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Abstract

Three-Dimensionally Printed Resonator with Piezoelectric Actuation and Machine Learning Calibration for In-Line Density–Viscosity Sensing †

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Abstract: Three-dimensionally printed cuboid-shaped flow cells featuring a rectangular vibrating plate in one of the sides, actuated by PZT piezoelectric films, were designed, fabricated, and tested. Instead of oscillator circuits based on single resonances, we use the frequency response of the cell in a range with multiple resonances, sensitive to the liquid properties. Machine learning techniques were implemented for training and calibration with water–glycerol mixtures at different temperatures. Various materials, fabrication parameters, and post-treatment processes were investigated. The calibration errors and resolutions are compared for different devices, conditioning circuits, and machine learning algorithms. Our results demonstrate the high potential of the low-cost sensor to monitor density and viscosity in aqueous solutions.

Keywords: 3D printing; piezoelectric; resonator; machine learning; viscosity

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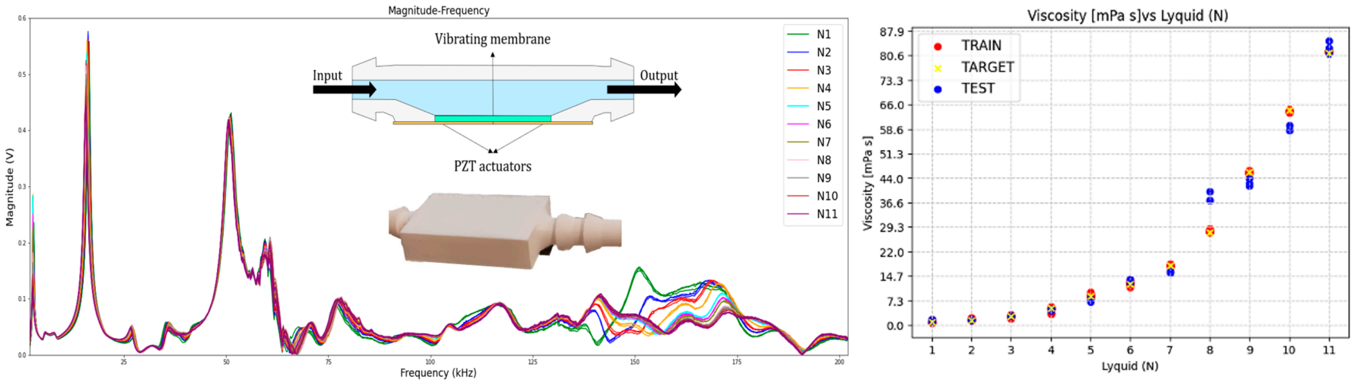
1. Introduction

The in-line monitoring of liquid properties, such as density and viscosity, is relevant to emerging low-cost and miniaturized IoT platforms in many application areas. Sensors based on piezoelectric MEMS have shown advantages compared to other technologies [1]. Alternatively, 3D-printed sensors with attached piezoelectric films have been used to monitor the liquid properties [2]. The flow cell and resonator can be combined in a compact device for flow-through monitoring in real time, featuring low-cost and rapid manufacturing compared to silicon-based MEMS devices, and with piezo actuators placed outside the liquid cell, preventing deterioration while sensing aggressive media. In this work, we explore the potential of these 3D-printed cells for sensing the density and viscosity of liquids flowing through them. A variety of simple conditioning circuits and machine learning algorithms are investigated, searching for smart and compact systems with enough accuracy and reduced cost.

2. Methods and Results

Flow cells were fabricated by stereolithography (SLA) printing. Various UV-curable polymer-based resins were compared in performance, such as ABS-like, glass reinforced Rigid 10K, and translucent Clear resins; two piezo patches were glued to the cell with an instant adhesive, and wiring and soldering of the electrical contacts were implemented outside the cell. Figure 1a shows a schematic of the assembled device and the spectra measured for a Rigid 10K cell with a vibrating membrane of $16 \times 5 \times 0.5$ mm^3 by exciting one patch with a 3.3 V sine wave and reading out the voltage generated in the second patch. Solutions of water and glycerol ranging from 0% to 85%, designated as N_i, $i \in$ [1,11], were circulated through the cells as in reference [3]. A dataset with 33 spectra was used to train a machine-learning model. Support Vector Machines (SVM), k-Nearest Neighbors (K-NN), Multi-layer Perceptrons (MLP), and Convolutional Neural Networks (CNN) algorithms were compared for the regression of the viscosity and density of liquids. The data are divided into 11 subsets, each with 3 spectra of a given N_i as a test set, and the remaining 30 as a training set, following a cross-validation strategy known as 'leave-one-out'. A pre-processing of the data was carried out, comparing the effects of different scaling techniques on the results of the models and performing a feature selection using typical techniques such as principal component analysis (PCA). Figure 1b shows one of the results obtained for the estimation of viscosity. A similar procedure was followed for the prediction of density, achieving better accuracy compared to viscosity.



(**a**) (**b**)

Figure 1. (**a**) Spectra taken with the N_i solutions with a cross-sectional scheme and a photograph of one of the fabricated cells in the inset. (**b**) Estimated viscosity of the N_i liquids with the machine learning model. Red symbols show the performance of the model in the training sets, blue symbols show the predictions on the test sets, and yellow symbols show the reference viscosity values for each solution.

The difference between the predicted and reference values gives an average of 2.4 mPa·s in the test sets (2.6% calibration error). For viscosities up to 20 mPa·s, the error is below 2%, whereas for higher viscosities, the spectra provided by the sensor are more similar and, consequently, the predictions are somewhat worse.

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