Comparison of the Spatial Distributions of Cavitation Damage with the Measured Diffraction Patterns for a High-Power Ultrasonic Transducer

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Comparison of the Spatial Distributions of Cavitation Damage with the Measured Diffraction Patterns for a High-Power Ultrasonic Transducer

By
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A thesis submitted to the faculty of the The University of Mississippi in partial fulfillments of the requirements of the Sally McDonnell Barksdale Honors College.

Oxford, MS
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Approved by

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ABSTRACT

The purpose of this study was to evaluate the performance of a model of the propagation of ultrasonic fields produced by an ultrasonic transducer, a device that uses a piezoelectric crystal to produce high-intensity ultrasonic waves. The transducer operates immersed in a water bath where it generates waves of sufficient intensity to produce non-linear phenomena that include acoustic streaming and cavitation. This study used a planar transducer to visualize the damaging effects of high-intensity ultrasonic waves targeted on acrylic plates. Seven plates were targeted and positioned from 8.5 to 11.5 cm from the transducer. The spatial distribution and degree of damage in the plates were compared to detailed measurement and numerical models of the field produced by this transducer under lower power operating conditions. The amount of damage to the acrylic plates depended on the distances of the transducer from the plate. The spatial distributions of the damage on the plates matched well with the measurements from the numerical model predictions.
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INTRODUCTION

Ultrasound refers to acoustic waves with frequencies above 20 kHz, which is the approximate upper limit of the range of human hearing. Ultrasound is typically generated using piezoelectric transducers, devices that are designed to convert electrical signals into ultrasonic waves. When a transducer is used to excite ultrasonic waves in water, a variety of phenomena can be observed including the formation of capillary waves, acoustic cavitation, acoustic streaming, and nebulization. Capillary waves represent the concentric circular waves produced on the surface perpendicular to the flow of pressure sources. When capillary waves on the surface of water are allowed to oscillate at a high frequency with enough intensity, the peaks of the waves can become sharp to the point that miniscule droplets are released, thus causing nebulization (see Figure 4).

Figure 1: Shows the production of capillary waves, seen as concentric circles, by the transducer from above the water (left) and below (right).
Acoustic cavitation (Figure 2) is the production of gas pockets within a fluid due, in this study, to the presence of an ultrasonic pressure field\textsuperscript{1}. Studies have shown that it is the combination of capillary waves and cavitation that give rise to the nebulization effect\textsuperscript{2}. Acoustic streaming (Figure 3) refers to a steady flow produced by the transfer of the energy in acoustic oscillations to direct flow. Alongside these phenomena, ultrasonic waves can also be absorbed by fluids and solids, resulting in the conversion of acoustic energy to thermal energy. Cavitation and streaming are also accompanied by heating but the absorption effect occurs with low intensity ultrasound as well, unlike the others which require higher power. Each of these effects are observed in the studies discussed in this thesis, but the ability of high power ultrasound to effect permanent change in acrylic samples through cavitation and heating is the primary focus of this work.

In the medical field, ultrasound is used in diagnostic imaging of the interior anatomy and is gaining ground as an effective therapy in cancer treatment. In therapeutic applications, the transducer is focused in order to maximize the effect on the intended region of the body and minimize any damage that the ultrasonic waves could have on
tissues outside of the focal zone. Focusing is provided by attaching acoustic lenses to the front of the transducer or using curved transducers. When using high-intensity focused ultrasound (HIFU) for noninvasive surgery, it is imperative to understand the physical phenomena that can arise and how they affect tissues. Therefore, it is important to study how materials and fluids are affected in such a field including the investigation of high power fields produced by planar (i.e., non-lensed) transducers. The aim of this study is to characterize the distribution and strength of the ultrasonic fields through damage done by the high power fields on acrylic plates. The data will then be used to assess the applicability of a numerical propagation code for characterizing high power fields.

Figure 4 (left): Production of acoustic fountain above water due to nebulization potentially caused by cavitation. Figure 5 (right): Frontal view of cavities in water produced by transducer.
MATERIALS AND METHODS

The experimental setup, depicted in Figures 6-7, consists of a transducer placed in a water bath powered by a radiofrequency (rf) power source. The transducer was custom-built in-house and is comprised of a piezoelectric disk with radius 2.5 cm mounted in a cylindrical brass housing. A radio frequency generator with a controllable power output (AG 1007 Ultrasound RF Generator) was used to produce sinusoidal signals at 1.21 MHz. The polymer plates used as targets were acrylic with dimensions of 6.0 x 6.0 x 0.9 cm. Each plate was cleaned with propyl alcohol prior to testing to remove any residue from the surface. The transducer axis and plates were aligned vertically using a mechanical mounting apparatus that permitted adjustments of the distance between them. The plates were partially submerged at the surface of the water.

![Image depicting experimental setup including radiofrequency generator, transducer, and acrylic plate at the water line of the tank.](image)

Figure 6: Image depicting experimental setup including radiofrequency generator, transducer, and acrylic plate at the water line of the tank.
Figure 7: A schematic containing the main components of the experimental setup.

Preliminary Studies:

First, a preliminary study was performed to find which type of environment surrounding the plate led to the most damage under the ultrasonic exposure. Three tests were performed in which the plate was in one of the following environments: completely submerged; submerged with the plate placed against the wall of the tank; and partially submerged with the 6 x 6 cm side of the plate only slightly under the surface. In each case, the plate received an exposure from the transducer operating at a frequency of 1.21 MHz and electrical power of 120 W for a duration of 6 minutes. When the plates were examined to determine the effectiveness of the environment in influencing the destructive effects, it was found that the partially submerged configuration was the most effective and thus was used in the subsequent studies.
Main Study:

The central study of this work involved the exposure of the plates at various distances from the transducer when only partially submerged. The initial distance between the transducer and the plate was 11.5 cm, and each subsequent test decreased the distance in increments of 0.5 cm down to 8.5 cm. For each test, a new plate was used and the transducer was moved upward toward the plate/water surface. The transducer was operated at 1.21 MHz, stepped up in power to 120 W in increments of 10 W, with full
exposures lasting for 6.5-7.0 minutes. After exposure, the plates were left in place until they were cool enough to handle.

The experimental data used as the basis of the comparison field patterns were acquired using a hydrophone scanning system, which took point-by-point measurements of the sound field in a plane parallel to the transducer face. The system uses a computer-controlled motorized gantry to move the hydrophone. The field acquired in this plane can be projected onto other parallel planes using the angular spectrum method\textsuperscript{3}. This method is a numerical technique that predicts how the field evolves as it propagates from one plane to another. The angular spectrum code can then predict the field pattern produced by the transducer at any distance based on the measurements from a single plane. From this point on, this will be referred to as the “hybrid” method since it involves a combination of experimental measurements and numerical modeling. The plates were examined using imaging software (Motic Images). The analysis involved comparing spatial distribution and the relative amount of damage on the plate to the ultrasonic patterns produced by the hybrid method.
RESULTS AND DISCUSSION

In the preliminary study, the effect of the environmental surroundings on the amount of damage incurred in a plate upon exposure was investigated. The plates from these exposures are shown in Figure 11. Damage was evaluated by observing the amount of surface melting that took place along with subsurface cavitation that formed foam-like structures inside the plates (the white color that is seen in the plate pictures). As discussed earlier, the results show that the partially-submerged plate exhibited significant damage from exposure and was subsequently used for the remaining study. The fully-submerged plate and the plate against the tank wall showed little to no signs of damage from exposure. The significant damage of the partially-submerged plate as compared to the other two scenarios is likely due to inefficient transfer of thermal energy to the surrounding air.

![Figure 11: Preliminary exposure test. Figure 11a: Submerged plate (left). Figure 11b: Partially submerged plate (middle). Figure 11c: Plate submerged against tank wall (right).](image)

Figures 12-18 display the damage pattern on the plates due to transducer exposure compared with the fields from the hybrid method. Each figure consists of the plate image from a given exposure distance along with the hybrid-predicted intensity plots from the same distance.
Figure 12a: Plate image at 11.5 cm (left). Figure 12b: 11.5 cm Intensity plot (right).

Figure 13a: Plate image at 11.0 cm (left). Figure 13b: 11.0 cm Intensity plot (right).
Figure 14a: Plate image at 10.5 cm (left). Figure 14b: 10.5 cm Intensity plot (right).

Figure 15a: Plate image at 10.0 cm (left). Figure 15b: 10.0 cm Intensity plot (right).
Figure 16a: Plate image at 9.5 cm (left). Figure 16b: 9.5 cm Intensity plot (right).

Figure 17a: Plate image at 9.0 cm (left). Figure 17b: 9.0 cm Intensity plot (right).
The white areas of the plate images depict damaged areas. In close comparison with the plate images and the amplitude plots, it was concluded that the intensity plots should be measured in the same sense concerning similar imaging patterns. Areas of intensity above 50 W/m^2 (sea-foam blue on the intensity scale) were chosen as the projected damage areas. The total area of impact for the ultrasonic field was a circle positioned at the central node with radius extending to the farthest point of damage in the image. The surface area of the damage was divided by the total area of impact in order to calculate the percent damages shown in Figures 18 & 19.
Figure 19: The calculated percent of damage on the plates compared to the area of impact from the ultrasonic field. Percent damage at corresponding distances: 11.5cm – 16.9%, 11.0cm – 19.3%, 10.5cm – 19.22%, 10.0cm – 10.5%, 9.5cm – 9.7%, 9.0cm – 6.03%, 8.5cm – 2.1%.

Figure 20: The projected percent damage compared to the area of impact from the ultrasonic field provided by the intensity plots. Percent damage at corresponding distances: 11.5cm – 15.69%, 11.0cm – 16.56%, 10.5cm – 15.89%, 10.0cm – 16.1%, 9.5cm – 15.76%, 9.0cm – 15.15%, 8.5cm – 14.91%.
The white areas of the plate images depict damaged areas. In close comparison with the plate images and the amplitude plots, it was concluded that the intensity plots should be measured in the same sense concerning similar imaging patterns. Areas of intensity above 50 W/m^2 (sea-foam blue on the intensity scale) were chosen as the projected damage areas. The total area of impact for the ultrasonic field was a circle positioned at the central node with radius extending to the farthest point of damage in the image. The surface area of the damage was divided by the total area of impact in order to calculate the percent damages shown in Figures 18 & 19.

The intensity and amplitude plots show that the greatest peaks occurred at the 10.0 cm distance. The 11.0 cm and 10.5 cm distances showed greater damage percentages though, correlating closely to the plates. From the method used in determining damage percentages, higher numbers only show that the ultrasonic field had a wider effect, not necessarily stronger. In Figure 19, the 10.5 cm plates show deeper and more complex damage within the plate, including a foam-like structure, which suggests that at 10.5 cm the ultrasonic field was focused enough to travel farther through the acrylic medium. Below 10 cm, the amplitude and intensity plots did not diminish as drastically as the acrylic images, though they did diminish noticeably. The hydrophone was entirely submerged in water and was not surrounded by any material that could reflect or disrupt the sound field, thus the data gathered was representative of the free sound field devoid of boundary effects at each location, whereas the plates reflected the field.

Comparing the acrylic plates at different depths, it can be seen that the most damage occurred at distances between 11.5 and 10.0 cm. As the distance decreased from
10.0 to 8.5 cm, the effect of exposure to the sound field diminished drastically. There are a number of explanations for this result. The reflection and transmission of ultrasound is governed by the acoustic impedances of the materials involved. The acoustic impedance of a material, $Z$, is defined by the product of its density and the speed of sound in the material\(^4\),

$$Z = \rho c.$$ 

The larger the impedance mismatch between two materials, the more energy is reflected from the interface. At the water-acrylic interface, the transfer of acoustic energy is fairly efficient with over 85% of the sound power transmitted. At the air-acrylic interface, only about 0.04% is transmitted, thus the acoustic energy entering from the bottom does not escape out of the top surface to a significant degree. Also, air has a relatively low thermal conductivity so the heat energy generated in the plate due to absorption does not leak into the air at a significant rate.

![Figure 21: Uninterrupted stream with nebulizations (left). Interference caused by halving the distance (right).](image)
Due to diffraction, planar transducers have a natural focus. The pattern and intensity of the field will thus vary with depth because of diffraction. Also, some of the sound energy is reflected back from the water-acrylic interface, and as the transducer-plate separation decreased, the power reflected back onto the transducer grows. This makes the transducer less efficient at generating ultrasonic waves from the applied rf signal. This can be seen by observing the reflected power reading on the rf power source. As the acoustic back-reflections on the transducer grow, the effective electrical impedance of the transducer changes resulting in an increase in the rf power reflected back from the transducer.

![Figure 22: Acrylic plate images from 11.5 cm (top left) to 8.5 cm (bottom right).](image)

When aligned (Figure 22), the plates demonstrate that the ultrasonic field maintained a relatively constant spatial distribution throughout each experiment within the study. The images in Figure 23 illustrate the consistency of the field pattern at the differing distances. Note the consistency of the three horizontal lines indicating damage (white bubbles) in Figures 23a and c, as well as the vertically inverse nature of 23a and c or 23b and d. The front and rear views of the aligned plates, in Figure 24, display what
the image of the ultrasonic field across a distance would look like from the perspective of the transducer and the plates.

Figure 23: Aligned plates show a consistent damage pattern suggesting that the ultrasonic field maintains a similar distribution among the various plates. Relative to sound propagation direction, 23a: left side (top left). 23b: top side (top right). 23c: right side (bottom left). 23d: bottom side (bottom right).
One clear conclusion that can be drawn is that the transducer does not behave like an ideal uniform piston source. Video footage taken of the exposure process displays that the acoustic streaming pattern was not established uniformly as the rf power was increased; also, prolonged usage of the transducer created irregular cavities and intensity areas. This suggests that effective use of a transducer would require a slow, warming process as well as limiting the duration in which the transducer runs at full potential.
This is suitable due to the knowledge that prolonged exposure on human tissue can be detrimental to undesired areas.

Figure 25: Transducer warming up over 20 seconds. Intended geometry at image 6. Image 7 depicts transducer following high power for a prolonged period of time in which the ‘Jolly Roger’ image begins to become apparent (rotated clockwise 120 degrees).
OBSERVATION OF NON-LINEAR PHENOMENA

Videos recorded in the course of this work captured examples of the non-linear phenomena that are mentioned in the Introduction. From these videos, the following picture-sequences show acoustic cavitation, trapping of these bubbles by the ultrasonic field, the fine structure of the field as evidenced by the positions of the smaller trapped bubbles, the onset of acoustic streaming, and the nebulization associated with the acoustic fountain.

Figure 26: Formation of acoustic fountain as power increases in chronological order from top left to bottom right.
Figure 26, above, shows the formation and growth of the acoustic fountain. The capillary waves cannot be seen from this perspective, but the combined capillary wave peaks can be seen beginning with the second picture. As the capillary wave intensity increases in conjunction with power at this high frequency, the peaks become sharper rapidly, thus leading to the nebulization effect that is pictured. As power increases, the acoustic stream generated by the ultrasonic field becomes more concentrated, as indicated by bubble field becoming narrower. Likewise, the bubbles that are visible within the stream increase in size as the power increases, suggesting that as power increases so does cavitation activity and bubble size.

Bubbles produced by acoustic cavitation oscillate in the nodes of the ultrasonic field. Since the water-air interface is highly reflective, a standing wave forms between the water surface and the transducer. Nodes, or areas of zero amplitude within the standing wave, form and can house the bubbles created by acoustic cavitation. As the sound field propagates, the air bubbles oscillate but remain in the same relative node for a period of time (in actuality, the bubbles reside slightly above the nodes due to buoyancy). Over time, the bubbles can jump into higher nodes before eventually escaping into the acoustic stream. The nodes can be visualized as lines of bubbles within the ultrasonic field, as seen in Figure 27. The varying lines represent the standing wave’s nodal lines, which can be differentiated by the distance from the transducer. The photographs in Figure 27 are taken in 5 second intervals to illustrate this.
Figure 27: Photos depicting bubbles that were created by cavitation trapped in the oscillating ultrasonic field. Photos were taken in 5s intervals and are depicted in chronological order from top left to bottom right.
Figure 28: Acoustic bubbles trapped in the nodes of the ultrasonic field. From top left to bottom right, the pictures run chronologically in 10 second intervals.

Figure 28 shows that the same effect can be visualized with a horizontal ultrasonic field. Despite buoyancy acting perpendicular to the direction of sound propagation, the bubbles remained in nearly the same positions over a longer duration than when the ultrasonic field is directed vertical. Figure 27 shows an image of the
ultrasonic cavitation field close to the transducer. The cavitation field within 2-3 cm of the transducer consists of a hollow cylinder made up of streams of bubbles angled slightly outwards. Inside the cylinder are streams of bubbles that form the shape of concentric hourglasses. In the space between the neck of the hourglass and the walls of the cylinder, there exists a space where there seemed to be zero fluid movement. The higher pressures from this space\(^5\) assist in the continuity of the trapped bubbles within the nodal lines and hourglass shape.

Using imaging software (Motic Images), the distance between the visible nodes in both the horizontal and vertical scenarios was found to be .25 cm. This distance was determined from the nodes that were visible to the camera and could represent distances over a number of nodes. The bottom left picture of Figure 27 shows a distinct “ladder” of bubbles in which each bubble, or rung of the ladder, gets closer to the rung above it with each step up. Figure 29, below, provides a perspective of the three-dimensional cylindrical shape provided by the outer limits of the cavitation activity.
Figure 29: The ultrasonic field forms an external hollow cylindrical shell. These pictures help show the 3-Dimensional nature of the field and how the cylinder also exhibits evidence of nodes.
Testing showed that force and momentum resulting from the ultrasonic field can be translated to materials or objects found within that field. When a rotatable plastic frame was placed in front of the ultrasonic field, the position and angle of the frame could be adjusted by raising or lowering the power supplied to the transducer. Further studies could investigate the ability to use a transducer to power locomotion.

Figure 30: In descending order, the pictures portray the effect of the sound field from 10 W to 160 W in 30 W increments.
CONCLUSION

The study showed that the pattern of damage on acrylic plates and different plate-transducer separations matched well to the predictions of the hybrid model in distribution with a good degree of correlation between the damage and field intensity. The processes giving rise to damage are due to non-linear high amplitude effects of the sound field while the hybrid model applies fields that are linear, low amplitude fields. This indicates that the distribution of ultrasonic energy at high power can be modeled reasonably well with the hybrid model. This is somewhat surprising given the dynamics of streaming and cavitation that occurs in the field at high powers, which could have the potential to modify the field in significant ways. The high power field cannot be measured with the hydrophone, as it would likely suffer damage. However, being able to confirm that the hybrid approach still has some ability to match the high power field is significant.
LIST OF REFERENCES


