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Acoustic Intensity Imaging Methods for *in-situ* Wave Propagation

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In the paper the author has described the visualization methods in acoustic flow fields and show 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 acoustic wave distribution in the flow field. Visualization of research results, which is unavailable by conventional acoustics metrology, may be shown in the form of intensity streamlines in space, as a shape of floating acoustic wave and intensity isosurface in three-dimensional space. In traditional acoustic metrology, the analysis of acoustic fields concerns only the distribution of pressure levels (scalar variable), however in a real acoustic field both the scalar (acoustic pressure) and vector (the acoustic particle velocity) effects are closely related. Only when the acoustic field is described by both the potential and kinetic energies, we may understand the mechanisms of propagation, diffraction and scattering of acoustic waves on obstacles, as a form of energy image. This attribute of intensity method can also validate the results of CFD/CAA numerical modeling which is very important in any industry acoustic investigations.

Keywords: scientific visualization, acoustic mapping, wave propagation, sound intensity, noise control.

1. Introduction

In the imagination of acoustic wave propagation, the energy distribution in acoustic fields, connected with the graphical presentation of the flow waves, are a new element in acoustic metrology. Introduction of these possibilities have greatly changed the approach to examining many acoustic phenomena and help to validate the numerical simulations, because all existing numerical models are not yet able to describe real acoustic wave propagation flows with sufficient accuracy.

Modelling of the wave impingement noise is a non-trivial exercise. It requires a numerical simulation with FSI (Fluid Structure Interaction) methods. Many times, a sufficient resolution of the local turbulence, complicated by the varying gas temperature and often complex geometry, is necessary. Modelling of this phenomenon requires representation of both the fluid and structure elements as well as their interaction. The feasibility of modelling of this phenomenon can be done using CFD (Computational Fluid Dynamics), a commercial code with both FSI and CAA (Computational Aero-Acoustic). Both fluid and structural dynamics need to be modelled and are described by different sets of equations. Once the flow and structure interaction has been solved, the surface velocity at the structure can be post-processed to calculate the sound intensity or power level at any predefined locations.

In recent years, considerable advances have been made in computational fluid dynamics (CFD) such that there is now available a number of commercial codes which can be used to predict the behavior of moving air. For example, the periodic vortex shedding behind a different shape of obstacles in turbulent air flow can be predicted using CFD. CFD techniques are also used to simulate the field flow, which contains the aerodynamic and nonlinear disturbance equations. Available techniques include steady Reynolds-averaged Navier–Stokes model (RANS) computations, in conjunction with stochastic models of the wave-number-frequency spectrum of the turbulence. This local flow solution has to be coupled to an acoustic numerical technique (CAA) for the prediction of acoustic far-field. The most practical formulations are the integral methods such as the Ffowcs–Williams–Hawkings equation (Ffowcs-Williams, Hawkings, 1969), the boundary element method (BEM), and the Kirchhoff integral. CAA synergistically complement CFD by providing the user with an extended set of analytical and numerical methods to simulate the generation and transmission of sound waves through fluids. CAA prediction of narrowband and broadband noise is closely related to turbulence modeling which is central to the correct prediction of aeroacoustic sources. The sound generated by vorticity in an unbounded fluid is called *aerodynamic sound*. There are two principal source types in free vortical flows: a *quadrupole*, whose strength is determined by the unsteady Reynolds stress, and a *dipole*, which is important when mean mass density variations occur within the source region. Equivalent sources, namely dipoles (associated with aerodynamic surface pressure forcing), and quadrupoles (associated with fluctuating velocities in the flow volume), may be directly captured through transient CFD calculations. The theory of aerodynamic sound was developed by Lighthill's acoustic analogy (Lighthill, 1952) which reformulated the Navier–Stokes equation into an exact, inhomogeneous wave equation whose source terms are important only within the turbulent (vortical) region. Using the Lighthill acoustic analogy combined with RANS model, we better understand the mechanism associated with component interaction noise. For prediction of the noise radiated by the flow over a smooth structures, the near-field turbulent flow is coupled to the far-field acoustic prediction model using Fflowcs–Williams and Hawkings computation method. An analytical study of flow included noise reported by Curle

(1955), Powell (1964) and Howe (1975) who decided to solve the problem as a diffraction at solid non-vibrating surface for low Mach numbers ($M \approx 0.1-0.3$) combining incompressible CFD – calculations with the acoustic analogy. They report on the results for the mean drag, mean pressure coefficient, Strouhal and Reynolds numbers, but only part of their works is comparable with real-life experimental results.

The aim of this study was to obtain information on low Mach number flows in order to improve understanding of the physics of acoustic power flow in real-life conditions and to provide well documented test cases to validate the theoretical CFD and CAA models.

2. Acoustic flow visualization

A steady flow produced by an acoustic field is called acoustic streaming and is an evidence of the generation of vorcity by the sound. The streaming acoustic velocity and mean pressure p satisfy the time-averaged equations of continuity and momentum. For linear acoustics, in absence of an external flow, the acoustic intensity $\mathbf{I}_a = p'\mathbf{v}$, where p' is the acoustic pressure perturbation and $\mathbf{v}$ is the acoustic particle velocity.

Sound intensity as a vector variable inseparably couple the acoustic particle velocity and acoustic pressure. This sound intensity measurement technique has been use to various studies on theoretical and applied acoustics. Application of the sound intensity method, including the presentation of space vector distribution of acoustic power, bring new insight into the nature of acoustic field formation in real conditions. Obviously, the acoustic waves in real conditions are different from the theoretical assumptions ascribed to free or diffuse field. It is a frequent occurrence that the sound intensity measurements in real live 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. Only when the acoustic field is described by flow parameters of wave in vector form, we may understand the mechanisms of acoustic wave propagation, as a form of transport energy. Sound intensity has this attribute, that is why it is so important in any engineering acoustic investigations. The measurement technique described in this work, as well as the method of graphical presentation of results, can also enrich the knowledge of the mechanism of acoustic energy flux through the real partitions.

In our work, visualization of results is shown in the form of *intensity streamlines* in space or as a *shape of floating acoustic wave* and *intensity isosurface* in plane and three-dimensional space. This type of acoustic wave description is unavailable by conventional acoustics metrology. In traditional acoustic metrology, the analysis of acoustic fields mainly concerns the distribution of pressure levels (scalar variable), however in a real acoustic field both the scalar (acoustic pressure) and vector (the acoustic particle velocity) effects are closely related.

3. Results of measurements

In the late 1870s Strouhal and Rayleigh determined that the wires within a stream of moving air generate tonal sound called "friction tones", because they were caused by the drag (i.e the friction) included by the passage of air over the wires. Since the later investigations of the sound generated by the relative motion of a slender body immersed in an ambient fluid. Today we have generally accepted that sound could be as well generated without the body undergoing vibrational motion. Analytical, computational and experimental work of the last decade widely reported the sound generated when a moving fluid interacts with a rigid obstacles of arbitrary cross-section.

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 conditions of working sources. Acoustic conditions in these areas are different from the theoretical assumptions ascribed to a free or diffuse field. 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.

Our investigations have addressed the opportunities for noise reduction at sources by first developing an improved understanding of the noise source generation mechanism. The considered and focused approach to noise reduction follows from understanding of the propagation of sound over complex shape and impedance structures. The development of understanding of the noise generation mechanisms in this work has resulted from testing of the models with different configurations.

The goal of this paper is to investigate *in-situ* field generated by the acoustic flow over the few w obstacles using the sound intensity measurement technique. Sound intensity data considered as direct measurement of the acoustic flow field divided into 1/3 or 1/12 octave band frequencies. Visualization of acoustic flow motion are shown in the form of a intensity streamlines in space, as a shape of floating acoustic wave or intensity isosurface in three-dimensional spaces, but in this work we mainly demonstrate the intensity streamlines picture.

In the first experiment, a flat plate palisade of obstacles is acoustically excited by broadband noise coming from linear acoustic source (in line situated 5 loudspeakers) will be investigated. This research is an introduction to understanding the sound propagation mechanism in periodic arrays of scatterers. Investigated models with palisades should represent very simplified rotating machines with a development of the wheel and noise propagation in arrays of scatterers region.

The approach used here is to use direct measurement sound intensity describing the flow field around flat barriers, illustrate the flow around them as an intensity streamlines. The study was conducted to describe and analyze the mechanism of scattering and energy transfer around the barriers.

During the tests inside the semi-anechoic chamber, barriers are fixed to a hard substrate dimension 2.0 m × 1.2 m. The line of acoustic sources is about 0.5 m before the first barrier. All the barriers are 100 mm high, 1.0 m long, and 2 mm thick. Cavities between two barriers are 250 mm long. Open cavities commonly found in mechanical construction and in architecture are subject to intense resonant pressure fluctuations and lead to intense noise radiation. The reduction of these fluctuations by active flow control is motivation for practical noise abatement in many industry fields.

Shapes of intensity streamlines describing the reaction of acoustic flow wave strike the thin single (left columns A) end double thin barriers (right columns B) shown in Fig. 1. This is a comparative test, what sort of reaction can we observed while a running acoustic wave hits a single or two obstacles during the

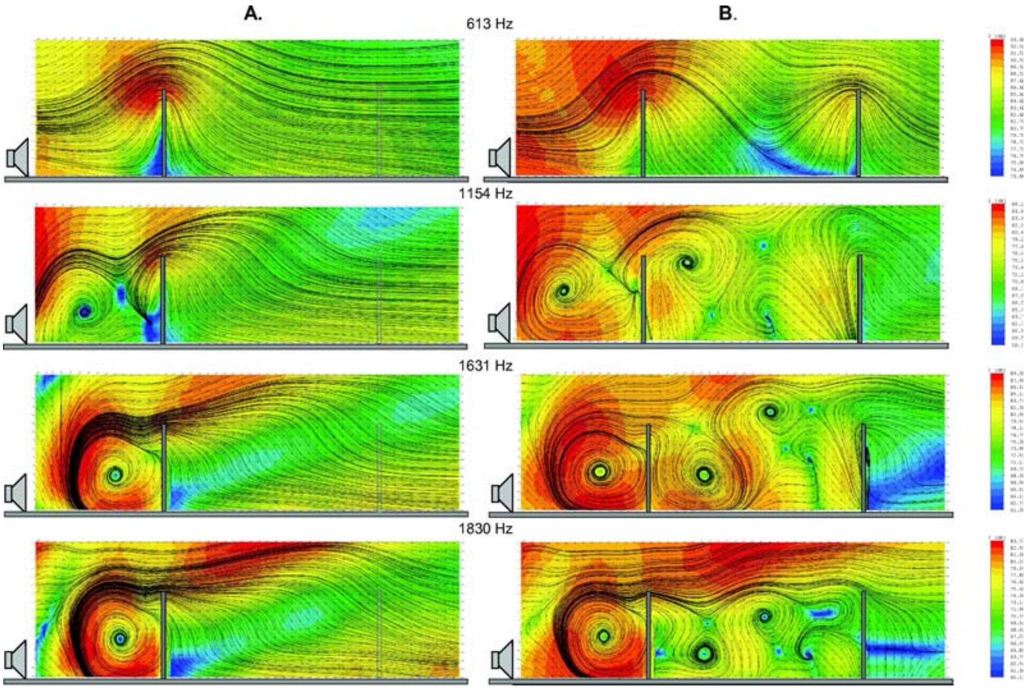

Fig. 1. Shapes of intensity streamlines describing the reaction of acoustic flow wave striking the single (left columns A) and double thin barriers (right columns B).

same excitation signal. The intensity streamlines shown in Fig. 1B contains broadband components, introduced by the turbulence between two barriers with cavity 250 mm long. The latter can be induced by two mechanisms: a wake mode mechanism, due to a periodical vortex shedding at the cavity leading edge, and a shear-layer mode mechanism, due to a feedback coupling between the flow field and the acoustic field.

Inside the 250 mm long cavity between two barriers, flows induce self-sustained oscillations by fluid structure interaction (may be also simulated with theoretical FSI models). The incoming flow separates at the cavity leading edge and lends itself to the creation of large spanwise vortices that grow over the cavity length. The impingement of these vortices on the downstream cavity edge creates an acoustic disturbance that travels upstream and excites the formation of new vortices at frequencies determined by a phase relationship around the feedback loop. The oscillations in wake mode have a significant impact on the mean flow outside the cavity.

The above theoretically described flow-acoustic feedback phenomenon can be also observed in our experimental research by looking at the vortex which rolls up at the cavity leading edge and the separated vortex convected downstream with the mean stream sound intensity lines (Fig. 1B). The verifying tests using an intensity technique have shown how cavities affect the shape of generated acoustic field. Figure 1 shows only a part of these studies as a sound intensity field distribution on the 2D plane passing through the middle of cavities (picture for a few selected frequencies).

In the next experiment, acoustic wave flow around a wedge-shaped barrier with a height of 700 mm and 22 degrees side angle has been studied. Acoustic flow has been tested for the case where the linear source of sound (pink noise generated from 5 loudspeakers arranged in a line) was at the base of the wedge, and in the second case when a sound source was placed at the height of the top of the wedge and the space movement was reduced from the top of the wedge, with a flat plate. Wave reaction in the form of sound intensity streamlines distribution are shown in Figs. 2 and 3. For both cases, results for a few selected frequencies in the bands of 1/3 or 1/12 octave have been shown.

Next experiment concerns the field generated by the acoustic flow over the cavity using the sound intensity measurement technique. The rectangular cavity, open on both sides, used in this experiment with 0.5 m depth and 0.2 m cavity lengths, was examined. The cavity ratio L/D is equal to 0.4. In these experiments, an acoustic wave flow is generated by 5 loudspeakers (broadband "line source") placed at 490 mm from the cavity leading edge. The 2D sound intensity flow measurements are carried out in plane with a dense grid containing 5265 cells in one plane.

Open intense cavity flows induce self-sustained oscillations by shear layer and acoustic wave interaction. The shear layer originates as the incoming flow separates at the cavity leading edge and lends itself to the creation of large spanwise

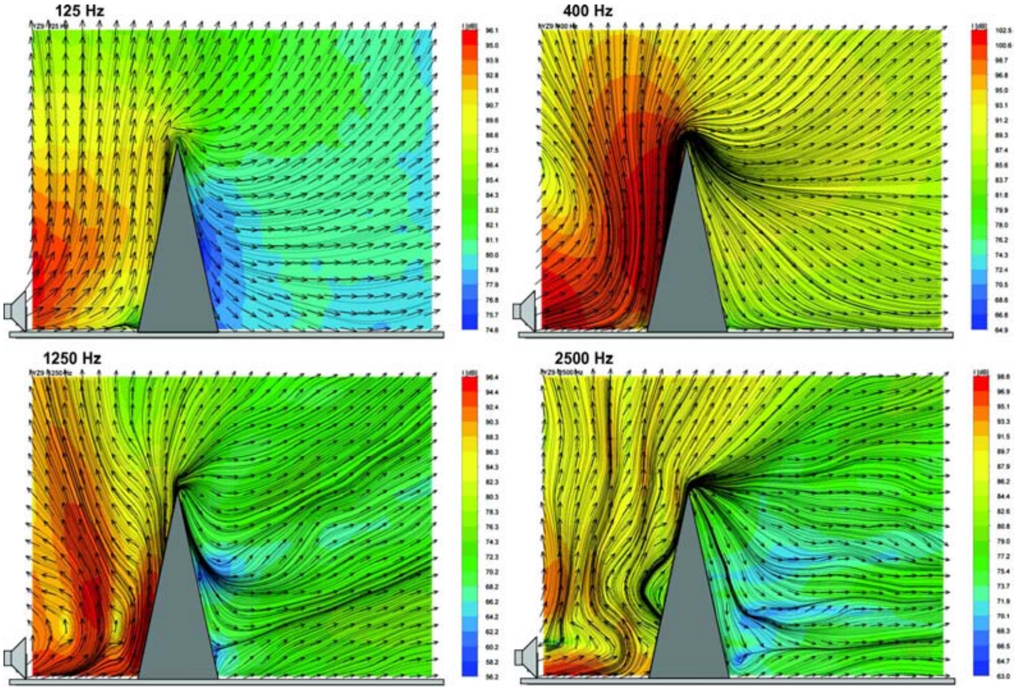

Fig. 2. Sound intensity streamlines around the wedge when the linear source operates at the base of the wedge.

vortices that grow over the cavity length. The impingement of these vortices on the downstream cavity edge creates an acoustic disturbance that travels upstream and excites the formation of new shear layer vortices at frequencies determined by a phase relationship around the feedback loop. The streamlines above the cavity are clearly deflected in the wake mode, whereas the shear-layer mode shows mean flow streamlines nearly horizontal across the mouth of the cavity. The oscillations in wake mode have a significant impact on the mean flow outside the cavity.

The above theoretically described flow-acoustic feedback phenomenon can be also observed in our experimental research by looking at the vortex which rolls up at the cavity leading edge, and the separated vortex convected downstream with the mean sound intensity streamlines (Fig. 4). The verifying tests using an intensity technique have shown how cavities affect the shape of generated acoustic field. Figures 4 shows only a part of these studies as a sound intensity field distribution on the 2D plane passing through the middle of cavities (picture for a few selected frequencies).

Real-life visualization of sound intensity stream flow over rectangular cavities confirm, that the radiated field induced by the cavity flow is greatly sensitive to flow modifications and depends on the size of the cavity. In order to better clarify the flow field over the different cavities, in this work the sound intensity mea-

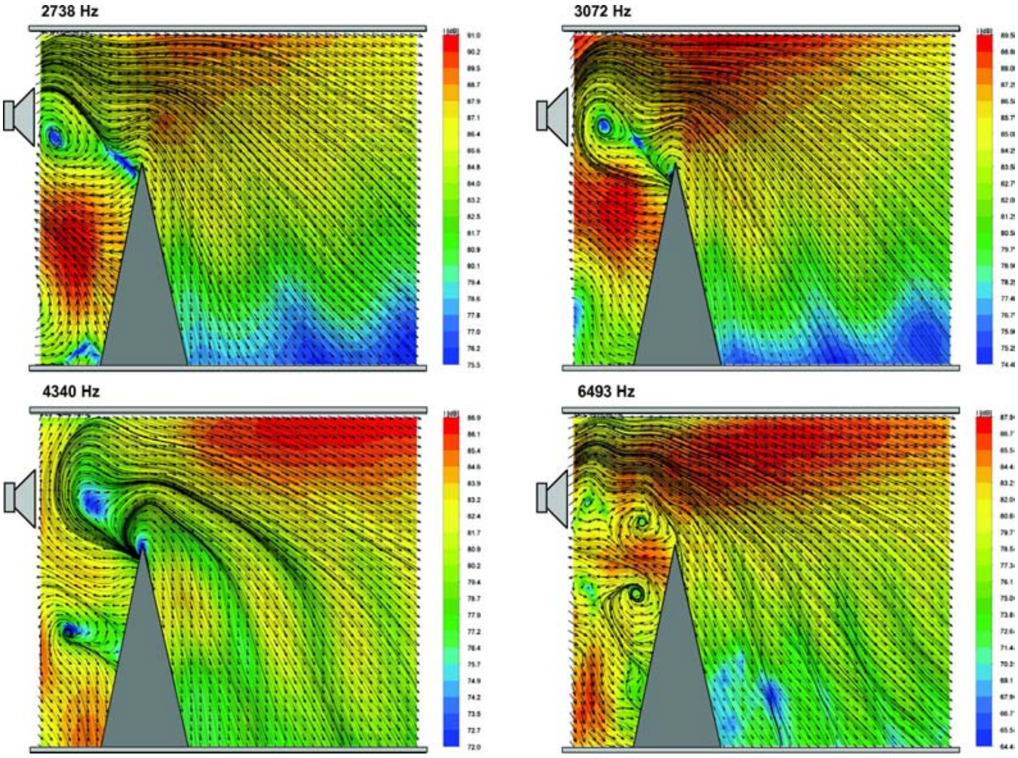

Fig. 3. The 2D sound intensity flow between two plates when the acoustic source was placed at the height of the top of the wedge.

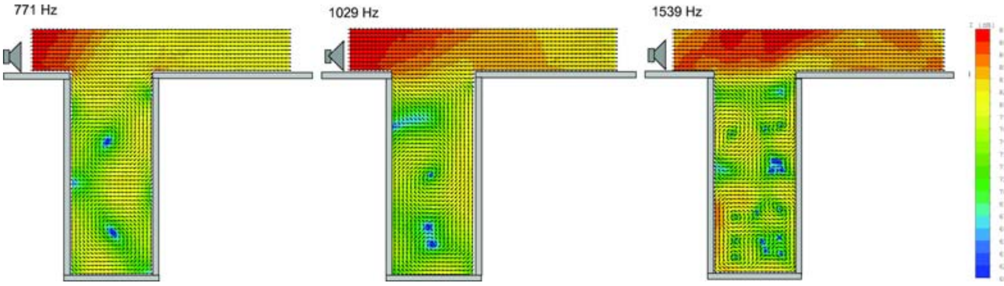

Fig. 4. Time-averaged intensity streamlines presented in the 2D plane as a flow wave distribution over a flat plane with rectangular cavities 0.5 m wide and 0.5 m deep – results for selected frequencies.

surements to study the flow visualization proved to be a very effective technique. This can provide further insights into the noise-generation mechanism. In particular, the investigation of the nonlinear interactions between modes, the phase relationship between the two corners of the cavity and the identification of the acoustic feedback path may help toward a better understanding of the process of the noise radiated by a acoustic cavity flow.

4. Conclusions

Our experiments confirm that acoustic flow in real live conditions is very complex, even for such extremely simple models of facility used in this study. These investigations may help the physical understanding of acoustic wave flow phenomena in real conditions measurement, showing both qualitative and quantitative flow diagnostics. The presentation of the vector distributions of real acoustic fields in the areas for which it is difficult to make a theoretical analysis (in the *direct field* and *near field*), can explain many particulars concerning the radiation character of sources, and scattering of wave around obstacles. Further research can focus on the importance of these interaction phenomena for more realistic engineering applications.

Experiments in our facilities can be also designed and conducted to produce validation and verification of computational results made by means of CFD/CAA programs. This combination of theoretical and experimental testing has been used to achieve the advanced results of numerical simulations and made simulations closer to the reality.

Finally, we hope that this kind of investigation will contribute to further developments in acoustic imaging studies to solve acoustic problems in engineering, more reliable technical diagnostics, and more accurate prediction of noise generated by aerodynamics perturbation.

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