Experimental Studies concerning Ultrasonic Cleaning

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Introduction

High-intensity ultrasound is nowadays widely used in industrial applications, including cleaning of precision manufactured mechanical parts. Increasing demands on the cleanliness of such parts require an improvement in the design and optimization process of ultrasonic cleaning systems. Due to the high acoustic intensity, cavitation is mostly present. To get a deeper physical understanding of the interrelations inside the cleaning bath, it is necessary to utilize precise simulation and measurement tools to determine the relevant parameters. We will be presenting results from measurements in a cavitating fluid, which is typical for industrial applications. Measurements with a hydrophone and a cavitation sensor are made and sonoluminescence images are taken to visualize the structure of the cavitation field. The results are compared with cavitation erosion tests and with finite element (FE) simulations in which the influence of cavitation is taken into account. Additionally, the influence of a probe in a non-cavitating fluid will be shown.

Distortion of the sound field by a probe

The following investigations with a laser vibrometer show the advantages of contactless measurements in sound fields over measurements with probes placed into the fluid.
In order to do this a glass tube with an inner diameter of 20 mm was closed at the bottom with a stepped horn transducer and filled with desalinated water. The thickness of the wall (5 mm) is quite large to avoid parasitic vibrations of the glass tube. The laser beam was sent through the resonantly vibrating fluid column ($f = 23{,}25\,\mathrm{kHz}$) and reflected on a reflector fixed behind it (see Figure 1). The plane standing wave inside the fluid locally changes the fluid density and with it the refractive index. This causes a change of the optical path length of the measured distance. Thus, a pressure change in the measured medium leads to a virtual deflection of the rigid reflector which is registered by the laser vibrometer [1]. Figure 1 shows the distribution of the pressure amplitudes measured in this way. In a second experiment a hydrophone with an outer diameter of 3 mm was placed into the fluid and moved incrementally along the tube axis. Straight below the tip of the hydrophone the laser beam was sent through the medium. The result of this vibrometer measurement is also shown in Figure 1 and indicates that – especially in a resonantly vibrating fluid column – using a contactless measurement technique can avoid the distortion that is caused by placing a probe into the fluid.
A laser vibrometer can't be used to measure in cavitation fields because the cavitation bubbles would disturb the laser beam on its way through the fluid.

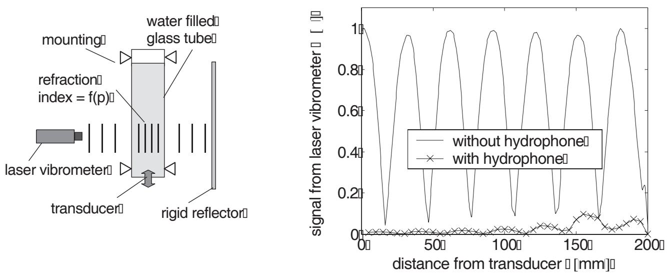

Figure 1: Standing wave in a glass tube – interference by a hydrophone (right). Setup for the measurements (left).

Standing waves in a cavitating fluid

The measurements presented in this section were taken in cavitating and hence extremely nonlinear fluids occuring in ultrasonic cleaning applications.

Measurements with a hydrophone

In these experiments a thick-walled stainless steel tube with an inner diameter of 20 mm was filled with degassed completely desalinated water. The driving frequency of the transducer at the bottom end was 27 kHz. Under these conditions a plane standing wave develops inside the tube that can be considered as an example for the sound fields in narrow holes or borings. Measurements were taken along the tube axis using a thin hydrophone which is resistant to cavitation [2]. Figure 2 shows the absolute values of the maximum pressure amplitudes measured along the axis. Here, the time signal was averaged over 256 times to smooth out the cavitation noise. The results were compared with those of FE simulations. In the simulation the influence of cavitation on the sound field propagation was allowed for by changing the material parameters. The areas in which the parameters were changed were determined through cavitation erosion experiments on a piece of aluminum foil. In these regions density, sound speed and nonlinearity parameter were set according to the formulas provided by Naugolnykh and Ostrovsky [3]. It was assumed that the volume gas concentration was $2 \cdot 10^{-6}$ and the Rayleigh attenuation coefficient β was 10^{-6}. In the other regions the normal parameters of cavitation-free water were used. Table 1 shows the nonlinear distortion factors derived

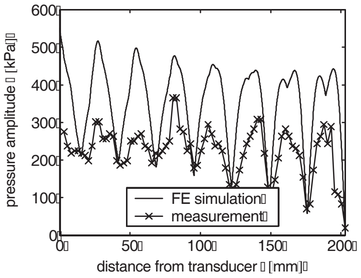

Figure 2: Comparison of experimental and numerical data for the cavitation field.

from the signals taken from the measurements and FE simulations. The factors k_2 to k_4 were spatially averaged over all points along the tube axis.

	k_2	k_3	k_4
measurement	0,23	0,07	0,14
FE simulation	0,35	0,15	0,05

Table 1: Spatially averaged nonlinear distortion factors

Measurements with a CCD camera

In ultrasonic cleaning applications multidimensional standing waves also occur. With the help of a sensitive CCD (Charge Coupled Device) camera a plexiglass tube was observed in complete darkness. The tube, which had an inner diameter of 140 mm, was closed at the bottom end with a vibrating membrane. The cavitation bubbles emit light sparks on implosion. This phenomenon is known as sonoluminescence. Figure 3 shows a sonoluminescence image taken with the CCD camera which clearly shows the zones in which light emissions occured. In order to establish a connection between these zones and the effects of cavitation, a thin piece of aluminum foil was exposed to the same sound field. A correlation between the sonoluminescent areas and the areas of cavitation erosion in the aluminum foil was apparent. Finally the sound pressure was measured with the thin ceramic hydrophone. The maximum pressure amplitudes lay within those regions in which sonoluminescence and cavitation erosion had been observed. Thereby, a correlation between the structures of the pressure field and the cavitation field and the zones of sonoluminescene could be shown.

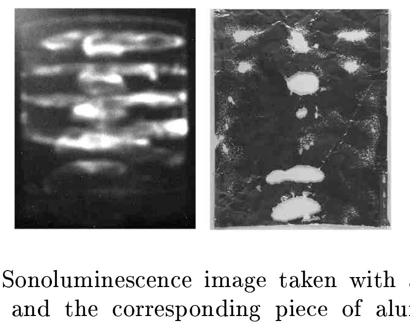

Figure 3: Sonoluminescence image taken with a CCD camera (left) and the corresponding piece of aluminum foil (right).

Measurements with a cavitation sensor

The so called cavitation sensor [4] allows monitoring of cavitation activity inside high-intensity ultrasonic fields. A thin piezoelectric polymer in the form of a hollow cylinder detects the high-frequency signals generated by cavitating bubble events. One of the key characteristics of the sensor is its spatial resolution. A special absorbing layer around the sensitive polymer allows to isolate the cavitation events within the cylinder itself from those produced in the fluid outside the cylinder. The measurements presented here were taken in the already mentioned plexiglass tube. The sensor was moved along the tube axis from the water surface to the membrane. Figure 4 shows the signal of the cavitation sensor compared with the eroded regions in the aluminum foil (see Figure 3) around the tube axis.

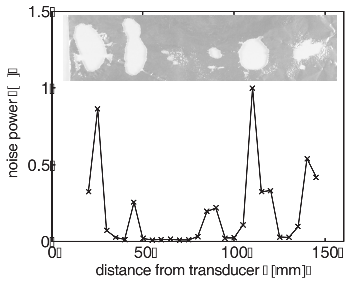

Figure 4: Correlation between the signal of the cavitation sensor and a cavitation erosion experiment.

Conclusion

We presented measurement results of standing waves in cavitating fluid. For a plane standing wave measurements of the sound pressure were carried out and the data were compared with those of FE simulations including a cavitation model. A satisfactory level of accuracy was achieved. In a multidimensional standing wave a good correlation between measurement results and the erosion structure in an aluminum foil could be demonstrated.

References

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