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ACOUSTIC FLOW FIELD RESEARCH WITH SOUND INTENSITY AND LASER ANEMOMETRY METHODS

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Abstract
The control of noise effects in machines and technical devices is one of the basic tasks in the construction of modern industrial products. 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.

Energy distribution images 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.

In the paper authors have described the sound intensity (SI) and laser anemometry (PIV and LDA) measurement methods used for the visualization of vector effects in acoustics flow fields and show how these methods may assist scientists to gain understanding of complex acoustic energy flow in real-life field. Sound intensity measurement technique has been successfully used in various studies on theoretical and applied acoustics. We have extensive experience in applying this method, but we can see that this method has some weaknesses: measurements can not be carried very close to the source (eg. at a distance of roughly <1 mm). Just in this region, so called *hydrodynamic acoustics near field* the sound is born and radiated to the environment. Since SI is the size of vector ($\mathbf{I_a}$=p $\mathbf{v}$), to describe the stream intensity, we need to know the value of *particle acoustic velocity* **v.** Measurements of this magnitude can be made using PIV and LDV techniques renames as an *Acoustic*-Particle Image Velocimetry (A-PIV) and as *Acoustic*-Laser Doppler Velocimetry (A-LDV). Experimental research conducted with the use of laser techniques, that is in a non-invasive way, will be an essential extension of the acoustics flow analysis conducted thus far in our team.

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 in the real coditions.

Key words: aeroacoustic, sound intensity, laser anemometry

INTRODUCTION

Aeroacoustics is the scientific discipline between fluid mechanics and acoustics. It considers sound generated by aerodynamics forces or motions originating from turbulent flows. Initially, experimental investigations were used to derive some empirical relations in order to estimate the noise emission of new technical products. However, owing to strongly increased computer performance, the numerical simulation of acoustic fields generated by fluid flow, computational aeroacoustics (CAA) has become very attractive (Ffowcs Williams, 1996).

The aim of proposed study was to obtain experimental information on low Mach number flows around obstacles, inside a ducts and cavities using sound intensity (SI), and particle imadge velocimetry (PIV) techniques in order to improve physical understanding of these flows and to provide well documented test cases to validate computational aero-acoustic models (CFD/FSI/CAA methods). On the basis of a large number of time-resolved or phase-resolved instantaneous velocity vector fields, the sound intensity and laser anemometry research techniques enables the possibility of independent determination of several main quantities of aeroacoustic parameters as: velocity fluctuations (u', v'), probability density functions and space-time-correlations of the velocity fluctuations, vorticity, acoustic streaming, average velocity profiles and the sound intensity stream. An additional benefit of experimental studies is the opportunity to improve the theoretical calculation methods used for numerical modeling of noise in turbulent flows. A number of relevant aspects of this topic are not covered with reasonable accuracy by the computation models existing today, although the noise contribution from each of the components of the acoustic flow needs to be accurately predicted. Furthermore the results of experiments with SI and PIV techniques provide valuable data for the validation of numerical codes.

In general, sound measurements have a shortcoming together with an advantage in comparison with classical fluid mechanic measurements. The shortcoming comes from the fact that acoustic velocities and displacements are generally quite small and vary rapidly in time. For instance at 1000 Hz, for an acoustic level of 100 dB SPL the velocity amplitude is about 5 mm/s and the displacement amplitude about 10^{-6} m.

The sound wave propagating into a homogeneous gas medium creates small local disturbances in density, pressure and velocity. The velocity fluctuations can be interpreted as the *acoustic particle velocity* (called also *acoustic velocity*). It is the perturbation velocity of a particle moving back and forth in the direction of the sound wave propagation. Here we'll force the mind that it is not the velocity of the wave propagation itself, which is called speed of sound or celerity.

Although acoustics consists in the propagation of an oscillatory disturbance of local pressure, particle velocity, density and temperature, sound measurement is often assimilated to pressure measurement. This is because for decades only pressure fluctuations were accessible and because their relation with the other oscillatory quantities is well known under linear acoustic approximation and in simple configurations. But in numerous situations, knowledge of acoustic particle velocity is important for the description of the phenomena involved. This is the case for instance in the study of near source acoustic fields, of minor losses in acoustic wave guides, or of oscillating viscous boundary layers which we are concerned with our study. The investigation of the vortex shedding and the interaction of the wake with the wall were the main scopes of the investigations performed so far. The basic objective of this research project is the development of measurement and evaluation techniques and tools for the visualization of complex acoustic wave flows. Mainly in these areas we are going to conduct our research using anemometric laser techniques. We want to adapt to the acoustic-flow studies commonly applied in fluid mechanics PIV and LDV research technique and provide guidance to indicate which of the measurement techniques are best for specific acoustic applications. If successful, the results of this study may be used for scientific purposes and to improve the effectiveness of abatement of noise generated by hydrodynamic and aeroacoustic sources. They can also give rise to provide a basis for standardization of scientific research methods with the use of acoustic laser anemometry.

SOUND INTENSITY TECHNIQUE IN THE ACOUSTICS FLOW FIELD

In most cases, investigations of acoustic fields are achieved by the measurement of the acoustic pressure using microphones but when a sound wave is propagating into a homogeneous gas medium it creates small local disturbances in density, pressure and velocity. The fluctuations depending on spatial location and time are considered to be small compared to the mean values (see Table 1). The velocity fluctuations can be interpreted as the *acoustic particle velocity* $\boldsymbol{v}$ (called also *acoustic* velocity). It is the perturbation velocity of a particle moving back and forth in the direction of the sound wave propagation. Between the sound velocity of acoustic waves c propagate in an elastic medium and the local acoustic particle velocity v is a fundamental difference – c>>v .

Such a correct description of the origins of sound has long been known from the theory of sound, but there is a bad habit of acousticians to use the descriptions of sound as acoustic pressure only. Meanwhile, a sound wave is a form of energy transport in the field and has the vectors features.

Acoustic intensity is a very useful energetic quantity since it gives information about the propagation paths and the amount of energy radiated. From an experimental point of view time-averaged acoustic intensity (rms values), also called active intensity and written here $\boldsymbol{I_a}$, is often more interesting than instantaneous value $I_a(t)$. Sound intensity as a vector variable *inseparably* couples the acoustic particle velocity and acoustic pressure ($\boldsymbol{I_a}=p\ \boldsymbol{v}$) and represents a stream of acoustic energy flowing in the field. This vector parameter of acoustic wave can be measured (*rms*) with special sound intensity probe and can be easily shown in a graphical form.

The acoustic particle velocity $\mathbf{v}$ and mean pressure p satisfy the time-averaged equations of continuity and momentum. For linear acoustics, in the absence of an external flow $<\rho\mathbf{v}>=<p'\mathbf{v}>/c_o^2=\boldsymbol{I_a}/\ c_o^2$, where p' is the acoustic pressure perturbation and $\boldsymbol{I_a}$ the acoustic intensity. Sound intensity can be directly measured and recorded as an acoustics flow field divided on normalized octave band frequencies (normalized acoustic filters 1/1, 1/3, 1/12, 1/24 octave band). In traditional acoustic metrology, the analysis of acoustic fields mainly concerns on the distribution of pressure levels (scalar variable), however in a real acoustic field both scalar (acoustic pressure) and vector (the acoustic particle velocity) effects $_p$are closely with phase and amplitude related. The acoustic field may be described as a spatial distribution of pressure and particle velocity, their amplitude p and $\boldsymbol{v}$ being proportional for plane traveling waves ($p=\rho\ c_0\ v$), where ρ is the density and c_0 is the sound speed. In terms of human perception of sound relationships between the acoustic wave parameters: particle velocity, pressure, particle displacement and sound intensity are presented in Table 1.

Table 1. Relationships between the acoustic planar wave parameters

v	**p**	**L_p**	**d** [m]		**I**	**L_I**
m/s	Pa	dB	20 Hz	20 kHz	W/m^2	dB
5 10^{-8}	2 10^{-5}	0	4 10^{-10}	4 10^{-13}	10^{-12}	0
0,5	200	140	4 10^{-3}	4 10^{-6}	100	140

The application of the sound intensity technique together with numerical 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. The visualization of acoustic energy flow in real-life acoustic 3D space fields can explain many particulars energetic effects (scattering, vortex flow, shielding area, etc.), concerning the areas in which it is difficult to make numerical modeling and analysis with the CFD-FSI-CAA methods.

The sound intensity measurement technique was in our team used for many years to examine the of acoustic energy flows in real acoustics fields. Our many years experiments confirm that flow acoustic imaginations in real-live conditions are very complex, even for extremely simple models facility. Various measurements with sound intensity technique were made to get a full picture of the dynamics of acoustic flow. These investigations allowed physical understanding of acoustic wave flow phenomena in real condition showing both qualitative and quantitative effects of the wave movement.

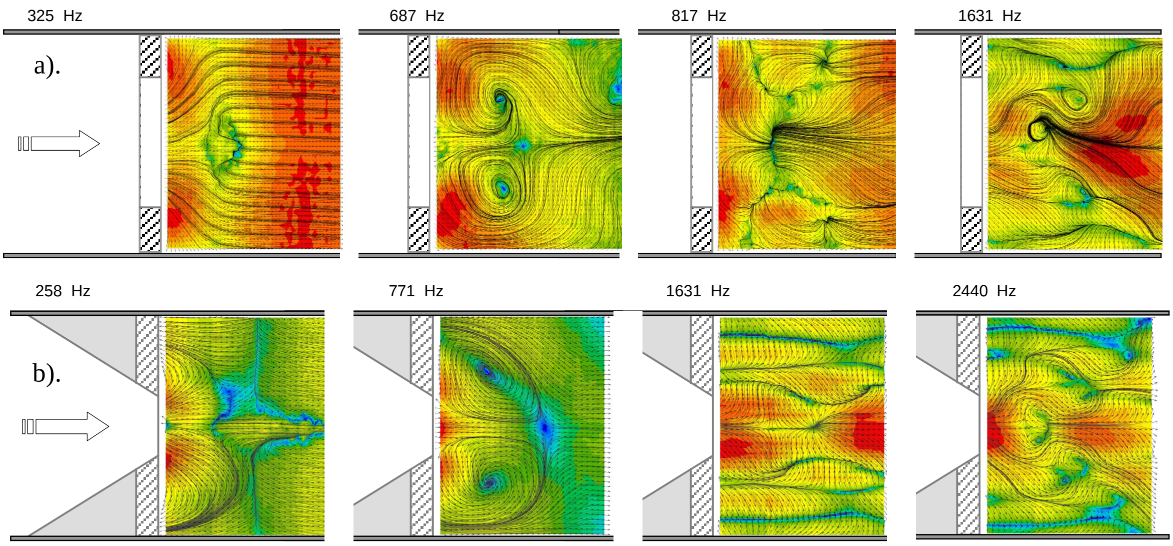

Fig. 1. The shape of the sound intensity field inside the waveguide for various frequencies in the region close to obstacles: a) - slit 300 x 127 mm, b) - baffle with a hole 127 mm

In figures 1 and 2 we show one of examples of our research made inside a model of acoustic wavegade with sound intensity measurement. The intensity distribution inside duct produced by the action of the axial and radial modes is extremely complicated because this propagating modes influence on each other. The image of the dipolar and quadrupolar sound generated by a flow inside a duct was obtained using a SI three-dimensional Microflown probe and a graphical possibility of our “SIWin” software.

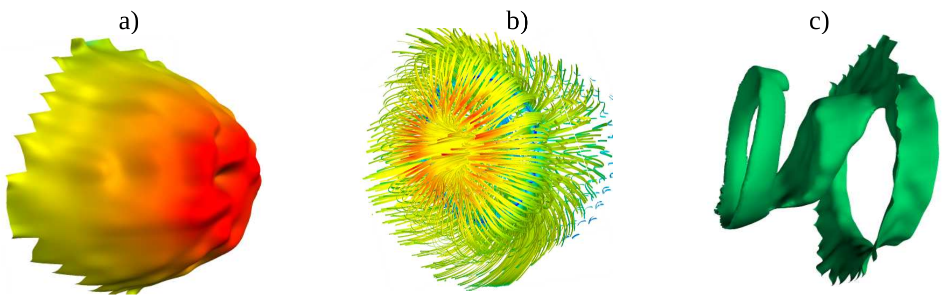

Fig. 2. Examples of sound intensity visualization in three-dimensional space close to the obstacle (conical baffle with a hole 127 mm, 817 Hz) shown in the form as a *shape of floating acoustic wave* (a), *intensity streamlines* (b) and as a *intensity isosurface* (c)

The 6 m long duct are excited with acoustic pink noise, so, the sound power along a duct is send without mean flow. The first part of measurements was done inside the pipe with circular diameter of 474 mm. The space around two type of obstacles (slit with dimensions 300 x 127 mm and the conical baffle with a hole 127 mm) was scanning with intensity probe measured the *x, y* and *z* components of sound intensity vectors. Measure are made in frequency band 50-5000 Hz and analyze in 1/3 and 1/12 octave band frequency. On the Figure 1 we show examples (2D) of this investigations for some 1/12 octave band frequencies. Examples of sound intensity visualization in three-dimensional space close to the conical baffle shown on the figure 2 in the form as a shape of floating acoustic wave (SI z component), intensity streamlines, and as a intensity isosurface. Direct measurement of the acoustic power flow around outlet of obstacles can explain a diffraction and scattering phenomena occur in this region.

ACOUSTICS WAVE FLOW RESEARCH WITH LASER ANEMOMETRY

Although nowadays the method of computational fluid dynamics (CFD) has been found to be of wide application in evaluating complex flows and improving the flow processes, its general reliability and applicability still need to be enhanced, especially through experimental validations (Castrejon-Pita *at al.*, 2006). Moreover, the CFD method is unable to replace measurement experiments which should be taken into account, aiming to investigate the flow and thus to optimize the related flow (Willatzen 2005).

Experimental flow measurements, as the indispensable measure to investigate and improve engineering and flow processes, have been greatly advanced, as the laser methods have found applications in this area. Contrary to the traditional methods of using the probes, the laser method obviously provides the most effective and accurate tools for non-intrusive flow measurements. Nowadays, the laser method for flow measurements has become very atractive, mainly because of a lot of fashionable applications of laser techniques everywhere (Lin 2006, Hain 2008, Haigermaser 2009, Zhang 2010). Optical methods of measuring velocity have many advantages over intrusive methods.

The most widely applied laser methods for flow measurements are doubtlessly the Particle Image Velocimetry (PIV) and the Laser Doppler Anemometry (LDA) also known as the Laser Doppler Velocimetry (LDV),. Both of these techniques have been used in the measurement of sound fields (Valiere 2009), but so far the main problem is that they are restricted to the measurement of simple fields such as a monotonic sound field, possibly with a mean flow. These two techniques can be seen as complementary because coupling LDA and PIV makes it possible to profit from the space advantages of the PIV together with temporal resolution of the LDA. While the PIV method is suitable to quantitatively present the flow distribution, the LDA method is mostly applied to accurately diagnose and quantify all types of flows. Thus, both of these measurement techniques are well suited for capturing complex flow in the investigation of:

- turbulence research,
- 3D-flow structure visualization,
- full 3D-vortex analysis,
- flow-structure-interaction.

Laser measurement systems are used to explore and map different types of flows. The ability of the signal processor to extract accurate velocity information is crucial to getting the needed information about the dynamic parameters of the particles flow (LaVision-FlowMaster, Fig. 1).

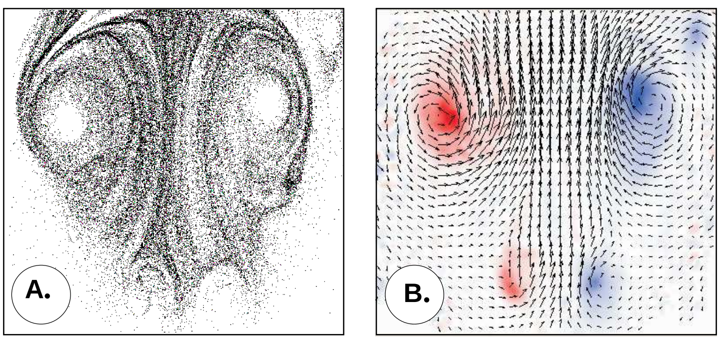

Fig. 3. Example illustration of disturbed flow (A) and the image of the 2D vector field distribution obtained with laser methods (B)

Adapting laser techniques to acoustic

Laser anemometry is a method which allows the non-intrusive instantaneous measurement of a field of vectors. The non-intrusive property of the laser measurements methods represents the greatest advantage against other methods using sensors for flow measurements. It is extensively used now in fluid dynamics to measure many situations from the motion of waves. LDA and PIV were first developed for fluid mechanics measurements and their application to acoustic flow is rather scarce compared to stationary flow (see SI technique). But the laser methods can be also adapted to provide an instantaneous flow and acoustic particle velocity and sound intensity mapping with the minimum disturbance of the sound field. Acoustic flow velocity measurements by means of PIV/LDA methods are based on random sampling of velocity events occurring when the seeded particles pass through the measurement volume. The available velocity sampling rate depends on particle concentration, particle size, flow velocity and other flow and optical parameters.

In general, sound measurements have a shortcoming together with an advantage in comparison to the classical fluid mechanic measurements. The shortcoming comes from the fact that acoustic velocities and displacements are generally quite small (see Table 1) and vary rapidly in time. The basic objective of our research is the development of measurement and evaluation techniques and tools for the visualization of complex acoustic flows. The PIV/LDA methods thus has fund its wide applications in measurements of internal acoustic flows such as the flows in ducts and turbo-machines.

For low Mach-number isothermal flow we will see that aeroacoustic sound production is entirely due to mean flow velocity fluctuations, which may be described in terms of the underlying vortex dynamics. This leads to the idea of using so called *vortex sound theory*. Vortex sound theory is not only numerically efficient but also allows us to translate the very efficient vortex-dynamical description of elementary flows directly into sound production properties of these flows in real-live conditions (Howe, 2003).

The advanced laser and computer technologies have greatly contributed to the development of advanced PIV/LDA technology. Corresponding to the professional publications of PIV/LDA mostly concern the basic principle of the methods and is related to studies of simple movements. Only few investigations and developments have been conducted with regards to acoustic laser anemometry. As has been perceived for a long time, it clearly lacks a supportive reference for PIV/LDA acoustical user in the practical applications.

Methodology of research

The accurate knowledge of the noise generation mechanism is a fundamental step for both theoretical modelling and practical applications leading, for instance, to the development of flow/noise manipulation techniques and noise suppression devices. Recent developments in terms of our capacity to both numerically and experimentally analyse the physics of turbulent shear flows have opened up new possibilities to improve our knowledge about the noise generation and propagation mechanism (Marretta 2003).

Today, the laser anemometric techniques are applied to an investigation of the spatial and temporal development of coherent structures in a turbulent flat-plate boundary layer flow in the vicinity of the edges (Sandberg 2007). Expected that known from studies of fluid mechanics measurement techniques, laser PIV and LDA should be also successfully adapted to experimental studies of acoustic flows in those areas.

The objective of our study is determined on the basis of a review of current knowledge on the acoustic theory of vortex flow and turbulent noise generation mechanism (from Lighthill'a 1952 to Howe 2008). Particular emphasis in our studies, we will put on specific topics relevant to the new perception of acoustic vortex field theory supported by experimental results performed on the physical models using laser anemometry techniques PIV/LDA including the well-known for as SI technique.

Laser techniques for acoustic boundary layer measurements

Although acoustics consists in the propagation of an oscillatory disturbance of local pressure, particle velocity, density and temperature, sound measurement is often assimilated to pressure measurement. This is because for decades only pressure fluctuations were accessible and because their relation with the other oscillatory quantities is well known under linear acoustic approximation and in simple configurations. But in numerous situations, knowledge of acoustic velocity is important for the description of the phenomena involved. This is the case, for instance, in the study of near source acoustic fields, of minor losses in acoustic waveguides, or of oscillating viscous boundary layers which we will be concerned in our we will focus our future investigations.

Detailed velocity measurements in boundary layer are of interest in the study of momentum and energy transport associated with many of the problems in fluid mechanics. Getting an accurate velocity map in this thin layer close to a surface demands the use of a noninvasive measurement technique such as LDA. The noninvasive nature combined with the small measuring volume of an LDA system makes the technique ideally suited to measure velocity in the boundary layer. The purpose of this experiment was to make velocity measurements as close to the wall as possible using an LDA system. This was done traversing the measuring volume by the free stream region in the flow to the wall of the boundary. The ability of the signal processor to extract accurate information in the boundary layer region is clearly exhibited.

Acoustic boundary layers are classically associated with thermoviscous losses, but are also linked with other phenomena of practical interest, such as acoustic thermoacoustic effect or Rayleigh acoustics streaming. Also, transition to turbulence in waveguides is expected to strongly depend on the dynamic of flow in the oscillating boundary layer. For the description of these phenomena, a precise mapping of acoustic quantities in the boundary layers, together with a good knowledge of their statistics, which involve a high time resolution, is necessary. Because the oscillating acoustic pressure is not affected by acoustic boundary layer, it is necessary to measure particle velocity directly. Reports of acoustic viscous boundary layer measurements are scarce, because this kind of measurement is difficult to perform as boundary layer effects induce rapid changes in the velocity amplitude and phase over a very near wall region. Difficulties acoustic surveys of the boundary layer has also determined that the layer thickness is very small ($\delta_{ac}=(2\nu/\omega)^{1/2}$) and is dependent on the frequency. For example, the audible range corresponds to oscillatory boundary layers from 0.02 mm (at 20 kHz) to 0.5 mm depth (at 20 Hz) and to acoustic velocity amplitudes from $5\ 10^{-8}$ m/s (at 0 dB) to $5\ 10^{-2}$ m/s (at 120 dB).

The concept and plan of study

Our research program is directed to enrich theoretical knowledge about the birth of sound in turbulent flow conditions of the acoustic wave, a better understanding of the mechanisms of noise generation and to identify more effective ways of its reduction. Aerospace and missile industries are also intensely involved in the study of acoustic turbulence sources. In all these studies aeroacoustics noise sources are examined theoretically and experimentally.

For low Mach-number isothermal flow we will see that aeracoustic sound production is entirely due to mean flow velocity fluctuations, which may be described in terms of the underlying vortex dynamics. This leads to the idea of using so called *vortex sound theory.* Vortex sound theory is not only numerically efficient but also allows us to translate the very efficient vortex-dynamical description of elementary flows directly into sound production properties of these flows in real-live conditions.

For applications with complex, inhomogeneous flows and flow-induced noise radiation, the very promising is to adopt a laser anemometry PIV and LDA technique to applied acoustics. Most of our research will be conducted on the two- and tree-dimensional cross flow inside cylinders with a free-end. The circular cylinder has proved to be a fruitful area of fluid dynamics research, due to its combination of a simple geometry and complex, unsteady flow features. The noise generating mechanisms inducts depend essentially on the radial components of the velocity fluctuations.

Our conviction as to the validity of the assumptions of the proposed technique of the acoustic laser anemometry is based on our experience which we acquired through investigations of flow acoustic method using sound intensity techniques.

Preliminary results of acoustic flow by PIV

For applications with complex, inhomogeneous flows and flow-induced noise radiation, want to adopt a laser anemometry PIV and LDA technique to applied acoustics. Laser anemometry is a method which allows the non-intrusive instantaneous measurement, even in the physically a very thin acoustic boundary layer space. The non-intrusive property of the laser measurements methods represents the greatest advantage against other methods using sensors for flow measurements because if the sound transducer is brought into the flow field, extra sound is generated by the body of transducer itself. This sound can lead to a contamination function, and this effect was called “probe contamination” (Henning *at a.* 2008). This effect can be avoided completely by using nonintrusive laser anemometry techniques.

Laser methods can be also adapted to provide an instantaneous flow and acoustic particle velocity with the minimum disturbance of the sound field. The noninvasive nature combined with the small measuring volume of the PIV and LDA systems makes the techniques ideally suited to measure the acoustic particle velocity in the boundary layer and wave interactions on the obstacles placed in the sound field.

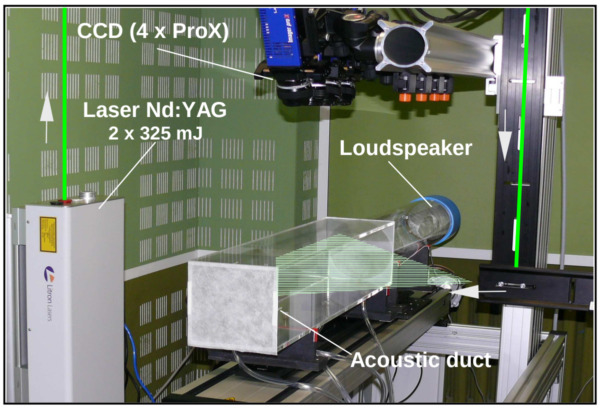

Fig. 4. Experimental setup – acoustic square waveguide model investigated with PIV technique

For the development of adaptation methods for PIV and LDA techniques for acoustics testing we have adequate testing concept and fully equipped laboratories and a modern measuring equipment. The research will be conducted in our newly opened Laboratory of Acoustic Laser Anemometry equipped with 2D the newest tomographic 3D PIV system (Tomo-PIV) made by LaVision Gmbh and LDA system made by ARTIUM Technologies Inc., an American company.

Proposed adaptation of the noninvasive laser methods for acoustical purposes (A-PIV and A-LDV) gives us the opportunity to explain many vibroacoustical phenomena and allows to complete missing knowledge about disturbed acoustic flows in real systems. We shall attempt to complete elementary knowledge about acoustic wave flows and reactions at the obstacles generating nonlinear effects of refraction, diffraction and diffusion of the wave in viscous-resilient environment. We will also try to enrich the knowledge of acoustic vortex-flow theory with emphasis on acoustic flow research in pipes and ducts, in so called acoustic waveguide. In the general outline acoustical research using laser anemometry are going to be conducted at the border region of the medium (in hydrodynamical acoustics boundary layer), therefore in regions very scarcely known or described through experimentation. Furthermore the results of experiment with PIV/LDA techniques provide valuable data for the validation of numerical CFD/CAA codes.

Scope of research is very broad, because it pertains to issues of fluid mechanics, aerodynamics as well as vibroacoustics. In this paper we present only our startups research. These are the results of our preliminary study, whose purpose is to know the capabilities of our new instruments. Figure 4 shows the experimental setup – acoustic square waveguide model investigated with PIV technique and a part of measurement results are shown on the Figure 5.

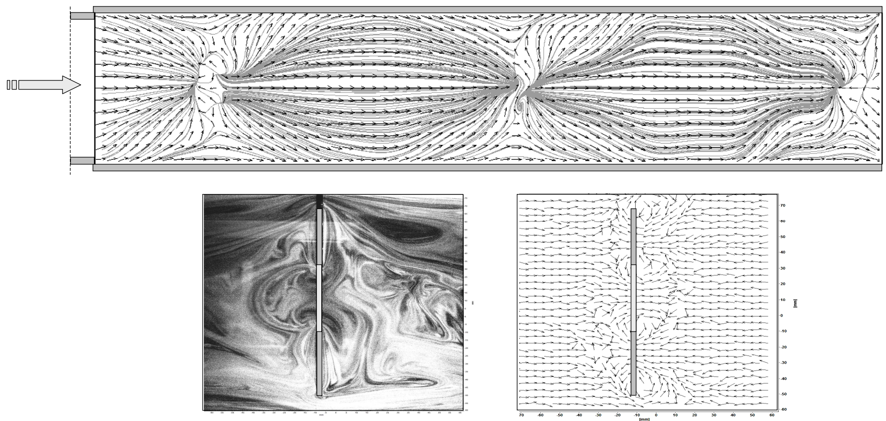

Fig. 5. The shape of the sound intensity field inside the empty square waveguide and distribution of acoustic particle velocity around a circular plate with a hole

CONCLUSION

In conclusion, we can set that by the direct measurement of acoustic power flow and graphically description of the results, we can explain a diffraction and scattering phenomena occur on the real acoustics flow field. The analysis of acoustic field with floating wave in space show that the sound intensity technique is very useful to the visualization of vector acoustic phenomena. The application of the sound intensity technique together with CFD/CAA 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.

If the laser methods for assessing the dynamics of the aero-acoustic fields turn out to be justified, we gain an effective tool for non-intrusive research of acoustic flows in broad range of acoustic particle velocity. The big advantage of the research is also true, that all the changes in dynamics of flow structure can be recorded and visualized as a function of time. Evaluation of space-time correlation of fluctuating velocity and vorticity fields explain the mechanism of formation of turbulence and in the wake region of flow. Studying the interaction of vortices with the structure of the test may be advisable to modify the model.

Application of laser techniques used in acoustics is not a new issue in the subject of research in the world. We can find some work in the literature on this subject (Ffowcs Williams 1996, Hann 1999), but it is still incomplete knowledge of flow acoustics. The final result of our study will be an assessment of the applicability and optimization of the various modern measurement techniques (SI, A-PIV and A-LDA) to property solve flow acoustics problems. It is expected that the conclusions of the research will enrich the current level of knowledge about the acoustic flows and improve the numerical modeling of acoustic phenomena generated in a turbulent boundary layers, in ducts and pipes, indoor cavities and structural niches around uneven surfaces.

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