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A measurement criterion for accurate mass detection using vibrating suspended microchannel resonators

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ABSTRACT

In this paper, a measurement criterion is presented to ensure the accuracy of mass detection using suspended microchannel resonators. The dynamic characteristics of the microchannel resonator with an added suspended particle are investigated to analyze and clarify the measurement principle for mass detection. It indicates that the vibration properties of the suspended particle have a significant effect on the measurement accuracy and the generation of systematic error. The fluid-structure interaction vibration of the particle driven by the resonator is solved by the lattice Boltzmann method integrated with the immersed boundary method. The effects of several important factors, including the particle density, fluid viscosity, and oscillating frequency, are studied and discussed. The results demonstrate that the Reynolds number and the density ratio are the two crucial parameters which affect the measurement accuracy and error generation. As the Reynolds number or the density ratio increases, the measurement precision degrades. Moreover, once the Reynolds number decreases to a critical value, the systematic error of mass detection reduces to zero. The measurement criterion can be taken as the guide to accurately detect the mass of suspended particle in the resonator.

1. Introductions

Great progress has been made to the mechanical resonators which can detect the mass of single molecules and nanoparticles [1]. The resonators are able to measure the mass as small as 10^{-21} kg [2,3] when operated in vacuum, which is benefited from the quite small effective mass and high quality factors. When mechanical resonators are employed to weigh single cells, viruses, protein aggregates, the resonators are usually needed to be operated in solution. In the aqueous environment, the resonators are subjected to viscous force, which can both increase the effective mass and severely decrease the quality factors (from about 1000 to 10,000 in vacuum to only 1–10 in fluid). Consequently, precision measurement of mass in the fluid is very challenging.

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To precisely measure the mass of particles in aqueous environments, Burg et al. [4] developed an ingenious device which constrained the fluid into the microchannel embedded in the resonator itself, known as suspended microchannel resonators (SMR). When the particle flows through the microchannel, the resonance frequency of the suspended microchannel resonator is varied, from which the buoyant mass (the mass of the particle minus the mass of the fluid it displaces) can be determined. Suspended microchannel resonators can be performed in vacuum and a high quality factor up to about 15,000 can be obtained. Using this device, Burg et al. [4] measured the nanoparticle in fluid with sub-femtogram resolution (1 Hz bandwidth). After the pioneering work, a number of researchers paid attention to suspended microchannel resonators [5–11]. Some investigators made efforts to improve the mass resolution. Lee et al. [1] decreased the size of microcantilever and embedded a channel, which was 2 μm wide and 700 nm tall, into the microcantilever. The resonator was able to measure the mass of particles in the aqueous environment with a resolution of 27 attograms in a 1 kHz bandwidth. Olcum et al. [6] further enhanced the mass resolution by increasing the resonance frequency, reducing the mass of microcantilever, and increasing the oscillation amplitude. Through the approaches, the mass sensitivity was increased and the frequency noise was reduced. Consequently, the mass resolution was improved to 0.85 attograms in a 1 kHz bandwidth. Modena et al. [12] introduced the correlation analysis to process the time-domain signal of suspended microchannel resonators and hence the dynamic range was extended by over five orders of magnitude. Using the method, the mass of polystyrene particles was detected with 300 zg resolution.

In addition to improving the mass resolution, some researchers focused on applying suspended microchannel resonators in different research areas and extending the functionality. Folzer et al. [13] firstly reported the direct measurement of the density of protein particles (0.2–5 μm in size) by using the suspended microchannel resonator. Grover et al. [14] developed a tool for weighing single cells using suspended microchannel resonators. The buoyant mass of cells in two fluids with different known densities was firstly measured, and then the density was calculated according to Archimedes' method. Bryan et al. [15] expanded Grover's method [14] by introducing the dual suspended microchannel resonators, which were two resonators connected by a serpentine fluidic channel. Using dual suspended microchannel resonators, the physical properties of two well-known cancer cell lines were compared. Olcum et al. [16] developed a general platform which independently and simultaneously actuated multiple modes of suspended microchannel resonators. The platform was employed for detecting nanoparticles flowing through the embedded channel and the results shown that by using four resonant modes, the individual position and mass of nanoparticles were determined with an accuracy near 150 nm and 40 attograms. Cermak et al. [17] presented an SMR-based approach for measuring growth rates of many individual cells with high throughput growth-rate. An array of suspended microchannel resonators was connected in series and separated by 'delay' channels, which provided cells enough time for growing as they flowed between resonators. The results demonstrated that the serial SMR array was able to precisely measure single-cell mass growth rates for up to 60 mammalian or 150 bacterial cells per hour.

The dynamic behaviors of the microcantilever underlie the applications of suspended microchannel resonators. Understanding the effect of the particle on the frequency shift of resonator is fundamental to the mass measurement. Sarid et al. [18] given the relation between the added mass and the variation of frequency, which was used by Burg et al. [4] for mass sensing. Dohn et al. [19] developed an analytical expression which related the frequency variation of a cantilever to both the mass and position of a particle attached on the cantilever. The expression was employed by Olcum et al. [16] to simultaneously determine the position and mass of particles flowing through the suspended microchannel resonator. It is noted that these expressions [18,19] were developed for the particle that was attached to the microcantilever, which can be called as attached particles. And the particles detected by microchannel resonators were suspended [4,14,15] in the fluid but not attached to the resonator. However, the relations of attached particles were usually directly used for detecting the mass of suspended particles. And to our knowledge, there was little research work focusing on whether this treatment affected the measurement accuracy or not. In this paper, the effect of the suspended particle on the frequency shift is analyzed and clarified by analyzing the dynamic model of the microchannel resonator. The vibration behaviors of the suspended particle are found to play a key role in the measurement accuracy and generation of systematic errors. Using the lattice Boltzmann method (LBM) integrated with the immersed boundary method (IBM), the influences of various factors on the vibration are investigated and discussed. According to the results and discussions, a criterion for accurate mass detection using suspended microchannel resonators is presented.

The paper is outlined as following. In Section 2, the dynamic model of the suspended microchannel resonator with an added suspended particle is studied. In Section 3, the problem is solved using the LBM-IBM method. In Section 4, the effects of various factors on the accuracy and systematic error generation are investigated and analyzed. The criterion for accurate mass detection using suspended microchannel resonators is presented and discussed. In Section 5, some conclusions are drawn.

2. Principle of mass measurement

The schematic of the suspended microchannel resonator is illustrated in Fig. 1, and it can be modeled as a microbeam containing internal fluid [20]. When the suspended microchannel resonator is used for mass detecting, the flow velocity is $\sim$mm/s and the displacement of the particle along the length direction per cycle is $\sim 10^{-2}$ μm [1,16], which is much lower than the length of the microcantilever. As a result, the flow velocity can be neglected.