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PMN-PT based smart sensing system for viscosity and density measurement

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ABSTRACT

This paper presents a smart sensing system for viscosity and density measurement of viscous fluids. The proposed system is based on the vibrational properties of a cantilever probe bonded with newly developed piezoelectric materials–Lead Magnesium Niobate/Lead Titanate (PMN-PT) transducer, which has a piezoelectric charge constant (d33) more than 3 times larger than that of traditional piezoelectric material Lead zirconate titanate (PZT). The proposed system utilizes a PMN-PT single crystal for actuation and laser vibrometer for vibration detection. Using the PMN-PT transducer, the measured viscosity and density of fluids were extracted by analyzing the vibrational properties of the smart probe. Finite element analysis was conducted with COMSOL Multiphysics for theoretical calculation and lab tests were carried out to verify and evaluate the simulation results. This smart sensing system can be applied to in-field, *in situ* and real-time monitoring of viscous fluids, such as blood, engine oil and early-age concrete.

1. Introduction

In fluid mechanics and engineering, viscosity plays an extremely important role in understanding and determining a fluid's characteristics and performance, especially in viscous fluid engineering such as petroleum pipelines, the food industry and automotive industry. Therefore, the topic of real-time monitoring of viscosity variation is considered by researchers to be one of the key factors to improve feedback control strategy and entire hydraulic performance. Researchers have made efforts to develop effective systems/approaches of real-time viscosity monitoring. Kong et al. [1] proposed an active sensing system that employs a pair of sandwich structure PZT patches as an actuator and sensor, and monitoring was implemented by analyzing the change of transferred electrical signals. Franco et al. [2] conducted experiments to aluminum and applied shear-wave coefficient to monitor the very early concrete viscosity change along with a novel signal processing technique which is mainly focused on the calculation of reflection coefficient magnitude in frequency band. Lu et al. [3] developed out a new method that involves the application of embedded piezoelectric sensors so that monitoring can be determined by analyzing the velocity curves. Wilkie-Chancelie et al. [4] designed an innovative sensor that is contacted to the viscous material and employs a reflected Lamb wave at the interface as the index to indicate the viscosity change of the material.

Piezoelectric-based sensors are considered adaptive for viscosity monitoring due to its quick-response, high-accuracy, and low-maintenance needs. Wilkie-Chancellier et al. [4] used a piezoelectric plate as the sensor and applied guided wave (Lamb wave) to monitor the mechanical impedance and then obtain the viscosity of the tested material. This method was found to be valid only when the tested material is a weak fluid, that is, it should have Newtonian properties. However, most viscous fluids are not that "weak" and their properties change with working condition and time, so this method is not adaptive for *in situ* monitoring. In addition, ultrasound propagation in viscous fluids is too complicated to be analyzed. Ultrasound will diffuse, dissipate, and scatter at boundaries between different phases and generate lots of noises.

In the authors' previous work, a series of experiments were conducted to verify the effectiveness of the prototype of a PZN-PT-based viscosity sensor for viscosity monitoring at elevated temperatures. Results show that the viscosity is an expression of the vibrational velocity of the sensing probe [5]. In this paper, a PMN-PT based viscosity sensor is designed and experimentally tested at room temperature and advanced finite element analysis is carried out for theoretical calculation of both viscosity and density measurement.

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2. PMN-PT single crystal based smart probe

2.1. PMN-PT single crystal

The single crystals of lead magnesium niobate-lead titanate solid solution, $[Pb(Mg_{1/3}Nb_{2/3})O_3]_{(1-x)}$ - $[PbTiO3]_x$ (PMN-PT), are a new generation of piezoelectric materials. The new material was formulated to exhibit very large electromechanical coupling coefficients, high piezoelectric coefficients, high dielectric constants, and low dielectric losses that results in improving bandwidth, sensitivity, and source level in applications [6]. Comparing to the traditional PZT material (i.e. PZT-4), PMN-PT has a higher electromechanical coefficient as well as a better Q factor which provides a narrow bandwidth frequencies and avoid noises [7].

Single crystal PMN-PT also has exceptional properties and is poised to revolutionize applications from medical ultrasound to adaptive optics and energy harvesting. The crystal exhibits five times of the strain energy density and significantly higher electromechanical coupling than conventional piezo-ceramics [8].

Fig. 1 shows the picture of PMN-PT single crystal plate resonator and Table 1 lists the main properties [9]. In comparison to other piezoelectric materials, PMN-PT has a larger coupling coefficient around $0.87 \sim 0.94$ which will provide better piezoelectric effect than other piezoelectric materials.

Table 1
Major properties of PMN-PT single crystals.

Properties	PMN-PT-A (PT = 0.27–0.30) for large signal	PMN-PT-B (PT = 0.30–0.33) for small signal
K_{33}^T @ 20 C	4500–5500	5500–6500
d_{33}^T (pC/N)	1400–2000	2000–3500
Coupling coefficient k_{33}	0.87–0.90	0.90–0.94
Y_{33}^E (GPa)	20–25	16–20
E_c (V/mm)	300	250
tanδ (1 kHz, 20 °C)	<0.005	<0.008
Depolarization temperature (°C)	>90	>75
Thermal conductivity (W/cm K)	0.0026	0.0025
Thermal expansion coefficient 10^{-6}/°C (20–70 °C)	9.5	>10

2.2. PMN-PT based smart viscosity probe

The dimension and the schematic representation of the smart probe is given in Fig. 2. A PMN-PT single crystal patch resonator was bonded on the aluminum cantilever with permanent nonconductive glue. Thickness mode (d_{33}) of the PMN-PT piezo material is applied as an actuation to excite an effective transverse mode when the free end of the cantilever immersed into the viscous fluid.

3. Finite element modeling

When cantilever immersed into the viscous fluid, its resonant frequency and vibrational velocity are changed as a part of damping effects. Generally, the resonant frequency are affected by Eq. (1) [10],

$$\omega_{fluid} = \frac{\omega_{air}}{\sqrt{1 + \frac{\pi}{4}\frac{b}{h}\frac{\rho_{fluid}}{\rho_{beam}}\tau}} \quad (1)$$

where b is the width of the cantilever, h is the length of the cantilever and τ is the correction factor while the peak-to-peak velocity is an expression of the viscosity, which is in terms of loss factor that can be extracted by logarithmic decrement method. However, different from the typical case, by which the entire cantilever is immersed in the viscous fluid, the proposed approach in this paper in more complex, so a FEM is carried out to provide a numerical simulation.

Fig. 3 shows the 3D finite element modeling with COMSOL Multiphysics. The problem is set up as a coupled acoustic-structure-electrostatics eigenvalue analysis. In this study, there are three physics in this study, Solid Mechanics, Electrostatics and Acoustic-Structure. The cantilever is involved in the Solid Mechanics physics. A fixed constraint is added to one end of the cantilever while the other end is immersed in the fluid and free to vibrate. The PMN-PT single crystal is subject to a Multiphysics-piezoelectric effect, which includes both Solid Mechanics and Electrostatics. Excitation voltage is applied to the top surface of the PMN-PT single crystal while the bottom surface is set as ground. Hard sound boundaries is setup as default in COMSOL Multiphysics to the viscous fluid. Frequency domain analysis is also added to the study. FEA analysis is conducted with 3 different types of engine oil and Table 2 gives the properties of them. Fig. 4 shows the results of the frequency domain analysis in COMSOL Multiphysics.

4. Experimental analysis

4.1. Experimental setup

The experiment is conducted with LabVIEW version 2015. The cantilever is fixed at one end while the other end is free to vibrate inside the viscous fluid. A sinusoidal wave is applied to generate a mechanical vibration (Agilent 33220A, Amplitude: 5 V, Frequency: sweeping from 10 Hz to 22 Hz with a resolution of 0.1 Hz). The peak-to-peak velocity is measured at the point that has a distance of d (=1 cm) from the free end by a laser vibrometer (Polytec

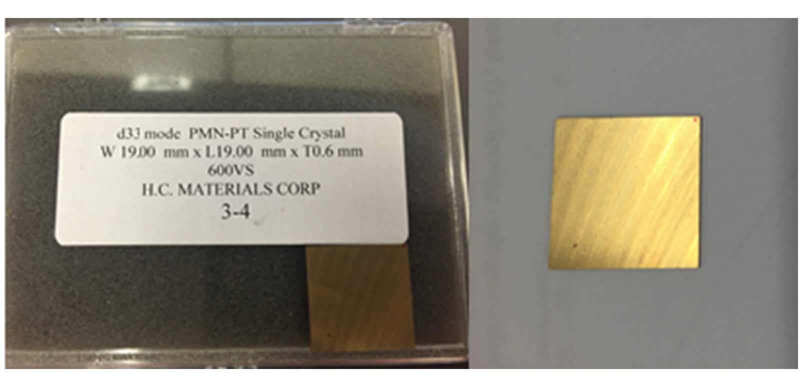

Fig. 1. PMN-PT single crystal plate resonator.