Measurement Of The Nonlinear Ultrasonic Parameter In Aqueous Solutions

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Abstract: This paper deals with the measurement of the nonlinear ultrasound coefficient β in aqueous solutions. Our aim is to show the possibility of using this parameter in ultrasound characterization of these solutions with the possibility of extending this technique to other complex media. The experimental determination of nonlinearity parameter is based on the quasi-linear approximation that allows us to derive an analytical expression of the second harmonic amplitude that takes into account the diffraction and the absorption effects. The experimental set up is composed of a piezoelectric disc transmitting at the fundamental frequency 2.2 MHz. The second harmonic is detected using a ring surrounding the disc and functioning at 4.4 MHz. The disc and the ring are both mounted on the same composed device and are both located in the same transversal plan to the propagation axis. The transmitted wave propagates through the sample and is detected by the receiver An appropriate signal processing permits the determination of the nonlinear parameter. The experimental results are promising and show a close correlation between the nonlinearity parameter, and the nature and the concentration of the compounds in the aqueous solutions studied.

I. Introduction

When an ultrasonic wave propagates through a medium, some variations in its acoustic parameters occur. The measurement of these variations makes it possible to characterize the medium. Generally in ultrasonic techniques we measure the changes of:

- The density ρ of the medium
- The sound speed c
- The acoustic impedance Z

The nonlinear parameter is related to the waveform distortion caused by the ultrasonic nonlinearity of the propagating medium. This phenomenon has to be explained by the variation of the sound speed according to the amplitude of the wave propagation through the medium [1]. Thus the spectrum of the wave spreads to higher frequencies. A sinusoidal wave's spectrum becomes richer by including harmonics. This harmonic generation results from the transfer of the energy from the fundamental to higher order harmonics and between these harmonics themselves.

The nonlinearity property is widely used in ultrasonic techniques for characterization of different media such as tissues [2, 3] and liquids [4].

Our aim in this paper is to study the effect of some chemical compound's concentration in aqueous solutions on their nonlinearity ultrasound parameter.

II. The nonlinearity parameter

The Taylor expansion of the state equation is given by [5]:

$$p = P - P_0 = (\rho - \rho_0)\left.\frac{\partial P}{\partial \rho}\right|_{s,0} + \frac{(\rho-\rho_0)^2}{2!}\left.\frac{\partial^2 P}{\partial \rho^2}\right|_{s,0} + \cdots \quad (1)$$

p is the variation of pressure, P is the total pressure, P_0 is the ambient pressure and s is the specific entropy.

Equation (1) can be written as:

$$p = P - P_0 = A\frac{\rho-\rho_0}{\rho_0} + \frac{B}{2!}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots \quad (2)$$

Where

$$A = \rho_0 \left.\frac{\partial P}{\partial \rho}\right|_{s,0} = \rho c_0^2 \quad (3)$$

$$B = \rho_0 \left.\frac{\partial^2 P}{\partial \rho^2}\right|_{s,0} \quad (4)$$

ρ_0 and c_0 are the values of ρ and c_0 in the unperturbed state respectively.

(3) and (4) yield

$$\frac{B}{A} = \frac{\rho_0}{c_0^2}\left.\frac{\partial^2 P}{\partial \rho^2}\right|_{s,0} \quad (5)$$

In another form

$$\beta = 1 + \frac{B}{2A} \quad (6)$$

Here, the *B/2A* defines the ratio of quadratic to linear terms in Taylor series. Therefore, it represents the fact that the density does not follow linearly the changes in pressure.

III. Determination of the nonlinearity parameter

III-1. Measurement methods

Two methods are usually used to measure the nonlinear ultrasound parameter. The thermodynamic method [6, 9] is more accurate but requires a complicated setup to measure the variation of sound velocity according to pressure and temperature variations. The finite

amplitude method [10-13] is based on a linear expression between the nonlinear parameter and the amplitude of the second harmonic. Significant progress has been made to improve this technique.
Law et. al. [10] use the Fourier expansion of Fubini's solution to derive an expression of the second harmonic using plan wave approximation. This technique was used for measuring the B/A parameter in biological media but neglecting the absorption and the diffraction effects. Correction terms for attenuation were added by Dunn et. al. [11]. Resolving the parabolic wave equation (KZK) with the quasilinear assumption makes it possible to derive an expression for the nonlinear parameter that takes into account the effects of diffraction and absorption [12-15]. This technique was, first, used by Labat et. al [12] for measuring the nonlinear parameter using a ratio of measured to theoretical amplitude of the second harmonic to avoid the problems linked to hydrophone calibration. Chitnalah et al. [14, 15] developed the technique for pulse echo systems. More recently Meulen and Haumesser [16] presented a measurement technique using a single transducer in pulse echo mode based on the solution of the KZK equation proposed by Zhang et al. [17]. Chavrier et al. [18] present a technique for plane waves and validated by measuring into the Butanediol.
This work is based on the expression of the nonlinear coefficient proposed by Chitnalah et al. [14, 15]Thus the nonlinear parameter is written as:

$$\beta = KU(z_0)\varepsilon \quad (7)$$

$$K = \frac{a^2\rho_0 c_0^2}{\eta_e}\frac{\eta_1}{\eta_2} \quad U(z_0) = \frac{U_1(z_0)}{U_2(z_0)}e^{-\alpha z_0} \quad \varepsilon = \frac{V_2}{V_1 V_0} \quad (8)$$

a is the radius of both of the source and the receiver, z_0 is the distance between the transmitter and the receiver, V_0 is the electrical excitation of the transmitter, V_1 is the electrical voltage corresponding to the fundamental, V_0 is the electrical voltage corresponding to the second harmonic, η_1 and η_2 are the receiver sensitivities for the frequencies of the fundamental and the second harmonic respectively, η_e is the transmitter sensitivity for the frequency of the fundamental, $U_1(z_0)$ and $U_2(z_0)$ are the averages of the fundamental and the second harmonic respectively at the receiver surface. $U_1(z_0)$ and $U_2(z_0)$ are calculated using the quasi-linear theory and the decomposition of the sound beam into Gaussian beams.

$$\beta = \xi\varepsilon c_0^2 e^{-\alpha z_0} \quad (9)$$

$$\xi = \frac{a^2\rho_0}{\eta_e}\frac{\eta_1}{\eta_2}\frac{U_1(z_0)}{U_2(z_0)} \quad (10)$$

ξ is a constant whish does not depend on the medium.

III-2. The experimental setup

The figure 1 shows the experimental setup. The transmitter is a piezoelectric disc with the central frequency equal to 2.2 MHz and the radius equal to 5 mm. The receiver is a probe composed of two piezoelectric elements: a 5 mm radius disc which detects the fundamental (2.2 MHz) and a ring for second harmonic detection (4.4 MHz) the ring is made such as its area is the same than the disc's one. Transducers are placed into a tank that contains aqueous solutions of NaCl, KCl and $CuSO_4$. The receiver is placed in the transmitter's focal plan.
A software was developed for the acquisition of the electrical signals corresponding to the fundamental and second harmonic [19]. Suitable signal processing allows us to determine the nonlinear parameter.

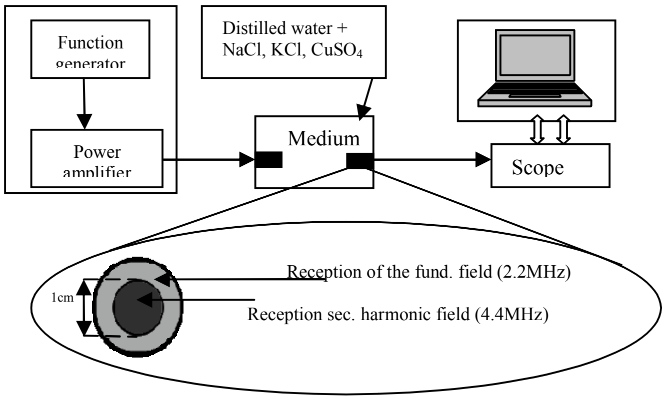

Fig. 1: The experimental setup

III-3. Results

We measured the variations of the ratio V_2/V_1 vs. V_0 for each aqueous solution. Figures 2, 3 and 4 show the results obtained for NCl, KCl and $CuSO_4$ respectively.
For low power supply the ratio V_2/V_1 is weak. That's due to the weak generation of the second harmonic into the material. Beyond the weak excitation phase the ratio increases linearly with the power supply.
In KCl solutions the desired ratio is more important than the other compounds' solutions. One can note, either, that the $CuSO_4$ present a more linear dependence of V_2/V_1 on V_0.
From equation (8) we deduce that the β parameter is linearly related to the slope ε of the curves. We linearized the curves in order to calculate their slopes, considering water as a reference medium($\beta = 3.5$). Thus we determine the constant ξ and then we deduce the nonlinear parameter of the studied materials. Table1 shows the values of the slope and the nonlinearity parameter.

Media	Concentrations	ε(mV^{-1})	β
NaCl	6 g/l	41.2	3.92
	10 g/l	55.6	4.98
KCl	2 g/l	80.1	5.48

	6 g/l	41.2	5.01
$CuSO_4$	2g/l	56.1	4.25
	4 g/l	43	3.63

Table 1: The slope and the nonlinear parameter values for the studied media

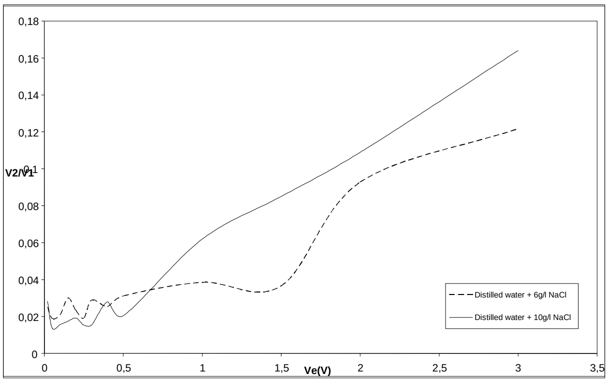

Fig. 2: Variations of the ratio V_2/V_1 vs. V_0 for the NaCl solutions

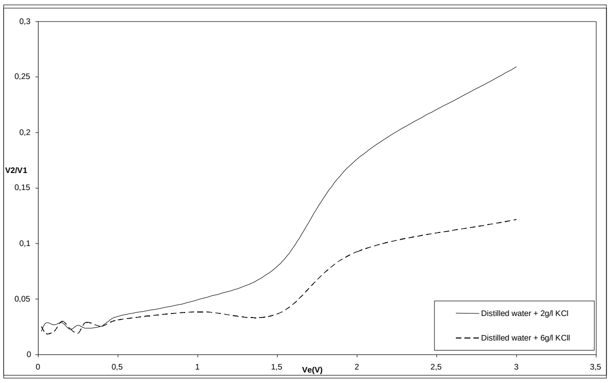

Fig. 3: Variations of the ratio V_2/V_1 vs. V_0 for the KCl solutions

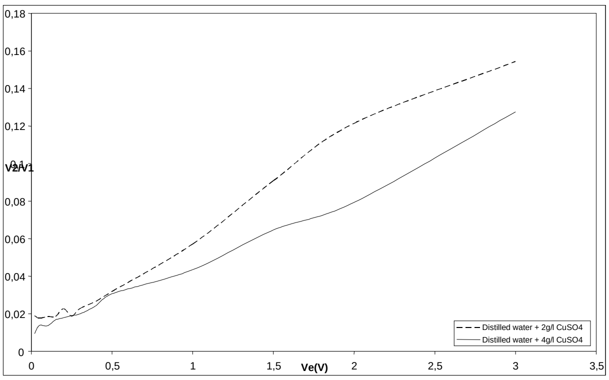

Fig. 4: Variations of the ratio V_2/V_1 vs. V_0 for the $CuSO_4$ solutions

IV. Conclusion

The obtained results show a close correlation between the nonlinear parameter and the concentration and the nature of chemical compounds solutes in distilled water. The present study, although preliminary, is promising and shows that β can be used to characterize some aqueous solutions.

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