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ACOUSTIC ENERGY DISTRIBUTION IN SPACE AROUND THE PIPE OUTLET

Stefan WEYNA

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

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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. In the acoustical practice, up until the last two decades, the study of vectors acoustic fields and noise flow visualisation are rather seldom. But direct measurement of the flow intensity sound as the energetic fields and graphically description of the results, can explain a diffraction and scattering phenomena occur on the real noise sources and solved in practical way a lot of engineering problems. Based on the research with intensity technique and using selected visualizations methods, in the publication are demonstrate in graphical form the sound intensity effects in the space around outlet region of cylindrical pipe. The duct model have a partly square and barrel shaped cross-section. The outlet research space was scanning with intensity probe measured the x, y and z components of sound intensity vector.

Direct measurement of the acoustic power flow around outlet can explain all diffraction and scattering phenomena occur in this region and the noise generated by inside flow and around outlet of duct is an environmental concern in engineering practice.

Key words: acoustic field, sound intensity, wave visualization.

1. Flow visualization

Over the last decade flow visualization has been widely applied to simulation and experimental studies [1, 2]; numerical computer techniques are used for flow visualization in fluid mechanics and aerodynamics studies. The literature term for this subject [3–5] is called CFD (Computational Fluid Dynamics); 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. 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.

Animation, which shows temporal relationships and creates virtual spaces, is truly spectacular, but requires high computation power and large ROM/RAM. Graphical stations (e.g. Silicon Graphics) that meet the requirements will be too expensive for average users for some time to come; however, even PCs may help create really advanced flow visualization techniques.

How we are going to present a flow depends on many analytical factors, but the most popular choice is streamlining in two or three dimensions. As thin streamlines are very difficult to present in three dimensions, especially in cases of vortexes and turbulences, they can be made more distinct by a ribbon strip or as a tube shape. A streamline is then shown as a tunnel flow [2] or as an image of a "wandering cloud" [6], or as a polygon [9].

The most common way of presenting flows in 3D 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 (*OpenGL*). This form is also suitable for presenting vortex effects in a flow field, and a twisting vortex flow.

Streamline and ribbon strip forms of flow visualization require a lot of processing. For example, one line requires several hundred integrations. Each integration has to be calculated with very high precision, which makes the CPU time processing even longer. In this case, second order Runge–Kutt method is the most efficient solution [7].

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 [8, 9]. 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.

2. Sound intensity measurements in acoustic flow studies

More than a two decade ago, a revolutionary measurement technique made it possible to measure and record the distribution of sound intensity vectors in acoustic fields.

Thanks to modern digital technology and fast AC/DC converters with high dynamics, it was suddenly possible to measure directly and visualize the distribution of acoustic power radiated by various sources. Many acoustic phenomena with vector properties, which previously had been measured only in an indirect fashion (through the measurement of acoustic pressure – a scalar value), could now be examined experimentally. Also some additional theoretical computations became possible.

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.

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 linearisations 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.

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. Sound intensity transducers

Modern equipment for measuring sound intensity was launched on the market in the 1980s. Today, this method frequently complements conventional methods used in acoustic metrology. Sound intensity amplitude may be determined by a:

- two-microphone method,
- cross correlation transform between pressures from two microphones,
- 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 in a distance Δr proportionate to the wavelength. The relative position of the microphones may vary, but the most effective position is when they are facing each other. The microphones are usually 1/2" or 1/4" condenser microphones.

A *pressure-velocity* probe is significantly different from the two-microphone probe. For example, the NE-216 probe, produced by NORSONIC S.A., is comprised 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 applied. The *Microflown Ultimate Sound Probe* – USP (made by Microflown Technologies B.V.) is a new type of sensor, as a practical alternative to pressure microphones [11]. It also uses mini accelerometers and laser vibrometers. The Microflown USP probe is a very compact and integrated sound probe that combines three orthogonally positioned particle velocity sensors and a miniature pressure microphone. The actual 3D sensor configuration without its cap is less than $5\,\mathrm{mm} \times 5\,\mathrm{mm} \times 5\,\mathrm{mm}$.

The Microflown 3D-USP, used as a scanning probe, was especially developed for measurements carried out very close to vibrating objects – the source of acoustic power. The USP effectively extends the traditional possibilities for complete sound intensity depictions of 3D energetic fields, by measuring three particle velocity vector components and the acoustic pressure. By minimizing the array distance to the sound source, we may investigate particle velocity levels in very near field conditions (a so-called hydrodynamic region), and the power acoustic flow may now be fully described in real-life experimental conditions.

4. Acoustic field modelling – the state of the art

The previous theoretical methods of acoustic field modelling deal with simplified cases, where it is easy to determine edge conditions in order to solve differential equations and if the processes are linear. That is why with complex acoustic phenomena, we separate elementary phenomena and analyse them separately. Meanwhile, only in some cases of mutual wave influence (linear systems) is it possible to apply the rules of elementary phenomena superposition to determine the resultant image. However, in the case of real acoustic fields, created by the simultaneous activity of various wave effects, no general mathematical description could do.

In three dimensional fields, acoustic radiation from vibrating structures, mutual interferences of waves, scattering effects, absorption by and diffraction on the obstacles, the emergence of standing waves – very well described as separate events – have not been successfully linked together in a synergetic model.

The emergence of technologies that can measure the vector of the acoustic wave intensity (the SI method) in three dimensional space, created a need for a suitable visualization, where spatial distribution of sound intensity vectors could be clearly shown and interpreted. The problem is how to create an image of 3D space and use modern visualization methods (animation, multimedia) to show the dynamics of acoustic phenomena in a turbulent flow field.

Visualization of results may involve depicting various acoustic phenomena, depending on the area of interest. In sound engineering, it may be an acoustic wave power density distribution in space, the wave dissipations, the evaluation of its motion within the medium, spatial diffusion and frequency irregularities of sound velocity. Technical acoustics could be interested in directional characteristics of industrial sources and the variables connected with reflection, scattering and diffractions on obstacles, which are used to draw maps of the noise levels and to evaluate the effectiveness of anti-noise monitors in industrial premises.

Sound intensity studies suggest that previous theoretical models and computer simulations of acoustic fields in restricted areas may be far removed from reality. It is because the distribution of the real fields is much more complicated than 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.

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.

Better understanding of a mechanism that conveys structural sounds and *back scattering*, especially in a near field of the source (through the analysis of a graphical distribution of the vector acoustic field) can be especially used in noise protection in rooms, and in technical diagnostics using vibroacoustic methods. Visualization and analysis methods may be important in research of inhomogeneous structures, in acoustic metrology (level of noise, transmission loss characteristics of partition, structure radiations studies), in structure mechanics (acoustic radiation characteristics, lowering the noisiness of mechanism, localization of sources), in acoustic protection of transportation devices, and sound-engineering.

5. The reason of the subject matter and methodology

Transforming vibrating energy into acoustic energy takes place on the boundary of two sources; as a result, acoustic waves appear outside the structure. Creation of the acoustic field round vibrating structures has been termed as the vibroacoustic effect, and, as it is a harmful phenomenon, it is deemed noise.

The control of vibroacoustic effects in machines and technical devices is one of the basic tasks in the construction of modern industrial products. The most important element here seems to be a proper design, allowing for dynamic consequences not only inside but also in the environment surrounding the device. A quality criteria for modern products is the largest possible reduction in vibroacoustic activity, and it is assessed by the examination of the acoustic field surrounding the source.

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. In many cases, general term formulas are identical to those from electromagnetic field analysis. 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. Stochastic phenomena in real-life conditions are best described by experimental studies on actual objects or on models build in certain scales.

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.

Studies on three-dimensional acoustic field and the efficient organization of time-consuming intensity examinations require an acquisition of data from robotic systems (visualization of the 3D flow field requires ten thousand or so measurements of the x, y and z intensity vector components). In our team, the acquisition of measurement data, and their numerical and graphical processing, is carried out with our own SIWin software (using $C++$, graphics with *OpenGL*) built for *Windows 9x/NT* and *Windows 2000*.

In post-processing and in choosing the most suitable form of visualization, we use modern achievements in flow visualization: animation and multimedia technologies. We also use and develop our own software for vector visualization of the acoustic field. Below, on the one of example we present a various visualization techniques using in research with analysing the sound intensity in outlet of flow duct.

6. Experimental set-up and measurement procedure

Noise propagation within a ducts is of practical concern in many areas of engineering industrial processes where fluid has to be transported in a such 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. We focus on the duct model with partly square and barrel shaped cross-section. In the beginning of the model duct is install loudspeaker (sound source) excited with white noise signal, so, the sound power flow along a duct is send without mean flow.

The experimental facility sketched in Fig. 1 has been developed for the study of incoming sound in space around the pipe with outlet diameter Φ = 566 mm. The outlet research area of the dimension $1150\,\mathrm{mm} \times 1150\,\mathrm{mm} \times 550\,\mathrm{mm}$ was scanning with intensity probe measured the x, y and z components of sound intensity vector inside each of 4840 cubic subareas.

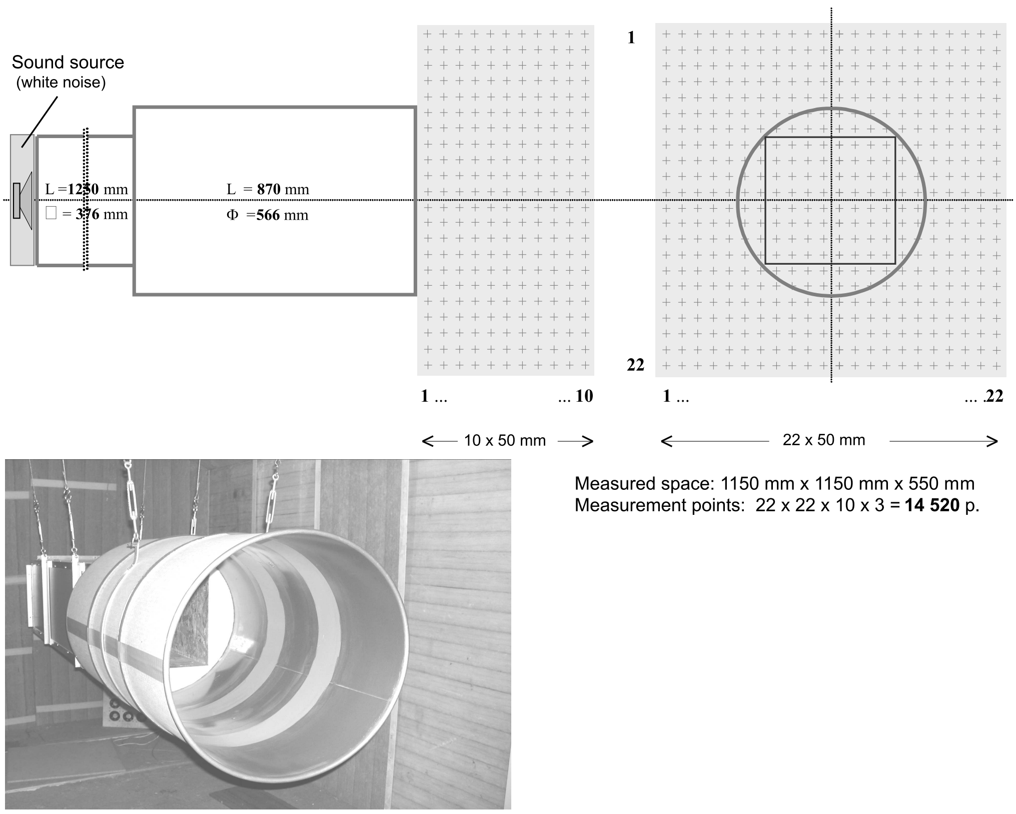

Fig. 1. The experimental facility sketch for study of outlet sound intensity distributions.

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. Visualization of the results shown in the Figs. 2–5 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 measure-

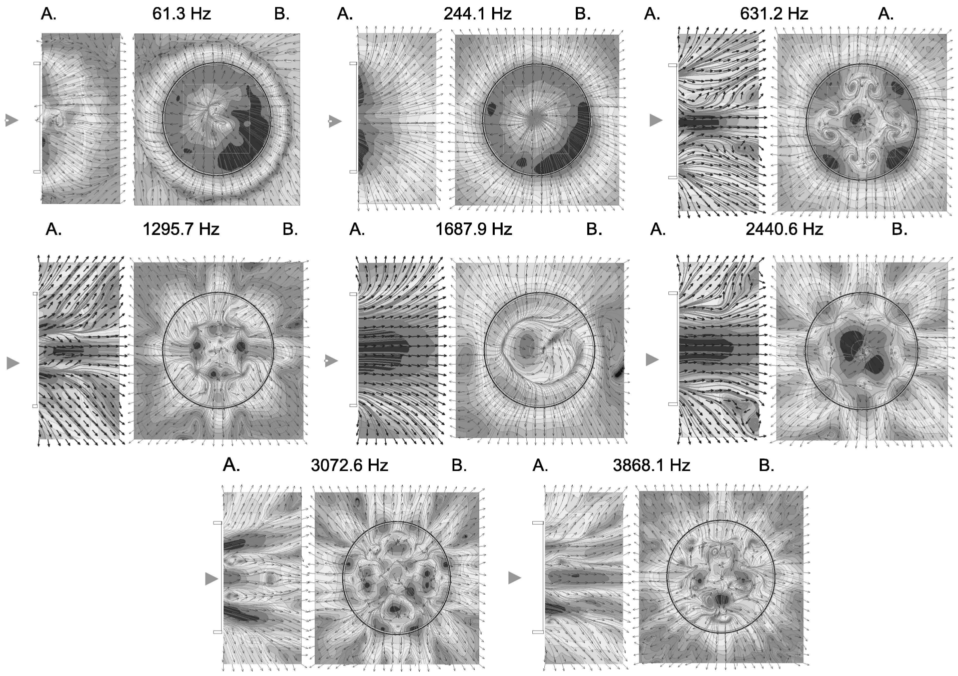

Fig. 2. Distribution of sound intensity field in the plane of symmetry axis of cylinder (A) and in the plane close to the outlet of cylinder (B).

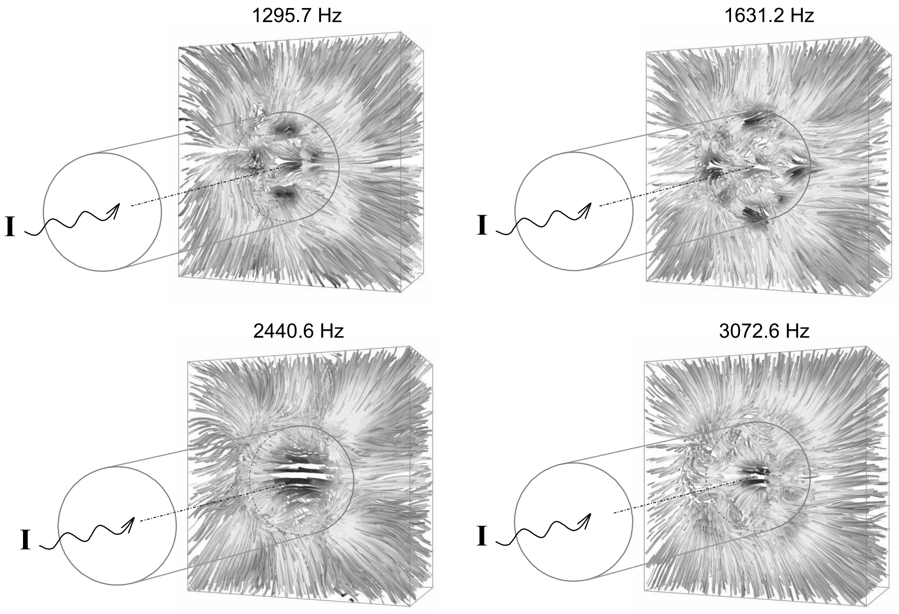

Fig. 3. Examples of intensity streamlines in the outlet region for some selected frequencies (shown from the rear side of measured space).

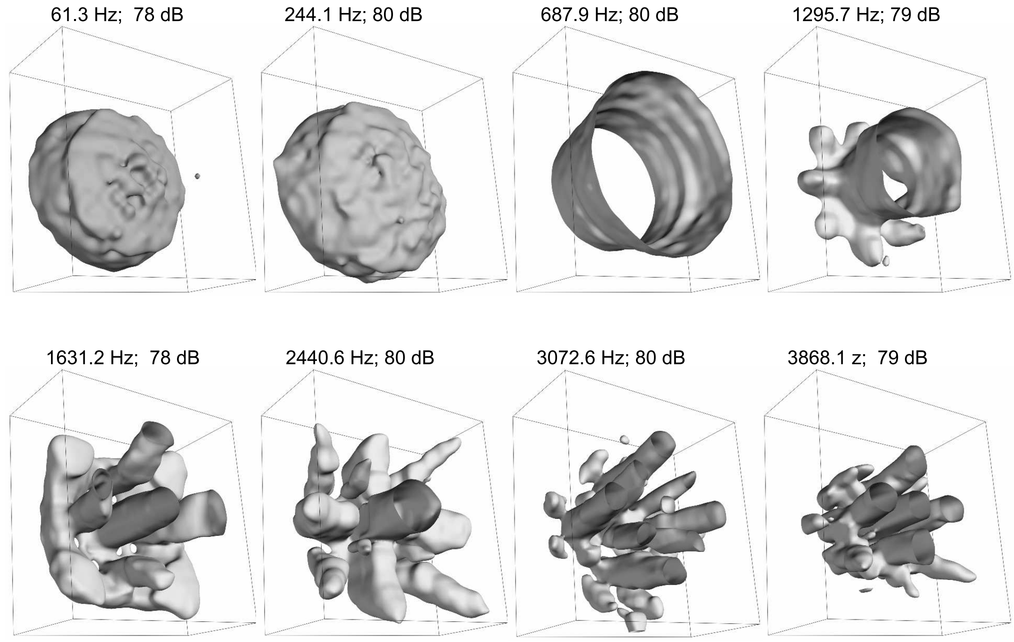

Fig. 4. Examples of intensity isosurface in the outlet region of cylindrical pipe for selected frequencies and levels of sound intensity.

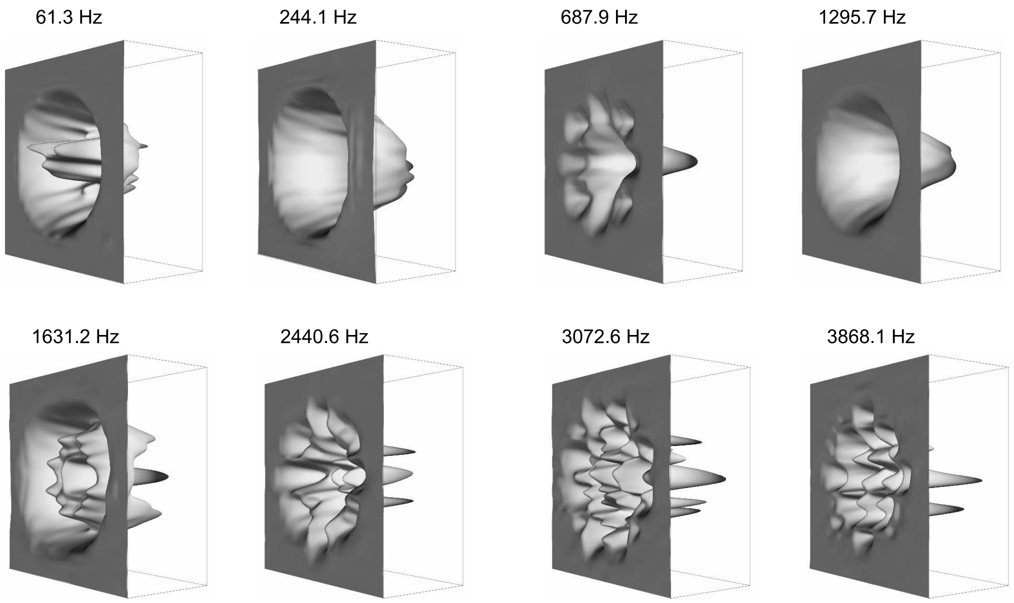

Fig. 5. Examples of the normal sound intensity component (as a shape of flow wave) in the measured plane close to end of cylindrical pipe.

ment of the acoustic power flow around outlet can explain a diffraction and scattering phenomena occur in this region.

The flow of acoustic energy as a intensity streamlines presented in the Figs. 2 and 3 shows the way of energy flow out of duct and in the Figs. 4 and 5 we show the examples of shape of the isosurface and shape of the floating intensity wave.

7. Conclusions

The analysis of radiation and the effects of placing obstacles in a homogeneous acoustic field, show that the sound intensity technique is extremely useful in visualization of vector acoustic phenomena; this form of presentation is new in experimental acoustic.

Static and dynamic forms of visualization of acoustic energy streamlines in a three-dimensional field significantly contribute 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 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 nonlinear phenomena occurring in acoustic fields.

The studies on vector acoustic phenomena carried out in real-life conditions may be compared with numerical models of acoustic fields, prepared with software available on the market (e.g. *SYSNOISE, ABAQUS/Acoustic, BEASY, COMET/Acoustic, FLO++* and many similar ones). Our own studies indicate that reductions applied in simulation models result in serious disparities between theory and real-life data [12–13]. 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. This methodology allows an objective re-evaluation of theoretical assumptions.

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.

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 such local vibration sources is very significant in limiting the noise radiated by devices and facilitates their structural and parametrical modification.

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