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Resonant Steel Tuning Forks for Precise Inline Viscosity and Mass Density Measurements in Harsh Environments

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Abstract

The principle of using steel tuning forks for viscosity and mass density measurements is investigated. From recorded frequency responses of fully immersed tuning forks, resonance frequencies and quality factors are evaluated and related to the liquids mass densities and viscosities. The benefit of these resonators is their mechanical rigidity which allows the application in harsh environments and mechanical cleaning processes without detuning or damaging the device. The setup was particularly devised that only the resonator itself but no excitation or read-out mechanisms get wetted by the sample liquid. The results obtained with a circular cross-sectioned tuning fork in different liquids are shown and discussed.

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Keywords: Tuning fork, viscosity, mass density;

1. Introduction

In the past, the applicability of mechanical resonators for sensing a liquid's (complex) viscosity and mass density was investigated, see e.g., [1]. A very promising approach for this task is the usage of electrodynamically driven and read-out mechanical oscillators. The investigated principles which were particularly designed to show their fundamental resonance frequency in the range from some hundreds of hertz to several kilohertz included, amongst others, oscillating membranes [2], [3], in-plane oscillating platelets [4], [5] as well as doubly clamped resonators. Theses sensors, showed significant cross sensitivities of their resonance frequency to temperature see e.g., [6] which limits the sensors accuracy and thus, should be kept as low as possible. In [7], a miniaturized quartz tuning fork was presented for viscosity and mass density measurements yielding a repeatability of better than 1 %. However, these quartz tuning forks are very delicate and thus might be easily damaged during cleaning or the regular measurement process. As an alternative to the aforementioned devices and to achieve improvements of low cross-sensitivity to temperature and mechanical rigidity, steel tuning forks showing their fundamental resonance frequency at nominally 440 Hz in air were investigated for viscosity and mass density measurement application. In this contribution, the setup for ferromagnetic tuning forks used for viscosity and mass density sensing is

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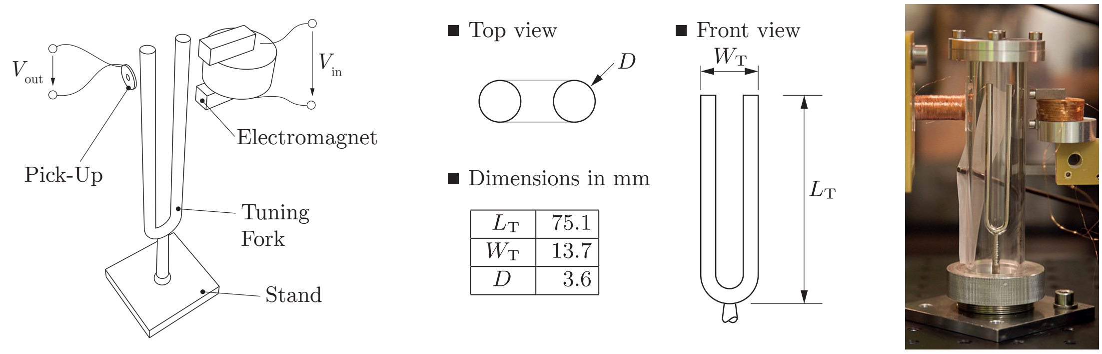

(a) Principle (b) Geometry (c) Photograph

Figure 1: a) Principle sketch of the tuning fork viscosity and mass density sensor, b) geometrical dimensions of the used steel tuning fork, c) photograph of the setup. The glass tube containing the sample liquid (visible in the photograph) is not depicted in the principle sketch.

outlined. Furthermore, measurements showing the response to viscosity and mass density for a circular cross-sectioned tuning fork are presented and achievable accuracies are estimated.

2. Measurement Setup

The principle of the measurement setup using a commercially available steel tuning fork is depicted in Fig. 1(a). The geometrical dimensions are given in Fig. 1(b) and Fig. 1(c) shows a photograph of the setup.

An electromagnet, used for excitation, is placed close to the end of the ferromagnetic tuning fork which is welded to a solid stainless steel stand. At the end of the second prong, an electrodynamic pick-up is placed, consisting of a permanent magnet in the middle of a copper coil. A sinusoidal Voltage $V_{\text{in}} = \hat{V}_{in} \sin(\omega\, t) + V_{\text{in,offs}}$ with a DC offset $V_{\text{in,offs}} \geq \hat{V}_{in}/2$ is used as input signal, exciting harmonic oscillations of the tuning fork. These oscillations induce a voltage in the pick-up, serving as read-out signal. By sweeping the excitation current's frequency (containing the frequency of the fundamental mode), the frequency response of the tuning fork is recorded.

For investigating the effect of the liquid's viscosity and mass density on the resonant behavior, i.e., resonance frequency and damping factor (which we define as the inverse of the quality factor), the tuning fork is completely immersed into the sample liquid. As a simple rule, higher viscosities yield higher damping and higher mass densities yield lower resonance frequencies. However, as shown in Sec. 3, viscosity and mass density also have a weak but non-negligible influence on resonance frequency and damping, respectively.

3. Measurements

3.1. Viscosity measurements

The response to viscosity was investigated by recording both tuning forks' frequency responses in five acetone-isopropanol solutions covering a viscosity range of 0.2 mPa·s to 2 mPa·s for mass densities of roughly 0.78 g/cm^3. After mixing, the viscosity and mass density of these solutions were measured with an Anton Paar SVM 3000 at 25 °C. The obtained values (as well as the ratio of mass isopropanol and acetone m_{I} and m_{A}) are given in Table 1. In every liquid, 100 measurements were performed.

3.2. Mass density measurements

For investigating the response to mass density, five solutions using acetone, isopropanol, ethanol, DI-water and glycerol were prepared. The liquids were mixed to obtain almost constant viscosities of 1 mPa·s but mass densities between 0.78 g/cm^3 and 1 g/cm^3. The values for viscosity and mass density of these solutions measured with a SVM 3000 at 25°C are given in Table 1.

Figure 2 shows recorded frequency responses obtained with the viscosity series liquids and the mass density liquids. Associated evaluated damping factors and resonance frequencies over viscosity and mass density respectively, are shown on the right hand side. The derivation of the model for $D = 1/Q$ (where Q is the quality factor) and resonance frequency f_{r} given in Fig. 2 is explained in [8].

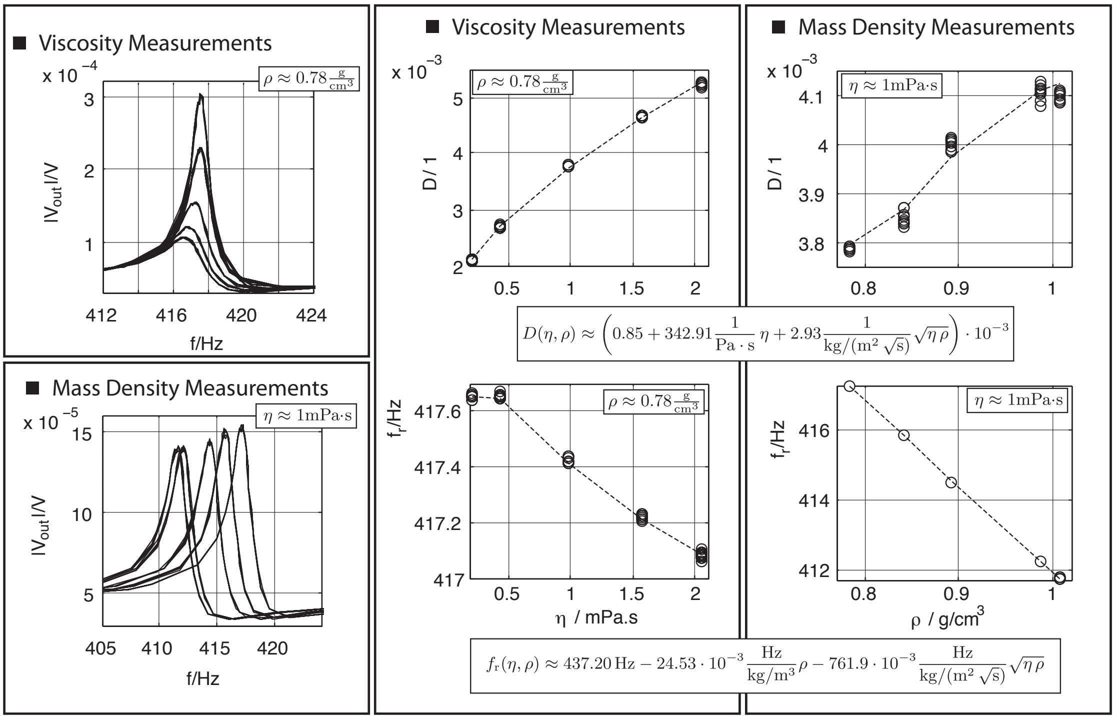

Figure 2: Measured and modeled results: Two sets of liquid series have been used to determine the response to viscosity and mass density. The viscosity series consist of liquids with viscosities of 0.2 to 2 mPa·s but almost constant mass densities of 0.78 g/cm^3. The mass density series features mass densities in a range of 0.78 to 1.0 g/cm^3 for an almost constant viscosity of 1 mPa·s. On the left hand side, the frequency responses are shown. On the right hand side evaluated damping factors (which is the inverse of the quality factor, i.e., $D = 1/Q$) and resonance frequencies are depicted in comparison with modeled results for both cases of viscosity and mass density series.

3.3. Data interpretation

Clearly, higher viscosities yield higher damping and lower resonance frequencies. The evaluation of the resonance frequency over viscosity, see Fig. 2, shows (almost) equal resonance frequencies for the first and second liquid, whereas one would suppose a clearly lower resonance frequency as it is the case for the three following liquids. This behavior can be explained, by the fact that the mass density of the second liquid is about 5.1 mg/cm^3 lower than of the first liquid, which shifts the resonance frequency upwards. (The first liquid is acetone and the second is a solution of 51 % mass isopropanol m_I and mass aceteone m_A.)

3.4. Estimation of resolution

To investigate the accuracy and the resolution of this viscosity and mass density measurement principle, the dissolving of rubber in ethanol was recorded during 150 hours, see Fig. 3. There, the change of the liquid's viscosity and mass density was 0.05 mPas (i.e. 5.3 %) and 0.0039 g/cm^3 (i.e. 0.5 %) respectively, which can be clearly detected. For comparison, the high

Viscosity Series T = 25°C		
$\frac{m_\mathrm{I}}{m_\mathrm{A}+m_\mathrm{I}}$ / %	η/(mPa·s)	ρ/(g/cm^3)
0	0.2069	0.7841
51	0.4334	0.7790
83	0.9803	0.7793
95	1.5764	0.7803
100	2.0543	0.7804

Density Series T = 25°C	
η/(mPa·s)	ρ/(g/cm^3)
1.0056	0.7849
0.9936	0.8411
1.0099	0.8931
1.0056	0.9870
0.9979	1.0073

Table 1: Left: Acetone-isopropanol solutions for viscosity measurements. Right: Solutions for mass density measurements.

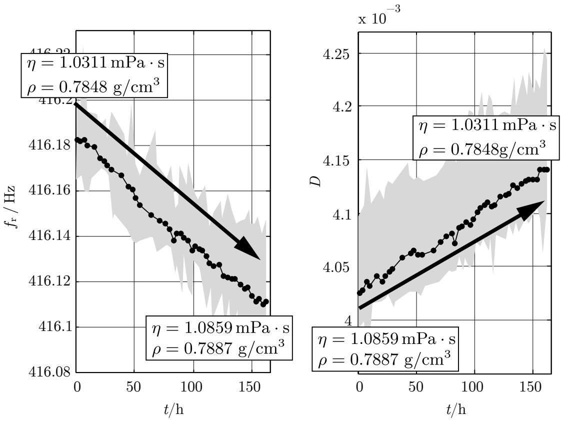

Figure 3: Investigation of the tuning fork sensor's resolution and accuracy: Resonance frequency and quality factor were recorded during 150 hours while rubber was dissolved in ethanol. The measurement was performed in a climate chamber, controlling the liquid's temperature at 25 °C. The values for viscosity and mass density evaluated before and after the long term measurement with an Anton Paar SVM 3000 at 25 °C are given in the figure above. The change of viscosity and mass density was 0.05 mPa·s (i.e. 5.3 %) and 0.0039 g/cm^3 (i.e. 0.5 %) respectively.

precision laboratory instrument Anton Paar SVM 3000 features a reproducibility of 0.35 % in viscosity and 0.0005 g/cm^3 for mass density and a repeatability of 0.1 % and 0.0002 g/cm^3, respectively. If an appropriate data analysis allows a discretization of the slopes depicted in Fig. 3 in ten steps, similar accuracies as they are achieved with high precision laboratory instruments will be obtainable with such tuning fork-based sensors.

4. Conclusion and Outlook

The usage of a steel tuning fork for viscosity and mass density measurements showed to be very promising for inline measurements and achieving good accuracies.

Regarding future work, an investigation of tuning forks with cross-sections other than circular (e.g. rectangular) will be performed and the differences in sensitivities to viscosity and mass density will be investigated. Furthermore, the maximum measurable viscosity range and cross-sensitivities to temperature have to be examined.

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