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IDENTIFICATION OF REFLECTION, DIFFRACTION AND SCATTERING EFFECTS IN REAL ACOUSTIC FLOW FIELDS

S. WEYNA

Department of Applied Vibroacoustics
Technical University of Szczecin
71-065 Szczecin, Al. Piastów 41
stefan.weyna@ps.pl

In contrast to the classically described acoustical fields with acoustical pressure distributions (scalar effects), the graphical presentation of the acoustic energy flow in real-life acoustic fields as a vector mapping, can explain many particulars concerning the areas in which it is difficult to make a theoretical analysis (direct and near field, vortex flow, effects of scattering on obstacles, reflection on partitions, efficiency of acoustics barrier, etc.). With the experimental application of the sound intensity (SI) measurement method in real-life fields as well as the technique of presentation the results in a 2D and a 3D graphical form, numerous examples illustrate the results of applying the SI measurement for practical problems presented in the article. Concerning the intensity vector distribution of the real near and fare field, the paper presents the paths of the acoustic energy flow over the barriers and the form of the acoustical radiation field of vibrating structures. This type of information enriches the knowledge about vector acoustic fields and the mechanism of the acoustic energy flux through the real partitions.

1. The study of wave fields

Sound being reflected from several limiting surfaces, together with the direct sound from the source, built up a sound field with such complicated patterns that even a most careful analysis is incapable of describing it completely. Such a problem is encountered mainly as an acoustic pressure distribution field in rooms or bounded spatial systems and can be solved theoretical and experimentally in several ways [2]. These study include the wave theoretical model, the geometrical acoustic model, the use of statistical methods, the psycho-acoustic approach or the physical modelling.

Morse and Ingard have theoretically calculated diffraction and scattering from various geometrical shape structures [12]. Basing on the theory, also numerical method can be used to write acoustical computer programs [1, 13]. The main numerical models are concerned with the geometrical presentation of the spherical sound propagation, that is to say that phase and wave spherically are ignored. In general, analytic models assume an omnidirectional source, reverberation absorption coefficients, especially reflecting flat surfaces, and air absorption quantified by the air absorption exponent. Each of these approaches provides useful information about acoustic pressure fields, but none currently offers a full vector mapping of the acoustic energy flow (vectors effect) in front and back of any scattering systems working in real environmental conditions. Interference, diffraction and scattering of waves make the real field very complex and modelling theoretically the acoustic efficiency of the barriers is difficult.

The acoustical design of the barriers is mainly empirical for two reasons: firstly, because of the lack of a precise theory of the acoustic flow fields around even simple barriers, and secondly because of the great variety and complexly of the acoustical environment in which the barriers are used. For a very long barrier, the distribution of the acoustical pressure can be easier to predict and the attenuation provided by a barrier of finite length between a point source and the receiver can be estimate by the procedure given in [11]. This and the even more commonly known theoretical methods have one weak point – the shadow area is mainly described as a pressure (potential) field and the description of the mechanism of the acoustic energy flow transported as a vector effect over the obstacles is practically omitted.

At normal conditions, the real features of barriers and interactions with the environment cause that their shielding efficiencies often differ drastically in comparison with the results of modelling with a theoretical prediction. The analysis of sound propagation is made today usually by the application of many commercial computer programs, but theoretical calculations and predicted results are not so often compared with experimental measurements for checking the accuracy of the programs (see [15, 16] comparing results of theoretical modelling with "SYSNOISE" v.5.3A and investigations of real-field measurements with the (SI method). Reflection of waves, having a wavelength similar or smaller than the obstacle dimension, scattered in all directions and the paths of the transported energy are not easy to predict theoretically. The degree of the discrepancy between modelling results and the real structure of the field formed over barriers grows proportionally to the degree to which the simplifying calculating assumptions differ from the conditions encountered in reality. The differences mainly result from the fact that a theoretical forecasting uses simplifications far too big or that it is impossible to obtain proper data on real physical features of the tested area.

This is one of the reasons why the experimental investigation fields using Sound Intensity technique (SI) are a useful tool for the analysis of the vector acoustic flow field distribution around the barriers. A properly used sound intensity method ensures the chance of displaying the acoustic energy flow distribution in any place of a restricted space, even within the near field. At the same time, it is a convenient technique making it possible to verify empirically the acoustic flow field at real-life conditions [3].

This paper motivates and illustrates how the SI technique has been applied to the analysis of the flow acoustic field resulting from measurement vector data. The main advantages of the research carried out with the application of a sound intensity technique consist in the fact that the measurements taken refer to energy dependencies of the field described by the intensity streaming flow and that they can be carried out in unrestricted environment. As has been pointed out, the advantages of a sound intensity technique presented may be used in acoustic metrology much more effectively than classical methods, e.g. to verify the theoretical methods of vector field modelling with check-up measurements taken in real conditions.

2. Introduction to the theory of the vector acoustic field

The spatial distribution of acoustic energy in a field restricted by partitions depends mainly on the ratio between the room dimensions and the wave length radiated by a source placed inside, or by acoustically active partitions of the room (structure-borne noise). In order to determine the parameters of an acoustic field by means of computational methods, one of the methods known from literature and based on wave, geometrical or statistical models can be used [9]. Each of the methods has different ranges of application and, while using them practically, they assume quite serious simplifications. It is even possible to formulate a hypothesis that no contemporary theoretical method used for modelling acoustic fields in acoustically small rooms gives a proper description of the energy distribution of the field.

The trials of applying field modelling to small parallelepiped rooms (e.g. to problems connected with acoustic protection of ships living quarters) also face numerous difficulties and limitations. 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 the 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: the potential and kinetic energy that fully explains the physical meaning of the wave phenomena, and makes possible to consider the mechanisms of propagation, radiation, diffraction or scattering. A good form of the illustration of scalar-vector phenomena occurring under 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 intensity probe ($p-p$ or $p-v$ type).

The visualisation of the distribution of the active and reactive parts of the acoustic field provides the possibility of a full analysis of the acoustic wave. A properly used intensity method ensures a chance of measuring the vector distribution in any place of the restricted space, even within the near field. At the same time, it is a convenient technique making it possible to verify empirically the field parameters determined by means of a computational method. The verifying tests using an intensity technique may show how much the theoretical image of the acoustic field distribution differs from the distributions obtained from measurements at real conditions. The differences result mainly from the fact that theoretical forecasting uses simplifications that are far too gross, or that it is impossible to obtain proper data on the real physical features of the area tested.

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

Although very useful in certain applications, the geometrical approach to room acoustics is not a satisfactory method for attempting to explain the behaviour of sound within an enclosure. A more adequate, but more difficult approach, is based upon wave acoustics, that is, upon the motion of sound waves within a three-dimensional enclosure. This method is characterised by the establishment of boundary conditions which describe mathematically the acoustical properties of the walls, ceiling, and other surfaces in the room [7].

One of the larger limitations in using classical wave theories of acoustic field analysis in real rooms is the great variety of the inside shapes of rooms and the heterogeneity of the absorption properties of partitions [14, 4, 9]. In most rooms, the floors are made of materials of a much higher absorption coefficient than the walls. The furniture and other equipment cause irregularities in the acoustic field. For this kind of rooms it is not possible to use Sabine's theory directly or its modification introduced by MILLINGTON, EYRING and KNUDSEN [10]. This results from the fact that the basic assumption for the use of these theories is field isotropy i.e. they refer to fields in which the energy density is the same at each point. Since there are no fields of purely diffusive nature in practice, it would be necessary to find out the degree to which the room under consideration meets the conditions resulting from a definition of a diffuse field. Thus the problem of the evaluation of field diffuses has become a question which has attracted many theoreticians and experimentators [12, 16, 17]. However, the analysis tends to refer only to limited frequency ranges corresponding to wave lengths comparable with the room dimensions, which results in neglecting interference phenomena.

3. Experimental flow visualisation

A description of the basic visualisation methods for the graphic description of the effects of fluid flow are developed and are described in literature [8]. Particularly vector field visualisation techniques have been developed over the past several years. Many of the techniques used in computer graphics flow visualisation have been adapted from the traditional methods practised in wind and water tunnels. Scientific visualisation consists in the use of computer graphics to create visual images which aid the understanding of these often immense data set. A visualisation system, by serving a dual role as a provider of exploration and exposition capabilities, have become indispensable in the analysis of *computational fluid dynamics* (CFD) results [18].

There is a host of CFD visualisation techniques which involve combinations of filtering, resampling and numerical integration. The results of these techniques are known to the users of the visualisation systems as vector plots, paths lines or isosurfaces. The two main types of line patterns used in experimental flow visualisation are path lines and stream lines. The path lines (particle path) are defined as the actual path traversed by a given fluid particle and the stream line is a line everywhere tangent to the velocity vector at a given instant. Streamlines are the most commonly used model for investigating the structure of flow fields. Another aid is the representation of each path line not as a curved line, but as a space-filling and shades narrow ribbon. Ribbons in space provide information regarding the rotational component of the intensity flow motion and may be twisted about the normal vector near the curved path. These models also provide visual causes to help to observe the interpreted a two-dimensional image.

Up to the last decade, studies of sound flow visualisation are rather seldom in the acoustical practice. At present, flow motion as the acoustic particle velocity may be measured experimentally using intensity probes, which can be used to collect the vectors data for the visualisation of all the wave phenomena occurring in the real physical space [15, 16]. In this paper, the author has described the visualisation methods in acoustics and showed how these methods may assist scientists to gain understanding of the complex acoustic energy flow in a real-life field.

Having the technical possibilities of measuring a sound intensity vector in the three-dimensional space, it was necessary to work out a proper form for the graphical presentation of the acoustic vector field distribution. The problem involved a way of demonstrating on a two-dimensional or three-dimensional form vector field.

A simultaneous measurement of the three components of the intensity vectors for the frequency intervals makes it possible to imagine the spatial placement of the vector at a given measurement point. Additionally, a graphical analysis of the field may include a picture of streamlines of the sound intensity flux. 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.

The intensity measurement during the research was carried out by means of a fixed point method [3]. The main measurement plane was divided into sub-area, each point being placed in the middle of a sub-area of 0.1 m by 0.1 m, into which all the measurement area was divided. The vector field distribution in the measurement plane, defined for each measurement point as the vector sum of three mutually perpendicular intensity components, was examined in one-third octave bands from 25 Hz to 6300 Hz. As an example of the intensity measurement vector distributions of acoustic fields in a model of ships accommodation for one source (loudspeaker), and for two sources placed close to the inner edges of the model are presented in Fig. 1. The analysis was carried out in the full acoustic 1/3-octave frequency range, however, for the lack of space, the results are shown only for 400 Hz.

A summary of discussing the results according to the model research for one source and for two sources makes it possible to evaluate the resultant effect of the interference of the direct waves and the reflected ones for each point of the measurement grid. As the frequency increases, the mutual amplitude and phase relations between the waves create field areas of a vortex flow nature. The rotational character of the field can also be seen in both cases, when driving at frequencies above 400 Hz, for which the model can be treated, in acoustical terms, as a big room.

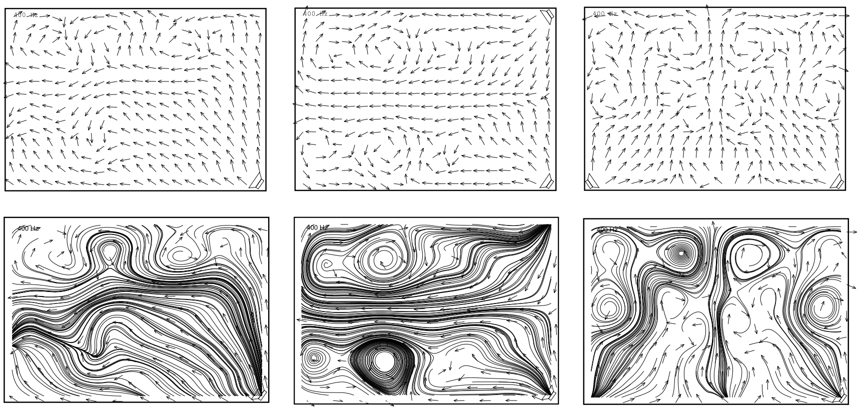

Fig. 1. Vector field distributions in the model of the ship cabin with acoustic sources inside: intensity vectors and intensity streamlines (frequency 400 Hz, 1/3 octave band).

In the theoretical description, it is usually assumed that a nonlinear character of the acoustic field with prevailing rotational waves can be encountered only in near fields, i.e. at distances from the source lower than a one wave length (MORSE [12]). A large number of direct measurements in a real acoustic field using intensity techniques, however, point to some differences from the theory.

4. Sound waves striking a barrier

In many practical situations in acoustics, the wave strike a structure and some of the acoustic energy is transmitted through the structure to another acoustic domain with wave diffraction and scattering effects. The solution of the direct scattering problem is of fundamental importance to many areas of techniques. The basic approach consists in modelling the interaction between the wave and the obstacle by differential or integral equations. Since the analytic solution is available only for a limited number of models, various approximations and simplifying assumptions are used for analysing the system.

The article presents the application of the sound intensity technique for the graphic presentation of the spatial distribution of the acoustic energy flow. As one of the results of the research, the graphic analysis of the sound intensity flux in the plane of the axis of symmetry of the barriers is shown in Fig. 2. The distribution of the acoustic flow field is analysed for different types flat barriers (I, T and Y shapes at the top) located in a three-dimension half space. The tests concern the vector streamlines (2D form) in the axis of symmetry of the objects for the acoustic excitation coming from a broadband loudspeaker installed on the lower surface position before the investigated barriers.

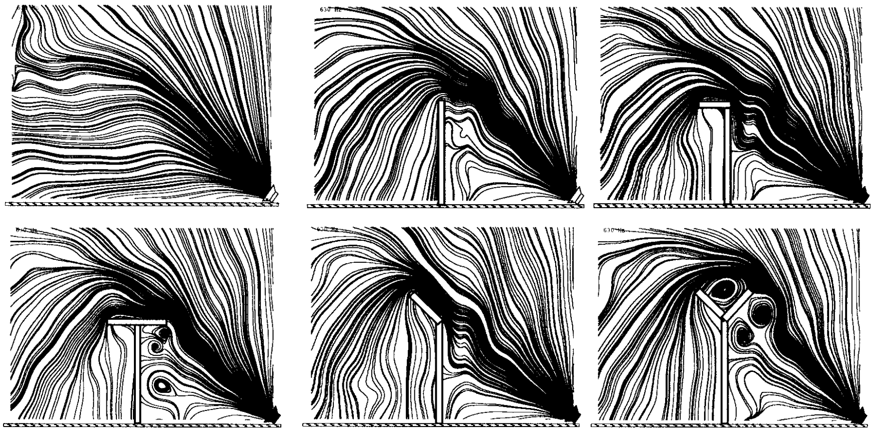

Fig. 2. Distribution of intensity streamlines around flat barriers of different shapes at the top.

The source signal was a stationary broad band pink noise. The measurements are carried out in third-octave bands and the flow map has been build in the frequency range between 25 Hz and 6300 Hz. In Fig. 2, only the results for 400 Hz can be found. Looking at the graphics, it seems that the shape at the top of barriers strongly influences the sound intensity streamlines formed around the barriers.

As the next example of the investigation, the tests concern the intensity streamlines in ribbon form in a 3D acoustic field. Excitation coming from a broad-band loudspeaker installed in front of the investigated obstacles. The distribution of the acoustic field shown in Fig. 3 is analysed around the flat barrier (dimension 0.6 m by 1.4 m) located in a three-dimension half space and for the wall divided by two next to the door rooms. We can clearly notice how much energy flows through the ceilings and the wall junction.

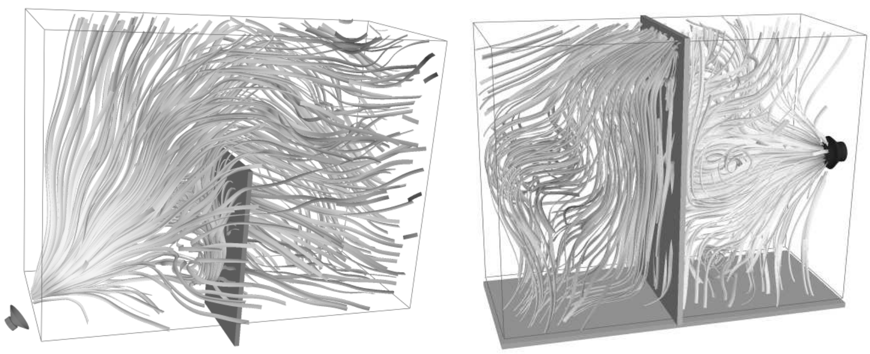

Fig. 3. Intensity streamlines in ribbon form around the barriers: hard barrier in a 3D half space and the wall between two next door rooms.

In Fig. 4 the shape of the sound shadows in a 3D space behind the obstacles: a hard rectangular plate, a sphere and a circular cylinder, are described. The shadow area represent the focusing of the sound energy and this could constitute a major acoustical problem in many cases. Such a problem could not be observed by using pressure data to present the acoustic field.

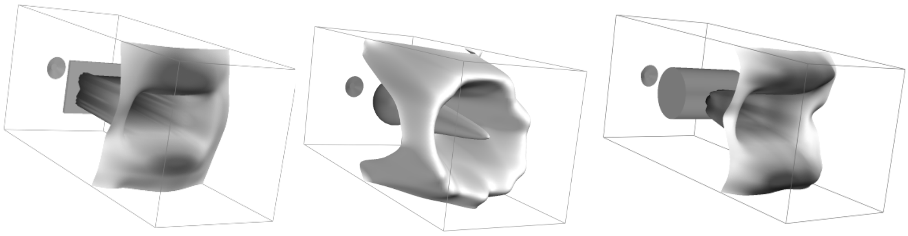

Fig. 4. The shape of the sound shadow in a 3D space behind the obstacles: a rectangular flat plate, a sphere and a circular cylinder.

5. Acoustic radiation of surface sources

The ability of conducting tests for the near-field area with external noises paves the way for the development of tests in real conditions. The wave properties described in the field of the source working in its natural environment allow one to analyse the field qualitatively as well as quantitatively, i.e. to evaluate its energetic distribution and visualize the wave distribution in the tested area.

The radiation from mechanically excited structures is usually associated with resonant of the modes, i.e. around their natural frequencies. The effectiveness of the sound radiation by the vibrating surface is the total radiated sound power normalized on the area and the velocity of surface vibration. As an example, for the ship accommodations the knowledge of the radiation characteristics of the partitions makes it possible to determine the resultant noise level of the inside caused by structural sounds of the partitions excited to vibrations. The sound power radiated by the structure can be measured directly by the intensity measurement technique. The images of the vector field distribution illustrates not only in what frequency range the particular elements of the construction radiate, but also how is the affect in the 3D field.

For the purpose of estimating their sound radiation characteristics, many structures of practical interest may be modelled sufficiently accurately by rectangular, uniform flat plates. Examples include walls and floors of buildings, factory machinery casings, parts of vehicle shells, etc. Figure 5 presents the results of the experimental investigation of the acoustic energy radiation into a three-dimensional space by a free handed rectangular plate mechanically excited by a point-force in the centre of geometry. The visualization of the result is accompanied by images of propagation of the energy flux streamlines or the intensity wave head as the acoustic radiation by an excited plate in the open space and at restricted field conditions.

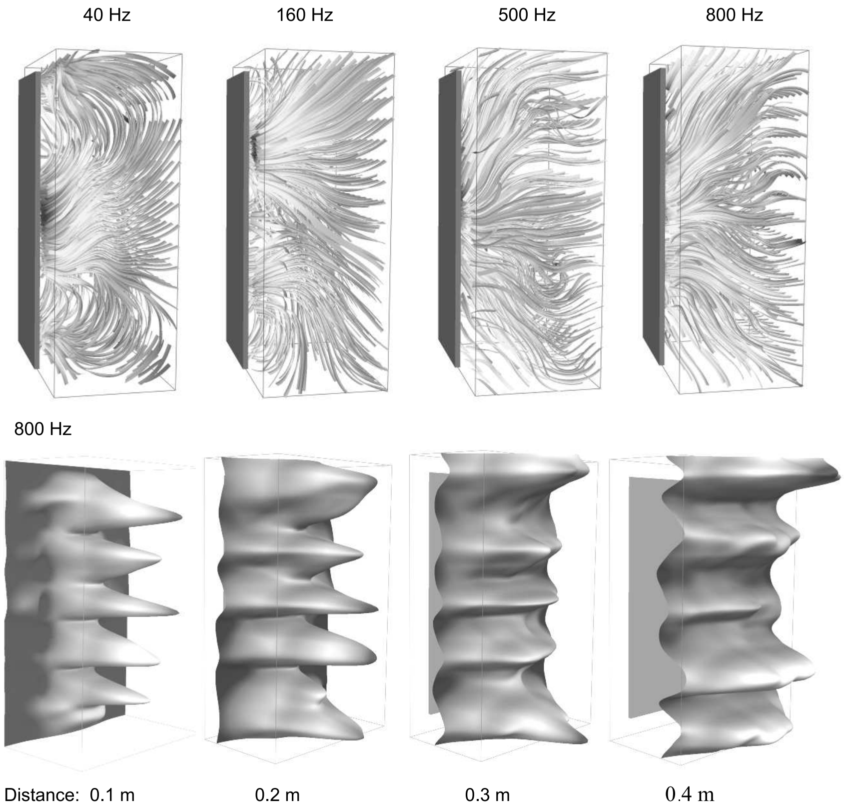

Fig. 5. Visualization of the acoustic energy radiated by a rectangular free hanged plate excited mechanically: intensity streamlines in a ribbon form and the wave head surface in front of the plate.

The hard flat plate of 0.6 m by 1.4 m was suspended on steal ropes fixed in the vicinity of the corners of a shorter side of the plate. The point forcing, using broadband noise of a constant amplitude of accelerations, was carried out by means of an electrodynamic exciter whose head was connected to the geometric centre of the plate with a thin steel bar. The SI measurement was taken with a fixed point method. The measurement space of $1.1\ \mathrm{m} \times 1.7\ \mathrm{m} \times 0.7\ \mathrm{m}$ was divided in 1309 cubic spaces of $0.1 \times 0.1 \times 0.1\ \mathrm{m}$, in the centre of which there were taken measurements of the components x, y, z of the intensity vector.

Examples of graphic images of the vector field generated into the three-dimensional space of a free hinged plate excited by a broad band noise is shown in Fig. 5, as intensity streamlines in ribbon forms and as wave head surfaces in space for 800 Hz (the acoustic image of the modal vibration of plate). Notice how these streamlines form a circular pattern surrounding each primary vortex close to the plate. The sound intensity as an acoustic wave head surface in the three-dimensional space represents the noise flow radiated by the vibrating plate.

6. Acoustic field inside the ship accommodation

In the evaluation of the interior noise of ships accommodation, an essential role is played by the dynamic state of the partitions forming the cabins. Depending on the mechanism of transmitting noise to the inside, the partition may be a source of airborne noise (transmitted from the area behind the partition) or a source of structural sounds as noise radiated by the vibrating structures (structure-borne noise). In practice, the noise occurring in the ship's accommodation comes mainly from structural sounds emitted by vibrating partitions. The ship's partitions, characterised by a high constructional heterogeneity (partitions made of panels of sandwich structure, walls with windows and doors), are surfaces of a heterogeneous distribution of vibrations, and the acoustic power radiated by such a surface source may be determined experimentally. In this case the sound intensity technique is a very useful tool in the research of noise abatement on ships.

The sound intensity method offers the possibility to identify the structure borne noise energy transmitted through different parts of the vibrating structure and is a useful information in the study of the phenomena of the acoustic field inside the ship accommodations. The aim of the research is to show the estimation of the sound power radiated from this partitions. As a result of the investigation a three-dimensional flow map of the time-averaged active intensity vectors is illustrated by different graphical methods.

One of the main advantages of marine vibroacoustic control by means of sound intensity analysis is that it enables one to identify the airborne and structure-borne energy transmitted through the different parts of the cabin partition, and to find the flanking transmission paths and the vibroacoustic bridges as an acoustic weak area on the considered partitions. This acoustic *hot points* and flanking transmission paths in the description of the energy transportation in real structures can not be find by the classical measurement method (with an acoustical pressure) and take play a very important role in engineering problems of noise abatement in small enclosures. The measurement technique as well as the way of visualization the results can enrich the knowledge of the mechanism of the acoustic energy flux through the real ships partitions.

The test results for the acoustic energy distribution inside the ship cabin are shown in Fig. 6. The selected results (for 200 Hz and 2500 Hz) described the sound intensity radiation by the cabin wall with windows as streamlines in the 3D space shape of the wave head close to the cabins window. Its shape confirms the fact that the directivity of the radiation from the real cabin partitions into the inside area may be disturbed much more than it results from the theoretical prediction models.

The noise occurring in the ship's accommodation comes mainly from structural sounds emitted by vibrating partitions. Ship's partitions, characterized by high constructional heterogeneity (partitions made of panels of sandwich structure, walls with windows and doors), are surfaces of a heterogeneous distribution of vibrations, and the acoustic power of such a surface source may be determined experimentally. By using the SI method to measure the radiated sound power directly, it should also be possible to determine the amount of the radiated sound power from different parts of the test partition. The usefulness of the sound intensity technique may be confirmed by the presented results.

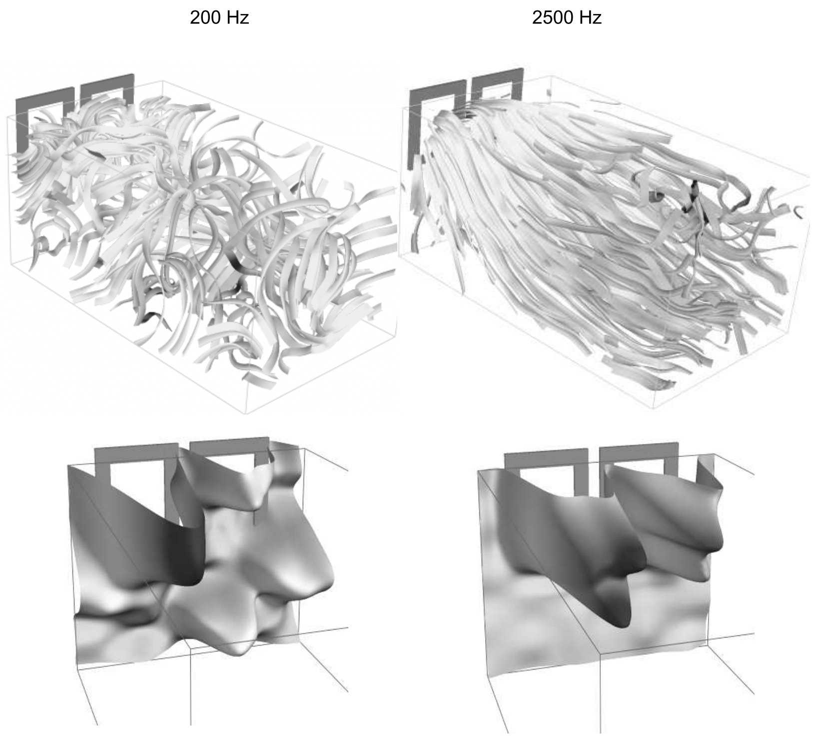

Fig. 6. The vector field inside the ship cabin – intensity streamlines in the cabin space and the intensity wave head surface which radiated from the cabin wall with windows.

The application of the sound intensity technique and the inclusion of a vector distribution image of the acoustic intensity characterizing the field may bring a new insight into the evaluation of the field formation in small limited spaces, for which the acoustic conditions differ considerably from the analytic dependencies which describe the phenomena occurring in a free or diffusive field.

7. Conclusions

Most acoustic vector fields encountered in practice are too complicated to be precisely modelled mathematically. The degree of discrepancy between the predicted results and the real structure of the field formed over a barrier, grows proportionally to the degree to which the simplified calculated assumptions differ from the conditions encountered in reality. The differences result mainly from either the fact that theoretical forecasting uses too sweeping simplifications or that it is impossible to obtain proper data on the real physical features of the tested area. This is one of the reasons why the experimental investigation fields using the sound intensity technique differ from those obtained from numerical simulating models. The described results of the investigation can enrich the knowledge of the scattering effects and of the influence of a partition on the formation of the acoustic energy flux around the obstacles.

The sound intensity as opposed to the analysis of the pressure distributions fields represents a more accurate and efficient solution if compared to the spatial sound fields modelled by computer simulation methods. The acoustic intensity technique is also a very useful method of the location of noise sources and provide the advantage that the measurements can be made in almost any environmental without the requirement of special facilities such as anechoic room, and the research can be made in the presence of a parasitic noise. This attribute of the intensity method is very important in any industrial acoustic investigations. The good agreement obtained by the experimental measurements encourages to use this method more and more in the future to predict the effect of the acoustic wave interaction on obstacles and the treatment of noise abatement in living and industry accommodations.

The tests of the acoustic energy flow and the presentation of the results in a graphic form shows that the presentation of the vector distributions in real acoustic fields can explain many particulars concerning areas for which it is difficult to make a theoretical analysis (direct and near field, effects of scattering, shielding area, etc.).

An important consideration for the flow acoustic wave visualization is the collection of the visualization methods and the effectiveness of these methods in the investigations of acoustic engineering. These techniques illustrate how the governing ideas can be put to practice to explore the acoustic vector field. The traditional visualization method with acoustic pressure distributions is not well suited to analyse these phenomena of the acoustic field.

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