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Electromagnetically driven torsional resonators for viscosity and mass density sensing applications[☆]

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ABSTRACT

In this contribution a conceptual study for torsional oscillators, which are electromagnetically driven and read out, is presented. The aim is to experimentally investigate the basic feasibility of a torsional resonator with application to viscosity and mass density sensing in liquids. Such a device is particularly interesting as cylindrical, torsional resonators for fluid sensing applications are hardly reported but unlike many other devices, yield pure shear wave excitation in the liquid. The design of first conceptual demonstrators for measurements in air as well as in liquids and their benefits and disadvantages is discussed in detail. A closed form as well as a reduced order model and measurement results obtained with first demonstrators are presented.

1. Introduction

Recently, we investigated various resonant sensors for liquid viscosity and mass density, see e.g., [1], which were particularly designed to be operated in the low kilohertz range. Amongst these devices, in-plane oscillating platelets, emitting mainly shear waves into the sample liquids, were investigated e.g., in [2,3] where millimeter sized metal platelets were used. In [4,5] similar miniaturized devices have been implemented in silicon technology. Generally used shear oscillating resonators, such as shear oscillating quartz crystals [6] and the aforementioned in-plane oscillating platelets, have in common that, besides the desired shear waves, compressional waves are also radiated into the liquid. These pressure waves result e.g., from non-uniform shear displacement [7,8], the resonators' finite thicknesses, and spurious out-of-plane modes e.g. from the plate itself or of supporting beams. Potential candidates for resonators which only emit shear waves into the test fluid are cylindrical torsional oscillators. First, such pure shear wave emitting devices are of special interest from a rheological point of view, when it comes to the analysis of complex liquids such as viscoelastic liquids. For pure shear wave deformation, the liquid can be described by a complex-valued shear modulus or a complex valued viscosity, which, in general, are frequency dependent quantities [9]. With oscillatory measurements, the values obtained at a number of discrete frequencies can be used to obtain a rheological spectrum. A second merit for cylindrical, torsional resonators is that, due to their geometry, they resemble concentric cylinder rheometers. Thus, they yield comparable measurements but extend the measurable frequency range of conventional rheometers which is usually limited at approximately 100 Hz. Third, cylindrical, torsional oscillators allow experimental comparison of measurement results obtained with the above mentioned in-plane oscillating resonators, which excite spurious compressional waves. Thus, by means of such a comparison the impact of these compressional waves could be experimentally estimated.

In-plane oscillating devices, oscillating rotational disks [10] and other resonators for viscosity and mass density sensors such as cantilevers [11,12], quartz tuning forks [13] and vibrating bridges [14,15] are based on a similar operational principle. Usually, the devices' frequency responses, containing a characteristic resonant mode, are recorded upon immersion in a sample liquid. The change of evaluated resonance frequencies and quality factors are then related to the liquid's mass density and viscosity.

In this work a feasibility study for electromagnetically driven and read out torsional oscillators for operation in liquids is presented. Two concepts for actuation and readout discussed in

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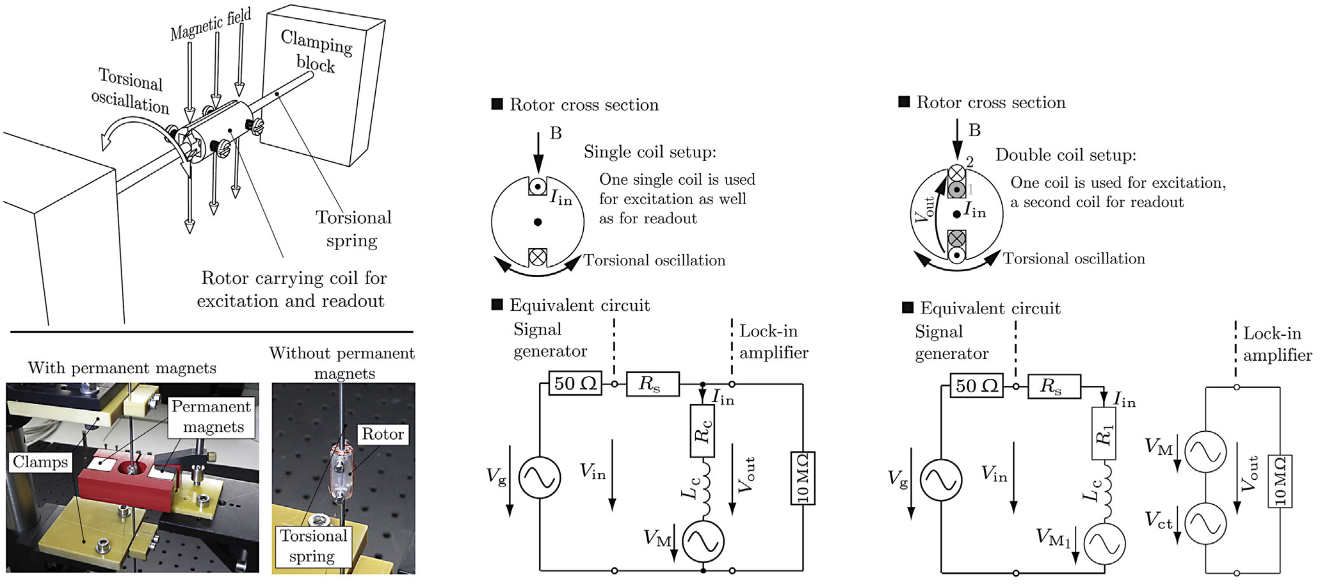

(a) Principle: sketch and photographs (b) Single coil (c) Double coil

Fig. 1. (a) Principle and photographs of first demonstrators allowing to record frequency responses in air, (b) cross section and electrical equivalent circuit of the demonstrator with a rotor carrying a single coil for excitation and readout by means of Lorentz-forces. I_{in}: input (excitation) current, B: external magnetic field, V_g: voltage of the signal generator, 50 Ω: output resistance of the signal generator, R_s: series resistance, R_c, L_c: coil's resistance and inductance, V_M: motion induced voltage, 10 MΩ: input resistance, (c) cross section and electrical equivalent circuit of the rotor carrying two coils. One coil is used for excitation, the other for read out, V_{ct}: induced voltage due to inductive crosstalk.

Section 2 were manufactured and the experimental analysis in air allowed investigating the benefits and disadvantages of both approaches. The analysis of measurements obtained with three different torsional spring diameters and various spring lengths allowed designing a demonstrator for measurements in liquids, which is explained in detail in Section 3. A closed form model for the resonator, relating the input to the output voltage, is derived in Section 4. In Section 5 evaluated results of measurements obtained with the cylindrical torsional resonator in ten different liquids are shown. Furthermore, the sensor's sensitivity and cross sensitivity to temperature are evaluated and compared to other sensor concepts.

2. Torsional resonator

2.1. Concept

The basic idea of the torsional resonator is to excite a cylinder to torsional vibrations by means of Lorentz forces acting on sinusoidal currents in a constant external magnetic field. For recording the device's frequency response, the excitation current's frequency is swept over a frequency range containing the resonant fundamental mode and simultaneously measuring the motion induced voltage on an electrical conductor, following the torsional oscillation. To implement this idea, a rotor (bobbin) is mounted on torsional springs, where two different principles were realized and compared. In the first approach, the bobbin carries one single coil which is used for both, excitation and read out, where in the second approach, two separate coils are used for these tasks.

2.2. Conceptual investigation in air

To investigate the functional principle of the electromagnetic torsional oscillator and to estimate the achievable range of resonance frequencies and signal strengths, a single coil type bobbin has been mounted and investigated on three torsional springs at various spring lengths. For this, a setup as depicted in Fig. 1(a) and (b) has been used. There, one hundred turns of a 80 μm thick copper wire were wound on a 3D printed bobbin with 8 mm in diameter and 22 mm in length, which was attached to tungsten rods with diameters of 0.58 mm, 1.6 mm and 2 mm serving as torsional springs. For each torsional spring, the same rotor was used so that only the effect of different torsional spring lengths and diameters could be examined. For attaching, the rotor was affixed with screws to the torsional springs, which were rigidly clamped at their ends with fiber-glass blocks through which the torsional spring lengths could be adjusted. The bobbin was placed in a magnetic field (denoted with B) provided by neodymium permanent magnets and set to torsional oscillations by means of Lorentz forces on sinusoidal currents (I_{in}) in the coil which was connected to a signal generator (V_g and 50 Ω output resistance) and a series resistance $R_s = 100\,\Omega$ which was used to limit the excitation current, to prevent from non-linear deflections. By sweeping the excitation current's frequency, the oscillator's frequency response can be recorded. In this case, for the sake of straight forward manufacturing, the coil's ends of the 80 μm thick copper wire were kept long enough for direct connection with the excitation and readout electronics. However, for a stable resonator, this wiring approach is not adequate. In the demonstrator used for measurements in liquids which will be presented in Section 3 this drawback has been overcome by connecting the coil's ends to the torsional springs for electrical connection of the resonator.

Fig. 2 shows the results of recorded frequency responses and evaluated resonance frequencies in air for tungsten rods with diameters of 0.58 mm and 1.6 mm for various spring lengths in comparison with theoretical results also presented in [16]. These results proved the basic feasibility of the concept and allowed designing a torsional resonator in the desired frequency range.

2.3. Single versus double coil setup

The benefits and disadvantages of using single or double coil setups were experimentally investigated. The cross sections of the rotors as well as the electrical equivalent circuits for both cases are depicted in Fig. 1(c) and (d). For the first case, a single coil with