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Low-cost electro-acoustic system based on ferroelectret transducer for characterizing liquids



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ABSTRACT

Several industrial applications require liquid characterization during manufacturing to ensure quality in their products. Examples of such products are those related to food and oil industries in which one of the concerns regards the different concentration of liquids in a mixture. In this context, it is presented a system based on ferroelectret transducers and low-cost technology to perform liquid analysis through acoustic measurements. The developed system is composed of three parts: a piezoelectric actuator, a medium chamber and a ferroelectret transducer (acoustic sensor). The system was assembled with a ferroelectret (with open tubular channels) housed on a cylindrical aluminum case (48 mm × 63 mm) in which a 24 dB preamplifier was mounted. The specifically designed chamber was manufactured in ABS plastic using a 3D printer and the piezoelectric actuator consisted in commercial piezoelectric ceramic which is connect to signal generator configured to generate a sinusoidal sweep between 0 Hz up to 50 kHz during 1 s. In order to characterize the device setup and validate the suitableness of the measuring system, three distinct mediums were analyzed (air, water and oil). Through the experimental tests it was identified, on time domain, distinct signatures for each medium, which were later used in a blind classification with a developed algorithm.

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1. Introduction

Liquid characterization has a great application potential in several productive and research sectors [1–6]. For instance, liquid analysis has a major influence in the food industry, especially in milk production and its derivatives, in which it is important to ensure high quality and fresh-like products with lower processes, time and costs [1]. Another example of its relevance is observed in the oil and gas extraction and petrochemical industries [2] in which precise and reproducible measurements of oil contamination are critical. These stringent requirements are monitored in order to identify environmental hazard, e.g. discharge of water contaminated with oil into the environment [2].

Depending on the application, a liquid substance can be characterized directly or indirectly, by means of its physical, chemical, optical, electrical and acoustic properties, using techniques, such as, chromatography, ultrasonic propagation and impedance measurements [5,6]. A highlighted topic in this area is the method based on the acoustic wave propagation, commonly known as

* Corresponding author. E-mail address: thamyrestamulla@usp.br (T.T.C. Palitó). the acoustic emission (AE) method. This sensitive technique employs acoustic sensors to detect acoustic waves (continuous or pulsed [7,8]) that are transferred to the medium. The propagating waves are then monitored according to their characteristics, such as attenuation and speed of propagation as a function of frequency. One of the advantages of this powerful technique is that it can be used as a non-destructive method with the possibility to be noninvasive and used in line applications [1,2,6].

The AE acoustic waves can be produced and detected by piezoelectric materials, which are increasingly popular and can be used as both actuators and sensors. Therefore, acoustic methods have being using piezoelectric sensors in many research areas, for example, in medicine for medical imaging applications [9], electrical engineering uses piezoelectric sensors for detecting and in some cases localizing partial discharges [10,11] and the water industry uses piezoelectric accelerometers for the optimization of flow rate measurement [12]. However, a reliable method requires expensive materials and technology, in this context, it is presented a low-cost electro-acoustic measuring system for characterizing liquids based on ferroelectrets, a different type of piezoelectric device and very suitable for acoustic measurements [13].







2. Design

2.1. Electro-acoustic system architecture

The electro-acoustic system developed for characterizing liquids is illustrated in Fig. 1 with a piezoelectric transducer (b), a medium chamber (c) and a ferroelectret transducer (d) in addition a function generator (a) and an oscilloscope (e) are also presented. In this system the function generator is programmed to produce a sinusoidal function (i), 10-volt peak-to-peak (V_{pp}), which drives the piezoelectric actuator causing it to transmit an acoustic signal (ii) through the medium (air, water or oil). The ferroelectret transducer, placed on the other side of the chamber, converts the acoustic signal into an electric signal (iii), which is amplified (iv) and measured by digital oscilloscope.

2.2. Piezoelectric actuator

The piezoelectric actuator is a component composed by piezoelectric ceramic disks adhered to a metal plate of brass or nickelalloy and coated with a metal layer. By driving the piezoelectric actuator with an electrical signal supplied by the external generator, it can produce sound waves with very low distortion even in high frequencies (kHz range) [14].

These buzzers are employed mainly in electronic devices – for example calculators, clocks, digital cameras and various alarms – to generate sounds. However, due to their reduced cost, these piezoelectric ceramics have been successfully used as sensors or actuators in several scientific studies with a wide range of applications [15–18]. For this study a piezoelectric actuator with a diameter of 35 mm was used to generate acoustic waves.

2.3. The ferroelectret transducer

Ferroelectrets are thin polymeric films with open or closed air cavities that are electrically charged with opposite polarities. This unique characteristic allows the porous films to behave like ferroelectric materials with the advantage of being highly flexible and easily processed [19]. The ferroelectric-like effect observed on most ferroelectrets is comparable to those obtained on piezoelectric ceramics, such as, lead zirconate titanate (PZT) and has stimulated applications.

Different types of ferroelectrets have been developed [19], here the transducer was assembled using ferroelectrets produced with fluorinated-ethylene-propylene (FEP) films and with open tubular channels. This ferroelectret was chosen due to its temperature stability (over 80 °C) and piezoelectricity around 160 pC/N [20].

PVDF (polyvinylidene fluoride) and PZT are both options for handcrafting and tests, each with advantages and drawbacks. For instance, PVDF is more flexible than PZT, however the last presents much higher piezoelectric coefficients. Ferroelectrets, particularly with open-tubular channel, are flexible as PVDF and presents piezoelectric coefficient in the same order of magnitude as PZT, with the advantage of resonance frequency control by changing its channels geometry [21].

The ferroelectret operation principles and its manufacturing process are well described in [20] and it consisted on laminating two 50 µm FEP films at 300 °C with a 100 µm polytetrafluoroethylene (PTFE) template film between them. The template was designed to create a ferroelectret with equally spaced open tubular channels (1.5 mm width and 100 μ m height). Changes in the width and height of the tubular channels of these piezoelectric sensors modify their response [21]. The films were carefully cleaned with acetone before the lamination to avoid grease or dust particles. After lamination, the template was removed from the fused FEP layers, forming a two-layer FEP structure with 10 open channels. Aluminum electrodes were evaporated on the outer layers of the structure and the electrical polling was performed applying a direct DC voltage of 3 kV for 10 s for polarization. The measurements performed by Medeiros et al. [22] on underwater applications demonstrated that this type of sensor can detect signals up to 80 kHz. Moreover, it was also demonstrated that this type of sensor presents a much better response in the direction mode [22], e.g., if the acoustic source is placed direct in front of the sensor. However, it is still possible to detect lateral sounds without significant sensitivity when compared with its orthogonal direction. The ferroelectret used on the transducer is shown in Fig. 2.

A cylindrical aluminum case (Fig. 3) was constructed to provide electrostatic shielding and electronic protection for the acoustic transducer in order to complete the transducer. In addition, this



Fig. 1. System architecture, which is composed by (a) a generator, (b) a piezoelectric actuator, (c) an acoustic chamber, (d) an acoustic transducer and (e) an oscilloscope.



Fig. 2. a) FEP ferroelectret with open tubular channel, employed as piezoelectric sensor (top view), b) Schematic drawing of a cross-section view of the open channels.



Fig. 3. (a) Exploded schematic representation of the ferroelectret transducer and respective photos from (b) front and (c) back.

aluminum case is also responsible for conditioning the metal electrodes, backing material and electronic circuit. The backing material made from nylon comprises the layer underlying the piezoelectric element and it is responsible for damping the vibration of the electromechanical sensor, which prevents reflections on the back of the active element and, consequently, avoids interfering with the receiving signal from the transducer. A four-way Mike type connector was used as a channel for powering the electronic circuit, which was performed externally by two 9 V batteries, and for the output of the electrical signal.

Inside the aluminum housing, an electronic circuit composed by a preamplifier, a high-pass filter and a differential amplifier was placed. The preamplifier stage was implemented to provide better impedance match between the piezoelectric sensor and the input of the integrated circuit INA129P that implements the differential amplifier. As showed in Fig. 4, the preamplifier consists of an arrangement around an N-type Junction Field Effect Transistor (JFET) field effect transistor BF245A, configured in selfpolarization. This circuit was designed to provide the output voltages V_0^+ and V_0^- (Fig. 4), which are two amplified versions of the input voltage V_{in} . This circuit combines a common-drain amplifier and common source amplifier with resistive source of generation. Therefore, the voltages V_0^+ and V_0^- are respectively:

$$V_0^+ = + \frac{g_m R_s}{1 + g_m R_s} V_{in}$$
(1)

$$V_0^{-} = -\frac{g_m R_d}{1 + g_m R_s} V_{in}$$
(2)

In which g_m is the transconductance of the JFET for the bias voltage $V_{BIAS} = 0V$. The variables R_d and R_s represent respectively the resistances connected into the drain and source of the JFET. Thus, the differential voltage of the preamplifier is:

$$\Delta V_{pre} = V_0^- - V_0^+ = -\frac{g_m}{1 + g_m R_s} (R_d + R_s)$$
(3)

since $R = R_s = R_d = 3.9 \text{k}\Omega$, the differential voltage at the output of the preamplifier results in:



Fig. 4. Schematic of the electronic circuit and respective blocks. In this circuit, the components are *D* (diode 1N4148), *J* (JFET BF245A), *IA* (INA129P'), $R_1 = 1M\Omega_R_2 = 100k\Omega_R_3 = 10k\Omega_R_s = R_d = 3.9k\Omega$, $R_g = 5.6k\Omega$ and C = 100 nF. Pins G_{S1} and G_{S2} of *IA* are for gain setting purposes.

$$\Delta V_{pre} = V_0^- - V_0^+ = -\frac{2g_m R}{1 + g_m R} V_{in} = \frac{7800g_m}{1 + 3900g_m} V_{in}.$$
 (4)

The measurements revealed a gain $(G_{pre} = \Delta V_{pre}/V_{in})$ of 1.6.

The high-pass filter was added after the preamplifier to eliminate the DC components of V_0^- and V_0^+ and simultaneously to filter spectral of components with low frequency, since their presence can saturate the differential amplifier that is located after the preamplifier. The high-pass filter is first-order with transfer function according to:

$$H\left(j\frac{f}{f_0}\right) = \frac{j\left(\frac{f}{f_0}\right)}{1+j\left(\frac{f}{f_0}\right)},\tag{5}$$

where $f_0 = 1/2\pi R_2 C$ is the lower cutoff frequency.

The instrumentation amplifier model INA129P serves two purposes: first, it converts the voltage ΔV_{pre}^* (the filtered version from ΔV_{pre}) from the differential form into a voltage V_{out} with single-ended form; and second, it provides an additional gain G_{IA} . This integrated circuit (IC) features low noise characteristics $(10 \text{ nV}/(\text{Hz})^{1/2})$ and a plane frequency response (constant amplification) up to 500 kHz due to the gain used (10 times the input signal). The gain G_{IA} of INA129P can be programed using an external resistor R_G [k Ω] between the terminals G_{s1} and G_{s2} and is:

$$G_{IA} = \frac{1+49.4}{R_G}$$
(6)

Therefore, $R_G = 5.6 k\Omega$ implies that $G_{IA} = 8.82$.

The electronic circuit is schematically represented in Fig. 4, where it is considered two electronic stages of amplification separated by a high-pass filter providing a final gain of approximately 24 dB, in which the preamplifier is responsible for a gain of 1.6 times (4.08 dB) and the instrumentation amplifier for a gain of 8.82 times (19.84 dB). To reduce external noise, two 9 V batteries were used on the circuit supply.

2.4. Acoustic chamber

The acoustic chamber, also described as medium chamber, with 60 mm in width, 60 mm in height and 70 mm in depth was fabricated in acrylonitrile butadiene styrene (ABS) using a 3D printer. Fig. 5a and b illustrate a CAD model with a view of both sides where the piezoelectric actuator and the ferroelectret transducer are placed. Fig. 5c shows a cross-section view of the model with an internal cavity (tube with diameter of 20 mm and length of 50 mm) and two syringes inputs, through them 20 ml of a specific liquid (water or oil) was injected.



Fig. 6. Schematic representation of the electro-acoustic measurement setup.

3. Experimental results

3.1. Measurement setup and methods

The electro-acoustic system was assembled according to the representation in Fig. 6 and the experiments were performed in three different mediums: air, water and oil, in this order. To investigate the system response on each medium, the piezoelectric ceramic was stimulated, directly, with a frequency sweep, produced in a function generator model Tektronik AFG 3022C with 10 V_{pp}, covering ranges up to 50 kHz, linearly, during a 1 s interval. The resulting acoustic wave was captured by the ferroelectret transducer and recorded in an oscilloscope (Agilent DSO-X 2002A), adjusted with a time window of 1 s (100 ms/div) and a delay of 500 ms so that the time scale is displayed in values from 0 to 1 s.

After adjustments, measurements were conducted initially in the air medium for five consecutive times. Later, to ensure reproducibility, the experiment setup was disassembled and reassembled five times and on each reassembling five new measurements were performed, providing a total amount of 25 measurements for the medium.

This procedure was also employed on water and oil measurements, however, for these procedures, the acoustic chamber was filled with 20 ml of the liquid under analysis and after conducting five consecutive measurements the liquid in the chamber was removed and the setup was disassembled to be cleaned with paper towel and alcohol. In total this procedure was performed five times, providing 25 measurements.



Fig. 5. A CAD model of the acoustic chamber: (a) view of the entrance of the piezoelectric diaphragm; (b) view of the ferroelectret transducer; (c) internal view.

The assembling and disassembling procedures were adopted not only for testing different samples of the same liquid, but also to verify the system robustness. The procedure was completed after performing measurements on the three mediums and repeating them again three times, in different days, resulting in 100 measurements for each medium.



Fig. 7. Response of the electro-acoustic measurement system to the medium: (a) air, (b) water and (c) oil.



3.2. Experimental results and discussions

Fig. 7a,b and c show samples of the acoustic signals detected by the ferroelectret transducer for air, water and oil, respectively. They are presented in the time domain for the same time window and to reduce redundant information only the third measurement of each experiment is plotted for each medium.

From the presented plots one can observe that the signals obtained in air show two regions, which are present in all measurements and they are placed at the time instants of $t_{pk,air1} = 0.08$ s and $t_{pk,air2} = 0.37$ s, while for the water medium, there is a peak at $t_{pk,water1} = 0.03$ s and a concentration at $t_{pk,water2} = 0.55$ s. For the oil, one can observe a third region that is present in all measurement, and these distinct densities are located at the time instants close to $t_{pk,oil1} = 0.03$ s, $t_{pk,oil2} = 0.29$ s and $t_{pk,oil3} = 0.53$ s.

Based on the graphs presented, it is observed that each medium presents a specific behavior/signature, which makes it easier to distinguish them visually. It is also possible to observe that for the same day of experiments, the signals remain stable. However, when different days of experiments are analyzed, a small variation in signal behavior is observed, but the areas highlighted remain practically at the same time instant. These small variations on the signal may be due to the fact that environmental conditions in laboratories are not fully controlled and because the acoustic measurement is susceptible to environmental noises.

Nevertheless, the selected locations ({ $t_{pk,air1}$, $t_{pk,air2}$ }, { $t_{pk,water1}$, $t_{pk,water2}$ }, { $t_{pk,oil1}$, $t_{pk,oil2}$, $t_{pk,oil3}$ }) were observed in all measurements and they were selected to define indicators for a feature extraction, where one could determine the medium under identification. The classification algorithm describing how these indicators were employed is further explained.

After observing a regular behavior in different mediums and singularities on each of them, a classification algorithm was developed to classify an unknown signal between air, water and oil. To develop this algorithm the most relevant regions and peaks of the mediums were considered and their amplitude averages were determined, to achieve this goal the acoustic signal was split into 10 equally spaced intervals of time and the most relevant were selected for the classification method [23]. For the air and water environments, two time intervals were analyzed: $I_{air,1} = [0, 0.1]s$ and $I_{air,2} = [0.3, 0.4]s$ and $I_{water,1} = [0, 0.1]s$ and $I_{water,2} = [0.5, 0.6]s$, respectively For the oil, three intervals were considered: $I_{oil,1} = [0, 0.1]s$, $I_{oil,2} = [0.2, 0.3]s$ and $I_{oil,3} = [0.5, 0.6]s$.

The concept behind the classification method is more evident through Fig. 8. The plots g_{air} , g_{water} and g_{oil} in Fig. 8a symbolic represent the signals acquired within the air, water and oil and their respective analyzed intervals. The graph illustrated in Fig. 8b is the bi-dimensional projection of all possible combinations of the g_{air} , g_{water} and g_{oil} indicators { $t_{pk,air1}$, $t_{pk,air2}$ }, { $t_{pk,water1}$, $t_{pk,water2}$ }, $\{t_{pk,oil1}, t_{pk,oil2}, t_{pk,oil3}\}$. For instance, all possible combinations of indicators for the signal g_{air} are composed by the set of four points $(t_{pk,air1}, t_{pk,air1}), (t_{pk,air1}, t_{pk,air2}), (t_{pk,air2}, t_{pk,air1})$ and $(t_{pk,air2}, t_{pk,air2})$. For the classification algorithm the points intercepting the 45° diagonal axis can be ignored, e.g., the points ($t_{pk,airj}$, $t_{pk,airk}$), where j = k. Therefore, it is considered only the point $(t_{pk,airj}, t_{pk,airk})$ or $(t_{pk,airk}, t_{pk,airk})$ $t_{nk,airi}$) for $j \neq k$, because one is the transpose of the other. The same applies to all the four combinations of points ($t_{pk,waterj}$, $t_{pk,waterk}$) for the water and to all the nine combinations of points ($t_{pk,oilj}$, $t_{pk,oilk}$) for the oil.

The points for a given medium air/water/oil in conjunction with the time intervals will define one or more classification regions of a medium. Additionally, few points can be discarded after the definition of classes due to their redundancy and overlapping with classification regions of other mediums. This statement is illustrated in Fig. 8b, where, two of these points are located in $(t_{pk,oil1}, t_{pk,oil2})$ and



Fig. 8. Illustration of the classification method: (a) conceptual signals g_{air} , g_{water} and g_{oil} acquired within the air, water and oil, respectively; and (b) bidimensional projection of the all possible combinations of the indicators { $t_{pk,air1}$, $t_{pk,water1}$, $t_{pk,water2}$ }, { $t_{pk,water2}$, { $t_{pk,water2}$ }, { $t_{pk,water2}$, $t_{pk,water3}$, t_{p

 $(t_{pk,oil2}, t_{pk,oil3})$. The remaining dots are plotted in Fig. 8b with shapes filled with black, which leads to four classification regions represented by the filled shapes in Fig. 8b. The classification algorithm can thus be applied as follows: a signal f(t) is acquired, its peaks and more interesting regions are extracted, points with the most suitable combinations are placed above the chart of Fig. 8b. The decision of the medium is taken by the majority of points that fall

within a given classification region (e.g., *air*, *water*, *oil*₁ or *oil*₂). If the event falls out of these regions, the Euclidean distance is considered instead. The points with the most suitable combinations are those ones with peaks nearby the points ($t_{pk,air2}$, $t_{pk,air1}$), ($t_{pk,water1}$, $t_{pk,water2}$), ($t_{pk,oil1}$, $t_{pk,oil2}$) and ($t_{pk,oil2}$, $t_{pk,oil3}$).

Fig. 9 shows the results of the classification regions obtained during four days of experiments with 25 signals for each medium



Fig. 9. Charts showing the classification regions of the mediums taken during four days of experiments.

and few of them showed in Fig. 8. It is worth of mention the fact that two classification regions can be merged to compose one by embracing the diagonal line passing by the origin, as in the oil case. Notice, that through this classification the measurements could be better distinguished.

4. Conclusions

This paper presented a low-cost electro-acoustic measuring system for characterization of three mediums. The experiments aimed to understand the behavior of the electro-acoustic system in the time domain for each medium (air, water and oil). From the results it is possible to notice that the measurement system is robust and that the signals obtained in the experiments can be employed in a classification algorithm to identify the medium under analysis. Further tests with mixtures of the three mediums are under analysis to verify possible changes in the acoustic signal. Nevertheless, it was demonstrated here that the ferroelectret transducer is suitable for detecting signals transferred through distinct mediums and it is sensitive enough to detect small variables that led to a classification method.

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