PAN
ARCHIVES OF ACOUSTICS
Vol. **38**, No. 2, pp. 211–216 (2013)

DOI: 10.2478/aoa-2013-0025

Experimental Acoustic Flow Analysis Inside a Section of an Acoustic Waveguide

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(*received April 11, 2013; accepted April 24, 2013*)

Noise propagation within ducts is of practical concern in many areas of industrial processes where a fluid has to be transported in piping systems. The paper presents experimental data and visualization of flow in the vicinity of an abrupt change in cross-section of a circular duct and on obstacles inside where the acoustic wave generates nonlinear separated flow and vortex fields.

For noise produced by flow wave of low Mach number, laminar and turbulent flows are studied using experimental sound intensity (SI) and laser particle image velocimetry (PIV) technique adopted to acoustics (A-PIV). The emphasis is put on the development and application of these methods for better understanding of noise generation inside the acoustic ducts with different cross-sections. The intensity distribution inside duct is produced by the action of the sum of modal pressures on the sum of modal particle velocities. However, acoustic field is extremely complicated because pressures in non-propagating (cut-off) modes cooperate with particle velocities in propagating modes, and *vice versa*. The discrete frequency sound is strongly influenced by the transmission of higher order modes in the duct. By understanding the mechanism of energy in the sound channels and pipes we can find the best solution to noise abatement technology.

In the paper, numerous methods of visualization illustrate the vortex flow as an acoustic velocity or sound intensity stream which can be presented graphically. Diffraction and scattering phenomena occurring inside and around the open-end of the acoustic duct are shown.

Keywords: sound intensity, laser anemometry, acoustics flow, sound visualization.

1. Introduction

Much of theoretical research concerned with acoustics provides useful information about pressure fields, but none currently offers a full mapping of the acoustic energy flow (vector effects) in the front and back of any scattering system working in three-dimensional space. In real environmental conditions, interference, diffraction and scattering of waves mode in the real field are very complex and difficult in comparison with the theoretical modeling. This is one of the reasons why the experimental investigations of acoustic field using sound intensity (SI) (Weyna, 2010b) or acoustic particle image velocimetry (A-PIV) (Weyna, 2012; Raffel *et al.*, 2007) techniques are such effective and serviceable methods. Besides, SI and A-PIV investigation techniques are very useful in locating noise sources, and they also provide the advantage that the measurements can be made in almost any environment.

Visualization of acoustic energy flow in real-life acoustic three-dimensional space fields can explain many particular energetic effects (perturbations and vortex flow, effects of scattering in the direct and near field, etc.) concerning the areas in which it is difficult to make numerical modeling and analysis with numerical simulation methods. The SI and A-PIV image represents a more accurate and really efficient information as compared to the spatial pressure acoustic field modeled. Both measurement techniques expressing energetic quantity give a very useful information about the propagation paths and the amount of energy radiated into the flow field. From experimental point of view, the time-averaged acoustic intensity (*rms* values) is often more interesting than its instantaneous value.

The article presents mainly the application of SI and partly A-PIV techniques to graphically show a spatial distribution the acoustic energy flow over obstacles with different geometrical shapes located in a three-dimensional space inside acoustic waveguides with different cross-sections. As a results of the research, the graphic analysis of the acoustic wave flux in two- and three-dimensional space is shown. Visualization of the results is shown in the form of vectors or streamlines in space and as the shape of a flow wave or an isosurface in space. Numerous examples illustrate the application of the SI measurement for practical problems useful for vibroacoustical diagnostics and noise abatement.

2. Sound Intensity

Acoustic intensity is a very useful energetic quantity, since it gives information about the propagation paths and the amount of energy being transported or radiated. Sound intensity, as a vector variable, *inseparably* couples the acoustic particle velocity and acoustic pressure ($\mathbf{I}_a = p\mathbf{v}$) and represents a stream of acoustic energy flowing in the field. This vector parameter of acoustic wave can be measured (as *rms* value) with special sound intensity probe and can be easily shown in different graphical forms.

The acoustic particle velocity $\mathbf{v}$ and the mean pressure p satisfy the time-averaged equations of continuity and momentum. For linear acoustics, in the absence of external flow, $\langle \rho\mathbf{v} \rangle = \langle p'\mathbf{v} \rangle / c_0^2 = \mathbf{I}_a/c_0^2$, where p' is the acoustic pressure perturbation and $\mathbf{I}_a$ is the acoustic intensity. Sound intensity can be directly measured and recorded as an acoustical flow field divided into normalized octave frequency bands (normalized acoustic filters correspond to 1/1, 1/3, 1/12, 1/24 octave bands). In traditional acoustic metrology, the analysis of acoustic fields mainly focuses on the distribution of pressure levels (scalar variable). However, in a real acoustic field both scalar and vector (the acoustic particle velocity) effects are closely related as far as their phase and amplitude is concerned. The acoustic field may also be separately described as a spatial distribution of pressure and particle velocity, their amplitude p and $\mathbf{v}$ being proportional for plane traveling waves ($p = \rho c_0 v$), where ρ is the density and c_0 is the sound speed.

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 peculiar energetic effects (scattering, vortex flow, shielding area, etc.) (Weyna, 2010a) concerning the areas in which it is difficult to make numerical modeling and analysis with the commonly used CFD-FSI-CAA methods.

3. Particle image velocimetry

The development of Particle Image Velocimetry (PIV), an optical measurement technique, which allows for capturing velocity information of whole flow fields in fractions of a second, has begun in the eighties of the last century. The time since then was again characterized by a rapid development of hard- and software for the PIV technique. Improved cameras, lasers, optics and software, led to a significant increase in performance. But also the range of possible applications increased drastically over the years.

PIV is nowadays used in very different areas from aerodynamics to biology, from fundamental turbulence research to applications in the turbo-machinery design, from combustion to two phase flows, and very intensively in micro devices and systems. Due to the variety of different applications of PIV and the large number of different possibilities to illuminate, record, and evaluate, many different technical modifications of the PIV technique have been developed (Raffel *et al.*, 2007; Tropea *et al.*, 2007; Lorenzoni *et al.*, 2012). Moreover, most publications (Siddiqui, Nabavi, 2008; Roch, Park, 2003) describe the problems from a specific point of view (e.g. in fluid mechanics). We therefore felt that it was the right time to compile the PIV knowledge and practice to the implementation in theoretical and applied acoustics.

The experimental setup of a PIV system typically consists of several subsystems (Fig. 1). In most applications, tracer particles have to be added to the flow to quantify the velocity field of fluid. These particles have to be to illuminated in plane of the flow at least twice within short time interval Δt between laser pulses (usually a double pulse Nd:YAG laser). The light scattered by the particles has to be recorded either as a single frame or a sequence of frames with special cross-resolution digital CCD or CMOS modern cameras.

The digital PIV recording area is divided in small subareas called "interrogation areas" (e.g. 32 × 32 pixels). The two-component local flow velocity vector v_x and v_y for the images of the tracer particles is

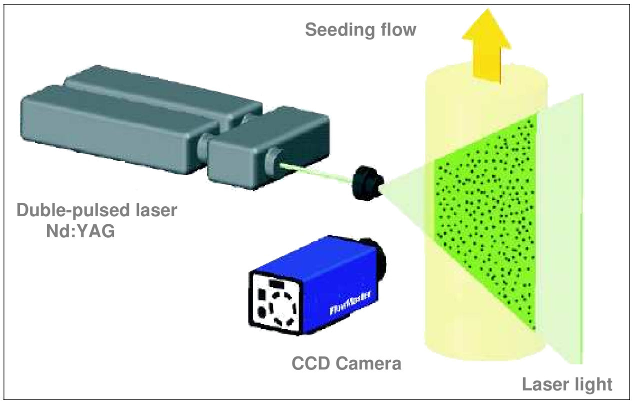

Fig. 1. The principle of operation of the PIV measurement.

determined and projected on the plane of the light sheet. High-speed recording with several thousand instantaneous velocity vectors is obtained within the period of the order of a second with standard computers. The processing algorithms are defined using the processing pipeline with a complete range of image processing tools. Innovative algorithm design and a comprehensive range of image pre-processing, processing, analysis, and display options are critical for accurate velocity measurements in the full range of potential applications.

4. Experimental research with SI and PIV techniques

Good understanding of the evolution process of acoustic wave motion in pipes and ducts is critical to development of engineering designs with the most attractive operating properties to achieve an optimized low-noise design of duct systems and low-noise emission characteristic. The detailed flow acoustic evaluation process of the in-duct flow structure has recently attracted attention of investigators (Ingard, Ising, 1967; Dalmond *et al.*, 2001).

The research presented in this paper also refers to studies of acoustic waveguides (denoted as number 1 and 2). In Fig. 2 we show a model of circular acoustic waveguide no. 1 where investigations with sound intensity measurement were made. The 6-m long open-end duct with internal radius 0.474 m was used as a model for an acoustic waveguide. At one end it was connected to a loudspeaker, a source of broadband acoustic signals. The duct was excited with acoustic pink noise, so the sound power along the duct was sent without mean flow. Initial measurement were made on a circular duct without any obstacles present in the duct. Afterwards, a tested obstacle in the form of conical baffle with a 127-mm hole was placed at a distance of about 2.2 m from the end of the duct.

The space inside the duct was scanned with sound intensity probe measuring the x, y and z components of sound intensity vectors. Measurements were made in the frequency band 50–6800 Hz and analyzed in 1/3 and 1/12 octave frequency bands. The image of the dipolar and quadrupolar sound generated by a flow inside a duct was obtained using a SI three-dimensional *USP Microflown* probe and our graphical post-processing *SIWin* software.

Another series of tests was carried out on a different model of the waveguide (number 2). For this model (Fig. 3), the study was carried out by two techniques – SI and laser A-PIV. Applying the method of SI, we can see that this method has one disadvantage: the field can not be measured very closely to the sound source (e.g. at a distance of roughly < 1 mm). In this region called the *hydrodynamic acoustics near field* the sound is born and radiated to the environment. Since SI is the size of vector, to describe the stream intensity we need to know the value of the *particle acoustic velocity* v.

The work in this part of the article is concerned with the measurement of acoustic particle velocity fields at the open-ended 750-mm long 150 mm × 150 mm square tube (Fig. 4). This part of the waveguide was connected with a pipe with diameter of 150 mm and length of 730 mm. At the end of this section there was the source of acoustic signals. The study was conducted in the area inside the square waveguide no. 2 and partly outside at the waveguide outlet.

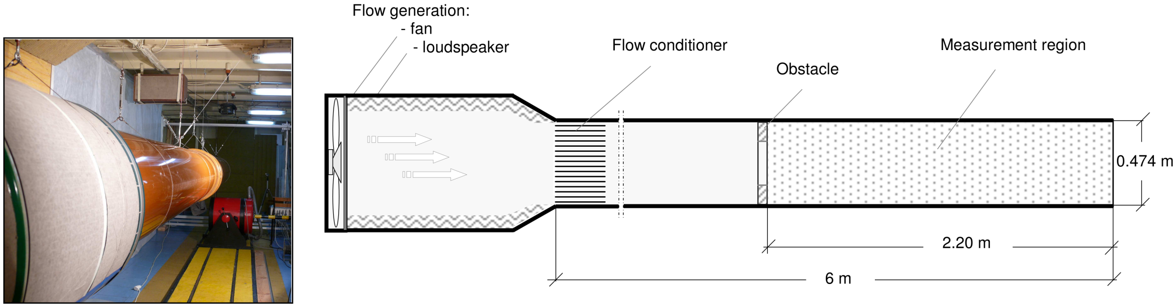

Fig. 2. Sound incident and scattered at an obstacle acoustic waveguide no. 1 of circular cross-section.

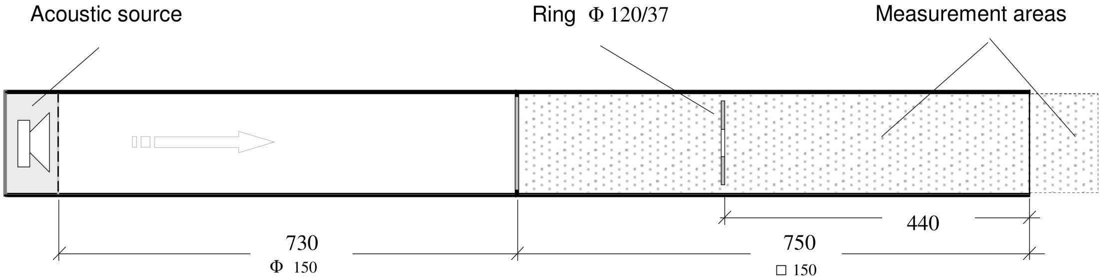

Fig. 3. Acoustic waveguide no. 2 with variable cross-section (partly round and partly square) used in the studies by SI and A-PIV measurement methods.

5. Sound intensity measurement results

In our investigation using SI technique we can see that the intensity distribution inside a circular duct produced by the action of the axial and radial modes is extremely complicated because this propagating modes influence each other.

In Fig. 4 we show some results of this investigations for 1/12 octave frequency bands where the sound intensity streamlines and the velocity vectors show the dynamic shape of the acoustics flow. Direct measurement of the acoustic power flow around outlet of an obstacle in the form of perpendicular diaphragm and a conical baffle with a 127 mm hole can explain a diffraction

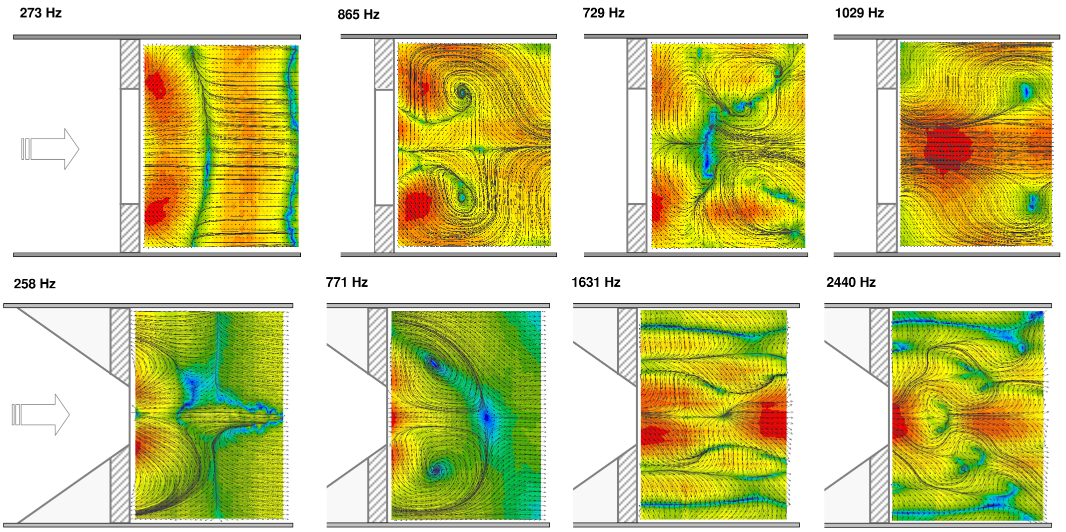

Fig. 4. Acoustic flow field close to obstacles – diaphragm and conical baffle – placed inside the circular waveguide no. 1.

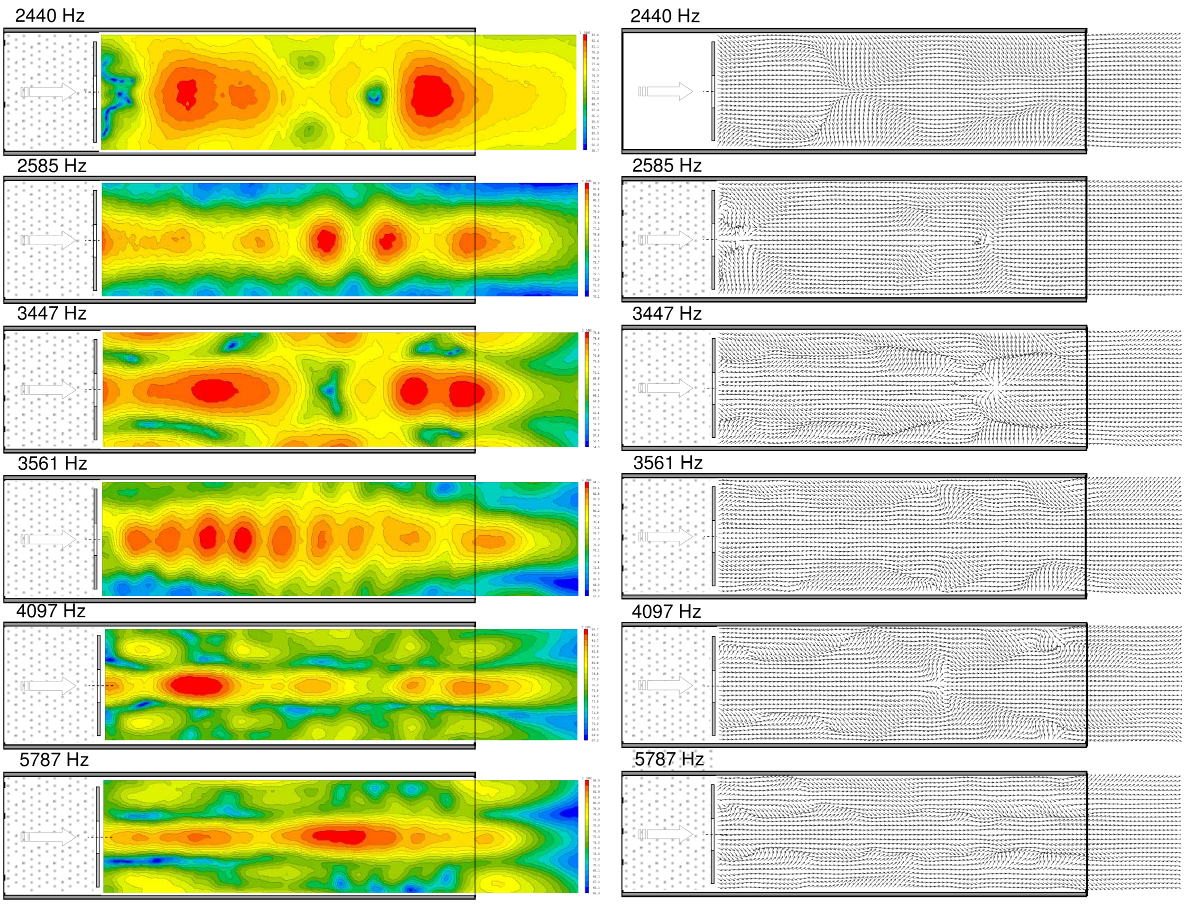

Fig. 5. Sound intensity field outside the ring-shaped barrier in a square acoustic waveguide – map of intensity and sound intensity streamlines (frequency 1/12 octave band).

and scattering phenomena occurring in the region close to the obstacles. The space behind the obstacles was studied in consideration of deformation of the acoustic field due to presence of the obstacles. Experimental results show the map of intensity traveling along the duct no. 1 and distribution of sound intensity streamlines of the generated flow.

In Fig. 5 we show one of examples of our research with sound intensity measurement made inside the square waveguide no. 2. With graphical form we can see the evolution process of flows in the measurement plane located 0.44 m from the end of the duct and partly outside the channel. In Fig. 5 we show some results of these investigations for 1/12 octave frequency bands where the sectional streamlines and the velocity vectors show the topological multi-cell structure of the flow for high-order modes.

6. Laser method measurement results

Laser methods can also be adapted to provide an instantaneous flow and acoustic particle velocity with the minimum disturbance of the source sound field. The non-invasive nature combined with the small measuring volume of the PIV system makes the technique ideally suited to measuring the acoustic particle velocity flow in the boundary layer and wave interactions on the obstacles placed in the sound field. The particle image velocimetry (PIV) is obviously used in fluid mechanics (Raffel *et al.*, 2007). The proposed adaptation of the noninvasive laser methods for acoustical purposes (A-PIV) gives us the opportunity to explain many vibroacoustical phenomena and allows to complete missing knowledge about disturbed acoustic flows in real systems (Henning *et al.*, 2008).

Figure 6 shows the experimental acoustic square waveguide model investigated with the PIV technique. In our measurement with laser PIV technique a fluid in square duct is seeded with tiny 1-μm DEHS synthetic oil particles which faithfully follow the motion of the flow and are illuminated in plane by a Nd:YAG, 325 mJ double pulsed laser with green light source. The 14 f/s CCD camera (Imager ProX-LaVision) was used to acquire raw PIV image for the study. This camera can take separate images at resolution of 2048 × 2048 pixels with minimum of 200 ns between images. It possible to program the delay, relative to an input trigger signal, and the exposure time of the first image. The second exposure continues for the time depending on how long the computer processes the first image. In this study, the time was 143 ms. These images were phase-locked with respect to the acoustic cycle by using a timing circuit. The interrogation area size was 32 × 32 pixels with a 50% overlap between adjacent interrogation windows. Up to 100 samples were used to determine the mean velocities of the flow fields examined. The CCD camera was positioned perpendicularly to the light sheet and focused on the illuminated fog particles. The observation window corresponded to a section of the volume with dimensions 120 × 120 mm. Figure 6 shows the experimental setup — acoustic square waveguide model no. 2 investigated with the PIV technique. A part of measurement results is shown in Fig. 7. For low Mach-number isother-

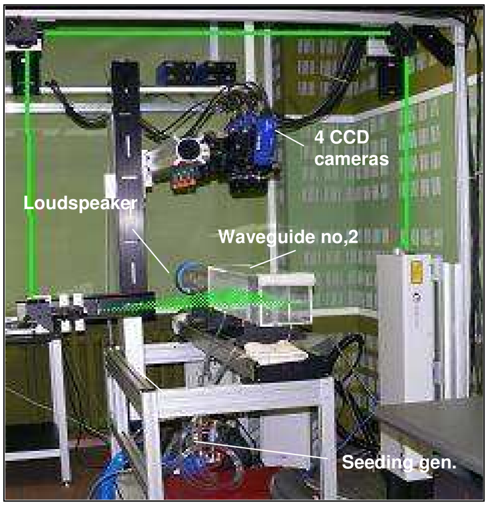

Fig. 6. Experimental setup – acoustic square waveguide model investigated with PIV technique.

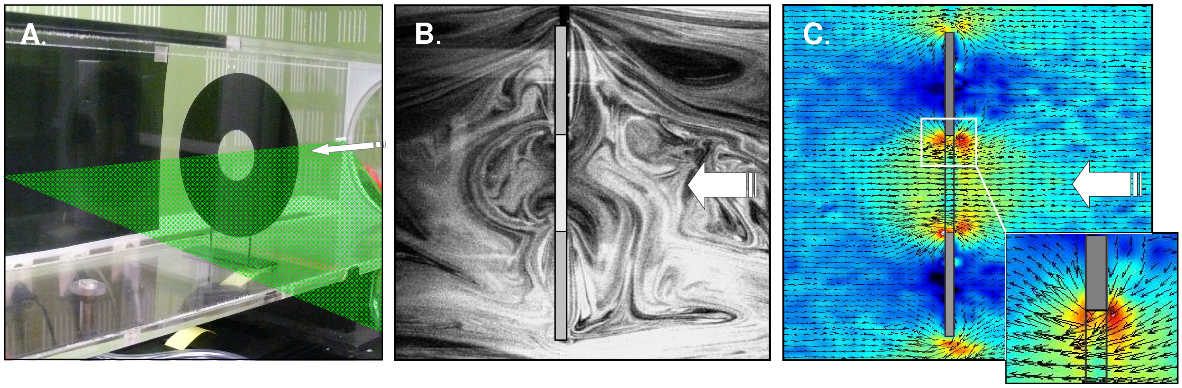

Fig. 7. Acoustics wave motion around a ring recorded using laser PIV method: A – acoustic square waveguide with obstacle to be lighted by laser sheet, B – cloud of seeding particle DEHS around obstacle, C – acoustic flow effects on the edge of an obstacle.

mal flow we can see that additional aeroacoustic sound production by the flow around the ring is entirely due to mean flow velocity fluctuations, which may be described in terms of the underlying vortex dynamics. The use of PIV technique can allow to see these vector properties of acoustic wave in a large-scale. Acoustic flow effects on the edge of an obstacle can be analyzed with great precision.

7. Conclusions

We can conclude that by the direct measurement of acoustic power flow and graphical description of the results, we can explain a diffraction and scattering phenomena occurring in the real acoustic flow field. The analysis of acoustic field with floating wave in space show that the sound intensity technique together with a particle image velocimetry techniques are very useful in visualization of vector acoustic phenomena.

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-invasive research of acoustic flows in broad range of acoustic particle velocity. The big advantage of the research is also the fact that with PIV measurements 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 in the wake region of flow. Studying the interaction of vortices with the structure of the test may be advisable when modifying numerical models of the flow acoustics.

The proposed adaptation of the non-invasive laser method for acoustical purposes offers 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 refraction, diffraction, and diffusion effects in waves propagating in viscoelastic environment.

Acknowledgment

The paper will be presented during the 16th International Conference on Noise Control 2013.

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