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3D-Printed Flow Cells with Piezoelectric Resonators and Machine Learning for Biofuel Characterization

Víctor Corsino[1], Víctor Ruiz-Díez[1], Andrei Braic[1], José Luis Sánchez-Rojas[1]
[1] Microsystems, Actuators and Sensors Group, INAMOL-Universidad de Castilla La-Mancha, 45004, Toledo, Spain,
Victor.Corsino@uclm.es

Summary:

Biodiesels serve as a greener alternative to conventional fossil fuels. Typically produced from vegetable oils, these fuels tend to have higher viscosity, which, if excessive, can result in reduced engine efficiency. Existing methods for analyzing these properties require expensive equipment, limiting practicality. To address these challenges, we propose multi-resonant 3D-printed sensors integrated with simple electronics and machine learning algorithms, offering a portable and cost-effective solution for precise biofuel property evaluation.

Keywords: 3D printing, resonances, machine learning, viscosity, biofuel.

Background, Motivation and Objective

Biofuels have gained popularity in recent years due to depletion of fossil fuel reserves, increasing energy demand, and the need to reduce emissions. Monitoring their physical properties is essential, as biodiesels, characterized by higher density and viscosity, can lead to injector deposits and interfere with the atomization process during combustion These issues may result in reduced engine performance and increased emissions [1,2]. Piezoelectric sensors have previously demonstrated the effectiveness to monitor diesel mixtures with lubricants [3], and there are established methods in the literature for measuring these properties in biofuels [4,5]. However, these methods often require expensive laboratory equipment and complex electronics, limiting their practical applicability. To overcome these challenges, we propose 3D-printed sensors capable of operating in multiple vibration modes, integrated into a microcontroller system equipped with deep learning algorithms for enhanced functionality.

Description of the New System

Resonators were developed using 3D-printed cells equipped with vibrating membranes activated by piezoelectric plates—one for actuation and the other for detection. The cells, fabricated in Rigid10K material, incorporated a cavity designed to connect the fluid with the vibrating membrane and facilitate liquid flow. Earlier research [6] explored similar cells, focusing on designs that resonate in a specific mode. The present work introduces a novel approach aimed at maximizing vibrational freedom to facilitate the emergence of multiple vibration modes. This was achieved by modifying membrane dimensions and geometry, incorporating pillars to increase the contact surface with the fluid and enable multiple interrogation points. Additionally, the influence of cavity height on sensing was examined to boost acoustic phenomena participation. Adjustments to plate size, geometry, and quantity were also examined to achieve a broader range of resonance peaks in the fluid. Figure 1 shows several examples of the resonators produced through this study process.

This methodology represents a significant departure from traditional research, which primarily focuses on analyzing properties through the quality factor and frequency of a single resonance. The use of advanced machine learning techniques enables comprehensive analysis across a broad spectrum of vibrations. This proves advantageous, as resonance peaks exhibit different variations depending on the fluid under examination, amplifying differentiation between liquids and providing enriched datasets for AI algorithm processing. Furthermore, this approach simplifies control electronics by incorporating a microcontroller that integrates data acquisition and processing. This results in a compact, portable, cost-effective, and highly precise device capable of monitoring the physical properties of fluids.

Results

The sensors were evaluated using two types of biofuel: pure diesel (DS0) with a viscosity of 2.35 mPa·s and density of 0.821 g/mL, and a mixture

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containing 90% diesel and 10% sunflower oil (DS10), with a viscosity of 3.011 mPa·s and a density of 0.829 g/mL. Different sensor geometries were tested by introducing the fluids sequentially without cleaning and recording spectra within the 1 kHz to 1 MHz frequency range at regular intervals to assess sensitivity and resolution. Selected results, presented in Figure 2, highlight the potential of these sensors for determining the physical properties of biofuels. The spectra were obtained using an Analog Discovery Digilent instrument, which will be replaced by a microcontroller-based system with transistorized circuits (illustrated in Figure 3) and integrated convolutional networks for direct fluid property estimation. The effectiveness of this system was previously validated using MEMS sensors [7]. Furthermore, the device will be tested with larger biofuel mixtures conforming to European regulatory limits to confirm its performance across the range of permissible viscosities.

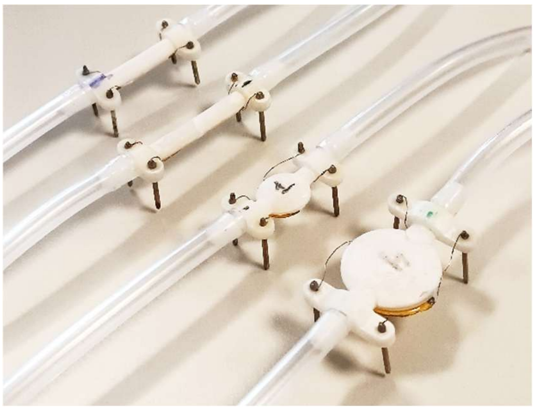

Fig. 1. Sensors with different membrane sizes and geometries.

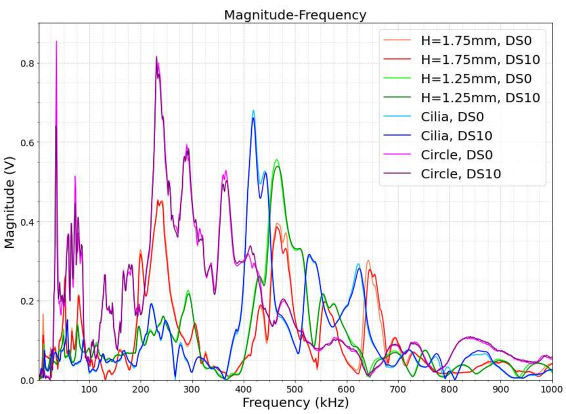

Fig. 2: Spectra for two biofuels obtained using sensors with varying cavity heights (H), membrane embeddings (Cilia), and geometries (Circle or Rectangle).

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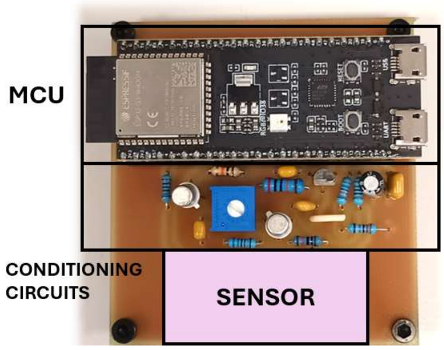

Fig. 3: Complete sensor system.

References

[1] L. Razzaq, M. Farooq, M.A. Mujtaba, F. Sher, M. Farhan, M.T. Hassan, M.E.M. Soudagar, A. E. Atabani, M.A. Kalam, M. Imran, Modeling viscosity and density of ethanol-diesel-biodiesel ternary blends for sustainable environment, *Sustainability*, 12(12), 5186 (2020); doi: 10.3390/su12125186.

[2] R. Estevez, L. Aguado-Deblas, A. Posadillo, B. Hurtado, F.M. Bautista, J.M. Hidalgo, C. Luna, J. Calero, A.A. Romero, D. Luna, Performance and emission quality assessment in a diesel engine of straight castor and sunflower vegetable oils, in diesel/gasoline/oil triple blends, *Energies*, 12(11), 2181 (2019); doi: 10.3390/en12112181.

[3] J. Toledo, T. Manzaneque, J. Hernando-García, J. Vázquez, A. Ababneh, H. Seidel, M. Lapuerta, J. L. Sánchez-Rojas, Application of quartz tuning forks and extensional microresonators for viscosity and density measurements in oil/fuel mixtures, *Microsystem technologies*, 20, 945–953 (2014); doi: 10.1007/s00542-014-2095-x.

[4] S. Goel, P.S. Venkateswaran, R. Prajesh, A. Agarwal, Rapid and automated measurement of biofuel blending using a microfluidic viscometer, *Fuel*, 139, 213-219 (2015); doi: 10.1016/j.fuel.2014.08.053.

[5] J. L. Camas-Anzueto, J. Gómez-Pérez, R. Meza-Gordillo, G. Anzueto-Sánchez, M. Pérez-Patricio, F.R. López-Estrada, M. Abud-Archila, C. Ríos-Rojas, Measurement of the viscosity of biodiesel by using an optical viscometer, *Flow measurement and instrumentation*, 54, 82-87 (2017); doi: 10.1016/j.flowmeasinst.2016.12.004.

[6] J. Toledo, V. Ruiz-Díez, J. Velasco, J. Hernando-García, J.L. Sánchez-Rojas, 3D-printed liquid cell resonator with piezoelectric actuation for in-line density-viscosity measurements, *Sensors*, 21 (22), 7654 (2021); doi: 10.3390/s21227654.

[7] V. Corsino, V. Ruiz-Díez, J. L. Sánchez-Rojas, Smart density and viscosity sensing based on edge machine learning and piezoelectric MEMS for edible oil monitoring, *Sensors and Actuators A: Physical*, 385, 116258 (2025); doi: 10.1016/j.sna.2025.116258.