Design of Autonomous Miniaturized Spherical Acoustic Sensor for Complexe Media Characterization

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***Abstract*—In this work, a spherical device (1 cm in diameter) composed of two assembled hemispherical shells integrating both the active element (piezoelectric ring) and the integrated electronics dedicated to coding, control and analysis was developed as an acoustic sensor. This autonomous sensor can operate simultaneously as a transmitter and a receiver around its fundamental frequency (32 kHz). Viewing these characteristics, operation within a sensor network could be envisaged and it will be possible to map the acoustic properties of a given medium characterized by a heterogeneous dispersion due to imposed dynamic motion.**

Keywords— sensor, spherical, acoustic

Introduction

In most processes using different raw matter in the domain of agro industrial as the cosmetic, pharmaceutic, …, product homogenization by mixing is often associated with several parameters such as time, motion, and the mixing system. These parameters lead to a change in the physical properties of the raw material that will influence the quality of the final product. Existing methods are unable to detect these changes, except in the case of some limited optical methods based on the visual aspect of the product studied [1].

In this step the physical properties of the medium evolve and define the achieving consistency. It is, therefore, essential to consider the whole process in order to obtain the quality required by the specifications.

The relative homogeneity of a mixture, inseparable from the observation scale, is difficult to achieve by discrete measurement. Depending on the observation scale, the instantaneous analysis of an elementary sample taken at random from the medium will not necessarily reflect the expected degree of product homogeneity. Establishing an even, consistent result is a difficult task.

In most cases, the homogeneity is estimated through sampling, which often results in technical problems linked in on-line levy. Unlike a mixture of fluids, the phenomena governing the distribution of mechanical properties in solid mixtures are still poorly understood resulting of the difficult to access of on-line measurement and consequently the lack of distributing model of matter components describing this mesoscopic scale. To address the problem of on-line mixture characterization, we propose a technique based on low-frequency acoustic waves generated by centimeter-sized spherical resonators with integrated electronics.

To develop further instrumentation in order to better understand and quantify the process of changing media in real conditions, a new low-frequency ultrasonic technique with a miniaturized elementary spherical sensor that behaves as a point source was examined. This new acoustic technique can operate with several networks of coupled sensors of the same type (coding, size frequency, etc.).

The optimization of its embedded electrical control architecture will enable this sensor to simultaneously manage tasks such as acoustic transmission/reception, remote data storage and/or transmission, as well as providing an extended autonomy, which is currently not available. This will enable the relations between the evolution of the physical properties of the wave and the structural changes during the formation of the media under study to be explored.

Given the technical characteristics of such resonators, these sensors will be able to deliver useful information regarding the evolution of the mechanical properties of a dynamic mixing system. This device will be able to dynamically monitor the homogeneity of some products, which often comprise the mixing of various elements, and indicate if they have been correctly dispersed in the mass. A decision threshold regarding the desired state set by the user must be included in the device in order to attain the optimal properties required throughout the entire volume.

I. Sensor Resonator Device

A. Mechanical component

The aim of the study was to design an autonomous ultrasonic device to control and quantify in situ some physical properties of evolving media.

Contrary to most ultrasonic transmission techniques, our goal was to obtain a low-frequency acoustic point source to generate a spherical wave in the medium. To do this, we used a piezo element for which the frequency was optimized to bring the entire mechanical structure of a small sphereinto resonance. The radius of such a sphere is smaller than the acoustic wavelength generated in the medium so it can be considered as an acoustic point source.

The resonator is a closed spherical shell composed of two hemispheres made of a material compatible with its future use (Plexiglas in our case). Its inner radius is about 10 mm and itis about 3 mm thick. Resonance of the overall structure occurs as a result of the vibrations produced by a piezoelectric ring (0.5 mm thick) clamped between the two hemispheres (Figure 1).

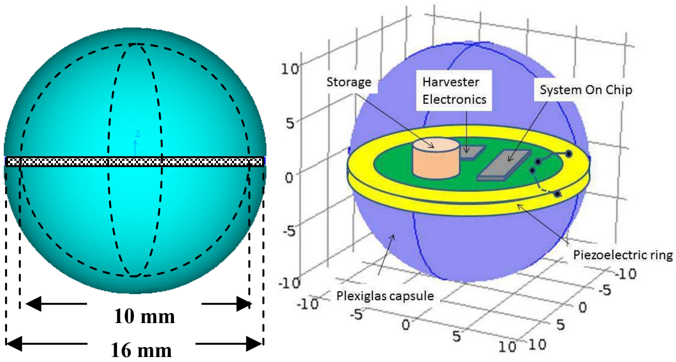

Figure 1: Illustration of the spherical resonator

B. Fndamental acoustic vibrational mode: Spherical motion

1) Analytical approach:

Many studies have been conducted in the field of mechanical vibration of spherical shells for axisymmetric modes. Based on an initial, purely theoretical study by Lamb, Baker [4] proved experimentally the existence of these modes of vibration. With the same aim, Wilkinson [5] and Kalnins [6] studied the vibration of a complete spherical shell while introducing the effects of transverse shear and rotational inertia, which was confirmed by Duffy [7].

According to the fundamental theory of Love [8] and the work by Kalnins [9], De Souza [10] uses the Lagrangian formulation to establish the equations of motion of a spherical shell. This study focus mainly on the "axisymmetric fundamental resonance mode" as the components of shear bending and rotational inertia were minimized, thus providing the natural radial frequencies of both the breathing and n_{th} mode of closed spherical shells by:

$$\mathbf{f_n = \frac{\lambda_n}{2\pi R}\left[\frac{E}{\rho(1-\nu^2)}\right]^{1/2}} \qquad (1)$$

Where R is the radius of the mid-surface of the spherical shell, ρ is the density, **E** is Young's modulus, ν is Poisson's ratio, $\boldsymbol{\lambda_n}$ is a non-dimensional frequency, and **n** is the mode number.

According to Wilkinson [5], the frequency parameter of the axisymmetric vibration modes of a thin spherical shell, in the torsionless case, are expressed as a cubic polynomial in λ^2.

For each value of $n \geq 1$, there are three distinct frequencies (three branches or three mode shapes), but only two branches are presented in this part of the study. These two lower and upper branches correspond to the membrane and bending modes, respectively (Figure 2). According to Duffey [12], the mode associated with n = 0 on the membrane branch is called the "fundamental mode", a pure breathing (elongation) mode of the spherical shell.

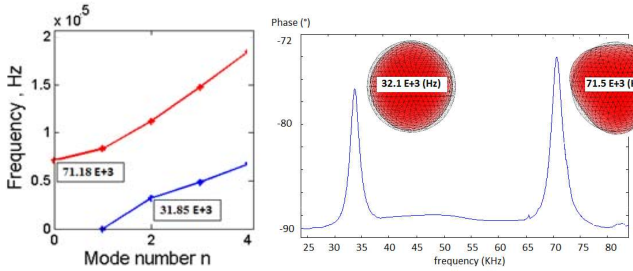

Figure 2: Natural frequencies of tortionless modes for the composite sensor

2) Experimental concept

The experiments were carried out using the whole sensor (Figure 3). The electrical impedance was measured to check that the calculated resonance modes were excited by the mechanical distortion produced by the piezoelectric ring.

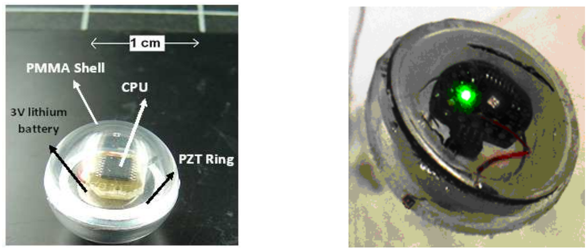

Figure 3: The autonomous acoustic sensor with the embedded electronics

As mentioned earlier, the notion of mixture homogeneity, which is inseparable from observation and segregation scales, remains difficult to achieve with current measurement techniques. The nature and rheology of the products can lead to complicated expressions for a certain number of parameters, especially their respective evolution during mixing.

Knowing the properties of a mixture on a spatio-temporal scale leads to a location in time: spatial information (i.e. location) and temporal information (i.e. date) are associated with each data item making our concept an asset.

Knowing in-situ information about the homogeneity of a mixture requires knowledge of the instantaneous position of the elements constituting the sensor network. The spatial identification of the transmitter at each instant makes it possible to trace the history of the latter and consequently provide access to the desired acoustic properties of the environment.

Figure 8 shows the principle of trilateration making it possible to know the distance between the transmitter and a receiver and consequently to determine the relative position of the transmitter with respect to a reference point.

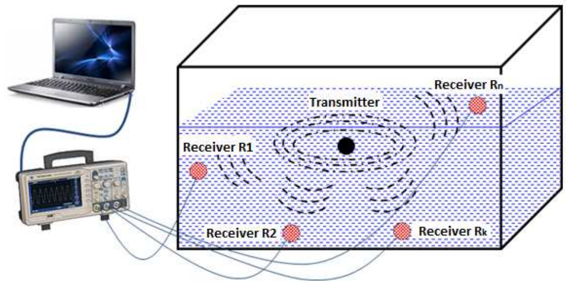

Figure 4: Schematic illustration of the measurement cell principle

Indeed, the network is composed of a transmitter at any position in the space and four receivers of known position, for the time being. Under the action of an electrical pulse generated by the module embedded in the emitter, the resonance of the structure is transmitted through the medium to the four receivers. The acquisition of the signals is ensured by a data acquisition module consisting of a high-resolution multi-channel oscilloscope.

This technique makes it possible to locate instantaneously a transmission source in motion, in a space (x, y, z). This approach will give access to the "local" physical properties of the material (through E / Ri; E: transmitter, R: receiver) by measuring the flight times of the wave (of the various receivers). In the case of a 3D measurement, the distance between the transmitter and the receiver corresponds to the radius of the spherical wave generated by the source.

C. Sensitivity on the physical state change of media

1) Sol- gel transition:

In this section, based on studies carried out by Nassar [14-15] on phase transition phenomena, we consider the gelation of milk as a model of a dynamic transformation of a medium. The goal was to estimate the ability of such a sensor network to deliver the relevant information sought throughout the transformation process. The latter can be broken down into two steps:

1. Milk, considered as a homogeneous medium.

2. Phase transition: dynamic environment

By reference to the velocity in water, we were able to measure a velocity of 1540 m/s in milk heated to 37 °C.

Figure 5 shows that the addition of 30 µl of rennet to 100 ml of milk modifies the physical characteristics of the signals received by a given receiver. This modification results from the evolution of the mechanical properties of the medium thus reflecting the sol-gel phase transition leading to a viscoelastic gel.

Using trilateration, the position of the transmitter (mobile) is known at all times. In fact, quantification of the flight times of the waves emitted by a transmitter in a random position in the space considered and received by the various receivers (clearly identified spatially) gives a velocity variation in the transition medium of 69 ± 6m/s.

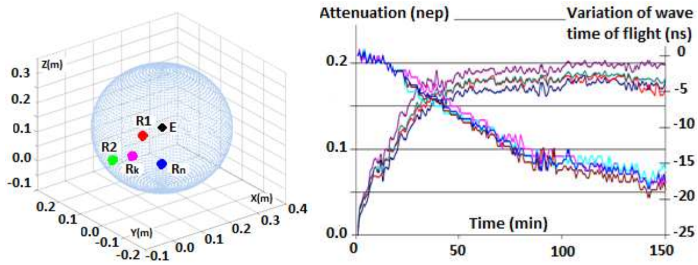

Figure 5: Kinetics of the sol-gel transition dimensions seen from different angles (3D) through different receptors dispersed in the medium studied

2) Heterogeneity sensitivity:

a) By concentration and size:

In this part, the concentration of the diffusers was considered to be variable in considered volume while the other parameters such as grain size (mean of 5 mm), the temperature of the medium, and the stirring speed were constant.

The curve in Figure 6a shows a decrease in the average energy received as a function of the concentration. This decrease is reflected by the variable number of diffusers in a given acoustic field. The signal emitted by the transducer then undergoes a greater or lesser dispersion as a function of the number of interfaces encountered during its propagation.

For the same purpose, the grain size was considered the main variable. Four different grain sizes and therefore four different levels were defined under identical operating conditions: 1, 1/2, 1/4, and 1/8.

Figure 6b shows that the increase in interfaces introduced by reducing the grain size for the same density, strongly influences the energy received.

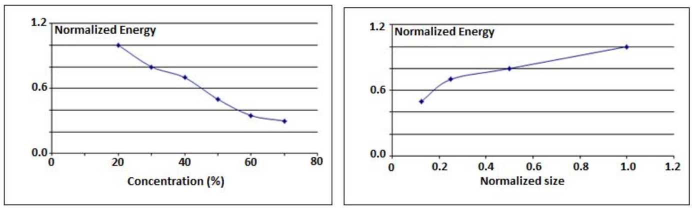

Figure 6: a) Impact of diffuser concentration on the ultrasonic energy received, b) Impact of diffuser size on the ultrasonic energy received

II. Conclusion

The study and design of a sensor able to meet industrial requirements in the field of standardization was the main objective of this work. We have proposed a concept of measuring elements based on miniaturized spherical sensors with embedded electronics.

A detailed description of the proposed resonator and its vibratory mechanical behavior has been consolidated with a numerical approach using finite element analysis.

The physical implementation of the sensor led us to an autonomous vibratory element. The power analysis (impedance and phase) of the overall structure showed very good agreement between the numerical and analytical results.

To validate this concept in a real environment, we adopted trilateration to define the position of the emitters in a given space. Through this approach, we were able to quantify the local effects generated by the choice of mechanical and thermal conditions. The sensors showed both considerable stability and sensitivity.

However, the analysis of the effect of factors of heterogeneity on the variation of the acoustic quantities: wave velocity (time of flight) and attenuation, gave a coherent view of the acoustic behavior of both the measuring system and the dynamic medium considered. The curves show all the critical phases in a complex evolutionary environment, knowing that there are few techniques which, under similar conditions, give access to the homogeneity degree through local physical properties sought. The evolution of the sensor towards an integrated intelligent version ensuring the conversion of the acoustic vibrations of the process opens up new prospects.

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