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Study of the sound field in thin polymer films induced by High-Intensity Focused Ultrasound

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Abstract
This contribution presents the study of acoustic effects occurring in polymer films irradiated by high-intensity focused ultrasound (HIFU), when the films are sandwiched between a solid waveguide transducer and a solid counterpart. Whereas the heating of polymer plates induced by HIFU was already reported in the literature, the acoustic effects in thin polymer films remain not fully understood. In order to investigate the sound field occurring in polymer films, measurements of the acoustic pressure in water between transducer and counterpart spaced from less than a wavelength in water are carried out using a membrane hydrophone. The measurements are compared to an acoustic finite element simulation modeling the sound field in water between the transducer and the counterpart. In order to evaluate the analogy between the acoustic pressure measured in water and the effective acoustic pressure occurring in polymer films, a second acoustic finite element simulation is conducted to model the irradiation of polymer films with HIFU in dry environment and compared to the simulation and measurements of the acoustic pressure in water. A direct correlation between measurements and simulation is found. The investigation reveals that complex interferences occur in polymer films. These findings are relevant for new joining processes of polymer based on HIFU.
Keywords: HIFU, Simulation, Sealing

1 INTRODUCTION

High-intensity focused ultrasound (HIFU) is growing of interest for industrial applications (sonochemical applications for surface treatment, forming, polymer heating and welding for example) [1, 3, 4, 5, 8]. Several authors investigated the thermal effects induced by HIFU in polymer samples both in water [2] and dry environment [3, 4, 5, 8]. They showed that polymer samples can be heated quickly and locally using HIFU. The investigation of HIFU-induced heating in polymer samples has been subject to many experimental studies of the thermal effects, but only a single paper describes the sound field between a solid waveguide and a solid counterpart in water [7]. This contribution is an overview of the above mentioned paper [7].

The aim of this contribution is to present an experimental method to determine the acoustic pressure in polymer films, sandwiched between a solid transducer and a counterpart. Because, to the best of authors knowledges, no method is known to measure the acoustic particle velocity in non-transparent polymer films, a method measuring the acoustic pressure in water and relating the results to the acoustic pressure in the polymer using simulation is presented. First, the experimental setup of the test bench used to measure the acoustic pressure, as well as the results obtained with this one are described. Second, the acoustic simulation method is depicted. Then, the acoustic experimental and numerical results are compared. Finally, the calculated acoustic pressure in water is compared with the calculated one in polymer films.

2 METHODS

2.1 Experimental set-up for sound field measurements

The aim of this experimental setup is to quantify the acoustic pressure amplitudes of ultrasonic waves generated by a transducer having a solid cone waveguide and occurring between a transducer and an aluminum counterpart.

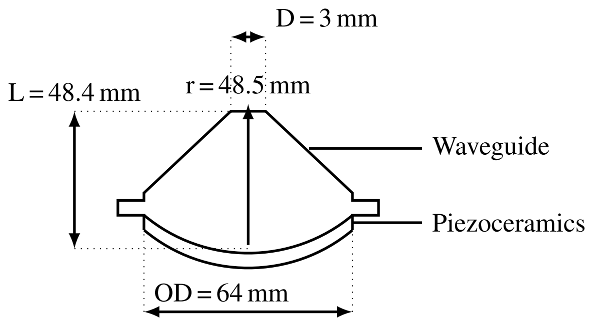


Figure 1. Transducer used in this study [3, 4, 5].

The transducer used consists of a spherical curved piezoceramics (PZ26) mounted on a cone-shaped waveguide made of aluminum [3, 5]. The flanges of the waveguide are clamped into the transducer housing. The characteristics of the transducer are summarized in figure 1. The transducer has a resonance frequency measured at f = 1 096 kHz.

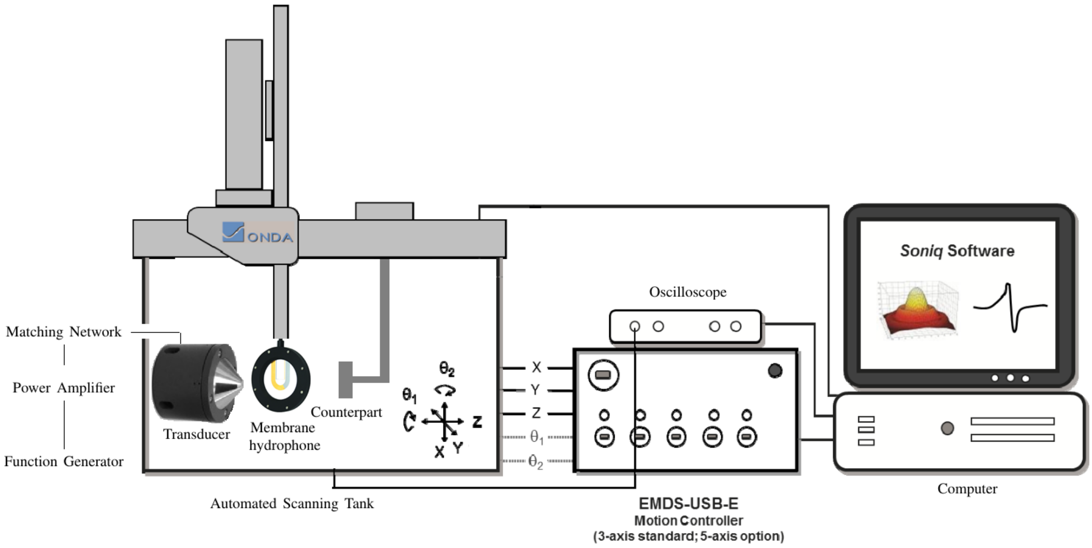


Figure 2. Experimental set-up for sound field measurement between waveguide and counterpart in water ONDA®[7]. Sinusoidal burst signal, 3 cycles, repetition period of 100 ms. Broadband PVDF membrane hydrophone: sensitivity 0.147 mV/kPa @ 1 MHz, PVDF-film thickness of 11 μm, active surface of 200 μm diameter [9], 100 ms waiting time between each measurements.

The transducer is mounted and fixed on a water tank panel. The counterpart as well as the membrane hydrophone are placed in front of the transducer waveguide tip (figure 2). The setups of the experiments are resumed in [7]. The distance between counterpart and waveguide is 1 ±0.2 mm.

2.2 Numerical acoustic simulation setup

A first numerical model based on axi-symmetric two dimensional transient dynamic explicit analysis of the ultrasound propagation in the transducer and the water is performed in Abaqus®(figure 3a). The transducer as well as the counterpart and the water are modeled. The transducer and the counterpart consist of hexaedral solid elements (8-node biquadratic, reduced integration). The water is described with hexahedral acoustic elements. The mesh size for both types of elements is smaller than $\lambda/20$. The parts of the model are contacted with each other using TIE-contacts.

The axi-symmetry of the model induces that the displacements in the radial direction are equal to zero on the axis of symmetry. The flanges of the waveguide are clamped as the test bench setup described above: no displacement in radial and axial directions. An acoustic pressure of zero is applied on the water surface to avoid the generation of pressure at the water surface (ideal soft boundary).

A second numerical model is built, considering polymer films instead of water gap (figure 3b). The boundary conditions, mechanical conditions as well as the types of elements and the mesh size are the same as the previous mentioned model. However, the water is replaced with the polymer film, modeled with solid elements (8-node biquadratic, reduced integration). The extern sides of the film are clamped. The contacts between the film and the counterpart as well as the transducer are modeled with TIE-contacts.

In both cases, the simulation is performed with a burst-signal having 3 cycles and a repetition period of 100 ms. A voltage amplitude of 500 mVpp is applied at the piezoceramics backside. With view to reduct the calculation time, the piezoceramics is approximated to a solid body under expansion for both models [7].

The material properties of the piezoceramics and the waveguide given by the manufacturer are used for the simulation because previous studies showed that the measured acoustic impedance and particle velocities at the waveguide tip match well with the calculated ones [5]. The waveguide made of aluminum has the following material properties: Young's Modulus of 70 GPa, density of 2700 kg/m^3 and Poisson coefficient of 0.33 [6]. A structural damping, determined using vibrometry, is included in the simulation (0.001 and 0.00112 for the piezoceramics and the waveguide respectively) [7].

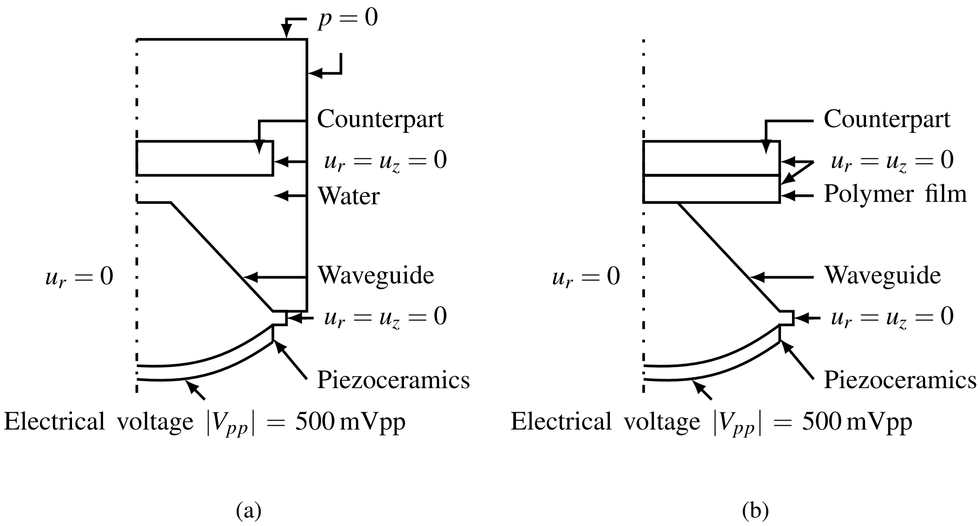
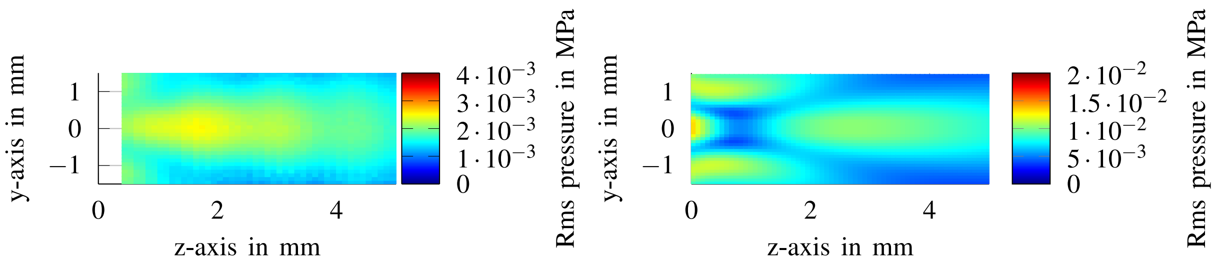


Figure 3. Simulation models: (a) In water, (b) In dry environment [7].

3 RESULTS

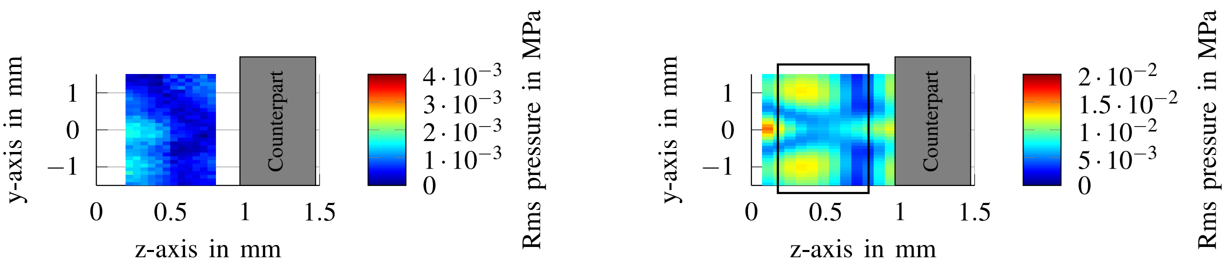
First, a reference measurement of the sound field is performed when the transducer irradiates in water without having a counterpart placed in front of it in order to quantify the propagation of the wave in free field [7]. Second, a simulation is built with the same setup in order to compare the simulation results with the experimental ones. A good qualitative correlation is found between the experimental and simulation results (figure 4). A focal region having the form of an ellipse, surrounding with two seconder pressure peaks is found in both cases. The calculated pressure amplitudes are, however, around 50 times higher than the measured amplitudes.



(a) (b)

Figure 4. RMS pressures in MPa in water (represented as effective pressure) at f = 1096 kHz: (a) Sound field measured behind the transducer in water without counterpart, (b) Calculated rms pressures in MPa in water [7].

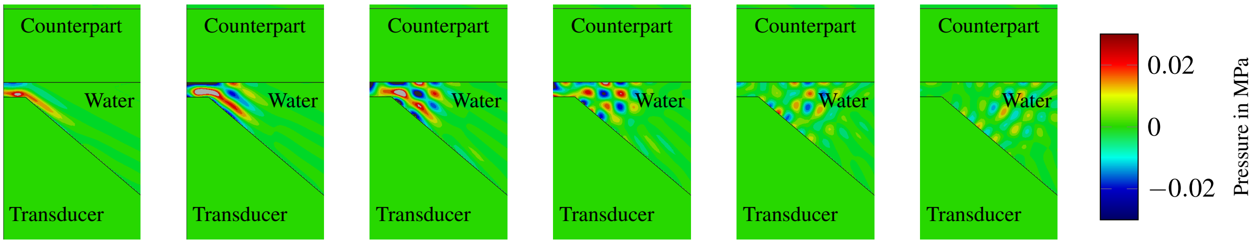
The same experiment is performed when a counterpart is placed in water in front of the transducer at a distance smaller than a wavelength in water (figures 2 and 3a). The similarities between measured and calculated sound pressures are difficult to identify (figures 5a and 5b), because the pressure was not measured at less than 0.2 mm of the waveguide tip and the counterpart surfaces in order to avoid any membrane hydrophone damages (figure 5a). The discrepancies between experimental and simulation results are caused by the transducer manufacturing deviations and the tolerance of the counterpart position for the acoustic pressure distribution, as well as, by the occurrence of a frequency decrease of the waves in small gaps (part of the frequencies are outside the bandpass filter) concerning the discrepancy of the pressure amplitudes [7]. As explained in [7], "there is neither sound focus nor wave superposition" in contrast to the reference measurements (figure 4). However, comparing the pressure illustrated in figure 5a with the pressure included in the black rectangle depicted in figure 5b, a small central pressure peak as well as side pressure peaks are observed in both models.



(a) Experiment (b) Simulation

Figure 5. Effective pressures between waveguide and counterpart for a distance of 1 mm at f = 1096 kHz. [7].

Figure 6 illustrates the temporal progression of the waves in water between the transducer and the counterpart. First reflexions of the focused waves occur at the counterpart as soon as the first wave travels through water, leading to complex interferences of the waves in the water gap. The superposition of the waves leads to a annihilation of the waves after 12.7 μs irradiation time.



(a) t = 8.7 μs (b) t = 9.7 μs (c) t = 10.7 μs (d) t = 11.7 μs (e) t = 12.7 μs (f) t = 13.7 μs

Figure 6. Calculated pressures between transducer and counterpart in water - gap size = 1 mm [7].
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A simulation of the acoustic pressure in polymer films (low-density polyethylene - the material properties can be found in [8]) sandwiched between the above described transducer and counterpart is performed. The same simulation setups, as described previously, are used. The water is, however, replaced with an air-environment and a polymer film clamped between the transducer and the counterpart (figure 3b). A boundary condition p = 0 is added to the polymer film surfaces in contact with the air-environment [7]. With view to simplification, the state change of the polymer films is not modeled.
The calculated acoustic pressure occurring in the polymer film presents the same distribution than the acoustic pressure in water (figure 7). The amplitudes of the acoustic pressures are for both similar as well.

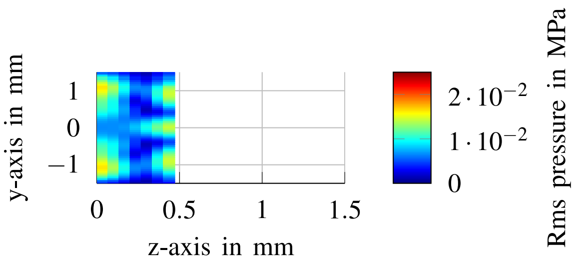

Figure 7. Calculated rms pressures in MPa in low density polyethylene, thickness = 470 μm (corresponds to half a wavelength in low density polyethylene) [7].
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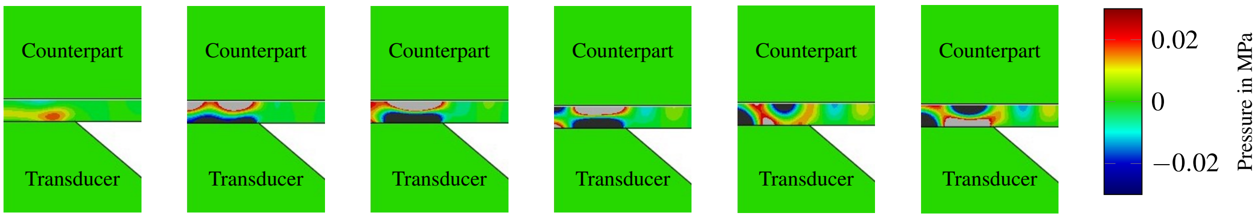
The analysis of the temporal progression of the waves in the polymer film reveals that the first wave reflexion at the counterpart occurs around 9.7 μs (figure 8). This is later than in water. However, the interference of the waves generates, in the case of the polymer film, a constructive superposition of the wave amplitudes. Annihilation of the waves is not observable when the irradiation time is smaller than 13.7 μs. This discrepancy between the acoustic pressure calculated in water and the ones calculated in polymer films can be explained with the air surrounding the polymer: The energy is not radiated sidewards to the transducer [7].



(a) t = 8.7 µs (b) t = 9.7 µs (c) t = 10.7 µs (d) t = 11.7 µs (e) t = 12.7 µs (f) t = 13.7 µs

Figure 8. Calculated pressures in low density polyethylene film upstream to the transducer. [7].

4 CONCLUSIONS

This contribution shows that it is possible to quantify the acoustic pressure occurring in polymer films, when the polymer film is included between a solid transducer and a counterpart, measuring the sound field in water between the transducer and the counterpart. The simulation of both configurations confirmed the validity of this method. These findings are relevant for future predictions of the acoustic pressures in polymer films induced with HIFU.

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