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Application of resonant steel tuning forks with circular and rectangular cross sections for precise mass density and viscosity measurements☆

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ABSTRACT

The feasibility of using commercially available steel tuning forks for viscosity and mass density sensing is investigated. For this task, the tuning forks are electromagnetically driven and read out to record their frequency responses containing the fundamental resonant mode upon immersion in a sample liquid. Evaluated resonance frequencies and quality factors are then related to the liquids' mass density and viscosity. The used electromagnetic actuation and readout principle allows that only the tuning fork which is placed in the center of a glass tube gets wetted with the liquid to be examined. All excitation and read out related structures and electronics are placed outside the glass tube and thus, are not affected or influenced by the liquid. A generalized model relating evaluated quality factors and resonance frequencies to viscosity and mass density is used to describe the tuning forks' sensitivities and furthermore to estimate required stabilities of apparent quality factors and resonance frequencies to achieve measurement accuracies similar to those of laboratory instruments. It is shown that relative accuracies in the order of 1% in viscosity and 0.1 mg/cm^3 in mass density are achievable.

1. Introduction

Lately, we examined the applicability of mechanical resonators for sensing a liquid's (complex) viscosity and mass density, see [1]. A very promising approach for this task is the use of electrodynamically driven and read out mechanical oscillators. The investigated principles featuring fundamental resonance frequencies in the range from some hundreds of hertz to several kilohertz include, amongst others, oscillating membranes [2,3], in-plane oscillating platelets [4,5], straight wires [6] and U-shaped wires [7,8]. Similar miniaturized devices are silicon cantilevers [9,10], quartz crystal tuning forks [11], doubly clamped silicon beams [12] and vibrating diaphragms [13] just to name a few examples of the relatively large variety of principles reported in literature.

The resonant principles mentioned above are all potential candidates for mass density and viscosity sensors. In some cases they were especially designed for specific applications, such as, e.g., the use of miniaturized devices for liquids where only tiny amounts of sample volumes are available [14]. As an alternative to these devices usually aiming at low viscosity measurements and furthermore serving as reference devices, conventional steel tuning forks showing a fundamental resonance frequency at nominally 440 Hz have been investigated in this contribution. A first investigation of such tuning fork based setups has already been presented in [15]. The motivation for such steel tuning fork setups is based on several arguments. First, due to the momentum balanced motion in the fundamental mode, the resonant behavior of tuning forks is less sensitive to clamping issues as it is the case e.g. for singly or doubly clamped beams and membranes. Second, the relatively large and solid structure is less prone to deteriorations, such as not perfectly cleaned surfaces, air bubbles, etc. Third, in comparison to doubly clamped structures in general, the cross sensitivity of their resonance frequency to temperature is small. Such cross sensitivities of the resonance frequency to temperature can be characterized, determined and modeled on the one hand but on the other hand, they limit the sensor's accuracy and thus, should be kept as low as possible.

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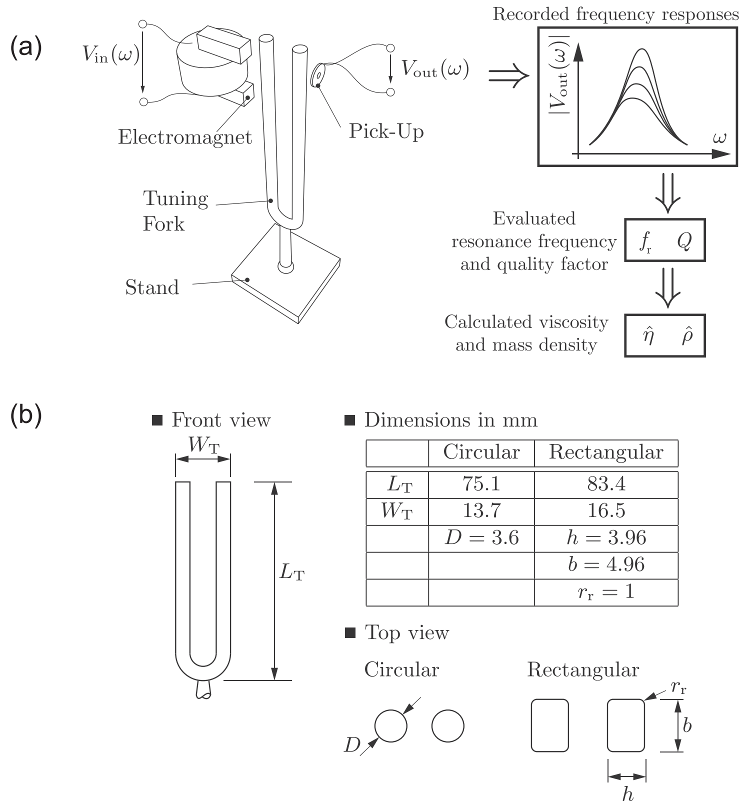

Fig. 1. Sensor principle: (a) A ferromagnetic steel tuning fork is actuated and read out with an electromagnet and an electromagnetic pick-up, respectively. Frequency responses are recorded for the completely immersed tuning fork and evaluated resonance frequencies and quality factors are related to the sample liquid's viscosity and mass density. (b) In the table above, the geometrical dimensions of the circular and rectangular tuning fork are given.

In this contribution, the basic setup for ferromagnetic tuning forks used for viscosity and mass density sensing is explained. Furthermore, measurements showing the response to viscosity and mass density for circular and rectangular cross-sectioned tuning forks are presented. The sensitivities of both tuning forks are discussed in detail and required stabilities for the resonance frequency and quality factor to achieve measurement accuracies of 1% for viscosity and 1 mg/cm^3 for mass density are estimated. It is furthermore shown, that with the investigated steel tuning forks accuracies in the order of 1% in viscosity and 0.1 mg/cm^3 in mass density are achievable.

2. Measurement setup

Fig. 1 shows a basic sketch of the setup for viscosity and mass density measurements using commercially available tuning forks with circular and rectangular cross sections. The measurement procedure is depicted in Fig. 1(a) and the geometries of the used steel tuning forks, both resonating at nominally 440 Hz in air in their fundamental mode are given in Fig. 1(b). Fig. 2 shows a photograph of the circular tuning fork setup.

The steel tuning forks were welded to a solid stainless steel stand and put into a glass tube (not depicted in Fig. 1(a)) which was sealed at both sides. To avoid corrosion, the tuning forks were gold-coated by electro-plating. An electromagnet, used for excitation, is placed (outside of the tube) close to the end of one of the ferromagnetic tuning fork's prongs. At the end of the opposed prong, an electrodynamic pick-up is placed, consisting of a permanent magnet in the center of a copper coil. A sinusoidal Voltage $V_{in} = \hat{V}_{in}\sin(\omega t) + V_{in,offs}$ with a DC offset $V_{in,offs} \geq \hat{V}_{in}/2$ is used as input signal, exciting harmonic oscillations of the tuning fork (ω is the angular frequency and t is the time). These oscillations effect an induced voltage in the pick-up serving as the read out signal. By sweeping the excitation current's frequency (containing the frequency of a resonant mode), the frequency response of the tuning fork is recorded.

The measured frequency response $V_{out}(\omega)$ is composed of three effects. First, a motion-induced voltage V_M in the pick-up coil resulting from the movement of the tuning fork's ferromagnetic prong. This voltage is proportional to the prong's velocity. The second measured signal component is an induced offset voltage V_{offs} due

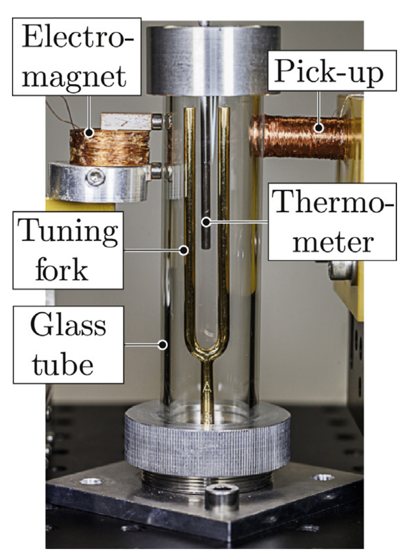

Fig. 2. Photograph of the measurement setup with a gold coated circular cross-sectioned tuning fork.