1aBA7. Electromagnetic hydrophone for high-intensity focused ultrasound (HIFU) measurement

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The electromagnetic hydrophone studied in this article is made of a metallic wire and eight magnets. When the wire is moved by ultrasound while submitted to a magnetic field, the Lorentz force induces an electrical current. If appropriate translations and rotations of the hydrophone are made, an hydrodynamic model provides a relationship between measured electrical signal and pressure in each coordinate. However, the potential influence of wire tension on electrical signal has not been included in this model. This study shows that tension has negligible effects. Characteristics of such electromagnetic hydrophone make it potentially of great interest for High-Intensity Focused Ultrasound.

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INTRODUCTION

Many current medical applications are using ultrasound to diagnosis or treat pathologies. In both case, precise characterization of the ultrasound probe is often needed. For example, in High Intensity Focused Ultrasound therapy, where an ultrasound beam is focused for heating tissues, any uncertainty in the focusing can have dramatic impact on the treatment. For this purpose, several devices are available for ultrasound beam characterization. The current gold standards are the piezoelectric transducers [1], which converts sound into electrical signal. However, these transducers can be fragile at high pressure, especially if cavitation bubbles are appearing. Conversely, fiber-optic hydrophones are more robust and resist well to cavitation, but have a lower sensitivity [2]. Schlieren imaging can also be used to map ultrasound pressure field, but the measurements are hardly quantitative [3].

An electromagnetic hydrophone was first introduced by Filipczynski using a thin wire stucked on an insulator inside a magnetic field [4]. This hydrophone is both sensitive and resistant to high pressure, especially to cavitation, but it lacks of spatial resolution. The design has been improved by Sharf et al. [5] to have a better resolution but with a much lower sensitivity. Grasland-Mongrain et al. recently proposed a wire-hydrophone [6] where a wire is moved by the ultrasound inside a magnetic field. Spatial resolution under the millimeter scale is obtained by making a tomography of the ultrasound field with translations and rotations of the hydrophone. An hydrodynamic model has been proposed providing a relationship between measurement and locale pressure. However, the potential influence of the wire tension has not been included in this model.

The aim of the present study is to estimate the effect of the wire tension on the electrical signal.

THEORY

The principle of an electromagnetic hydrophone is schemed on figure 1. It is made of a thin wire placed in a permanent magnetic field.

FIGURE 1. Principle of the electromagnetic hydrophone: an ultrasound beam makes an electrical wire to move inside a magnetic field created by two magnets. This induces a measureable electrical current, shown to be proportional to the local pressure.

If the wire is small compared to the ultrasound wavelength and the Reynolds number sufficiently high, the velocity $v$ of a cylinder modeling the wire placed in a moving fluid should be related to the velocity $u$ of the fluid [7] through the relation (1):

$$v = \frac{2\rho}{\rho_0 + \rho} u$$

with $\rho$ the density of fluid and $\rho_0$ the density of wire.

On another hand, for a plane wave, we have the relation (2) between fluid velocity $u$ and pressure $p$:

$$u = \frac{p}{\rho c}$$

with $\rho$ the fluid density and $c$ the ultrasound wave speed. If the wire is conductive and placed in a magnetic field and the ultrasound beam is considered as a plane wave, the induced voltage by Lorentz force $e$ can be calculated through the relation (3):

$$e = \int \vec{v} \wedge \vec{B} dl = \int \frac{2}{\rho_0 + \rho} \frac{p}{c} \vec{B} dl$$
with $B$ the intensity of the magnetic field and $dl$ the elementary integration length over the wire. The wire can be translated and rotated to make a tomography of the pressure field [8], giving the equation (4) for estimating the pressure in each coordinate:

$$p(x,y) = \frac{\rho c}{B} \int_0^\pi E(k, \theta)|k|e^{i2\pi k_0 d \theta} dk$$

Having for example $p = 1$ MPa, $\rho = 1000$ kg.m$^{-3}$, $c = 1500$ m.s$^{-1}$ results in a fluid velocity $u_0$ of approximately 1 m.s$^{-1}$. At an ultrasound frequency of 1 MHz, giving a period of 1 $\mu$s, the displacement will be of the order of 1 $\mu$m, which is quite small compared to the wire diameter and suggests that the wire tension must be high to have any effect on signal. This hypothesis will be challenged in this article.

**MATERIAL AND METHODS**

The aim of the experiment was to gradually increase the wire tension of the electromagnetic hydrophone wire and to look at the effect on the electrical signal.

The electromagnetic hydrophone is made of eight 35x20x20 mm$^3$ neodymium magnets (HKCM Engineering, Eckernfoerde, Germany) regularly placed in a cylindrical PVC housing of 12 cm (exterior) and 4.6 cm (interior) diameter, as shown on figure (2). This special arrangement of magnets called Halbach array [9] creates an homogeneous magnetic field around the wire. The sensitive part of the hydrophone is an insulated copper wire placed in the middle of the magnetic field. The wire has a diameter of 70$\pm$7 $\mu$m and is about 1 m long. The resistance between the two extremities is 0.8$\pm$0.2 $\Omega$.

**FIGURE 2.** Picture of the electromagnetic hydrophone. It is made of 8 magnets placed as an Halbach array inside a PVC housing. The sensitive part is a wire in the middle. Its tension can be increased by two screws (not visible on the picture).

In order to look at the influence of the wire tension, a generator (HP33120A, Agilent, Santa Clara, CA, USA) created a 250 kHz signal with 3 sinusoids per pulse at a pulse repetition frequency of 250 Hz. A 200 W power amplifier (200W LA200H, Kalmus Engineering, Rock Hill, SC, USA) amplified the signal. A 250 kHz, 50 mm in diameter, focused at 50 mm, air-backed transducer was converting the electrical signal into an ultrasound wave. The electromagnetic hydrophone was placed at the focal point. The electrical signal induced on the the wire was amplified by a 1 MV.A$^{-1}$ current amplifier (HCA-2M-1M, Laser Components, Olching, Germany) with an input impedance of 50 $\Omega$. The signal at the output of the amplifier was then observed with an oscilloscope (WaveSurfer 422, LeCroy, Chestnut Ridge, NY, USA; DPO 3012, Tektronix, Beaverton, OR, USA). The tension of the electromagnetic hydrophone wire was initially loose (300 kPa) and was increased gradually with two screws until disruption which occurs at 220 MPa [10]. The tension at each step was evaluated by modeling the shape of the wire as a parabole. By measuring the amplitude of the deviation from the horizontal line, the applied tension [11] could be deduced.

To quantify the influence of the tension on the signal, the correlation coefficient $R$ as defined in (5) has been used. This coefficient is equal to 1 when two signals $\Psi_1$ and $\Psi_2$ are identical, -1 when exactly opposite and 0 when uncorrelated. In the wire tension experiment, the correlation coefficient has been calculated between the first signal when the wire was loose and the subsequent signals when a tension was applied.
FIGURE 3. Experiment on the wire tension: a function generator emits an electrical signal through 200 W amplifier to an ultrasound transducer. The ultrasound emitted by the transducer makes the wire to move inside the magnetic field, inducing an electrical current in the wire. This current is amplified and observed on an oscilloscope. The tension of the wire is increased gradually with two screws linked to the wire.

\[ R = \frac{\sum \Psi_1 \Psi_2}{\sqrt{\sum \Psi_1^2 \sum \Psi_2^2}} \] (5)

RESULTS

The electrical signal on the wire versus time as acquired by the oscilloscope for two different tensions is plotted on figure 4. The amplifier creates a small constant .25 V bias. The part between 0 and 20 \( \mu s \) corresponds to electromagnetic parasite emitted by the transducer during ultrasound emission. The electromagnetic signal due to Lorentz force appears between 60 and 100 \( \mu s \).

FIGURE 4. Electrical signal on the wire submitted to a 250 kHz ultrasound pulse versus time as acquired by the oscilloscope. Two signals corresponding to two different wire tensions have been plotted.

On a quantitative point of view, the correlation coefficients obtained in (5) versus tension are provided in table 1.
TABLE 1. Wire tension in MPa versus correlation coefficient between each signal and the reference signal with a tension equal to .3 MPa

<table>
<thead>
<tr>
<th>Tension (MPa)</th>
<th>.4</th>
<th>.7</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>20</th>
<th>40</th>
<th>50</th>
<th>80</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>.984</td>
<td>.984</td>
<td>.975</td>
<td>.977</td>
<td>.979</td>
<td>.966</td>
<td>.976</td>
<td>.980</td>
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<td>.978</td>
<td>.971</td>
<td>.987</td>
<td>.983</td>
<td>.983</td>
</tr>
</tbody>
</table>

**DISCUSSION AND CONCLUSION**

In the presented design of the electromagnetic hydrophone, the wire tension has a negligible effect on the acquired signal. This was observed qualitatively on figure 4 which show two very similar signals and quantified with a correlation coefficient in table 1. The correlation coefficient between the first signal taken as reference and other signals at higher tensions have small variations which seems furthermore independant.

In the hydrodynamic model proposed in [6], the wire was taken as loosely held and followed locally the fluid displacement. When dealing with tension of the wire, it can also be noted that the value of the tension sets the resonant frequency $f_n$ of the wire:

$$f_n = n \frac{c}{2L} = \frac{1}{2L} \sqrt{\frac{T_0 S}{\mu}}$$

with $c$ speed of sound in the wire, $T_0$ tension, $S$ wire section, $\mu$ weight per length unit, $L$ total wire length and $n$ the harmonic index. By taking $T_0 = 220$ MPa (at most), $S = 1.5 \times 10^{-8}$ m$^2$ for a 70 $\mu$m diameter wire, $\mu = 1.3 \times 10^{-4}$ kg.m$^{-1}$, $L = 15$ cm, the resonance frequency $f_0$ is equal to 15 Hz. The non negligible harmonics will be mostly under 100 Hz: this is far below the working frequencies and resonance does not have any effect on the signal. The hypothesis was consequently acceptable, the wire can be considered as loose, following the fluid movement due to ultrasound.

Thanks to these results, the hypothesis to apply the hydrodynamic model are less restrictive and any construction and use of such hydrophone are simplified.

Further studies should refine the hydrodynamic model by estimating the upper and lower pressure measurements limits of the hydrophone. Other characterization as directional and frequency response would also give more comparable elements with other types of hydrophones.

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**REFERENCES**