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Optimal Length Determination of a Glass Waveguide to Maximize Ultrasound Transmission

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Abstract — **The generation of ultrasonic waves by a remote way, inducing magnetic fields to magnetic nanoparticles, is an important scientific advance that has been demonstrated in other works. With this technique, it could be avoided some problems of conventional ultrasound related to attenuation. In this work, a glass tube waveguide to transmit 1 MHz ultrasound was studied in order to find an optimal length in which ultrasonic waves are transmitted with the minimum losses. The length of the waveguide is an important factor that modifies the transmission of a signal trough it; some optimal tube lengths can be used to obtain the best ultrasonic transmission with the proposed waveguide were found.**

Keywords — **Waveguide, ultrasound, glass tube, magnetic field, magnetic nanoparticles, ferrofluids.**

I. Introduction

Ferrofluids are part of a new class of magnetic materials. These are composed of small colloidal magnetic particles dispersed and stabilized in a carrier liquid having in combination both fluid and magnetic properties [1]. The magnetic nanoparticles contained in the ferrofluid are stabilized by the coating with a long chain surfactant, whose objective is to avoid the precipitation of the particles due to the Vander-Waals forces [2]. The particles act as a magnetic monodominium, so they have a superparamagnetic behavior [3]. At the present time, ferrofluids have some applications in medicine, such as contrast agents in biomedical imaging (MRI and X-Ray CT) and drug carriers [4][5].

Usually, gradient magnetic fields are used for manipulating these magnetic nanoparticles, which can be commonly generated by electromagnets or permanent magnets [6]. Recent studies have shown that it is possible to generate ultrasonic waves from the induction of a magnetic field to magnetic nanoparticles [7][8]; it has been proved that, the nanoparticles oscillate mechanically at a frequency $2f$, where f is the frequency of alternating magnetic field [9]. This oscillation produces measurable ultrasonic waves whose parameters are the result of diverse phenomena occurring between the magnetic and the fluidic forces[10].

The use of ferrofluids to produce ultrasound when excited by a magnetic field could improve the ultrasound effects in deep structures. The main advantage of this application is that the ultrasound losses at the first layers of tissues can be avoided. Due to the complexity of biological tissues, ultrasonic losses are produced by different mechanisms, but mainly by absorption and scattering. This technique could solve some of the complications that conventional ultrasound techniques have nowadays [11], since the nanoparticles can be sent to any part of the body [12], and the magnetic field do not suffer important attenuation through air and bones [13].

Our group is working on the generation of ultrasonic waves by induction of magnetic field to magnetic nanoparticles, which is made by applying a magnetic field of 500 kHz to a ferrofluid placed in a glass tube. The produced ultrasonic signal is measured by a hydrophone placed at the other side of the glass tube. The objective of this paper is to study the ultrasound propagation through a glass tube in order to find an optimal length that permits the maximum ultrasound transmission. This will validate our approach and will permit to determine the usefulness of the glass tube as a waveguide, in which an ultrasound wave of 1 MHz is transmitted with the minimum losses.

II. Methodology

A. Waveguide design

The goal of this project is to produce ultrasonic waves with nanoparticles excited by a magnetic field. This is planned to be carried out using a ferrofluid into the bottom extreme of a glass tube, which will be introduced in the oscillating magnetic field of 500 kHz (RMCybernetics, UK). However, we would like to analyze the behavior of the glass tube as a waveguide in the range of the frequency of the produced ultrasound waves. To measure these waves, a hydrophone will be placed at the upper extreme of the tube at a minimum distance of 113.9 mm, which was chosen to prevent the hydrophone being influenced by the magnetic field and reduce the heating due to magnetic induction.

To validate the glass tube as an ultrasound waveguide, we propose a setup in which an ultrasonic signal is produced with a planar transducer of 1 MHz commonly used for therapy. This was placed at 5 mm from a glass tube of 6 mm of inner diameter, 8 mm outer diameter and variable length. In both the model and the experiments different lengths were analyzed to find an optimal length in which we can obtain the largest acoustic pressure transmitted from one endpoint to the other.

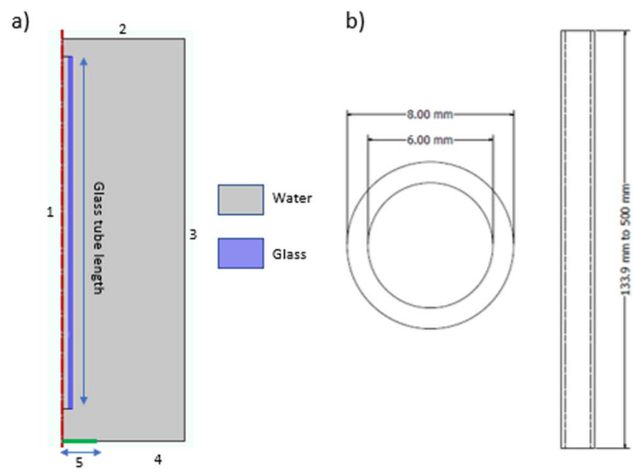

Fig. 1. a) Axisymmetric geometry used to obtain a optima length of glass tube waveguide. b) glass tube dimensions.

B. Finite element acoustic model

The analysis of the acoustic behavior of the glass tube was made in COMSOL Multiphysics (COMSOL INC., USA) which is based on the finite element method (FEM). Figure 1 shows the 2D axisymmetric geometry of the model, in which the waveguide is submerged in water to transmit the ultrasound to the hydrophone that is planned to be inserted at the upper end of the glass tube.

The final mesh was determined by convergence of the solution after minimizing the error without considerable increase in the model solution time. For this, it was necessary to make preliminary tests with different values of wavelength (λ), which is given by

$$\lambda = \frac{c}{f} \tag{1}$$

where c is the speed of sound (m/s) in the medium and f the frequency (Hz). For a glass tube waveguide length of 113.9 mm, simulations were carried out for different mesh sizes between $\lambda/4$ and $\lambda/20$ to find the smallest possible error with a larger mesh size to reduce the processing time. The optimal mesh size that permitted a solution in a tolerable solving time with an acceptable error (relative to the finest mesh) was $\lambda/8$; this mesh was used for the entire parametric study in which the length of the glass tube was varied. The length of the waveguide is varied in steps of 0.1 mm up to 500mm.

The boundaries were configured in accordance with the experiments. Based on Fig. 1, boundary 1 is the symmetry axis; boundaries 2 and 3 were set to have an the same acoustic impedance of water to decrease the reflection of waves at the external boundaries; boundary 4 was set as a rigid wall to simulate a rigid baffle condition; and boundary 5 represents the acoustic pressure source [14]. Material properties were set according to the manufacturer. Table 1 summarizes the properties of the materials used in this paper.

TABLE 1.
ULTRASONIC PROPERTIES OF MATERIALS FOR ACOUSTIC MODELS.

Material	Density (kg/m^3)	Speed of sound (m/s)
Water	997	1500
Glass	2210	5190

The instantaneous pressure P at any point of the medium is given by (2)

$$P = P_0 + p \tag{2}$$

where P_0 is the statical pressure and p the incremental variable of pressure, which propagates thanks to elasticity. Assuming the acoustic waves propagates in a medium without losses, the pressure at any point and time can be determined by:

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p) \right) = 0 \tag{3}$$

After assuming the pressure separable into spatial and time components, and considering an harmonic pressure source radiating during a very large time, the Eq. (3) can be simplified to the Helmholtz equation for harmonic conditions [15] given by

$$\nabla \cdot \left(-\frac{1}{\rho c}(\nabla p) \right) - k_{eq}^2 p = 0 \tag{4}$$

where the wave number $k_{eq} = \omega/c$, where ω is the angular frequency.

C. Experimental configuration

Experimentation was made using with the optimal lengths of the glass tube obtained from the simulation. It was performed using a 1 MHz transducer model ME7310 (Mettler Electronics, USA) with a nominal diameter of 40 mm, which emitted a 0.025 W/cm2 sinusoidal ultrasound field of produced by a signal generator AFG3021B (Tektronix, USA); the emission transducer was placed 5 mm from the glass tube. The hydrophone used to perform the acoustic pressure measurements was an HNP-1000 (Onda Corp., USA) with a sensitivity of 220 nV/Pa and maximum operating temperature of 50°C. This hydrophone is connected to an AH-2010 preamplifier (Onda Corp., USA) with a gain of 20 dB. Data was registered with an oscilloscope TDS2042B (Tektronix, USA).

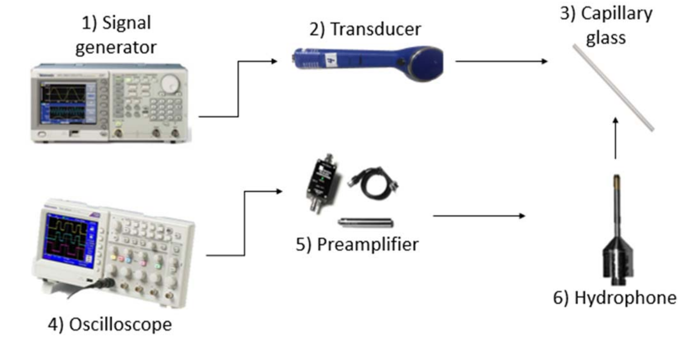

Fig. 2. Experimental setup. The hydrophone was inserted into the upper end of the glass tube, and the transducer was radiating from the bottom part of the tube.

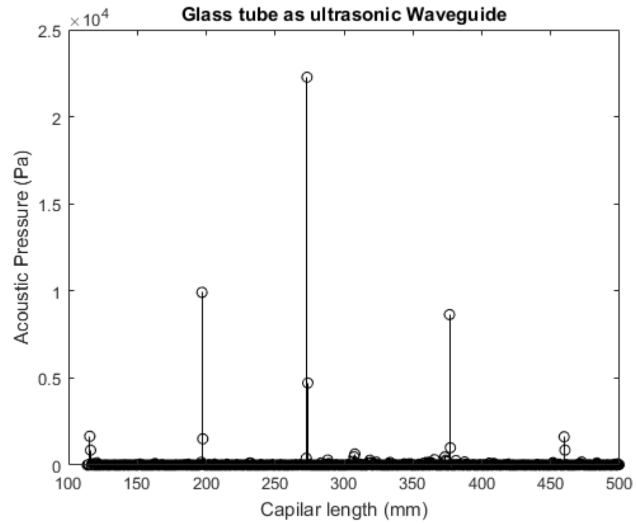

Fig. 3. Acoustic pressures obtained on the FEM model using a glass tube as ultrasonic waveguide varying the length between 113.9 mm to 500mm.

III. Results and Discussion

The study was conducted for a single frequency of 1 MHz. It is necessary to carry out a deeper study including the frequencies that are below the oscillation frequency of the nanoparticles, because the ultrasonic waves generated by the induction of the magnetic field to the nanoparticles include a wide range of frequencies of lower amplitude than the oscillation frequency. It would also be important to find other optimal tube lengths with different diameters, but also considering that it could be complicated to manufacture any diameter tube; some restrictions should be applied.

A. FEM model

The number of results of this study is relatively large (3861 results); so, it was necessary to export the data to MATLAB (Mathworks Inc., USA) in order to process them. Fig. 3 shows the average of absolute acoustic pressure at the output of the glass tube for different tube lengths. Figure 3 shows a maximum point in 273 mm (peak 3), corresponding to an acoustic pressure of 22.2 kPa; the 273 mm of length are equivalent to 182λ. Figure 4 shows the modeled acoustic pressure distribution along the glass tube obtained in this maximum peak of transmission

Other peaks we also found in the results of the simulation, these peaks were found with glass tube lengths of 115.5 mm (77λ), 196.5 mm (131λ), 376.5 mm (251λ) and 459 mm (306λ). The difference in the glass tube length between the peak 1 and 2 are similar to the difference between the peak 4 and 5, 54λ and 55λ respectively. In all cases of the highest peaks, the next glass tube length 0.1 mm greater than the previous one, also has a high peak compared to the rest. The peaks 1,5 and 2,4 they are also very similar in amplitude.

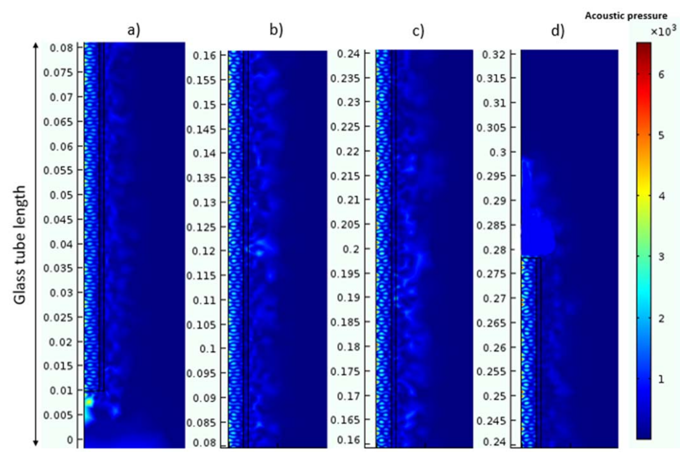

Fig. 4. Acoustic pressure distribution obtained on the FEM model using a glass tube of 273 mm (best case) as ultrasonic waveguide. The length of the glass tube was divided into four parts. a) from 0 mm to 80 mm, b) from 80 mm to 160 mm, c) from 160 mm to 240 mm and d) from 240 mm to 320 mm.

B. Experimentation

The waveguide length of 273 mm is the best option to transmit the ultrasonic waves with 1 MHz frequency through the glass tube. It is important to consider that all maximum peaks obtained in the simulation are multiples of λ. The other peaks found in the FEM model could be related to other less efficient (but still important) transmission modes, probably related to a harmonic behavior (to study in future). It is crucial to consider that in this work, we obtained these values with a single tube diameter; this means that by varying the tube diameter, we would obtain other values of optimal length, and probably other modes of transmission.

Table 2 summarizes and compares the results obtained by the FEM model and experimentation. The results obtained in the FEM model show good agreement with experimental measurements. The model can be considered a good representation of the glass tube as ultrasonic waveguide. However, it is required to implement corrections into the FEM model to obtain a better match between FEM model and experimentation.

TABLE 2.
COMPARISON OF THE RESULTS OBTAINED IN THE SIMULATION AND EXPERIMENTATION

Capillary glass length	Experimentation	Simulation
115.5 mm	2.40 kPa	1.65 kPa
196.5 mm	7.36 kPa	9.91 kPa
273.0 mm	18.91 kPa	22.27 kPa
376.5 mm	6.18 kPa	8.64 kPa
459.0 mm	2.32 kPa	1.62 kPa

IV. CONCLUSION

The length of the waveguide is an important factor that modifies the transmission of a signal through it. It is necessary to carry out a deeper study in which some conditions would be varied, such as the frequency of the ultrasound transmitted, the waveguide material and its diameter.

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