AN EXPERIMENTAL STUDY OF SOUND INTENSITY DISTRIBUTIONS IN REAL ACOUSTIC FLOW FIELD

S. Weyna Szczecin University of Technology, Faculty of Maritime Technology, Poland

1 INTRODUCTION

In the acoustical practice, up until the last two decades, the study of vectors acoustic fields and noise flow visualisation are rather seldom. To day, flow motion as the acoustic particle velocity may be measured experimentally using *sound intensity* (SI) probe, which can be used to collect the data to visualisation all the phenomena occurring in investigated acoustic vector fields, even in three dimensional space. Visualization system, by serving a dual role as a provider of exploration and exposition capabilities, have became indispensable to the analysis of *computational fluid dynamics* (CFD) results. The sound intensity has become one of the most interesting measurement techniques employed in solving vibroacoustic problems as well as in acoustic metrology, which simplifies the technique of measurements thus effectively replacing classical methods. Measurements can be conducted in the near field and in the presence of secondary and parasitic noise. This is a crucial asset in tests involving industrial acoustics and that is why the method is significant both practically and cognitively [1].

Application of the sound intensity method, including the presentation of space vector distribution of acoustic power, may bring new insight into the nature of acoustic field formation in real-live conditions of working sources. Acoustic conditions in these areas are much different from the theoretical assumptions ascribed to free or diffuse field [2]. It is a frequent occurrence that the sound intensity measurements in real conditions may show great disparity between the theoretical assumptions of the acoustic fields distribution and the actual measurements. The disparity results mainly from simplifications accompanying the analytical methods due to lack of complete data concerning physical properties of an investigated object.

In the paper authors have described the visualization methods in acoustic flow fields and showed how these methods may assist scientists to gain understanding of complex acoustic energy flow in real-life field. A graphical method will be presented to determine the real vector distribution in 3D flow wave field. Visualization of research results are shown in the form of a *intensity streamlines* in space and as a *shape of floating acoustic wave* and *intensity isosurface* in three-dimensional space, which is unavailable by conventional methods using a microphone.

Direct measurement of the flow intensity sound as the energetic fields and graphically description of the results, can explain diffraction and scattering phenomena occur on the real acoustical barriers and solved in practical way a lot of engineering problems. For instance, the flow of acoustic energy presented as a transmission path described by the intensity streamlines (they a graphically change on the ribbons) shows the way of energy flow in three dimension acoustic field. Showing the paths along which it is transmitted may be very useful when the necessity arises to visualize “the shape of noise" radiated by vibrating mechanical structures (machines, vibrating heterogeneous plates, equipment's, etc.) and can show their activity also in limited spaces. This is a form of qualitative analysis for stationary fields, which consists in a complex evaluation of the paths along which the acoustic energy of a radiating source is transported.

In the paper, experimental studies carried out on real models and structures are documented with graphical records of acoustic fields created by surface sources (radiation of vibrating structures) and the effects of wave interference on obstacles and barriers placed in the flow field. This graphical description allows us to assess the effects of the mutual influence of the sources and examine the energy distribution of actual acoustic sources. Traditional methods of acoustic metrology, based on acoustic pressure distribution, do not offer such possibilities

Based on the research with intensity technique and using selected visualizations methods, in the publication are demonstrate many examples of vector space distribution of the real-live acoustic field, illustrate the application of the SI measurement for practical problems at the acoustical diagnostic and noise abatement. Analysis of the results makes it possible to obtain much new information about energetic and geometric distributions of the acoustic fields. The measurement technique described, as well as the method of graphical presentation of results, can enrich the knowledge of the mechanism of acoustic energy flux through the real partitions.

2 SOUND INTENSITY IN ACOUSTIC FLOW FIELDS

Many theoretical discussions on acoustic field distribution consider cases with initial and edge conditions. However, in real systems, wave relationships are so complicated that the introduced edge conditions may cause large discrepancies between the theoretical models and the real-life ones. Even the initial experiments (using the sound intensity technique) proved that routine linearization's cause differences between the expected results and the real image of the field that are too large. The differences are usually either due to far-fetched simplifications, or result from the lack of all necessary data.

Understandably, theoretical descriptions of the acoustic field deal with simplified cases, where it is easy to determine properly the edge conditions to solve the differential equations. Actual acoustic fields, created by a simultaneous action of various wave effects, cannot be explained by some general mathematical descriptions. That is why elementary acoustic phenomena are discussed separately and only in some cases is it possible to apply superposition rules to determine the final image.

Most acoustic fields encountered in practice are too complicated to be precisely modelled mathematically. Complicated relations occur both in the near field, and all over the field area produced by sources working in small-restricted areas. Stochastic phenomena in real-life conditions are best described by experimental studies on actual objects or on models build in certain scales. The image of a acoustic field produced in such a surrounding is the resultant effect of the obstacles appearing in a source radiation path, as well as of the influence of scattered reflections together with their phase and amplitude relations. The results of studies using sound intensity technique contribute to the theory of sound and general knowledge about the physics of flow acoustic phenomena, especially in near acoustic fields.

The literature seldom contains publications in which the results of analytical model calculations are verified by experimental tests. At its best, such an analysis concerns only a distribution of pressure levels i.e. a scalar parameter of an acoustic field. However, in a real acoustic field, there is a close connection between scalar and vector effects represented by the acoustic pressure and particle velocity. It is a scalar-vector description of an acoustic field character represented by two forms of mechanical energy; potential and kinetic energy that fully explains the physical meaning of wave phenomena, and makes it possible to consider the mechanisms of propagation, radiation, diffraction or scattering. A good form of illustration of scalar-vector phenomena occurring in real conditions is the application of the sound intensity technique in tests in which the product of the pressure and particle velocity of the acoustic wave is measured by means of a proper measurement probe ("p-p" or "p-v" type). The visualization of the distribution of the active and reactive parts of the acoustic field gives the possibility of a full analysis of an acoustic wave. A properly used intensity method ensures a chance of measurement of the vector distribution in any place of the restricted space, even within a near field. At the same time it is a convenient technique, making it possible empirically to verify the field parameters determined by means of a computational method.

Nevertheless most analytical dependencies describing the phenomena occurring in an acoustic field refer to a free and diffusive field, or possibly an acoustic field in homogeneous ducts at frequencies below cut-off frequencies. For such fields, treated usually as fields with propagating plane waves, pressure and acoustic intensity are in phase (free field), or, as in the case of a diffuse field, interference phenomena are neglected for the frequencies corresponding to the wavelengths for shorter than the compartment dimensions. In reality, however, there are no compartments, which could be fully qualified as containing free or diffuse fields.

In traditional acoustic metrology, the analysis of acoustic fields concerns only the distribution of pressure levels (scalar variable). In a real acoustic field both scalar (acoustic pressure) and vector (the acoustic particle velocity) effects are closely related. Only when the acoustic field is described by both potential and kinetic energies may we understand the mechanisms of propagation, diffraction and scattering of acoustic waves on obstacles, as a form of energy.

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. Introduction of these possibilities have greatly changed the approach to examining many acoustic phenomena. This new 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 criteria as strict 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 fields with presence of *parasite* noise, which is a significant advantage in research done in industrial conditions.

3. VISUALIZATION OF ACOUSTIC ENERGY FLOW IN SPACE

Over the last decades flow visualization has been widely applied to simulation and experimental studies; numerical computer techniques are used for flow visualization in fluid mechanics and aerodynamics studies. The literature term called CFD methods, along with the development of numerical methods and the increase in processor capacity, more and more relevant ready-made software is available on the market [3,4]. Also, developments in visualization algorithms, managed by complex databases, progress in computer graphics, multimedia technologies and network communication, all contribute to the development of flow visualization techniques.

Modern forms of vector flow visualization 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 the available graphic systems that give the user the ability of choosing the most convenient presentation form [5,6].

This short summary shows that flow visualization is not a new area and it already possesses some traditional forms. However, they are rarely used to describe acoustic phenomena, despite the fact that acoustic fields (represented by sound intensity) have been known in sound theory for a long time. The little 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.

The literature on the subject indicates that the visualization of vector acoustic field effects is a domain still waiting for more efficient methods. 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 with results presented in various graphical forms.

4. DESCRIPTION OF THE INVESTIGATIONS

The sound intensity method applied in acoustic metrology, simplifies the technique of measurements and effectively replaces classical methods [1,2]. Measurements can be conducted in the near field and in the presence of parasitic noise. Wave phenomena registered in the region of sources working in their natural environment allow one to analyse the field both qualitatively and quantitatively, i.e. to evaluate its energetic distribution and to visualize the wave distribution in the tested area. One of the main advantages of SI technique is the possibility of identifying the energy transmitted through different parts of composite panels and walls. This is a crucial asset in tests involving industrial acoustics.

The main advantages of research carried out with a sound intensity technique consist in the fact that the measurements taken refer to energy dependencies of the field, and that they can be carried out under real conditions. As has been pointed out, the presented advantages of the sound intensity technique may be used in acoustical measurements much more effectively than classical methods, e.g. in verifying the theoretical methods of field modelling with check measurements taken under real conditions. The tests on model systems and the presentation of the results in graphical form show that the application of the principles of phenomena superposition in theoretical methods of acoustic field modelling should be carried out with great care. The investigations have shown that in reality the turbulent character of the field may cover all the compartment space; thus it may reach beyond the area attributed mainly to the acoustic near field.

Presentation of pathways on which the acoustic energy is conveyed, is especially useful in the visualization of complex acoustic sources (machine diagnostics, radiation of vibrating inhomogeneous structures) and in explaining their action in real-life conditions. It is a form of a qualitative analysis that appeals directly to 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 non-linear phenomena occurring in acoustic fields.

4.1 Flow Wave Reflection from Hard Plate

The aim of the tests carried out was to describe a distribution of sound intensity vectors in reflected field of a acoustically hard surface. The research room was in the laboratory which, in acoustic terms, may be regarded as a seem diffuse field. The source of waves was the small loud-speaker supplied with white noise which was radiated oblige at a 60°from distance of 1,3 m to the plate. The tests on the reflected field were carried out in a measurement plane of 2,1 m by 1,2 m placed in the semi anechoic room. The measurement plane was divided into 252 elementary surfaces of 0,1 m by 0,1 m in the middle of which sound intensity components xy were measured.

Geometrical-added, mutually perpendicular components x,y are presented as a distribution of intensity vectors in the measurement plane in a form of arrows. The component amplitudes keep proportionality in compliance with the arrow length.

Additionally, a graphic analysis of the reflected field may include a picture of streamlines of scattered sound intensity flux. It is a certain form of qualitative analysis for stationary reflected fields which consists in a complex evaluation paths along which the acoustic energy is transported.

An analysis of field distribution was in 1/3 octave frequency bands from 80 Hz to 5 kHz. Some examples of field pictures are shown on Figure 1.

a). b). c).

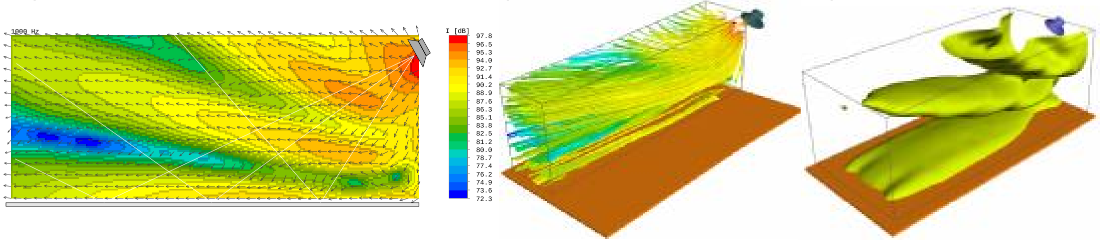

Figure 1. Sound intensity wave reflected from a hard plate; acoustic source - loudspeaker oblige 60^{o} – a) intensity vectors map, b) intensity streamlines (half space), c) intensity isosurface

Comparing the field distribution for whole tested frequency bands it can be stated that the nature of resultant field is really complex. It results from the fact that the shape of reflected field is affected not only by acoustic laws of reflection but also by other elementary phenomena connected, e.g., with physical condition of the medium (temperature and humidity fluctuations within the tested field), dynamic reaction of the plate stimulated by incident wave (stimulation of modal and bending vibration with secondary acoustic radiation) and interference of multi-reflected waves.

At sound oblique incident, it can be stated that it is not possible to find any relations between the nature of reflected wave distribution and geometric law of reflection. For most cases of frequency it may be seen that there is formed a close-to-surface wave running tangent to the reflecting surface and there is separated an area of clash between a direct wave and a reflected wave, which, in the distribution picture, is shown in a form of a distinct saddle point. For lower frequencies, it can be noticed that there are formed violent flows in a form of acoustic wave vortex.

4.2 Rectangular Plate Inside 3D Field

Examples illustrate how the application of the SI measurement may be help for solution a practical problems at the acoustical diagnostic and noise abatement. On the experimental measurements a graphical methods presented the real-live vector distribution in 3D flow wave field.

The tests concern the application of sound intensity technique to graphic presentation of spatial distribution the acoustic energy flow around flat, hard-acoustics rectangular plate of dimensions 0,52 x 0,32 m^2 and thickness 25 mm located in a anechoic chamber and excited by axially travelling incident wave (stationary broad band pink noise) coming from loudspeaker on a distance 0,6 m central, before to the plate. The measurements are curry out in one-third- and one-twelfth octave bands and vectors map have been build in the frequency range between 25 Hz and 6300 Hz.

On the Figure 2 the distribution of intensity field around the rectangular plate is show. The SI measurement was taken with a fixed point method. Around the plate the measurement space of 0,69 x 0,51 x 0,51 m^3 was divided on 6647 cubic, in the centre of which there were taken measurements of *x, y* and *z* components of intensity which give a 19041 measured SI vectors using as a data to graphical visualizations. Figure 2 are show examples of vector field distribution an acoustic reflections and shadow formed around the plate. The intensity streamlines and shape of wave as well as the intensity isosurfaces are presented for some selected frequencies. Using the intensity streamlines seems to be very useful and meaner way for representation the transport paths of acoustic energy in environmental conditions. We can see that direct flow wave excited on the front surface together with back wave made in the field many vortices and curls (effect of backscattering). In the second part of our research, the investigations of sound intensity stream distributions will be made in the space around the one corner of the plate. In the image of energetic acoustic field we can show the intensity streamlines in ribbon form in the three-dimensional space close to the lower corner of plate (see Fig. 2d).

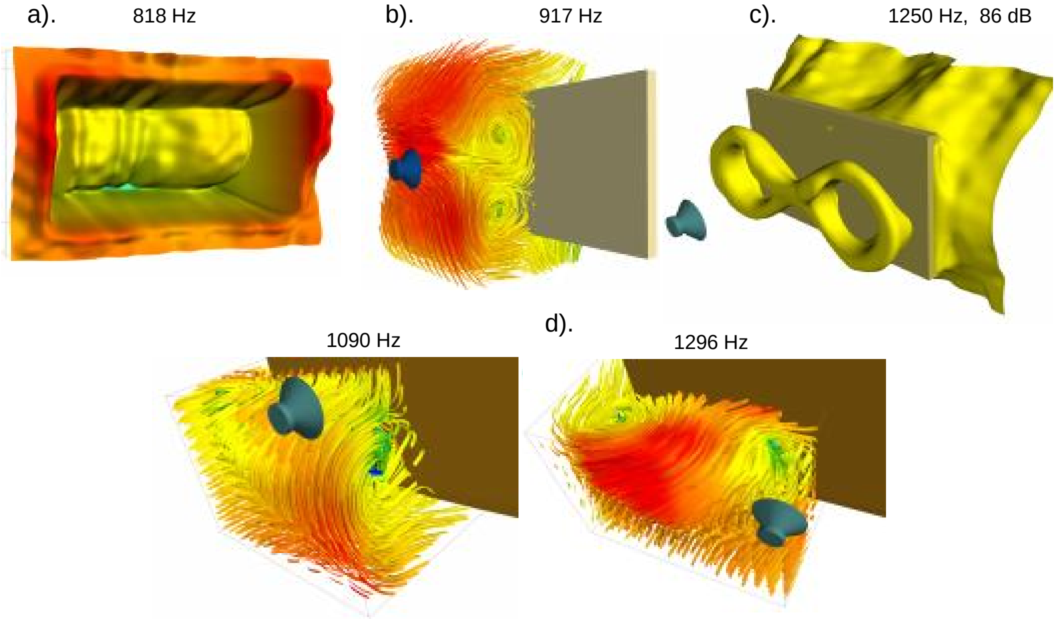

Figure 2. The normal intensity component for some selected frequencies as a shape of wave (a) in a rear side of plate together with reflected intensity streamlines - in ½ space of measurement (b) and intensity isosorface around the plate (c). Distribution of intensity streamlines is also shown around one corner of the plate (d)

4.3 Acoustic Flow Around Cavity

The next example presents an experimental study of sound intensity stream flow over a flat plate with rectangular deep cavity (0,2 m wide and 0,5 m deep). The tests concern the vector distribution of the field excited by traveling incident wave coming from the loudspeaker line array system. In the line array, individual radiators five of complete loudspeaker arranged in a straight line (a sound column), have relatively narrow vertical radiation patterns, which vary strongly with frequency. As attractive as same of the performance characteristics of line arrays may be, they all have inherent limitations. First, the directivity advantages of a line array are present in the vertical plane only (along the length of the array). The horizontal directivity of a line array is only as good as the performance of the individual devices used to form the array. Secondly, line arrays are made up of discrete elements, as opposed to a continuous line source.

Figures 3 shows a fragment of these studies as a sound intensity field distribution on the plane (a) and also, as streamlines in three-dimensional investigation space(b). The verifying tests using an intensity technique have shown how much cavity influence on the shape of the flow field. Please put your attention on the vortex effects in the niche for frequency 800 Hz.

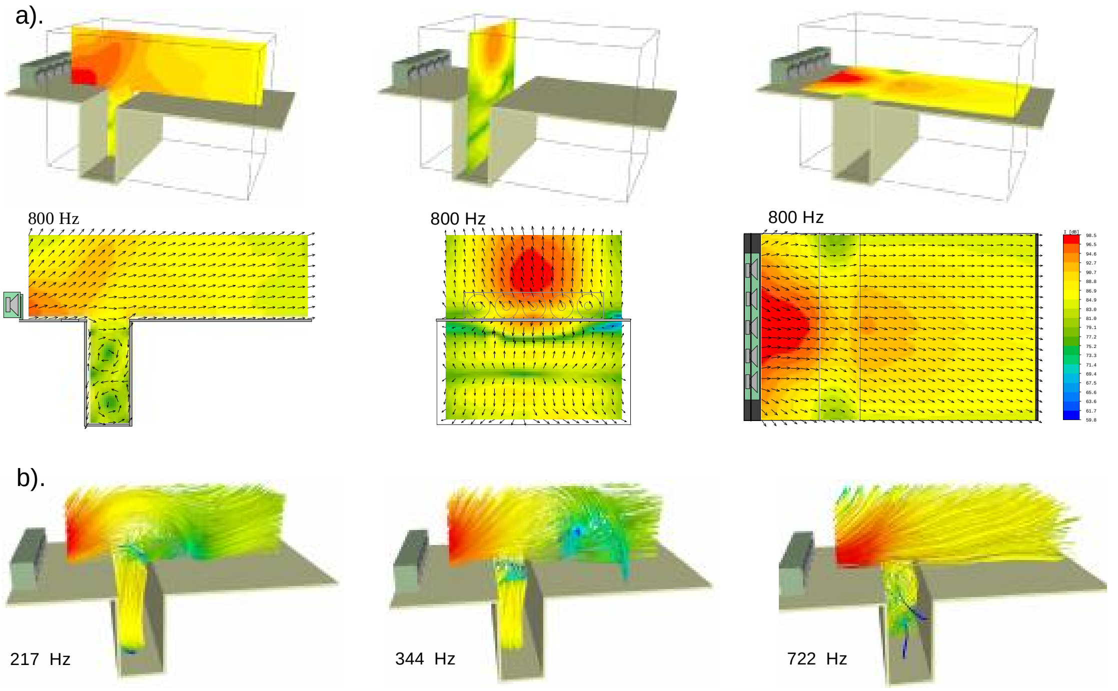

Figure 3. Distribution of flow field for the loudspeaker line array system radiated over a flat plate with rectangular deep cavity (0,2 m wide and 0,5 m deep): a) intensity map and vectors in the selected measured plane, b) intensity streamlines in 3D space (only half of the space is shown)

4.4 Vectors Field Clouse the Outlet of Pipe

Noise propagation within ducts is of practical concern in many areas of engineering industrial processes where fluid has to be transported in piping systems as ventilating and air conditioning, engine exhaust and around gas turbine. The noise generated by inside flow and around outlet of duct is an environmental concern in engineering practice. Seeing that, one distinguishes basic mechanism of broadband noise generation exhaust engine systems is incoming–turbulent noise. Therefore, our attention in experimental research is first placed on the analysis of the sound intensity effects in the space around outlet region of cylindrical pipe. In the beginning of the model duct is install loudspeaker (sound source) excited with white noise signal.

The flow of acoustic energy presented in the Figure 4 shows how the way of energy flow out of duct. The experimental facility sketched in figure has been developed for the study of incoming sound in space around the pipe with outlet diameter D=566 mm. The outlet research area of the dimension 1150 mm x 1150 mm x 550 mm was scanning with intensity probe measured the *x, y* and *z* components of sound intensity vector inside each of 4840 cubic sub areas.

Visualization of the results shown in the Figure 4 as a sound intensity distributions in plane close to end of duct, intensity streamlines in space, shape of sound intensity isosurface and as a shape of floating acoustic wave. Direct measurement of the acoustic power flow around outlet can explain a diffraction and scattering phenomena occur in this region.

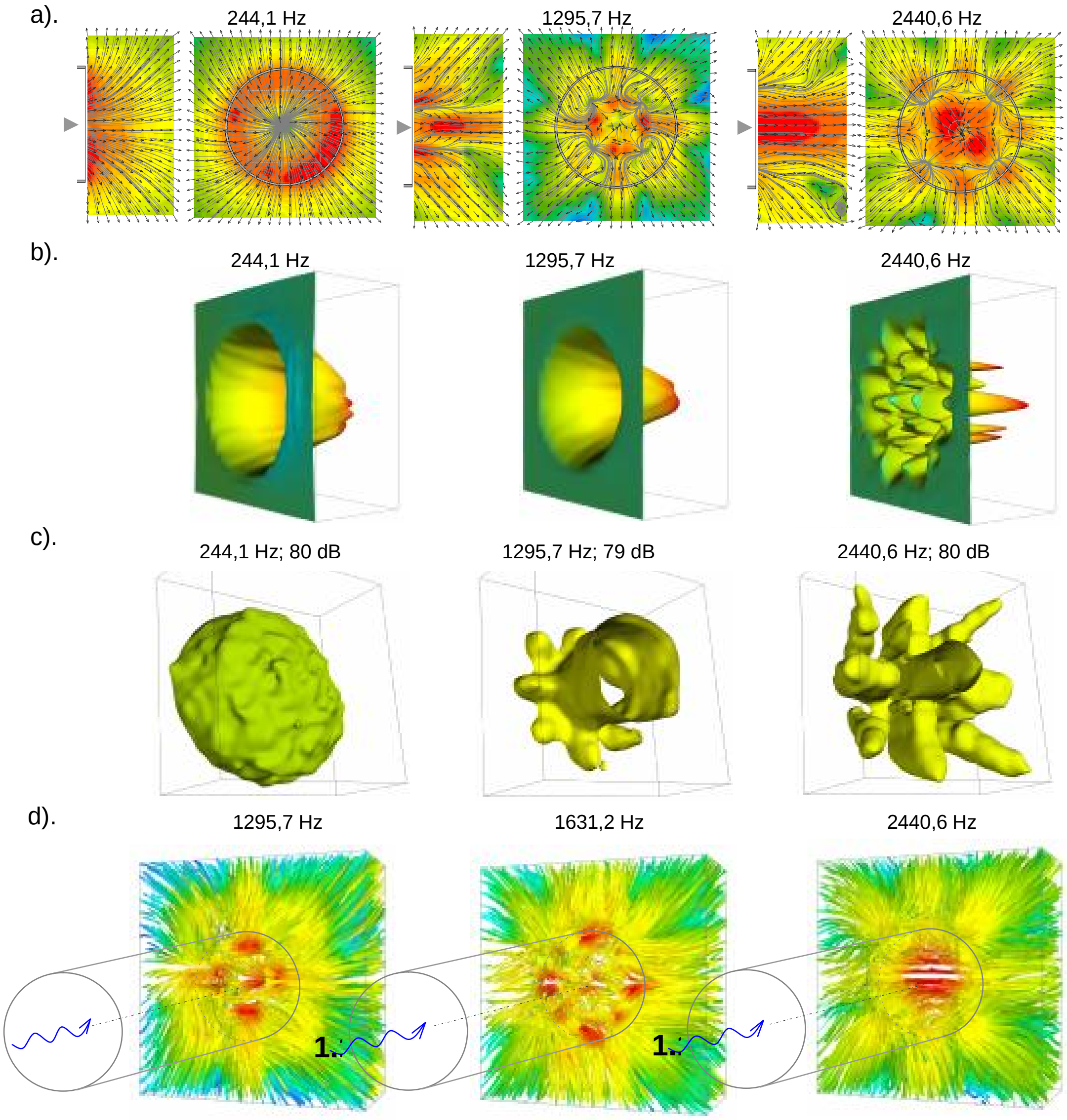

Figure 4. Distribution of sound intensity in space close to the outlet of cylinder field for some selected frequencies: a) – intensity map, b) - shape of flow wave, c) - intensity isosorface in the outlet region, d) - intensity streamlines (shown from the rear side of measured space)

5. CONCLUSIONS

The analysis of acoustic field with floating wave in space, show that the sound intensity technique is extremely useful in visualization of vector acoustic phenomena. This form of presentation is new in experimental acoustic. Vector visualization of vibroacoustic phenomena, in contrast to pressure methods, significantly improves acoustic diagnostics of machines and devices by a precise localization of noise-radiating sources (*hot points*).

The application of the sound intensity technique together with FEM/BEM 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 the structure. Direct energy analysis of acoustic fields was not possible earlier because the classical studies used a converter (microphone) measuring pressure changes, but pressure is a scalar element of acoustic waves. Only when direct measurements of sound intensity (as streamlines of acoustic energy - a product of acoustic pressure and acoustic particle velocity) became possible, could the wave distribution be analysed in the form of wave acoustic energy transport.

The presentation of the vector distributions of real acoustic fields in the areas for which it is difficult to make a theoretical analysis (*direct field* and *near field*), can explain many particulars concerning the radiation character of surface sources with heterogeneous vibration distributions.

Vector visualization of acoustic fields, controlled in real-life machine operation conditions, allow us to analyse the radiation energy of the device and its separate construction elements, such as drive circuits and power transmission circuits, and local secondary sources, such as casings, supports, and systems. Precise indication of the local vibration sources is very significant in limiting the noise radiated by devices and facilitates their structural and parametrical modification.

The studies on vector acoustic phenomena carried out in real-life conditions may be also compared with numerical models of acoustic fields, prepared with commercials software available on the market. Experimental investigations indicate that simplicity applied in simulation numerical models result in serious disparities between theory and real-life data [7,8]. In such cases the sound intensity studies carried out on physical models may link theory with practice by introducing limits to reductions, so that the simulation reflects real-life physical effects.

6. REFERENCES

1. Fahy, F. J. - Sound Intensity. Elsevier Applied Science, London (1989).
2. Crighton D. G. *at all - Modern Methods in Analytical Acoustics.* Springer-Verlag, London, (1966).
3. Dickinson R. R. - A Unifield Approach to the Design of Visualization Software for the Analysis of Field Problems. Proc. *Threedimensional Visualization and Display Technologies*, 173-180, Spie (1989).
4. Gerald-Yamasaki M. - *Visualization of Computational Fluid Dynamics.* Comp. Fluid Dynamics Revue (1995).
5. Hafez M. *at all - Computational Fluid Dynamics Review 1995.* John Wiley & Sons, Chichester, (1995).
6. Williams E. G. - *Fourier Acoustics – Sound Radiation and Nearfield Holography.* Academic Press. San Diego, London, New York (1999).
7. Weyna S. - An Image of the Energetic Acoustic Field in a Parallelepipeded Room Models. Acta Acustica. Intern. *Journal on Acoustics* , Vol. **82**, 72-81, (1996).
8. Weyna S. - Identification of Reflection and Scattering Effects in Real Acoustic Flow Field. *Archives of Acoustics,* Vol. **28**(3), 191÷203 (2003).