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Mapping 3D sound intensity streamlines in a car interior

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ABSTRACT

Sound source localization techniques in a car interior are hampered by the fact that the cavity usually is governed by a high number of (in)coherent sources and reflections.

In the acoustic near field, particle velocity based intensity probes have been demonstrated to be not susceptible to these reflections allowing the individual panel contributions of these (in)coherent sources to be accurately determined.

In the acoustic far field (spherical) beam forming techniques have been used outdoors in the free field, which analyze the directional resolution of a sound field incident on the array. Recently these techniques have also been applied inside cars, assuming that sound travels in a straight path from the source to the receivers.

However, there is quite some evidence that sound waves do not travel in a straight line. The Maritime Institute of Stetting in Poland made numerous 3 D sound intensity measurements demonstrating an erratic pattern of sound intensity streamlines [1], [2]

His approach was transferred from a lab to an actual car cabin upon request of a larger European car manufacturer.

At 900 positions inside the car the 3D intensity is measured with a 3 D sound intensity probes using three particle velocity sensors. Such a probe is not susceptible to the pressure-intensity index. Several speakers that are driven in sequence are used as controlled sound sources.

The results demonstrate that even with a single sound source, the 3D intensity streamlines are strongly bending, suggesting that far field techniques do not point towards the sound source.

INTRODUCTION

A number of different types of experimental approaches exist to localize and quantify sound sources in cabin interiors, all having their specific strengths and weaknesses. The aim is always to detect the acoustically weak part of the vehicles in order to define appropriate counter measures.

In the near field several techniques are used such as window-based methods [3], [4], intensity measurements [5], laser scanning vibrometry measurements [6], and holographic technologies [7].

In the far field, spherical beam forming [8] has been introduced. The concept assumes that sound waves travel in a straight line from the sound source to the receiver. This assumption was verified in this study.

For that purpose, a four channel three dimensional sound intensity probe is used to measure the intensity levels inside a vehicle at a large number of measurement positions. Several loudspeakers are placed inside the car and powered in sequence to study the influence of different the locations of the source. To get a good impression of the location of the measurement points, the inner geometry of the car is digitized with a specially designed tool.

As it can be difficult to display 3D intensity information in a 3D environment, an attempt is made to make the results more understandable using various visualization techniques.

THEORY

Sound intensity is a vector value which has both a magnitude and direction.

Intensity probes that are based on three pairs of two closely spaced pressure microphones are difficult to use because of their size, and more important it is difficult to measure in a highly reflecting car interior, as it is susceptible to a high pressure intensity index. Particle velocity based sound intensity probes are not susceptible to this index.

Here a three dimensional intensity probe is used that is based on the measurement of the 3-dimensional particle velocity [9] and the sound pressure in one position, see Figure 1. The procedure to derive the intensity and the specifics of the method are can be found in [10], [11].

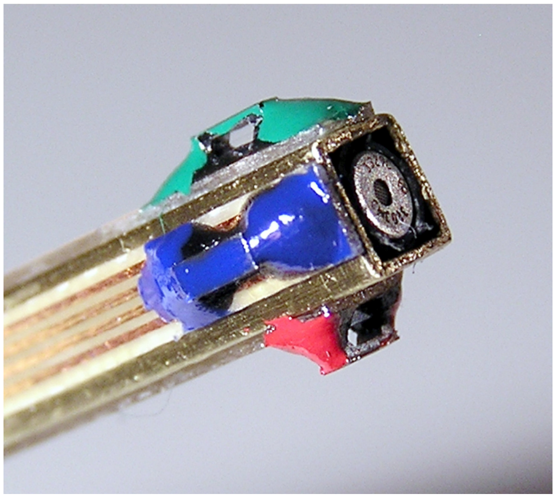

Figure 1: 3D sound intensity probe based on three orthogonally particle velocity sensors placed around a 1/10" pressure microphone.

GEOMETRY MEASUREMENT

Figure 2. The inner geometry is measured with a mechanical digitizing "Octopus" arm

The intensity measurements are plotted together with the geometry of the car. As there was no CAD data available of this car, the inner geometry was digitized with a special measuring unit (Figure 2). The rotation in each joint of this mechanical arm is determined with potentiometers, and thus the position of the measurement tip known with sufficient accuracy. The measurement time is close to one hour.

INTENSITY MEASUREMENTS

In one day, the 3D intensity is measured at 900 points in the car interior, with 10cm spacing between each point. The measurement points are shown in Figure 3 and Figure 4.

Some positions could not be reached because of the geometry of the car and obstructing objects (e.g. the seats). Also the area around the right back seat is not measured because of the test engineer controlling the probe position sitting there. The engineer on the right back seat might have an influence to the sound field, so that should be kept in mind analyzing the measurement results.

In the next paragraph the results are plotted in several cross-sections are also shown in these figures in blue (cross-section Z-0.4, Z0, Y0.4).

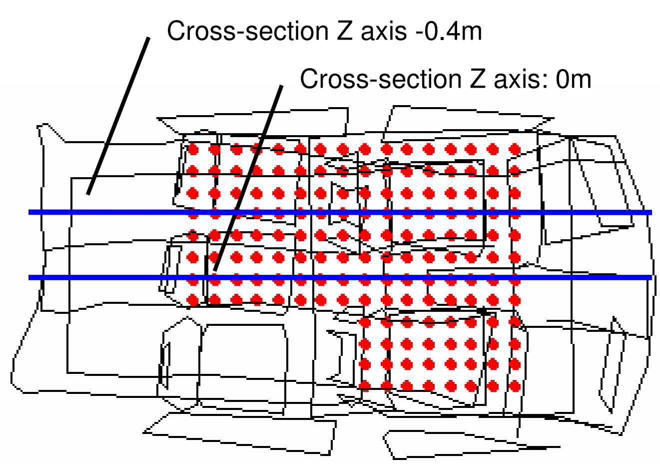

Figure 3. Top view of the car: the area around the test engineer is not measured.

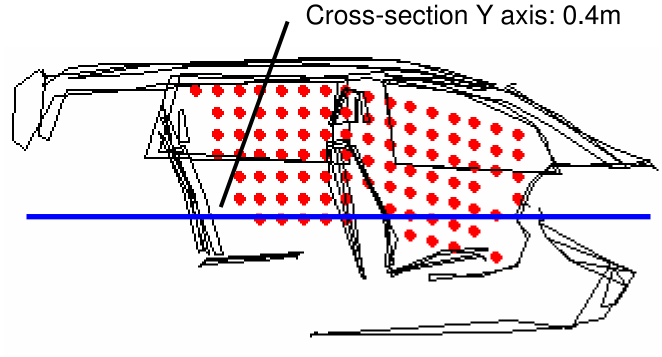

Figure 4. Right view of the car: the measurement points follow the curvature of the roof top

SOUND SOURCES

Several simple loudspeakers were placed inside the car and driven with a white noise signal. In four measurement sets different speakers were turned on (Figure 5):

- Two speakers in the front doors
- Two speakers on the dashboard
- One speaker in the trunk
- All five speakers on

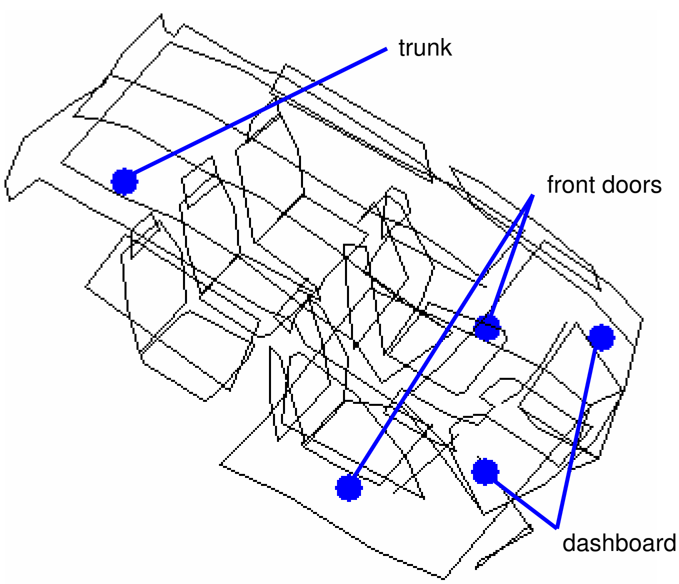

Figure 5. Position of the loudspeakers

MEASUREMENT RESULTS

The visualized of the sound intensity field via streamlines is inspired by the work of prof. Weyna, see e.g [1], [2].

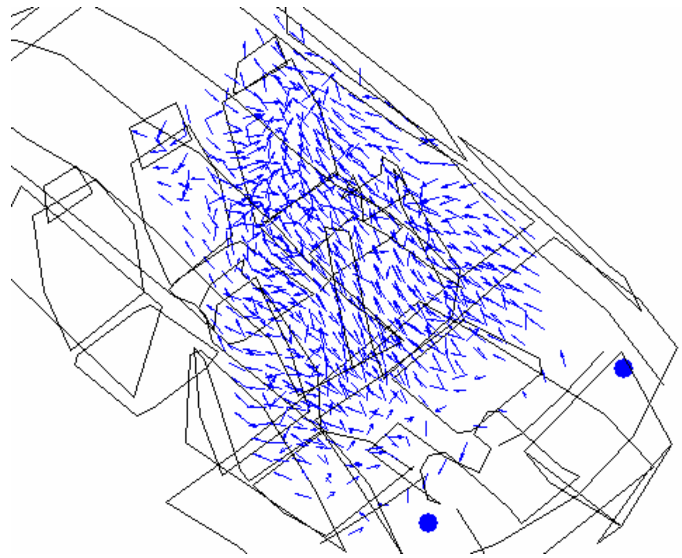

Figure 6. Normalized intensity vectors. Range 300Hz to 450Hz. Dashboard speakers on

In Figure 6 the mean value of the three dimensional intensity between 300Hz and 450Hz is plotted. A plot of a certain cross-section such as Figure 7 is easier to understand. The position of the plane is shown in Figure 3 and Figure 4. In this cross-section, and in this particular frequency range, most intensity vectors point nicely away from the two sources that are located on the dashboard, then around the front seat, and to the back of the car.

However, some things are different then expected. Some examples are marked with a circle in the picture.

The intensity points into the roof on the back of the car. Also, the right of the head rest of the front seat the intensity directs into the head rest. This could perhaps be due to a positioning error of the intensity measurements, but it could also be true partially absorption, or transmission through the head rest. It would be interesting to measure the intensity close to the surface of the head rest, or to support this idea by separate absorption or transmission measurements.

Furthermore, just below the head rest to the left, there is one vector pointing towards the source, instead of to the back of the vehicle. And the intensity vectors point from the bottom of the front seat instead of towards it. The reason for the last two phenomena is unclear. It is not likely that it is caused by an incidental measurement error; when a different slice (Z-0.3 or Z-0.5) is plotted the same behavior is shown.

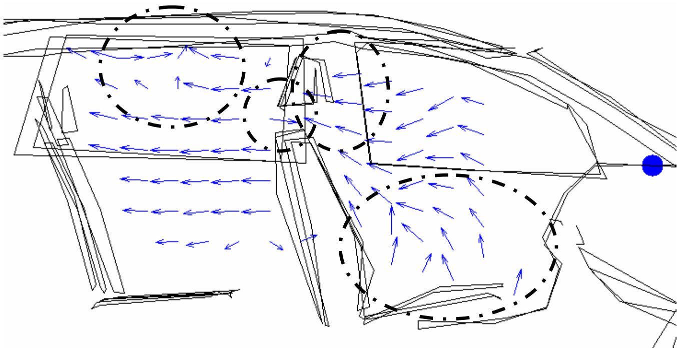

Figure 7. Cross-section of normalized intensity in plane Z-0.4. 300Hz-450Hz. Dashboard speakers.

From this intensity vector cross-section, streamlines can be computed. Streamlines are curves that are fitted tangent to the intensity vectors. They originate from a defined set of starting points and follow the direction of the intensity vectors. An example is plotted together with the actual intensity levels displayed as a colormap in Figure 8. Higher intensity levels are shown as a red color. The positions that are not measured are set to zero and displayed as dark blue in the image (area of the seat and several points on the edges).

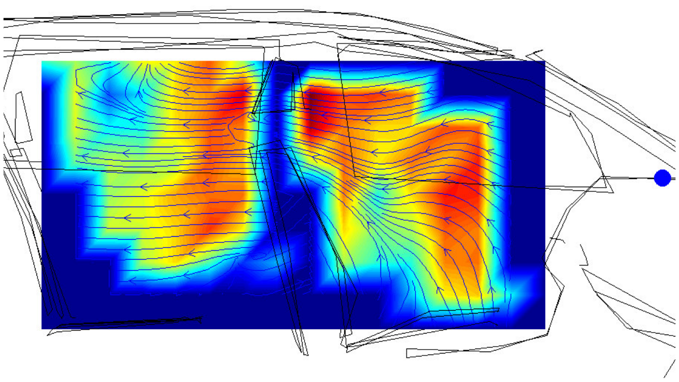

Figure 8. Cross-section with streamlines in plane Z-0.4, with the intensity level as colormap. 300Hz-450Hz. Dashboard speakers.

At higher frequencies (Figure 9) the intensity field is much more complex. Even vortexes are present, similar as the vortexes that are normally visualized with smoke at for instance the tip of a wing in a wind tunnel. This phenomenon is earlier measured by S. Weyna [1], [2]. The measurement point that is indicated with the circle in the figure might be a wrong measurement. In cross-sections Z-0.3 or Z-0.5 the behavior is not shown.

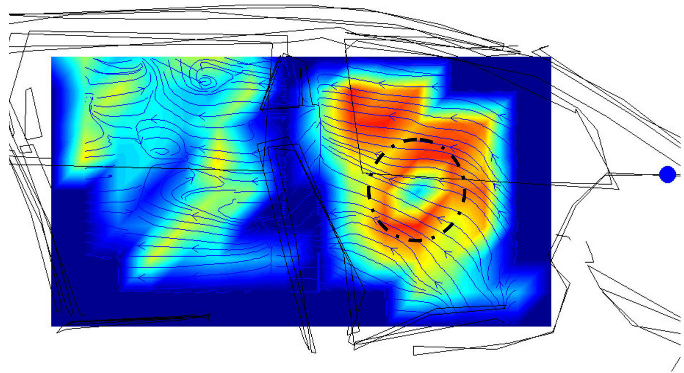

Figure 9. Streamlines in cross-section Z-0.4. 2500Hz to 3000Hz. Dashboard speakers

In the previous figures a cross-section was taken at the left of the vehicle, where most intensity vectors pointed around the seat. Next a cross-section is plotted at Z0; the middle of the car (Figure 10 and Figure 11). Here the streamlines flow between the front seats as can be expected. But in the back of the car a much more complex sound field is present.

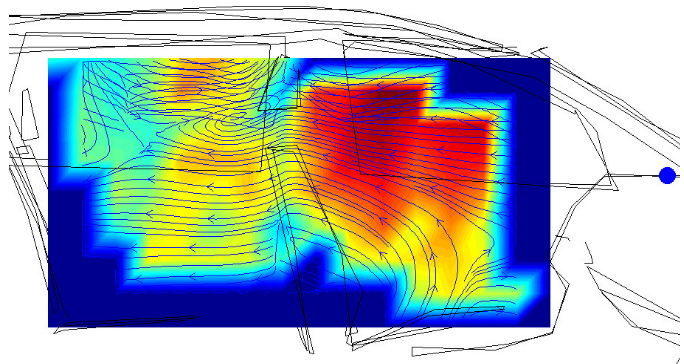

Figure 10. Streamlines in the middle of the car: plane Z0. 300Hz - 450 Hz. Dashboard speakers

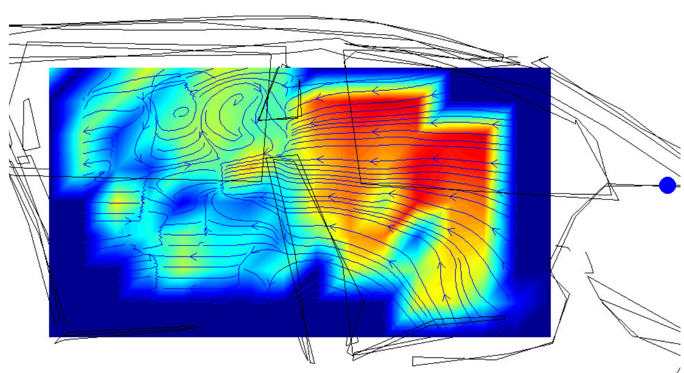

Figure 11. Streamlines in the middle of the car: plane Z0. 2500Hz - 3000Hz. Dashboard speakers

Some more examples of the complexity of the sound field are Figure 12 to Figure 14. Here the 3D sound intensity streamlines are plotted of three different frequency ranges. The sound intensity streamlines follows a totally different path with different given frequency ranges. The color of the streamline is determined by the intensity value of the nearest measurement point. High intensity values are colored red, low values blue.

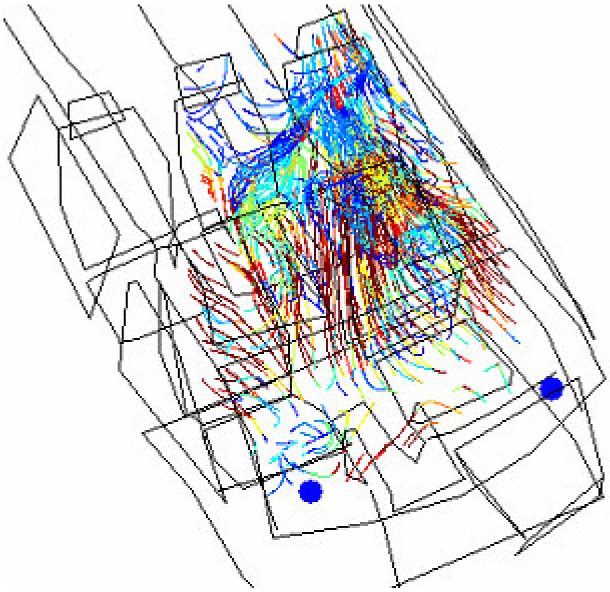

Figure 12. 3D intensity streamlines. 300Hz to 450Hz. Dashboard speakers

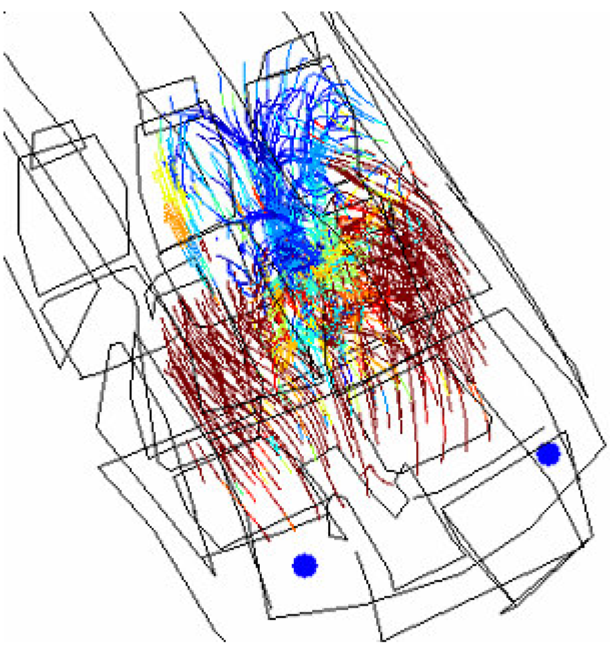

Figure 13. 3D intensity streamlines. 200Hz to 300Hz. Dashboard speakers

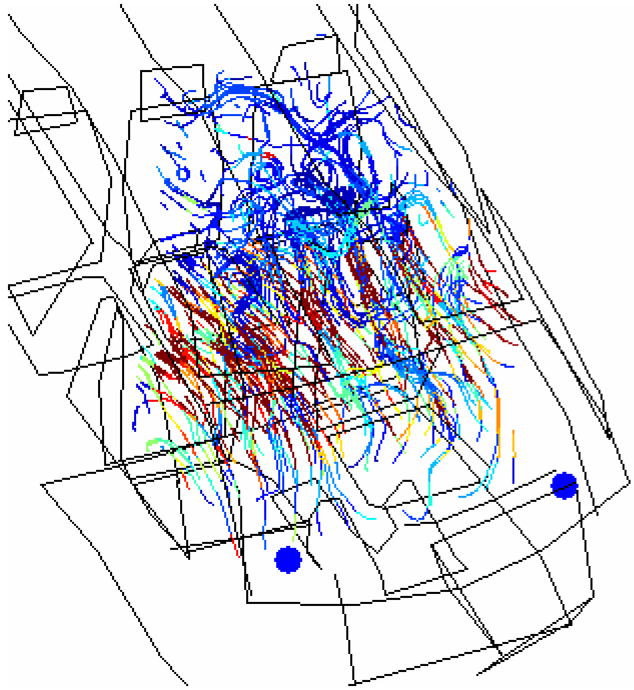

Figure 14. 3D intensity streamlines. 2500Hz to 3000Hz. Dashboard speakers

Observing all intensity vector plots, attention has to be paid to the fact that the test engineer might influence the sound field during the measurements. For the calculation of the streamlines also the spatial resolution of the measurement points and the errors inherent to the trajectory algorithm have to be considered, e.g. user settings, the crossing of streamlines over an area with zero intensity instead of ending it.

Furthermore, the amount of seeding points (starting points of the streamlines) is limited for the calculation of the three dimensional streamlines to reduce computation time. In these 3D plots all outer measurement points are used as starting lines for algorithm, but not the points in between.

Despite of the limitations of the used algorithm, the plots show a highly complex sound field. Both the direct vector visualization and the streamline plots show that on many positions inside the car, the intensity does not point towards the sound source, which is the assumption of far field techniques.

Next the sound intensity streamlines are visualized when different sources are turned on. In sequence, first the two dashboard speakers are turned on (Figure 15), \ then the speaker in the trunk (Figure 16), then the two speakers in the front doors (Figure 17). Finally all five speakers are turned on (Figure 18). A cross-section of the Y axis is taken at 0.4 meter (see Figure 4). The frequency range is 300Hz to 450Hz. In some of these cases there is a complex interaction objects like for instance the seats and the exterior of the car, even when only one single source is turned on (the single speaker in the trunk).

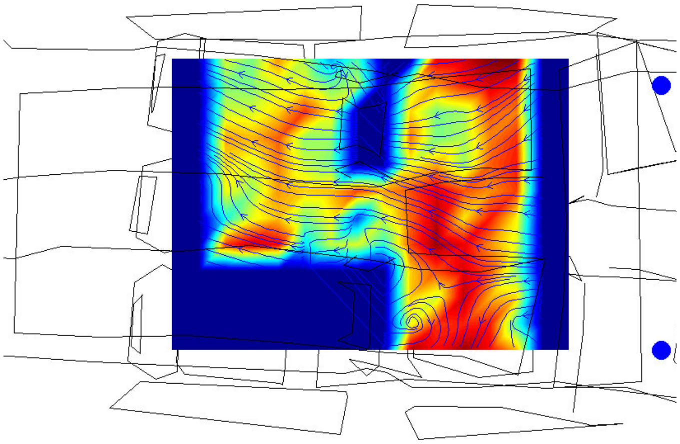

Figure 15. Two dashboard speakers. Cross-section Y0.4. Frequency range 300 to 450Hz.

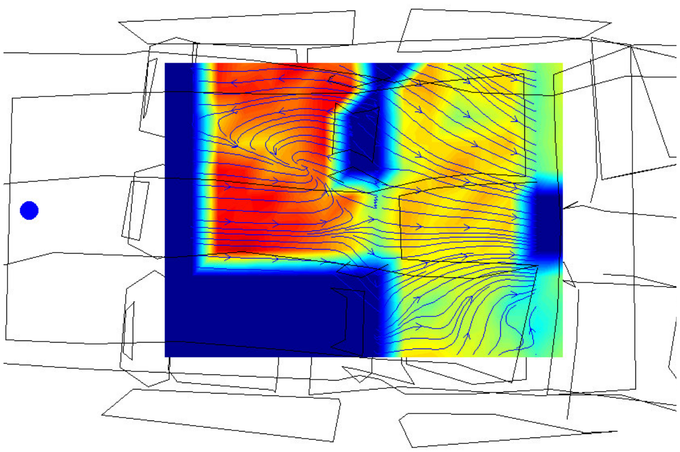

Figure 16. Speaker in trunk. Cross-section Y0.4. Frequency range 300 to 450Hz.

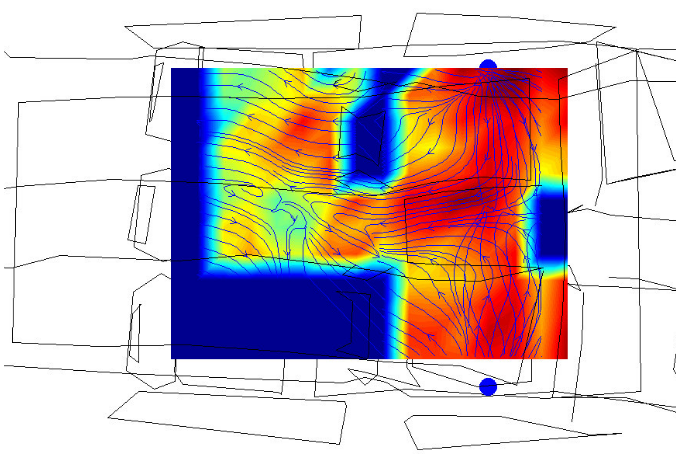

Figure 17. Two speakers in front doors. Cross-section Y0.4. Frequency range 300 to 450Hz.

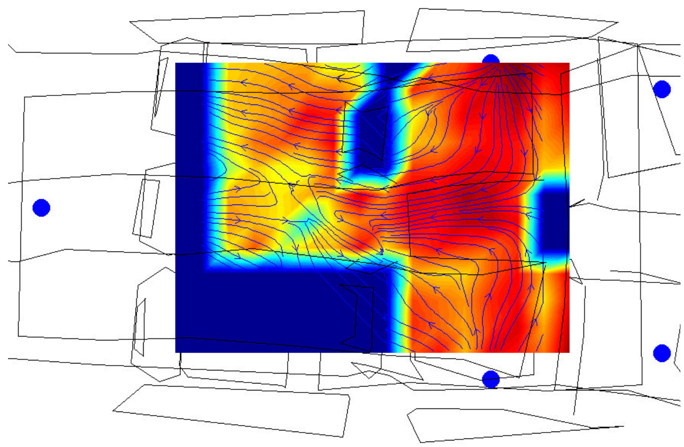

Figure 18. All five speaker. Cross-section Y0.4. Frequency range 300 to 450Hz.

CONCLUSION

The measurements show that the direction of the 3 D sound intensity vector is highly dependent of the position and for sure not moving in a straight line. It is therefore very difficult to expect any far field technique to point directly to the source.

In this paper the interaction of the sound sources and their reflections is visualized, via three dimensional sound intensity measurements, which are taken at taken at a high number of measurement points. To get an understanding about the actual position the inner geometry of the car was digitized with a special measuring unit. Several examples show that the sound intensity field is heavily depending on for example the position of the source, the geometry of the car and objects like the seats, and on the frequency.

The three dimensional plots of intensity can be difficult to analyze. Therefore the results of several cross-sections are shown, which are easier to interpret. The intensity vectors in a plane are plotted. From these vectors the streamlines are calculated (curves that are fitted tangent to the intensity vectors). They are combined with a color map of the intensity level.

Some locations could not be measured due to obstruction of the car itself, and the location of the test engineer on the right seat on the back of the car. The presence of persons or large equipment in the car during the measurements might have an influence on the results, and this should be avoided in future measurements. The ultimate goal is to measure the sources created by the car itself on a roller bench, maybe using an automated unmanned procedure.

Some limitations have to be considered when the results are analyzed such as the spatial resolution of the measurements (10 cm spacing in either direction). In some cases the streamline algorithm continues over an area with zero intensity instead of ending it. One of user settings for these streamlines is the amount of seeding points (starting points of the streamline). In the 3 dimensional streamline plots the amount of seeding points is limited to reduce computation time.

Such three dimensional intensity measurements could be used as input data for numerical models or to verify them, but also as an alternative method.

Even though there are some criteria to apply such stream line functions, the 3 dimensional intensity measurements can give further insight to the complexity of sound field.

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