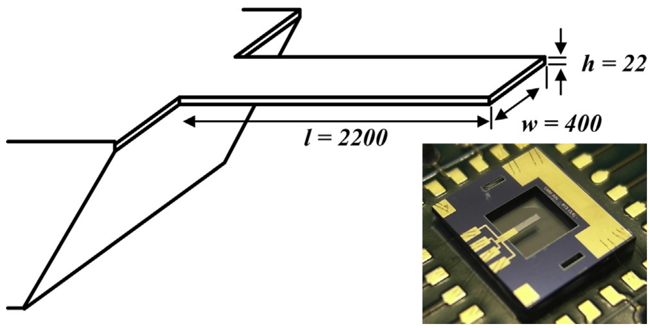

Fig. 1. Schematic diagram and photo of the piezoelectric microcantilever with all dimensions given in μm.

more, the influence of the fluid's compressibility is also investigated and discussed.

2. Experiments

2.1. Measurement details

The microcantilever used in this work is shown in Fig. 1, the inset shows the resonator chip mounted on a printed circuit board. A comprehensive description of the fabrication process can be found in Ref. [13]. The fabricated resonator, together with an electronic circuit (also depicted in Ref. [13]), is placed in a custom-built vacuum chamber, where the pressure can be evacuated to high vacuum (pressure lower than 10^{-4} mbar) or be filled with different gases under controlled pressures. Fig. 2 shows the schematic diagram of the measurement setup used to characterize the resonator behavior. The harmonic frequency response of the device is obtained by using a single sweep of the actuation frequency across the resonance frequency. . Five noble gases (He, Ne, Ar, Kr, and Xe) and N_2 are used to observe the resonator performance variation. The noble gases are chosen in this investigation since they have similar properties. They are all monatomic gases with gradually increasing density ρ and decreasing speed of sound C_0 under standard conditions as their orders increase in the periodic table. Ne has the highest dynamic viscosity of all gases considered; He has the lowest density and a relatively low viscosity (H_2 was not used here for

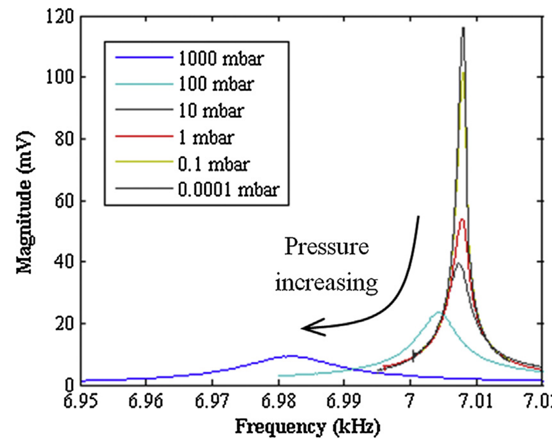

Fig. 3. Resonant measurements of the cantilever under different pressures in N_2 environment for the first flexural mode.

safety reasons). A list of these gases with their properties at 20 °C and 1000 mbar is given in Table 1.

To investigate the gas loading effect, some care must be taken to remove the intrinsic damping of the cantilever. The intrinsic damping ${Q_{int}}^{-1}$ in the experimental data was obtained by operating the cantilever in vacuum; this damping was subsequently removed from the experimental data ${Q_{meas}}^{-1}$ mathematically, leaving only the damping due to the fluid ${Q_{gas}}^{-1}$ (= ${Q_{meas}}^{-1} - {Q_{int}}^{-1}$) to be analyzed [15].

2.2. Measurement results at atmospheric pressure

The resonator was tested under controlled pressure from high vacuum to normal atmosphere. There is a slight shift in the resonance frequency but a dramatic reduction in the Q factor, as demonstrated by the example resonance curves shown in Fig. 3, which is the measurement for the resonator in N_2 environment for the first flexural mode.

In order to determine the performance dependence on the gas species, the resonator was tested in the chamber filled with different specific gases under atmospheric pressure. Fig. 4 presents the resonance curve variations for this resonator vibrating in its first flexural mode with different gases at atmospheric pressure. The

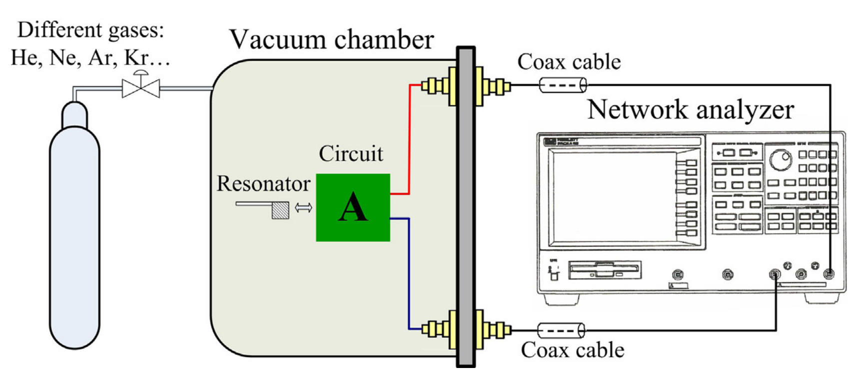

Fig. 2. Schematic diagram of the measurement setup.

Table 1
Properties of the gases at 20 °C and 1000 mbar [14].

	He	Ne	Ar	Kr	Xe	N_2
ρ [kg/m^3]	0.18	0.90	1.78	3.71	5.90	1.25
η [Pa s 10^{-6}]	19.68	29.70	22.80	25.38	23.00	17.90
C_0 [m/s]	1007	461	319	221	178	343