EXPERIMENTAL STUDIES OF STANDING WAVES IN FLUID MEDIA

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Abstract

High intensity standing waves in the low frequency range of ultrasonics are very important for many industrial applications. Here cavitation often occurs.

In this paper we will be presenting the results of our research into using various measuring techniques for standing wave fields. Measurements were carried out in cylindrical containers filled with water, both with and without cavitation. Hydrophones and a laser vibrometer were used as measuring instruments. The results of our experiments, when compared with those of the finite-element (FE) simulations, showed a high level of agreement.

Introduction

High intensity ultrasonic waves are often used for industrial purposes, e.g. cleaning precision manufactured components or in sonochemistry. In the mentioned examples, the transducers work in continuous mode as opposed to using sound bursts.

A standing wave field builds within the radiated medium due to this continuous insonification and reflections at the interfaces (walls of the container, components, cleaning medium/air).

Because of the complex interaction of standing waves and high intensity effects, many of the mentioned systems which use high intensity ultrasonic waves are still being designed empirically. In order to optimize such apparatus the standing wave field inside the medium must be known as precisely as possible. This paper investigates measurement techniques for standing waves in fluids to be used in the design process of industrial ultrasonic applications.

Firstly, we will describe techniques which make it possible to characterize ultrasonic systems consisting of a transducer and a container filled with fluid by means of experiments.

Next, measuring techniques will be described, which allow the sound field inside the container to be measured and represented visually. The measurements were made both in non-cavitating and in cavitating and hence extremely nonlinear fluids.

The measured pressure values are compared with FE-simulations.

Characterization of the ultrasonic systems

Defining the input parameters for the FE-simulation

One of our aims was to compare the sound pressure values gained from the experiments with those of the FE-simulation. In order to do this, the acoustic irradiation in our experiments and in our simulations must be identical. One way to ascertain this is to precisely model the entire construction of a transducer in the FE-simulation.

In the above mentioned industrial applications prestressed piezoelectric sandwich transducers are usually employed. Because of this many important parameters for FE-modelling are difficult to obtain (e.g. mechanical prestress of the transducer, material parameters of the backing elements and the adhesive between transducer and the wall of the container). For this reason matching the amplitudes of deflection of the sound radiating surface is an appropriate alternative to ascertaining identical sound generation in simulation and experiment. The velocity at the transducer surface was measured with a laser vibrometer, thereby calculating the amplitudes of deflection by integration. Figure 1 shows the velocity amplitudes on the bottom of a commercial cleaning bath. The maximum values occured between the four transducers.

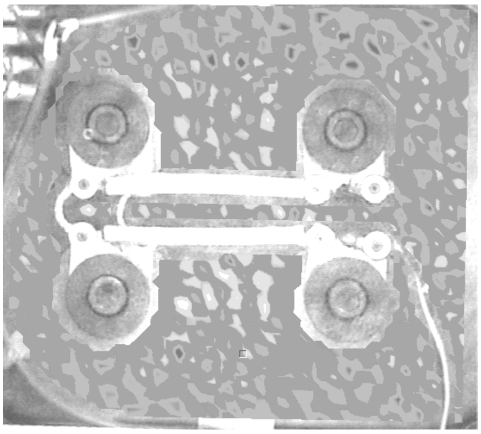

Figure 1: Distribution of the velocity amplitudes on the bottom of an ultrasonic cleaning bath measured with a scanning laser vibrometer.

These deflection values will be used as input parameters in the FE-simulations which are presented in this paper.

Defining the acoustic resonances of ultrasonic systems

When comparing experimental and numerical data it is of particular importance whether the system is driven in resonance or in antiresonance. In case of a resonance the system reacts fairly sensitively to slight variations of parameters (driving frequency, filling level, attenuation parameters) while in the case of antiresonance the system is quite stable.

To achieve high sound pressure amplitudes in the fluid it is important to drive the piezoelectric transducer close to one of its electric resonances. Both electric and acoustic resonances of an ultrasonic system can be found by examining electric impedance curves. The impedance curve of a system, consisting of a transducer and an empty container, can be determined using an impedance analyzer. The electric resonances show up clearly. When observing the whole system with a filled reactor, one can see that the electric resonances are shifted and further resonances occur due to the fluid load. These correspond with the resonance frequencies of the liquid volume within the container, which can be calculated analytically for the fluid-filled half-closed cylindrical volume used in our experiments. Figure 2 shows such two impedance curves demonstrating the electric and acoustic resonances and the high level of agreement with the analytic formula. The equidistant acoustic resonances show that a plane wave forms due to the large relationship between wave length and inner radius of the cylinder.

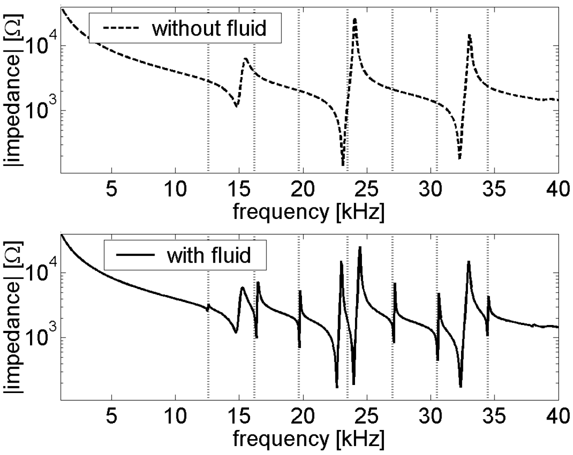

Figure 2: Measured impedance curves of an ultrasonic system (filling level 203mm, inner diameter 20mm) with and without medium. The vertical dotted lines show the analytic values of the resonances of the fluid column.

Investigations of a propagating wave

The technique described above used to determine the amplitudes of deflection of a transducer was verified by measurements in a propagating wave. The transducer was placed in a measuring tank (100*50*50cm³) lined with sound absorbing material and activated with an amplitude modulated sinusoidal voltage signal (sine burst). In this setup the emitted wave cycle did not interfere with its reflections and as a result no standing wave field occurred.

The pressure signal was measured with a PVDF (Polyvinylidene Fluoride) needle hydrophone at different distances from the vibrating surface along the acoustic axis (see Figure 3). The results were compared with those of linear FE-simulations and in addition with analytic solutions, in which the transducer was considered as a piston.

In this comparison, both, the signal form and the decrease in amplitude with increasing distance from the vibrating surface show a high level of correspondence.

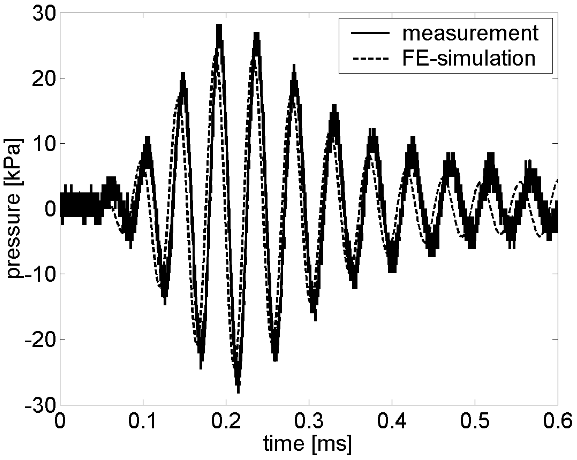

Figure 3: Pressure pulse recorded 10mm away from the radiating surface.

Investigations of standing wave fields

Wave propagation in the reactor

After the preliminary examinations of pulsed signals, standing wave fields were investigated. During these investigations stainless steel tubes of differing lengths and diameters were used as test reactors. The lowest cut-off frequency of such a tube (considered rigid edged) is [4]

$$f = \frac{c}{2\pi \cdot r_i} \cdot 1{,}8412$$

where the effective sound speed is c and the inner radius of the tube is r_i.

Below this frequency a plane wave propagates. The cylindrical symmetry has the advantage of allowing simulations of angle-independent modes of the fluid column to be carried out axis symmetrically. This saves calculation time significantly. Moreover, analytical formulas are available for certain cases.

With ultrasonic waves in fluids, tubes made of solid material such as stainless steel cannot be presumed to be rigid. As the tube wall also vibrates, a perfectly symmetrical sound excitation is difficult to achieve and, hence, it is practically impossible to take any measurements in standing wave fields above the first cut-off frequency. Below the first cut-off frequency the vibration of the wall has the effect of altering the effective sound speed in the liquid [1].

Pressure measurements in a plane standing wave in a non-cavitating fluid using hydrophones

For the experiments a thick-walled tube with an inner diameter of 20mm was constructed. The excitation frequency was varied between 16 and 32kHz and, therefore, below the first cut-off frequency, which is in this case 43kHz.

In the framework of these experiments resonance curves were recorded by varying the frequency while keeping the amplitudes of deflection constant. For the resonance curves the maximum pressure amplitude in the fluid inside the tube was recorded. The constancy of deflection amplitude was achieved by monitoring the deflection using a 3D laser vibrometer focussed on a point on the casing surface of the transducer. The amplitude was varied as required by changing the electrical input values of the transducer.

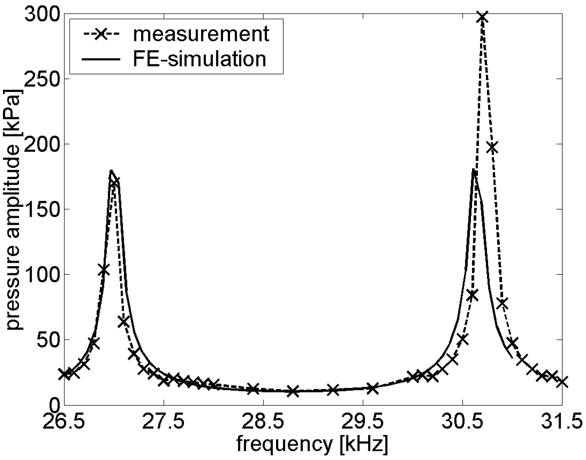

Figure 4: Resonance curve for a thick-walled water-filled tube

Figure 4 compares the measured maximum pressure amplitudes in the fluid with the result from the linear FE-simulation. The amplitude of deflection was set to 40nm in this experiment. Over the entire frequency range both results corresponded well. Near acoustic resonance frequencies disparities in amplitude and position of resonance were observed. These disparities were due to slight differences between experiment and simulation (value of attenuation parameters, small variations in filling level, possible onset of cavitation due to high pressure amplitudes).

Pressure measurements in a plane standing wave in a non-cavitating fluid using a laser vibrometer

A laser vibrometer was used to avoid distortion caused by placing a probe into the fluid. Using this instrument the distribution of the pressure amplitudes in a plane standing wave could be shown qualitatively. In order to do this the thick-walled stainless steel tube was replaced by a glass tube with the same inner diameter. The laser beam was sent through the medium and reflected on a reflector fixed behind it. The sound field 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 [2]. Figure 5 shows the distribution of the pressure amplitudes in a glass tube measured in this way. The results gained with this technique can be distorted by the vibrations of the glass tube which lead to a difference in the ratio of water to air distance.

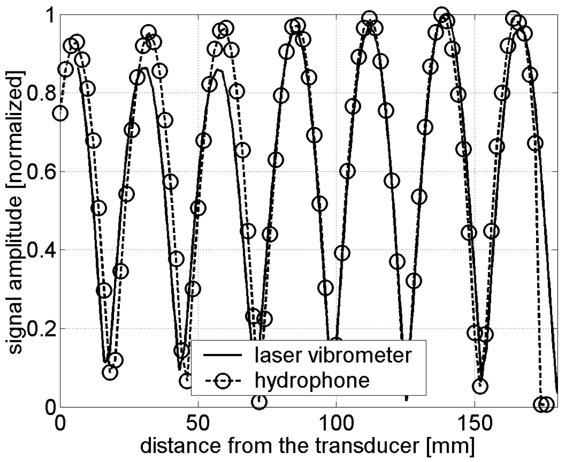

Figure 5: Showing the standing wave structure in a water-filled glass tube using a laser vibrometer

Pressure measurements in a plane standing wave in a cavitating fluid using hydrophones

Proceeding from the linear pressure region considered so far, the amplitude of deflection of the transducer was raised to reach the region of nonlinear sound propagation. In our experimental situation nonlinear effects which occur in high pressure amplitude sound waves (e.g. distortion of the wave form) could not be observed separately from cavitation. It is known that cavitation itself leads to nonlinearity in the medium [5].

The measurements presented here were taken in the thick-walled stainless steel tube with an inner diameter of 20mm. In this case the amplitude of deflection was 430nm. Degassed completely desalinated water was used as fluid. The driving frequency of the transducer was 27kHz. Measurements were taken along the tube axis using a thin ceramic hydrophone (diameter 3mm) which is resistant to cavitation [3]. Figure 6 shows the absolute values of 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 [5]. 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.

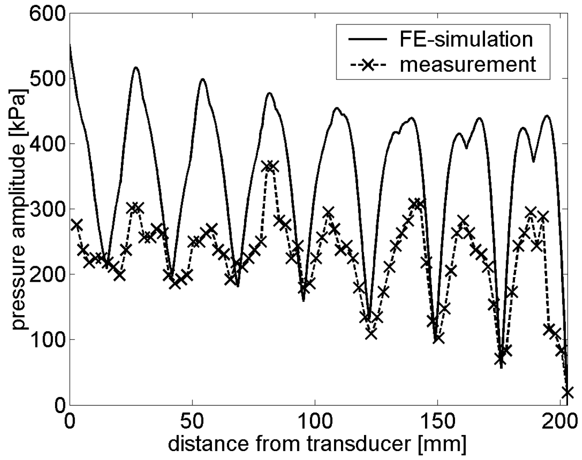

Figure 6: Comparison of experimental and numerical data for the cavitation field

Table 1 shows the nonlinear distortion factors derived from the signals from the measurements and FE-simulations. The factors k2 to k4 were spatially averaged over all points along the tube axis.

Table 1: Nonlinear distortion factors

	measurement	FE-simulation
k2	0,23	0,35
k3	0,07	0,15
k4	0,14	0,05

Multidimensional standing waves in a cavitating fluid

In the above mentioned industrial applications multidimensional standing wave fields also occur. With the help of a sensitive CCD-(Charge Coupled Device) camera a transparent synthetic tube was observed in complete darkness. The tube, which had an inner diameter of 140mm, was closed at the bottom end with a transducer. The cavitation bubbles emit light sparks on implosion. This phenomenon is known as sonoluminescence.

Figure 7 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.

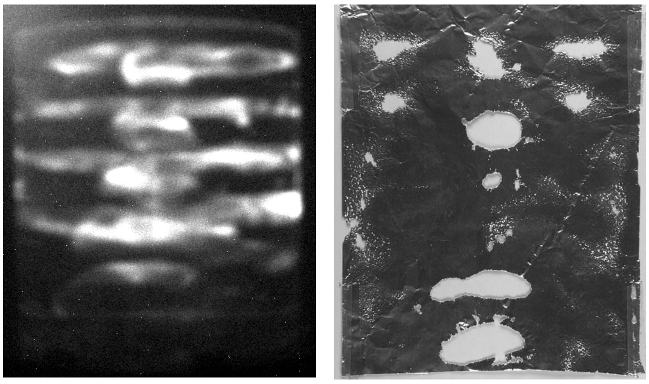

Figure 7: Sonoluminescence image taken with the CCD-camera and the corresponding piece of aluminum foil.

Thereby a correlation between the structures of the pressure field and the cavitation field and the zones of sonoluminescene could be shown.

Conclusion

We presented measurement results in plane standing acoustic wave fields. These were compared with results from the linear FE-simulation and a high level of correspondence could be found.

For a standing wave in a cavitating nonlinear fluid, which is typical for industrial applications, measurements of the sound pressure were also carried out. These data were compared with an implemented cavitation model in our simulation program and a satisfactory level of accuracy was achieved. The connection between the pressure measurement results and the structure of the cavitation field could be proved.

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