ARCHIVES OF ACOUSTICS
32, 4, 859–870 (2007)

SOME COMMENTS ABOUT THE EXISTING THEORY OF SOUND WITH COMPARISON TO THE EXPERIMENTAL RESEARCH OF VECTOR EFFECTS IN REAL-LIFE ACOUSTIC NEAR FIELDS

Stefan WEYNA

Szczecin University of Technology
Maritime Faculty of Technology
Al. Piastów 41, 71-065 Szczecin, Poland
e-mail: weyna@ps.pl

(*received June 15, 2006; accepted September 30, 2006*)

Classical studies on the descriptions of acoustic field in an area of a near field, in accordance with the relations formulated by Kirchhoff, Huygens or Rayleigh's integral formula, are commonly known. It is also known that typical interference phenomena, such as diffraction and scattering of acoustic waves, appear in an acoustic field of the real sources as a result of mutual reactions of component waves. Today these vector effects of the acoustic wave occurring in the area of a near field can be simple measured directly with the use of a sound intensity technique.

This article presents a few examples of the application of a sound intensity technique to the graphic presentation of the spatial distribution of the acoustic power flow over various geometrical shapes of structures located in a three-dimensional half space. The results of these studies contribute to the theory of sound and general knowledge about the physics of flow acoustic phenomena, especially in the near acoustic field. As a result of research, the visualization analysis of the sound intensity flux in 3D space is shown. The visualization of acoustic power flow in real-life acoustic fields can explain many particular energetic effects (scattering, vortex flow, shielding area, etc.), concerning areas where it is difficult to make numerical analysis.

Keywords: theory of sound, wave flow, sound intensity.

1. Introduction

Much of the theory covering acoustic wave characteristics, propagation, and interactions with objects, was developed many years ago. The problem in all predictive work lies in devising methods of applying this theory to real-life applications. In real-life acoustics there are a few examples of problems which may be solved by analytical means. The main examples used in analytical studies are those of the propagation of waves from points, dipole lines, and flat plate sources. Analytical methods may be used to consider how a single wave propagates through a fluid. It may be done for several waves close to each other, and so account for such effects as mutual interference. However, they all ultimately depend on the source being one of the four basic types above, and all rely on the summation of waves, rather than a general solution to the behavior of waves within a fluid.

Numerical methods may be defined as ones requiring discretisation of the problem. Thus they include finite and boundary element approaches. The governing equation for waves propagating in a fluid is the general (linear) wave equation

$$\nabla^2 u = \frac{1}{c^2} \cdot \frac{\partial^2 u}{\partial t^2}. \tag{1}$$

Here, u is the velocity potential at some point in space and time, and c is the speed of sound in the fluid. If it is assumed harmonic, this reduces to the Helmholtz equation

$$\nabla^2 u + k^2 u = 0. \tag{2}$$

One known solution to this is a relation known as a Green function, which satisfies the Helmholtz equation throughout the domain, except at a source point (where there is a singularity). The derivation of a solution for the Helmholtz function for any real-life problem involves a complex integration of terms, typically over a surface, to derive Green's formula [4, 6, 10]. Such work is beyond the scope of mutual calculations for any but the simplest problem.

Numerical methods have the advantage that they are applicable to a wide range of problems types. However, they are hard to compute, and may involve large models if physically large problems are to be analysed at high frequency.

Analytically derived methods tend to be much simpler to perform than numerical ones. This often enables their use at higher frequencies than numerically based methods but they tend to be very limited in terms of the types of problem for which they are truly valid. As major approximations tend to be made in their use, analytically derived methods are less accurate for real-life problems than those based on numerical systems.

For complex geometric problems, the finite element method provides a general solution. The finite element formula, when applied to acoustic elements, is generally based on the use of pressure as the primary variable; that is, a solution of pressure distribution throughout the modelled field is determined first. The mathematics of the method are well documented and will not be described here.

Numerical finite element models are also useful for predicting structural dynamic responses. These results can be used in an acoustic finite element/boundary element (FE/BE) modeller to predict acoustic responses, including far-field radiation, intensity vector fields, acoustic power and so forth [11]. The BE methods may mainly be used successfully for the prediction of acoustic radiation and scattering in an infinite or semi-infinite domain. The major advantage of the BE method is that only the surface of the structure (or obstacle) has to be modeled and discretized. The contribution from the far-field boundary at infinity ($r \to \infty$) can be removed automatically by applying the Sommerfeld radiation condition (which expresses the energy conservation principle), that is

$$\lim_{r\to\infty} \left[r \left(\frac{\partial \mathit{\Phi}}{\partial r} + ik\,\mathit{\Phi} \right) \right] = 0, \tag{3}$$

where $\mathit{\Phi}$ is the velocity potential and k is the wave number.

In real flow conditions, waves being reflected from several limiting surfaces, together with the direct sound from the source, build up a sound field with such complicated patterns that it is practically impossible to be described completely. Such a problem is encountered in rooms or bounded spatial systems, and can be theoretically and experimentally described several ways. These include mainly the wave theoretical model, the geometrical acoustic model, the use of statistical methods, psychoacoustics approach and physical modeling [3]. Computer programs are concerned with the geometrical presentation of the spherical sound propagation, that is to say that these models assume an omni directional source, reverberant absorption by the air, specularly reflecting flat surfaces, and air absorption exponent.

Generally, it is difficult to accurately model the dynamic response of actual structures using numerical techniques. A major obstacle in acoustic radiation prediction could be removed if a numerical structure dynamics model, with its uncertainty in modeling assumptions, could be replaced with an experimentally derived model. An experimentally derived dynamics model can inherently model actual boundary conditions, material properties and geometry for both the shape and dynamic response of a structure. By combining the experimentally derived dynamic response models with a numerical FE/BE acoustic code, an improved, cost effective, experimental/numerical method (hybrid system) for predicting both dynamic and acoustic response can be achieved.

The analysis of sound propagation within enclosed spaces is usually performed by commercial computer programs such as PAFEC, CHIEF, ABAQUS and other. The programs enable two and three dimensional solutions, leading to a better understanding of the phenomena within acoustic fields and wave reactions to obstacles.

Also, the near field holography (NFH) method is a powerful experimental technique for analyzing sound fields near sources. Conventional near field holography is based on measurements of the sound pressure. A combination of the normal fluid velocity and pressure very near or on the surface, allows us to calculate the active intensity and thus we obtain the total power radiated from the surface [12].

We can sum up that real acoustic fields, created by simultaneous actions of various wave effects, cannot be explained by general mathematical descriptions. Acoustic radiation from vibrating structures, mutual interference of waves, scattering effects, absorption by and diffraction at obstacles, the emergence of standing waves – all very well described as separate events – have not been successfully linked together in a synergetic model. This is why elementary acoustic phenomena are discussed separately and in only some cases is it possible to apply superposition rules to determine the final image. Stochastic phenomena in real-life conditions are best described by experimental studies on objects or models build to certain scales.

The main goal of the work presented here is to show some experimental measurements to demonstrate visualization of energy flow in real-life 3D acoustic fields, which may be compared to results calculated numerically with commercial codes. The results of studies using this sound intensity technique contribute to the theory of sound and general knowledge about the physics of flow acoustic phenomena, especially in the near acoustic field.

2. An experimental study of acoustic intensity flow visualization

In recent years, considerable advances have been made in computational fluid dynamics (CFD) such that there are now a number of available commercial codes which can be used to predict the behaviour of moving air [7, 8]. Also, developments in visualization algorithms, complex databases, computer graphics, multimedia technologies and network communication, all contribute to the development of flow visualization techniques. Numerical computer techniques used for visualization in fluid mechanics and aerodynamics has been widely applied in simulation studies of flow visualization [5].

Modern forms of vector flow visualization in physics are often quite different. One can use a traditional distribution of vectors in the form of arrows, isosurface distribution maps or streamlines (pathways where the flow takes place). Flows shown in two or three dimensions are created by available graphics systems that give the ability to choose the most convenient presentation form.

The most common way of presenting intensity stream flows in 3D space is as a flat ribbon strip comprised of a few thin lines. A 3D effect is achieved by using colourful and shaded bands with a simultaneous 3D lighting. This form is also suitable for presenting vortex effects in a flow field, and a twisting vortex flow.

This short summary shows that flow visualization in physics is not a new area and it already possesses some traditional forms. However, they are rarely used to describe acoustic phenomena. The low level of interest in the acoustic flow (energy transport in the acoustic field) has been mainly due to the limitations in the ability to directly measure vector effects.

Literature on the subject indicates that the visualization of vector acoustic field effects is a domain still waiting for more efficient methods [4, 10]. Even in numerical simulation methods, the acoustic field models concern mostly pressure effects rather than energy transport. Inseparable effects of the wave motion – the acoustic particle velocity (v) and the resultant changes in pressure (p) – are described by one vector acoustic variable – sound intensity – which nowadays can be measured directly. This technique makes it possible to measure and record the distribution of sound energy in acoustic fields and directly visualize the distribution of acoustic power radiated by various sources. Many acoustic phenomena with vector properties, which had previously been measured only in indirect methods, can now be examined directly by experiment.

Energy distribution images in acoustic fields, connected with the graphical presentation of the energy flow (derived from direct measurements) are a new element in acoustic metrology. The introduction of these possibilities has greatly changed the approach to examining many acoustic phenomena. This measurement technique has been applied to various studies on theoretical and applied acoustics, greatly simplifying the methods of research. This is because it does not require as strict criteria as in traditional measurements, and the precision of direct measurements in real-life situations does not vary from laboratory experiments. The measurements can be carried out in a near field and in the real-life fields with the presence of *parasitic* noise, which is a significant advantage in research carried out in industrial conditions.

Useful equipment for measuring sound intensity was launched on the market in the 1980s. Today, this method frequently complements conventional methods in acoustic metrology and the sound intensity value may be determined in different ways: by a two-microphone method, a cross correlation transform between the pressures from two microphones and by direct measurement of pressure and acoustic particle velocity.

The first two methods may be carried out with an intensity probe built from two omni-directional pressure microphones (*pressure-pressure* probe) placed at a distance Δr proportionate to the wavelength.

A *pressure-velocity* probe is significantly different from the two-microphone probe. This probe consists of a 1/2" condenser microphone (for pressure measurements) and two pairs of crystal microphones (for velocity measurements of the acoustic wave, according to a method based on the Doppler effect). The two pairs of crystal converters are on one ring, with the condenser microphone in the middle. The ring diameter is about 70 mm.

The aforementioned advantages of the sound intensity technique may be used in acoustic metrology much more effectively if a new 3D-USP miniature intensity probe is used. The *Ultimate Sound Probe* – USP (made by Microflown Technologies B.V.) is a thermodynamic type of sensor, as a practical alternative to pressure microphones [1]. It is a very compact and integrated sound intensity transducer, combining three orthogonally positioned particle velocity sensors and a miniature (0.1 inch) pressure microphone. The actual 3D sensor configuration without its cap is less than 5 mm $\times$ 5 mm $\times$ 5 mm.

The Microflown 3D-USP, used as a scanning probe, was specially developed for measurements carried out very close to vibrating objects – the source of the acoustic power. By minimizing the array distance to the sound source (for example to 1 mm), we may investigate particle velocity levels in very near field conditions (inside the so called hydrodynamic region). The power acoustic flow in this region may now be fully described in real experimental conditions.

3. Results of investigation

Examples illustrate how the application of the sound intensity measurement may help solve the practical problems of acoustic diagnostics and noise abatement. In the experimental measurements, graphical methods presented the real-life vector distribution in a 3D flow wave field. Traditional methods of acoustic metrology, based on acoustic pressure distribution, did not offer such possibilities.

The tests concerned the application of the sound intensity technique to the graphical presentation of spatial distribution of the acoustic energy flow around flat, hard rectangular plates. Two plates, 0.52 m $\times$ 0.32 m, one 25 mm thick and the other 2 mm thick, were located in an anechoic chamber and excited by an axially travelling incident wave (stationary broad band pink noise) coming from a loudspeaker at a distance of 0.6 m from the centre, in front of the plate. The measurements using a USP intensity probe were carried out in the one third and one twelfth octave bands, and vector maps were built over the frequency range 25 Hz to 6300 Hz.

In Fig. 1, the geometry set-up and the distribution of sound intensity streamlines around the thick (25 mm) rectangular plate are shown. The sound intensity measurement was taken using a fixed point method. Around the plate, a measurement space of $0.69 \times 0.51 \times 0.51$ m^3 was divided into 6647 cubic, in the centre of which, measurements of the x, y, z components were taken, which gave 19041 measured sound intensity vectors to be used as data for graphical visualizations.

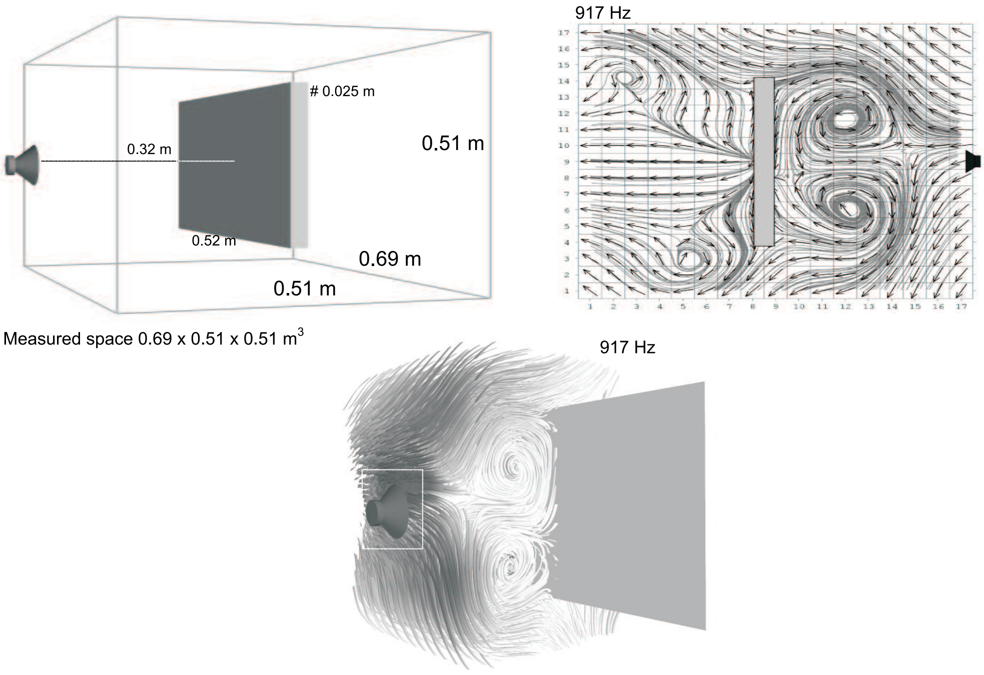

Fig. 1. The geometry of experimental set-up and distribution of intensity streamlines in the plane of symmetry axis of the plate (2D) and in 1/2 space of measurement (3D). Source is 0.6 m from obstacle.

Figure 2 shows examples of the vector field distribution in the acoustic shadow formed around the rear side of the plate. The intensity streamlines and shapes of waves in this area, as well as the intensity isosurfaces, are presented for selected frequencies. Using intensity streamlines seems to be a very useful and economical way for presenting the transport paths of acoustic energy under environmental conditions. We can see that the direct flow wave excited on the front surface, together with the back wave made many vortices and curls in the field (effect of backscattering).

In the second part of this research, the investigations of sound intensity stream distributions were made in the space around the corner of an acoustically hard, thin (2 mm) plate. The set-up is shown in Fig. 3, where also the distribution of intensity streamlines in the plane for some of 1/12 octave band frequencies is shown. The image of the energetic acoustic field shows the intensity streamlines as ribbon forms in the three-dimensional space close to the lower corner of the plate (Fig. 3b). In this measurement, compared with the previous one, we used a more compact measurement net.

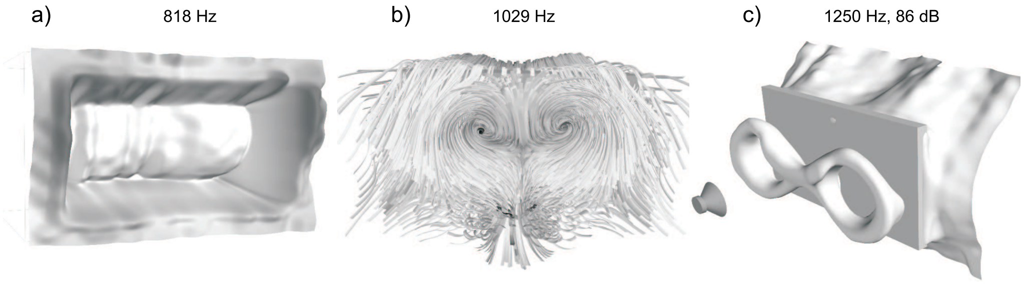

Fig. 2. The normal intensity component as a shape of wave (a) in a rear side of plate together with intensity streamlines (b) and intensity isosurface (c) for some selected frequencies.

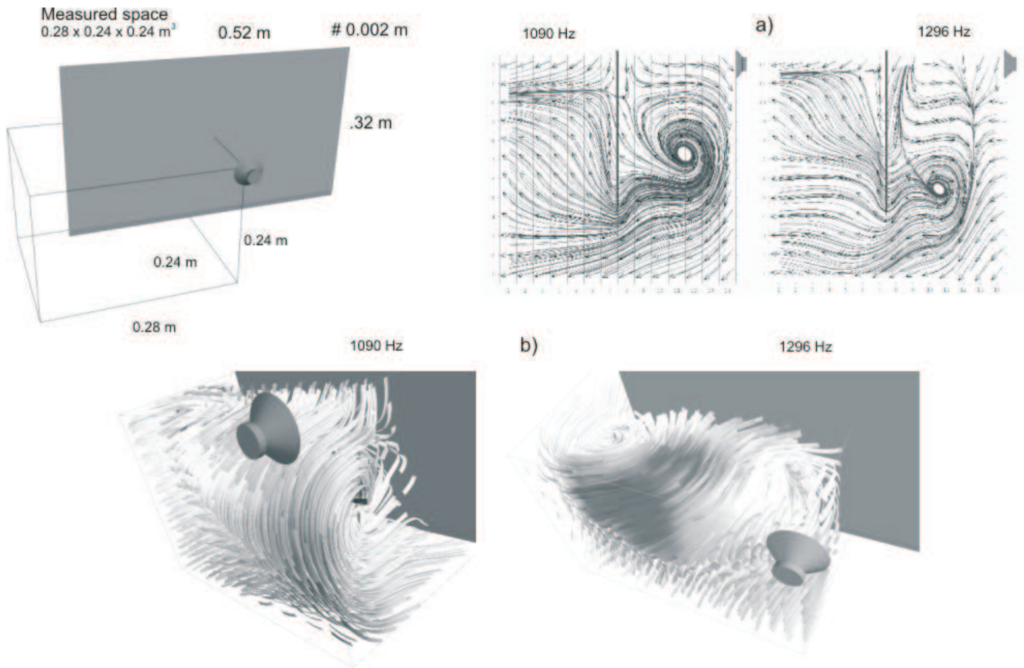

Fig. 3. Experimental set-up and distribution of intensity streamlines in the plane of symmetry axis of measured space (a), and intensity streamlines around a one corner of thin (2 mm) plate.

It can be seen that the sound intensity streamline distributions on both sides of the plate are strongly dependent on the frequency and phase of the source signal. When the phases are opposed over a certain part of the front and rear of the plate (reflected and sink waves), the effect is cancellations in the space distribution. The direct and back waves made many vortices and curls in the field.

The investigated sound intensity distribution as the energetic interaction between Helmholtz resonators and acoustic flow fields will be shown in the next experiment.

Resonators were built using laboratory flasks (50 ml, 250 ml and 1000 ml) made from thick glass. Calculated resonance frequencies were 79.3 Hz, 319.2 Hz and 478 Hz respectively. The resonators were fixed onto a hard plate (0.6 m $\times$ 2.4 m), distributed symmetrically in three groups: 5 $\times$ 50 ml, 3 $\times$ 250 ml and 3 $\times$ 1000 ml (Fig. 2). The board with resonators was suspended in a room with a semi-diffusive field created by a broadband white noise source.

Results obtained with the sound intensity method were presented using a 3D graphical description of the acoustic field vector distribution. Figure 4 shows the results of the vector studies analyzed in normalised 1/3 octave band filters: 80 Hz, 315 Hz and 400 Hz, which contain the resonance frequencies of the examined systems. As can be seen, 3D imaging of acoustic energy absorption by the Helmholtz resonators is much more pronounced. The usage of a linear scale rather than a logarithmic one (in dB) enables a more graphic presentation of "energy suction", not only in the case of a basic (resonance) frequency but also its harmonic components.

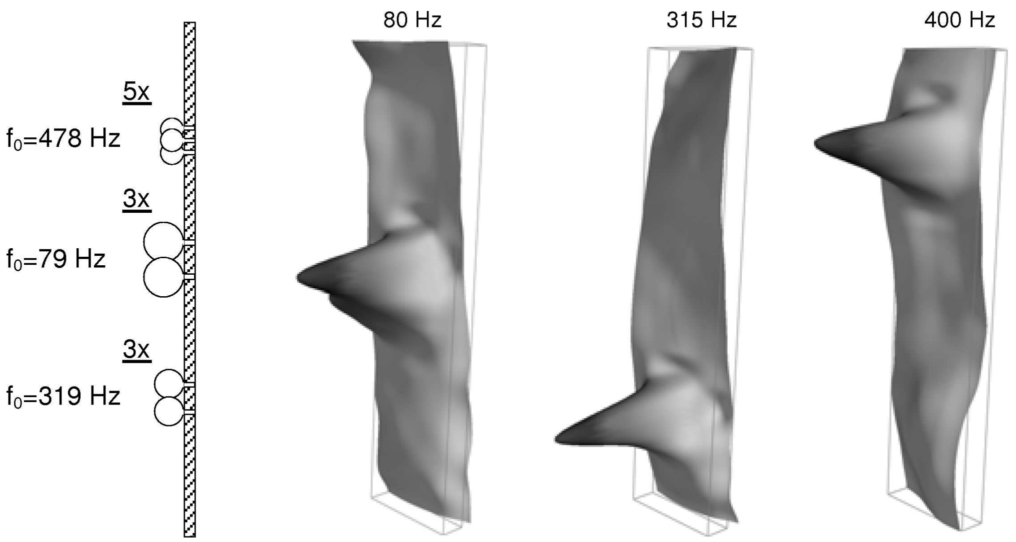

Fig. 4. Distribution of Helmholtz resonators in a simple suspended hard plate and graphic presentation of energy absorption by the separately groups of the resonators.

Another experiment examined how the activity of a Helmholtz resonator is influenced by changes in the impedance of the medium inside the resonator. The comparison of results for the resonators filled with atmospheric air and those filled with rock wool (28 kg/m^3) is presented in Fig. 5.

To sum up, the results of examining Helmholtz absorbers with the sound intensity method show that the 3D imaging of the energy flow in an acoustic field around the grouped resonators greatly enriches the interpretation of the acoustic energy absorption of such a system. We may notice the results of energy absorption, even on the model

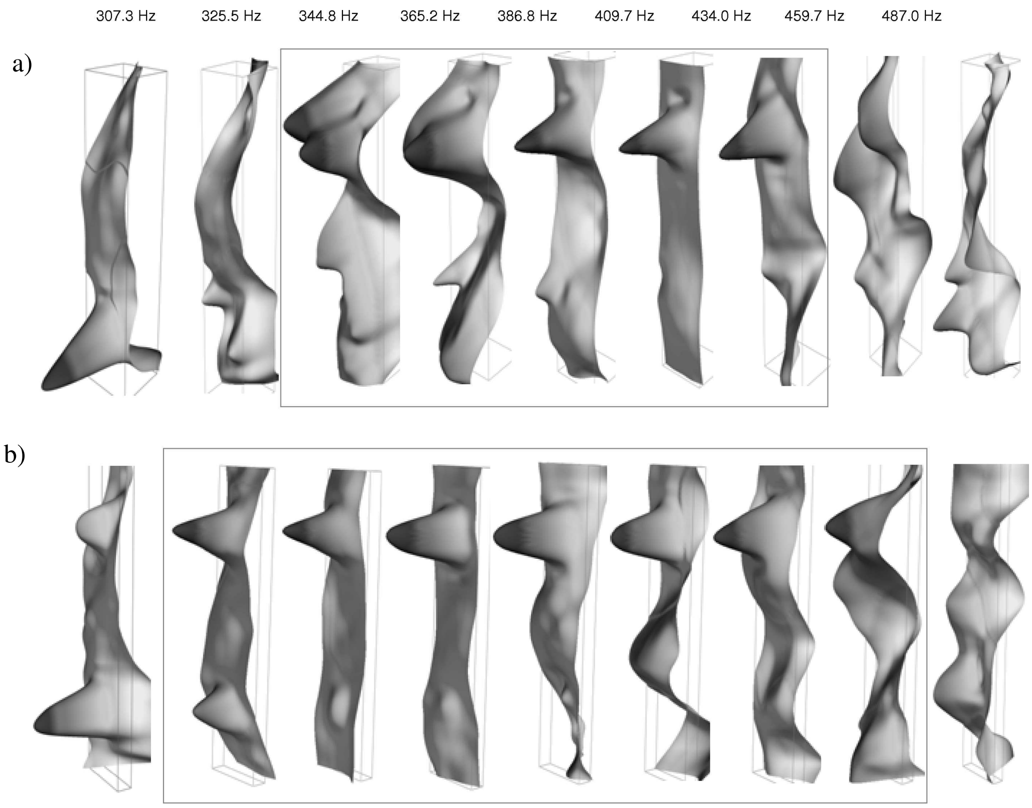

Fig. 5. The comparison of noise absorptions for the resonators ($f_0 = 409$ Hz) in 1/12 octave band filters: a) filled with air, b) filled with rock wool (28 kg/m^3).

of one resonator, which is impossible to achieve using the pressure method. The experiment also shows that the analysis of the resonators' activities in a 3D field, presented with an adequate graphical technique, is very pronounced and the results are easy to interpret.

The sound intensity method was also used to examine the energy effects of acoustic wave reflection against the acoustic hard plate dimension 1.4 m $\times$ 2.1 m $\times$ 0.025 m.

The source was directed at an angle of 60 degrees to the plate's surface. In acoustic analyses of acoustic wave reflection this case is deemed particularly difficult for theoretical modelling due to the simultaneous interference and scattering of waves, with amplitude/phase relationships between them. The experiment describes in a graphical way the vector occurrences in a real-life system.

Figure 6 shows a fragment of these studies as a vector field distribution of a surface perpendicular to the plate (a) and also above the plate, as streamlines and isosurfaces (b, c). According to isosurface image, we may observe the development of a surface Rayleigh wave, very important in analysing fluid structure interactions.

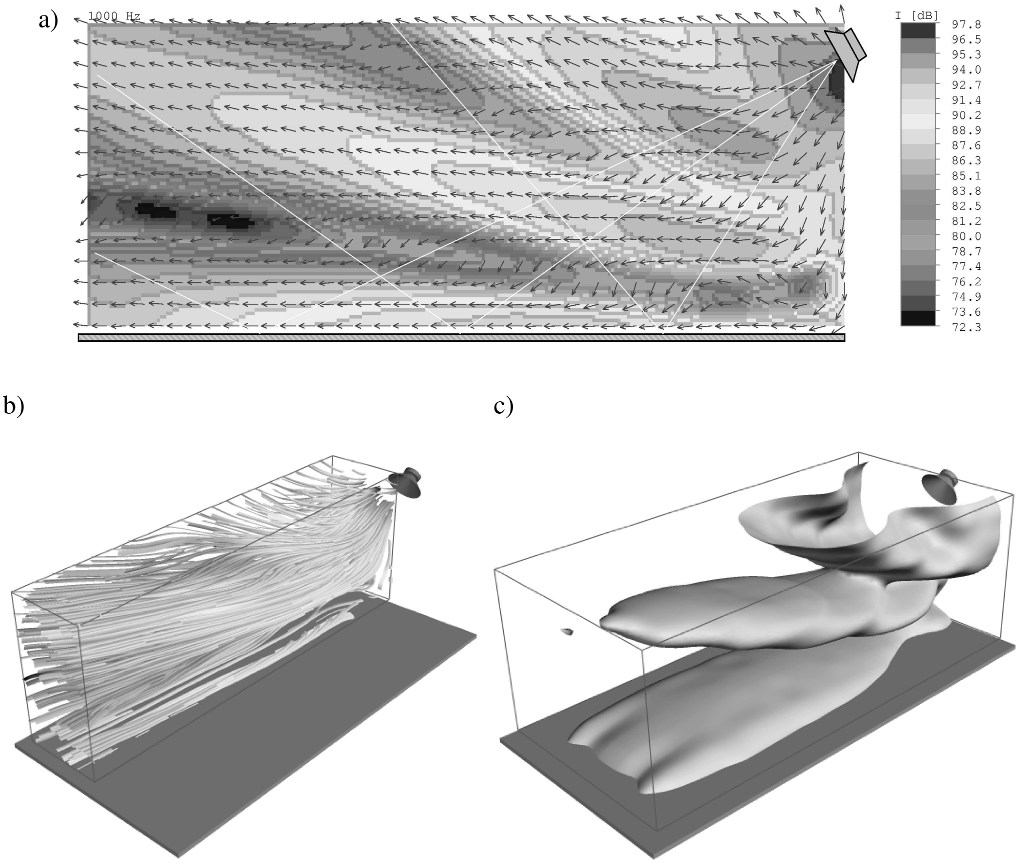

Fig. 6. Sound intensity wave reflected from a hard floor for, frequency $f = 1000$ Hz: acoustic source – pink noise, loudspeaker oblige 60°, isosurface 88.5 dB.

4. Conclusions

Sound intensity studies suggest that previous theoretical models and computer simulations of acoustic fields in restricted areas may be well removed from reality. This is because the distribution of the real fields is much more complicated than was previously expected. One may also conclude that dynamic acoustic phenomena that take place in real structures and systems, are usually unstable and even small changes in wave flow variables or the geometry of the elements in space, may lead to radical changes in the field.

Visualization of acoustic energy in a three-dimensional field significantly contributes to a more comprehensive interpretation of acoustic radiation mechanisms in limited spaces. Presentation of pathways on which the acoustic energy is conveyed, is especially useful in the study of complex acoustic sources and explains their action in real-life conditions. This is a form of a qualitative analysis that appeals directly to the imagination;

observation of acoustic wave distribution in the air and the assessment of wave reaction to obstacles and acoustic barriers in their way, becomes more "tangible" and helps in complementing the theoretical knowledge of nonlinear phenomena occurring in acoustic fields.

Visualization of vibroacoustic phenomena as vector parameters, in contrast to pressure methods, significantly improves acoustic diagnosis of machines and devices by precise localization of noise-radiating hot spots. Precise indication of such local vibration sources is very significant in limiting the noise radiated by devices, and facilitates their structural and parametrical modification. The application of the sound intensity technique together with FE/BE methods has improved the quality of acoustic diagnostics and has made it possible to visualize energy wave phenomena (vector distribution) in a vibrating structure, or in an acoustic field around a structure. Direct energy analysis of acoustic fields was not possible earlier as classical studies used a converter (microphone) measuring pressure changes, a scalar element of acoustic waves. Only when direct measurements of sound intensity became possible, could the wave distribution be analysed in the form of a wave acoustic energy transport.

Studies of vector acoustic phenomena carried out in real-life conditions may be compared with numerical models of acoustic fields which have been prepared with commercial software available in the market, but experimental investigations indicate that simplifications applied to numerical models result in serious disparities between theory and real-life data [13, 14]. In such cases the sound intensity studies carried out on physical models may link theory with practice by limiting simplification, so that the simulation reflects real-life physical effects.

References

[1] DE BREE H-E. *et al.*, *Three-dimensional sound intensity measurement using microflown particle velocity sensors*, MEMS'99, Orlando 1999.

[2] BOSTÖM A., *Acoustic scattering by a sound-hard rectangle*, J. Acoust. Soc. Am., **90**, 6, 3344–334 (1991).

[3] CREMER L., MÜLLER H., *Principles and applications of room acoustics*, Applied Science, London 1982.

[4] CRIGHTON D. G. *et al.*, *Modern methods in analytical acoustics*, Springer-Verlag, London 1966.

[5] DICKINSON R. R., *A unified approach to the design of visualization software for the analysis of field problems*, Proc. Threedimensional Visualization and Display Technologies, Spie 173–180, 1989.

[6] FILIPPI P. [Ed.], *Theoretical acoustics and numerical techniques*, Springer–Verlag, Wien 1983.

[7] GERALD-YAMASAKI M., *Visualization of computational fluid dynamics*, Comp. Flow Dynamics. – Rev, 1995.

[8] HAFEZ M. *et al.*, *Computational fluid dynamics review 1995*, John Wiley & Sons, Chichester 1995.

[9] KRISTENSSON G., *Acoustic scattering by a soft eliptic disc*, J. Sound Vib., **103**, 487–498 (1989).

[10] MORSE P. M., INGARD K. U., *Theoretical acoustics*, McGraw-Hill, New York 1968.

[11] MUNSON B. R. *et al.*, *Fundamentals of fluid mechanics*, Wiley and Sons, New York 1994.

[12] WILLIAMS E. G., *Fourier Acoustics – Sound radiation and nearfield holography*, Academic Press, San Diego, London, New York 1999.

[13] WEYNA S., *An image of the energetic acoustic field in a parallelepipeded room models*, "Acta Acustica" Inter. Journal on Acoustics, **82**, 2–81 (1996).

[14] WEYNA S., *Identification of reflection and scattering effects in real acoustic flow field*, Archives of Acoustics, **28**, 3, 191–203 (2003).