Current Applied Physics 16 (2016) 927–930

Contents lists available at ScienceDirect

Current Applied Physics

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

Nanomechanical fluctuations of microcantilever under turbulent mixing

Seunghwan Kim, Taejoon Kouh*

Department of Physics, Kookmin University, Seoul 136-702, South Korea

ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form
6 April 2016
Accepted 16 May 2016
Available online 19 May 2016

Keywords:
Microcantilever
Turbulent mixing
Thermomechanical fluctuations

ABSTRACT

Here, we describe the motion of a microcantilever under water, being stirred by a rotating stir bar. Specifically, the thermomechanical fluctuations of the microcantilever are monitored as a function of the rotation frequency of the stir bar and compared with those under stationary water and in air. While the measured probability density functions both in air and stationary water show well-defined Gaussian distributions in displacement, with increasing rotation frequency of the stir bar, we note the growing tail of the probability density function as well as high level of the noise power spectral density, which can be attributed to the turbulent fluctuation within the water, caused by the motion of the stir bar. The work presented demonstrates the cantilever-based mechanical probing of the fluid motion.

1. Introduction

A microcantilever, having a simple vibrating mechanical structure, has been proven to be useful in diverse technological applications. Some of examples are probing of various surface morphologies in the typical atomic force microscopy applications [1], detecting remote infrared radiation for imaging and spectroscopy [2], and rapid monitoring of the bacterial resistance to antibiotics as a novel biological sensor [3]. Also, the microcantilver is well-suited for exploring the physical processes in nature with its high spatial and temporal resolutions. Current displacement detection techniques have sensitivities down at the limit of the thermomechanical fluctuations and the small perturbation caused by the surroundings can be easily detected.

Recently, a detailed investigation of air flow through a microchannel with a microcantilever has been reported [4]. Especially, this study described the noisy transition to turbulence by watching the nanomechanical motion as a function of air flow velocity — correspondingly, Reynolds number — caused by the turbulent fluctuations in the channel along with the resulting probability density function. This clearly indicates that the microcantilever can provide a direct means of probing the flow instability by coupling the mechanical motion with the dynamics of the surrounding air. Considering recent progress and interests in microfluidics as well as the role of fluid dynamics in modern technology, this monitoring scheme based on a microcantilever would be beneficial and can be complimentary to current techniques like anemometer and particle image velocimetry.

Since the turbulent nature of fluid can be seen in any fluid flow, to make such a scheme easily employed, one need to carefully assess if it is applicable in different types of fluids other than air. This work presented intends to find out whether this mechanical probing based on a microcantilever is feasible even in highly damped water. To demonstrate this, we intentionally agitate the water with a rotating stir bar, while monitoring the vibration of an immersed microcantilever as a function of the rotation frequency. This turbulent mixing generated by a rotating stir bar is a technique routinely used in many laboratories, but its detailed mechanism is still a quite complex problem [5]. However, since we are only interested in the observation of the response of a microcantilever vibration to the fluid motion, rather than investigation of the flow itself, this works as a simple and effective way of generating strong and turbulent fluid flow around the microcantilever.

2. Experiment

At the beginning of the experiment, the dynamic property of a microcantilever, having a dimension of $l \times w \times t = 225\ \mu m \times 28\ \mu m \times 3\ \mu m$, is identified in air. Later, this cantilever is fully immersed in water, contained in a small beaker, and a stir bar with a length of 2 cm is located at the bottom of the beaker(Fig. 1 (a)). The distance between the stir bar and the

* Corresponding author.
E-mail address: tkouh@kookmin.ac.kr (T. Kouh).

http://dx.doi.org/10.1016/j.cap.2016.05.011

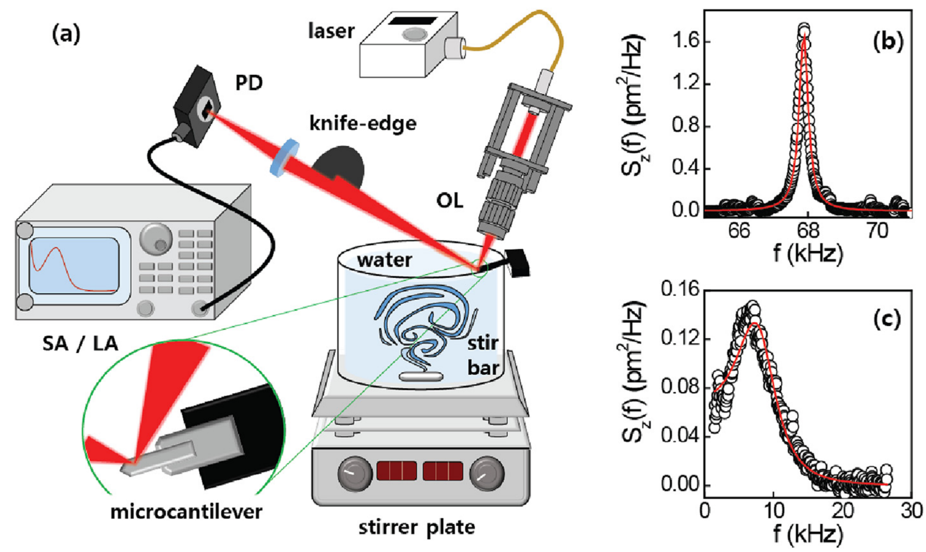

Fig. 1. (a) Schematic of the experimental set-up. A microcantilever with a dimension of $l \times w \times t = 225$ μm × 28 μm × 3 μm is immersed in water. The water-filled beaker with a stir bar is placed on a magnetic stirrer plate, which can generate the turbulent mixing of water via the rotation of the stir bar with various speed. Light, focused on a microcantilever with an objective lens(OL), is reflected onto a photodetector(PD). A knife-edge, placed in front of the photodetector, blocks a part of the incoming light and modulates the intensity of the light reaching the photodetector as the microcantilever vibrates. The optical signal is measured with spectrum analyzer(SA) and lock-in amplifier(LA). Frequency spectra of the microcantilever near the resonance in (b) air and (c) water are shown. The dotted lines are fits to the resonance line-shape.

cantilever is about 5.5 cm, ensuring no direct hitting of the cantilever by the stir bar. The beaker is placed on top of a magnetic stirrer plate, which can generate the rotation of the stir bar with various stirring speed.

To monitor the motion of the microcantilever, the optical transduction technique based on the beam deflection [6] utilizing a knife-edge is employed. In this scheme, a light reflecting from the microcantilever is refocused onto a photodiode after passing through a knife-edge, blocking a part of incoming light. The motion of the microcantilever modulates the amount of light incident on the photodiode after the knife-edge, resulting in the change in the optical signal depending on the motion of the cantilever. The optical signal is measured with a spectrum analyzer to obtain the frequency spectrum of the optical power spectral density, and the in-phase and quadrature-phase of the optical signal is measured with a dual-phase lock-in amplifier for the displacement probability distribution [7].

In the noise measurements, we notice the low-frequency noise from the detection circuitry and laser, which found to be behaving as $1/f^{1.91}$, as well as white noise. These are subtracted from the observed noise spectral density in the subsequent measurements to determine the mechanical motion of the cantilever only. Also, while taking N number of samples for the displacement probability function, to ensure the independent sampling, the sampling time is chosen to be larger than the ring-down time of the cantilever, which is determined by Q/f_r where f_r and Q are the resonance frequency and quality factor of the cantilever.

The measured optical power spectral density $S_V(f)$ of the cantilever vibration is related to the displacement spectral density $S_z(f)$ as $S_z(f) = S_V(f)/R^2$ for the given optical transduction gain of R. To convert the optical signal to the displacement of the oscillating cantilever — to determine the value of R, we turn to equipartition theorem, which states that at temperature T, the mean-square-amplitude $<z^2>$ of the thermomechanical fluctuation of a microcantilever is equal to k_BT/κ where k_B is Boltzmann's constant and κ is the stiffness of the microcantilever [8]. Considering that $\langle z^2 \rangle = \int S_z(f)df$ and κ of a cantilever, having a elastic modulus of E, is given as $Et^3w/4l^3$[9], one can determine R based on the equipartition result, which gives the value of R in this work to be about 19.1 μV/ pm. This transduction gain is large enough to observe the mechanical fluctuations of the microcantilever as well as the displacement probability distribution in water while varying the stirring speed and the attendant degree of the turbulent mixing in water.

3. Results and discussion

The displacement spectral densities of the microcantilever — originated from the thermomechanical fluctuations — both in air and water are shown in Fig. 1(b) and (c), which follows the expected resonance line-shape. In air, the cantilever shows the resonance frequency f_r of 67.9 kHz and quality factor Q of 213. In water, f_r is around 6.7 kHz and Q is about 1.2. The decrease in both f_r and Q is due to the mass-loading and increasing dissipation caused by the surrounding water [10,11]. Also, the in-phase, X and quadrature-phase, Y outputs from a dual-phase lock-in amplifier are displayed in xy-plane with $N = 5000$ data points for both in air and water. These are taken at resonance frequency with the measurement bandwidth of 250 Hz(Fig. 2(a)). As one can expect from a random-walk process, the fluctuation of the cantilever motion fills in the plane, centered around the origin. Since each data point reflects the in-phase and quadrature-phase of the cantilever displacement at the given instant, the scatter of the data points indicates how large the mechanical motion of the cantilever is. The region of xy-plane, covered by the thermal noise of the cantilever, shrinks in water for the given bandwidth compared to the wide scatter of the data points in air due to the smaller amplitude of the cantilever motion in highly dissipative water. To further see the Gaussian nature of the thermal noise, from the in-phase component of the lock-in noise measurement in Fig. 2(a), the displacement probability density function is calculated. This shows that the cantilever fluctuation follows the random Gaussian distribution as expected(Fig. 2(b) and (c)).

These spectral and statistical measurements on the microcantilever, immersed in water, are repeated while rotating the stir bar with the rotation frequency, ω_s up to $2.67\pi\ s^{-1}$, and compared to