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SOUND FIELD DESIGN FOR ULTRASONICALLY ASSISTED COMPOSITE CASTING

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Abstract. *In the process of composite casting, two metals are cast simultaneously into the same mould. This process can be applied, for example, to the joining of copper and aluminum in heat sinks with very high thermal conductivity.*

We have investigated the process of ultrasonically assisted composite casting by experiments with aluminum and Magnesium, using copper plates as a separation layer. First experiments, which were performed without ultrasound showed that the connection between copper and aluminum was poor. Based on the hypothesis that the main reasons for the poor connection were impurities and oxide layers on the plate, the application of ultrasound was proposed. And, indeed, it was possible to achieve better connection qualities when ultrasound was applied.

In this contribution we report studies on a process where aluminum is cast into a mold, in which a solid block of copper is already present. The ultrasound is applied while the melt is still liquid. To achieve a good connection between the entire copper block and aluminum a high energy ultrasound field is generated, which triggers cavitation all over the copper block's surface. The shape of the sound field depends on the radiation characteristics and on the impedance matching of the ultrasonic horns of the excitation system. Various types of horn designs have been studied and evaluated.

1 INTRODUCTION

Complex heat sinks, consisting of several parts and often manufactured from aluminum and copper, are installed in today's electronics to dissipate heat produced by processors with steadily increasing power. Conventional manufacturing and assembling methods show shortcomings regarding thermal conduction and process complexity. Composite casting offers the opportunity of manufacturing heat sinks consisting of different metals in one production step during master forming.

For good heat transport between the individual components of the heat sink and good cooling performance of the overall system, a low thermal contact resistance is mandatory. To minimize the contact resistance of the connection between the components a large contact area with minimal defects is needed. For joining the individual parts three basic methods are commonly used: mechanical joining (pressing in), soldering or clamping in combination with heat-conductive paste.

Of these joining techniques soldering provides the best heat conduction (Solder in Figure 1). Mechanical joining leaves local air-filled cavities with poor thermal conduction (0,025 W/mK) at the interfaces of the individual parts. Using heat-conductive paste the air is replaced and a better thermal conduction (10,5 W/mK) can be achieved. For soldering heat sink components, tin-based solders are used which have the highest thermal conduction (66 W/mK) of the mentioned joining methods. Compared to the values of thermal conduction of the base materials (aluminum and copper), the values achieved by the mentioned joining methods are more than three times smaller.

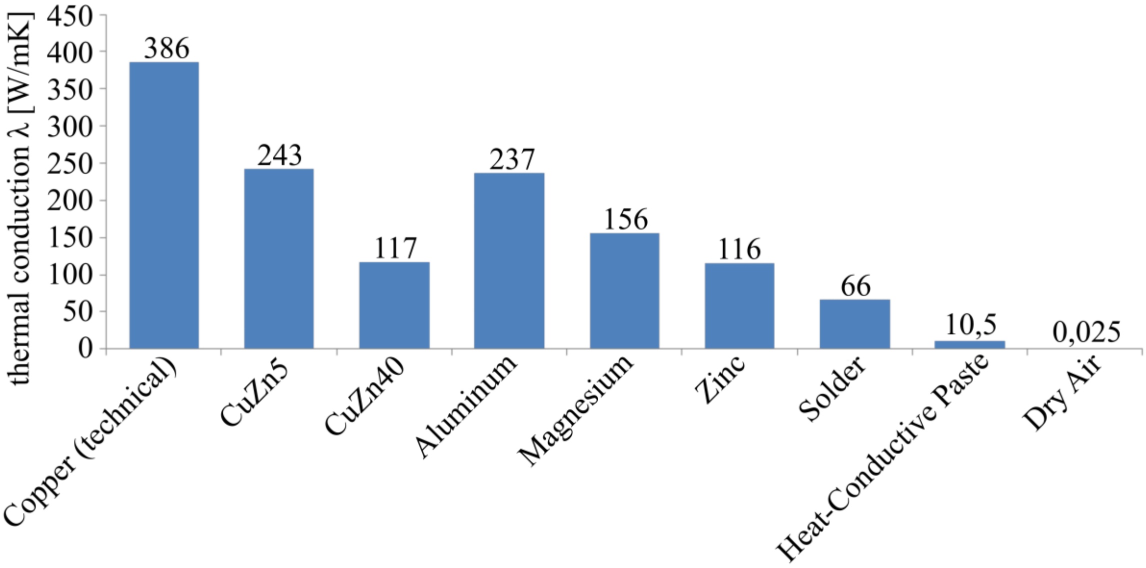
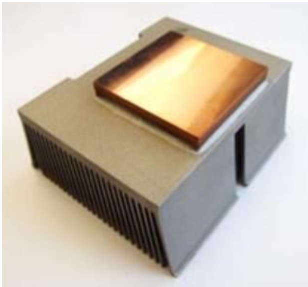


Figure 1: Thermal conduction in comparison [1-3].

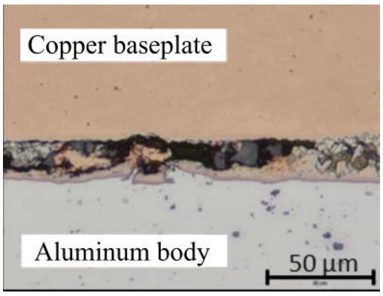
Soldering provides better thermal conduction than the other joining methods. Aluminum heat sinks with soldered copper base plate, joined, however, with insufficient process management, can have an irregular soldering seam, as can be seen in Figure 2. The soldering seem, shown in Figure 2 b), shows air entrapments and contamination in the composite zone at the centre of the joined metal parts.

Composite casting, from an economic and technological point of view, is an attractive technology for the implementation of the presented material combination. The manufacturing steps master forming and joining are integrated into one step.

Many process steps needed for the preparation and conduction of an alternative soldering process are eliminated or already integrated into the casting process. Composite casting produces a cohesive connection between the individual parts, which provides high heat conduction.



a) Aluminum heat sink with copper baseplate



b) Soldering seem in the centre of the heat sink

Figure 2: Soldering seem of a CPU-cooler.

Casting experiments revealed difficulties in the connection of solid copper parts with aluminum melt. As main reason poor wetting due to oxide layers on the copper's surface, leading to insufficient connection between the two metals, were determined [4-6]. To clean the surface and improve wetting, the application of ultrasound and thereby the onset of cavitation was proposed. Experiments in which copper disks were excited with ultrasound and submerged in aluminum melt showed improvement of the connection between disks and melt which was ascribed to cavitation [7].

In further experiments aluminum melt is to be cast into a mold, in which a solid block of copper is already present. In these experiments the melt has to be sonicated in order to trigger cavitation on the copper block's surface. To get an impression of the sound field that forms in the melt and to optimize the sound field, finite element simulations of the experimental setup were carried out.

2 EXPERIMENTAL SETUP

In simulations of the sound propagation the physical quantities, in particular speed of sound and density of the fluid, have to be entered as parameters. For aluminium melt these data are difficult to access and usually need to be acquired in experiments. Therefore in the simulations presented in this article, the parameters for water, which is a well-studied liquid, have been used. Another advantage of this choice is that the acoustic field in water can be measured using a laser vibrometer, while this is impossible in liquid aluminum.

The setup for the casting experiments and the simulations is shown in figure 3. In the sketch on the left the principle of sonicating the melt, while a solid copper block is present in the mold, is shown. The centre of figure 3 shows a CAD-model of the experimental setup. Here the vibration structure, consisting of a piezoelectric transducer and a horn, is partially submerged in a glass tank filled with water. The content of the tank is modelled using two-dimensional finite elements.

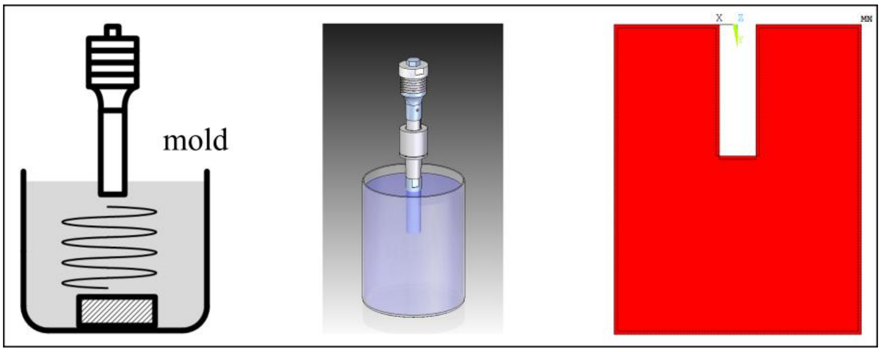


Figure 3: Left: Sketch of experimental setup; Centre: Experimental setup as CAD drawing; Right: Two-dimensional geometry modelling the fluid for finite element computations.

Horns with different geometries were modelled. CAD-models of four geometries are shown in figure 4. The first horn on the left has a diameter of 30 mm and a plane tip. The next horn has the same diameter but a convex tip. At the centre right position a horn with a conically shaped tip is shown. The diameter at which the conical part starts is 40 mm. For calculations the conical horn was modelled without the stepped diameter on the shaft. The same applies to the fourth horn, shown on the right side of figure 4. This horn again has a plane tip, but the diameter at the end is 40 mm.

FE-computations were conducted using ANSYS. Only the fluid was modelled and the immersed horn was considered as a cavity in the model. The immersion depth was the same for all horns.

Modal analyses were performed for the different resulting fluid geometries. The frequency range considered in the analyses was 18 to 20 kHz. This is the preferred frequency range for the casting experiments. One of the calculated eigenvectors was chosen to be suitable to produce cavitation at the bottom of the vessel. Harmonic analyses were performed in which the selected eigenvector should be excited. Here, the frequencies calculated in the related modal analysis were used for each horn. For the calculations the elements on the outer edges and at the bottom of the vessel were configured to have no displacement in any direction. For the harmonic analyses a displacement of 1 µm in longitudinal direction was applied to the nodes that form the negative of the horn geometry. Lateral contraction of the horns was neglected.

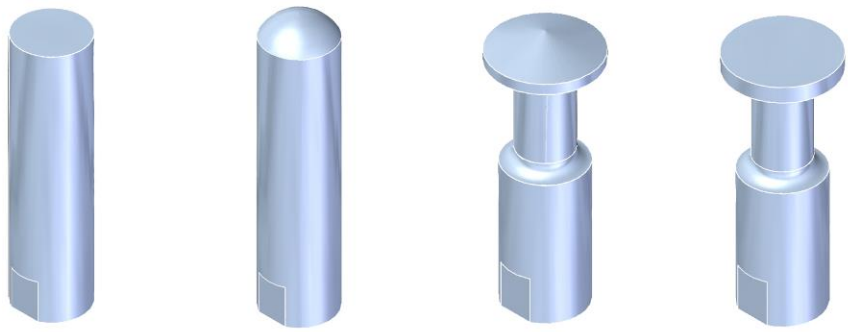


Figure 4: Different horn geometries used in simulations.

Two different element types were used to create the fluid models for the simulations. These element types are recommended by the software vendors for acoustics simulations in fluids. The first type was FLUID29, a two-dimensional axisymmetric acoustic fluid element, which includes speed of sound and density as material properties. The acoustic wave equation solved when this element type is used is given in Eq.1:

$$\frac{1}{c^2}\frac{\partial^2 P}{\delta t^2} - \nabla^2 P = 0 \qquad (1)$$

In this equation c is the speed of sound, P the acoustic pressure and t time. Assuming an inviscid, compressible fluid, no attenuation within the fluid is taken into account. Further assumptions made for solving Eq. 1 are that there is no mean flow in the fluid and the mean density and pressure are uniform throughout the fluid.

Using this element type to create the geometry, only half of a two-dimensional cross-section has to be modelled. This 2-D section can then be expanded by rotation around the longitudinal axis. The resulting three-dimensional model can represent rotationally symmetrical sound propagation only. Other propagation modes can not be calculated on the basis of the applied model building.

The second element type used for modeling the fluid geometry was FLUID220. This element type is a three-dimensional acoustic fluid element of higher order with 20 nodes on each element, exhibiting quadratic displacement. In contrast to the previous element type, models build with FLUID220 elements do consider attenuation within the fluid. Apart from speed of sound and density, viscosity needs to be specified as material property. When FLUID220 elements are used equation 1 is solved applying the same assumptions as when modeling with FLUID29 elements.

First the expanded two-dimensional models are used for analysis. The three-dimensional element type is then used as a comparison.

3 RESULTS

In this section the results of modal and harmonic analyses are presented for the different horn shapes shown in figure 4. The calculated pressure variations have to be interpreted as changes to the static pressure of 100.000 Pa. For all simulations the cavity representing the horn was excitation with a harmonic displacement of 1 µm.

The eigenvector for the plane horn, 30 mm in diameter, and the corresponding simulated harmonic propagation of sound are shown in figure 5. The frequency calculated for the eigenvector is 18119,8 Hz. For the harmonic analysis 18119 Hz was used as excitation frequency.

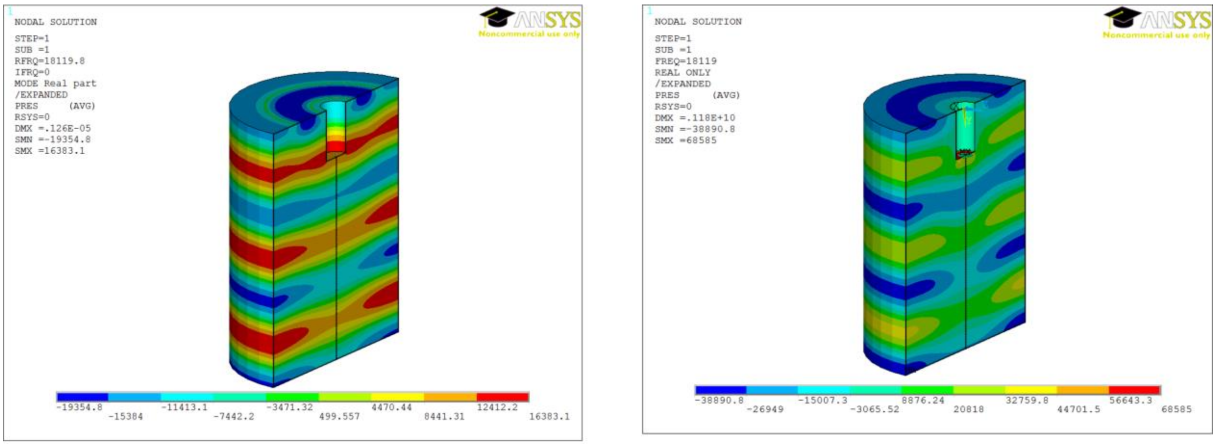


Figure 5: Results for plane horn using FLUID29 elements; Left: Eigenvector at 18119,8 Hz; Right: Pressure distribution radiated by plane horn with 30 mm diameter at 18119 Hz.

The eigenvector, that was chosen to be excited, shows alternating areas of maximum and minimum pressure over the entire width of the vessel. This pressure distribution is well reproduced by the harmonic excitation. The eigenvector is excited by the harmonic analysis. It is noteworthy that the maximum pressure calculated in the harmonic analysis occurs at the tip of the horn.

Figure 6 shows the eigenvector for the convex horn and the corresponding simulated harmonic propagation of sound. With 18109,4 Hz the frequency for the eigenvector differs slightly from the frequency calculated for the plane horns mode. Like before the results were calculated with FLUID29 elements. For the convex horn the eigenvector looks similar to the one calculated for the plane sonotrode. Only the areas of maximum and minimum pressure have an altered grading over the width. The harmonic analysis reproduces the distribution of maximum and minimum pressure zones well. Again, the eigenvector is excited by the harmonic excitation. Compared to the plane sonotrode (figure 5), the calculated pressure values are smaller be factor 20 and higher. Again, the maximum pressure occurs at the tip of the sonotrode.

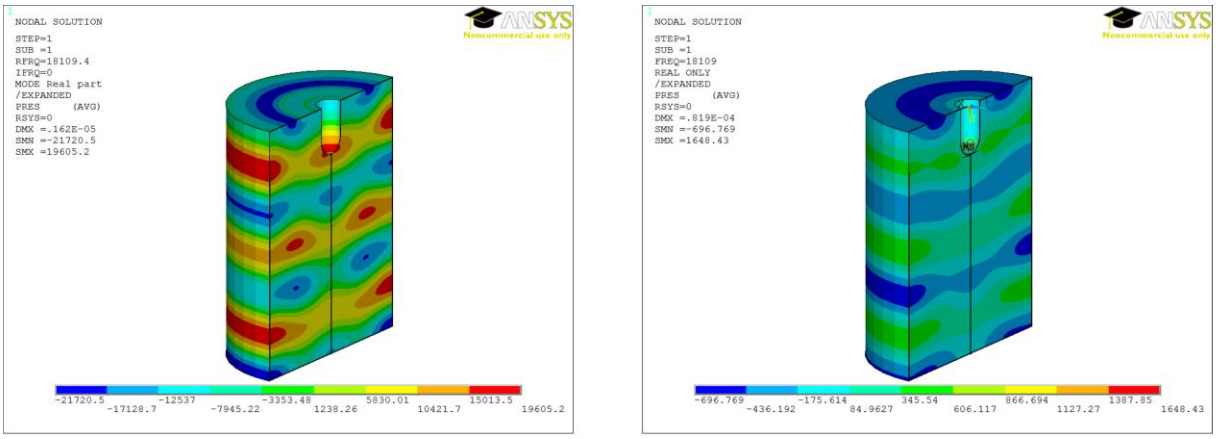


Figure 6: Results for convex horn using FLUID29 elements; Left: Eigenvector at 18109,4 Hz; Right: Pressure distribution radiated by convex horn with 30 mm diameter at 18109 Hz.

For the modal analysis with the conical horn the start frequency had to be changed to 17 kHz to calculate the desired eigenvector. The results of the calculations for the conical horn are shown in figure 7. The eigenvector looks quite similar to the ones already discussed. Its frequency of 17860 Hz is lower then the frequency for the convex and plane horn. The harmonic analysis shows, that the eigenvector can not be excited with this horn geometry. The maximum pressure occurs at the plane backside of the conical horn's tip. A magnification of this area is shown in figure 8.

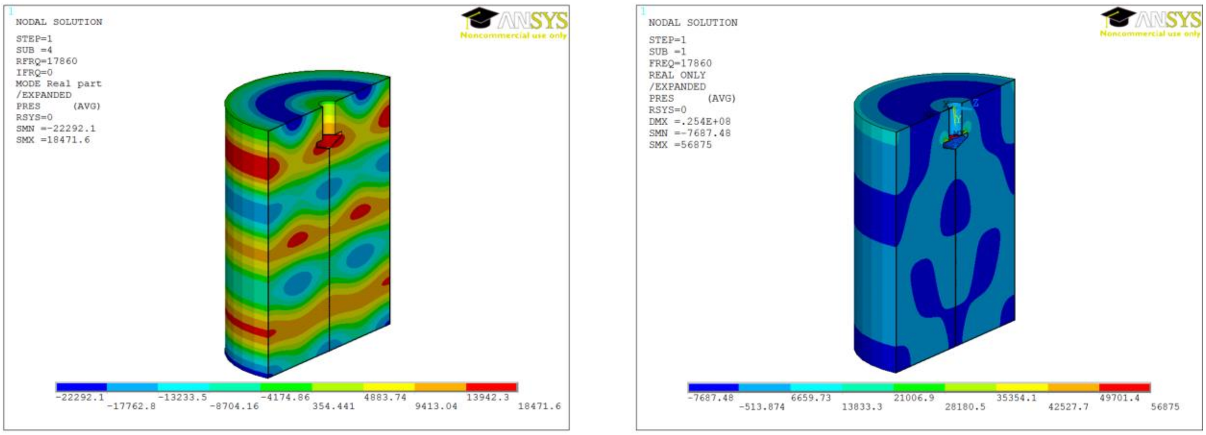


Figure 7: Results for conical horn using FLUID29 elements; Left: Eigenvector at 17860 Hz; Right: Pressure distribution radiated by conical horn with 40 mm diameter at 17860 Hz.

The maximum pressure occurs on the flat backside of the increased diameter of the horn. Figure 9 shows the eigenvector for the plane horn with a diameter of 40 mm and the corresponding simulated harmonic propagation of sound. The zone in which the maximum pressure appears for the eigenvector is on the backside of the horn's tip. The maximum and minimum pressure zones extend over the full width of the vessel. In the harmonic analysis the maximum pressure also occurs at the tip of the horn. In contrast to the eigenvector the zone of maximum pressure is at the bottom of the horn. This is a difference to the eigenvector. A magnification of this zone is shown in figure 10.

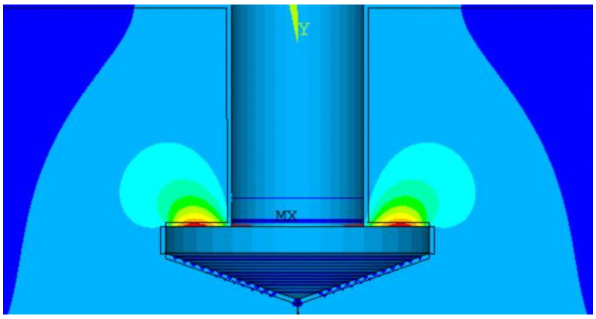


Figure 8: Magnification of the pressure distribution at the conical horn simulated with FLUID29 elements.

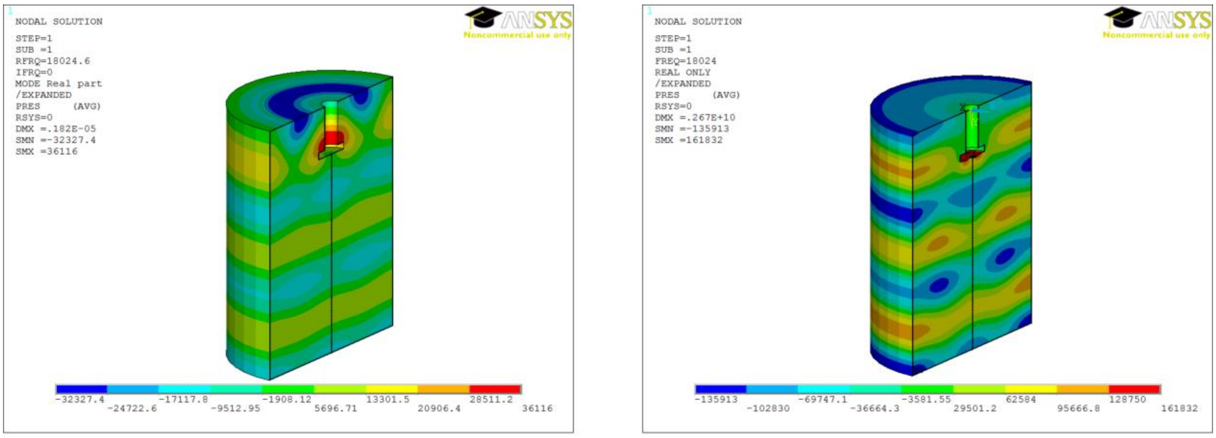


Figure 9: Results for plane horn with 40 mm diameter using FLUID29 elements; Left: Eigenvector at 18024,6 Hz; Right: Pressure distribution radiated by plane horn with 40 mm diameter at 18024 Hz.

The pressure distribution calculated by the harmonic analysis shows, that the eigenvector can be excited well with the maximum pressure occurring at the bottom of the horn. In this simulation the calculate pressure values are the highest. The minimum pressure value even exceeds -100.000 Pa. This would lead to a negative absolute pressure which is obviously not possible. The reason for this may be a linear model used by the software to calculate the pressure. From this result it can be concluded that the plane horn with a diameter of 40 mm generates the highest pressures.

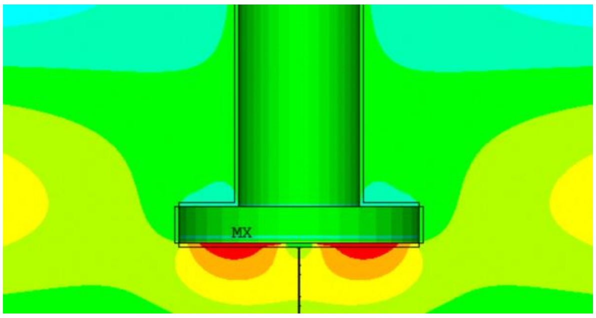


Figure 10: Pressure distribution from harmonic analysis at the plane horn with 40 mm diameter simulated with FLUID29 elements.

The results discussed so far were calculated on the basis of models, which can only provide rotationally symmetric results. Figure 11 shows the eigenvector for the plane horn with a diameter of 30 mm and the corresponding simulated harmonic propagation of sound calculated with three-dimensional FLUID220 elements. The used model is formed as a three-dimensionally volume, and not by rotation about an axis of symmetry. Therefore, this model can provide pressure distributions, which are not only rotationally symmetrical. This difference is already evident in the modal analysis. A modal analysis for the two-dimensional models in the range from 18 kHz to 22 kHz provided 6 eigenvectors. The same analysis for the three-dimensional model for the same frequency range resulted in 65 eigenvectors. Only four of these eigenvectors were rotationally symmetrical.

From these four eigenvectors the one that is most similar to the eigenvectors calculated for the two-dimensional models was chosen for comparison. It can be seen that the shape of the sound field calculated with FLUID220 elements is rotationally symmetrical as well. A difference is an additional maximum pressure zone at the bottom of the vessel. This additional zone appears due to the higher frequency of the eigenvector. The frequency this vector occurs at is 20785,5 Hz. The difference in frequency may be explained by a finer mesh in the three dimensional model. With the same average element size and a higher number of nodes for each element for the three-dimensional model, the grid is finer.

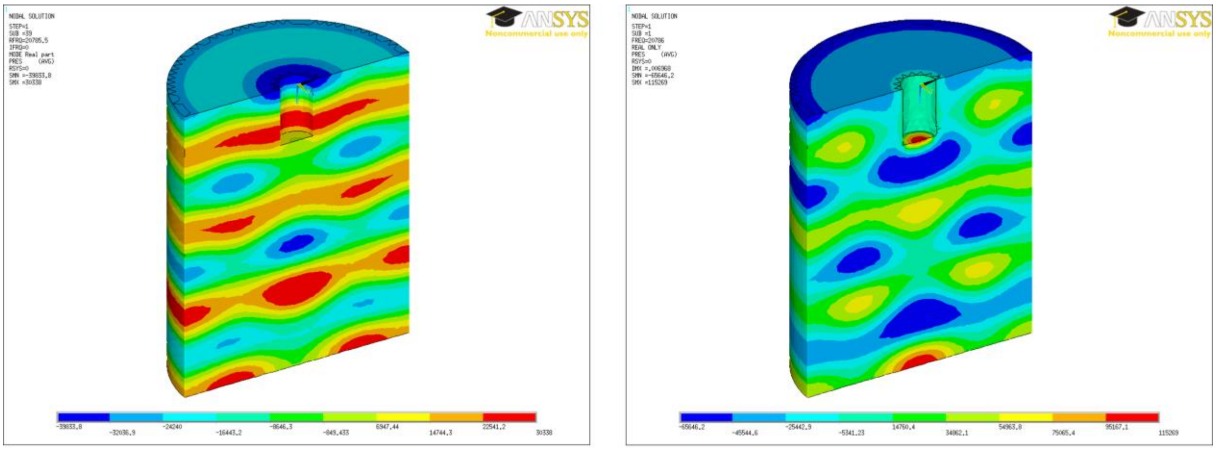


Figure 11: Results for plane horn with 30 mm diameter using FLUID220 elements; Left: Eigenvector at 20785,5 Hz; Right: Pressure distribution radiated by plane horn with 30 mm diameter at 20786 Hz

The harmonic analysis performed for the three-dimensional model shows that the eigenvector is excited. The zones of maximum and minimum pressure are in phase. Also the pressure zones extend over the entire width of the vessel. Compared to the two-dimensional solution the maximum and minimum pressure values are higher in the 3D-model. The calculated maximum pressure occurs not only at the tip of the horn, but also at the bottom of the vessel in the additional maximum pressure zone.

4 CONCLUSION

The shape of the sound field that is formed in a container filled with water was designed using different shaped horns at a rotationally symmetrical pressure distribution mode. The fluid geometry was modelled with two different element types: One two-dimensional, rotationally symmetrical, and one three-dimensional element type. With the two-dimensional element type only rotationally symmetric pressure distributions could be calculated, while the three-dimensional element type also provided non rotationally symmetric results. A rotationally symmetric eigenvector with similar shape for all horn geometries was chosen to be excited harmonically. This eigenvector could be excited to different degrees with the horns. Differences in the calculated maximum and minimum pressure values could also be observed. For the plane horns the highest pressures were calculated. With the conical horn with an increased diameter at the tip it was impossible to excite the eigenvector. For all horns the highest pressure occurred at the tip of the horn. This could already lead to cavitation at the horn before this effect occurs in the fluid, leading to erosion at the horn.

From the presented results it can be concluded that the horns geometry as well as the excitation frequency have an influence on the shape of the sound field. The horn's shape also leads to differences in pressure values, which are highest for a plane horns. Therefor the horn geometry to favour is a horn with a plane tip and a large radiating surface. Overall the calculation with three-dimensional elements is reasonable, because also not axially symmetrical sound propagation can be calculated and viscosity can be considered. A disadvantage of a three-dimensional model is of course the higher computation time.

To verify the simulation results, the sound field generated by an ultrasonic transducer in a glass tank filled with water will be measured with a laser vibrometer in further experiments.

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