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ACOUSTIC VELOCITY WITH MEAN FLOW MEASUREMENTS IN THE AIR BY MEANS OF LASER DOPPLER VELOCIMETRY

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Abstract
Flow distribution images in acoustic fields, connected with the graphical presentation of the acoustic waves gives new possibilities of interpretation of dynamic phenomena occurring in real fields. One of the new insights into the nature of acoustic field formation in real conditions of working sources is the Laser Doppler Velocimetry. LDV is a non-intrusive technique to measure particle velocity widely used in fluid experimental mechanics for years. The technique has an established position when concerning mean flow measurements but for acoustics flow it needs some sophisticated signal processing. In this article we present some concepts and results of processing real acoustic signals obtained from LDV system using modern time-frequency techniques. The advanced signal processing methods allow to obtain not only the mean part of the flow velocity, but also the pulsating part connected with other acoustic energy.

Key words: aeroacoustics , flow acoustics, acoustic LDV

INTRODUCTION

Flow distribution images in acoustic fields, connected with the graphical presentation of the acoustic waves gives new possibilities of interpretation of dynamic phenomena occurring in real fields. Introduction of these possibilities has greatly changed the approach to examining many acoustic phenomena. It also facilitated ways to visualize the flow of acoustic energy. One of the new insight into the nature of acoustic field formation in real conditions of working sources is the sound intensity technique but laser Doppler velocimetry (LDV) seems to be also very useful in applications of acoustic.

It is a frequent occurrence that the sound velocity measurements in real conditions may show great disparity between the theoretical assumptions of the acoustic fields distribution. The disparity results mainly from simplifications accompanying the analytical and numerical methods due to lack of complete data concerning physical properties of an investigated object.

Laser Doppler Velocimetry is a non-intrusive technique to measure particle velocity widely used in fluid experimental mechanics for years (Albrecht H-E et al., 2003). The technique has an established position when concerning mean (or mass) flow measurements.

In that case the measuring system registers signal from the photo-detector which frequency is proportional to the speed of particle overflying over the measurement volume. Due to small size of measurement volume (ellipsoid 200um) we can assume that on such short distance the speed is constant, so the generated burst has constant frequency. The speed of can be estimated with standard FFT method. The whole burst is analysed with Fourier transform and as a result it gives one sharp frequency band which corresponds to the measured velocity. Signal to noise ratio in FFT data is also used to reject low-quality or corrupted bursts. So every burst gives us only one value of velocity. In the figure 1 a sample burst signal and its spectrum was shown.

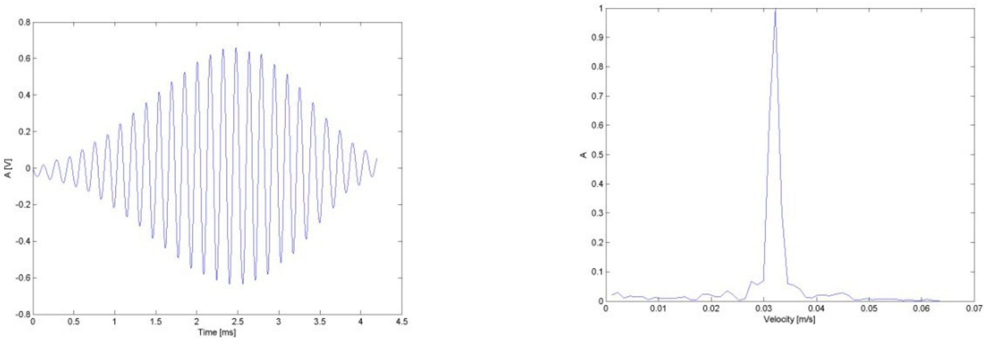

Figure 1: LDV burst signal for constant velocity mass flow and its spectrum (normalised)

This type of data is acquired in random instants of time. From the signal processing point of view, the measurement system is a nonuniform time-resolved measurement data acquisition system, so when high data rates comparing to the frequency of signal changes are obtained during measurements, the uniform time-resolved resampling can be applied to acquired data and classic signal analysis can follow. Because of that considerations the software offered by the manufactures enables presentation only as non-homogeneously sampled time waveforms or as histograms (fig. 2).

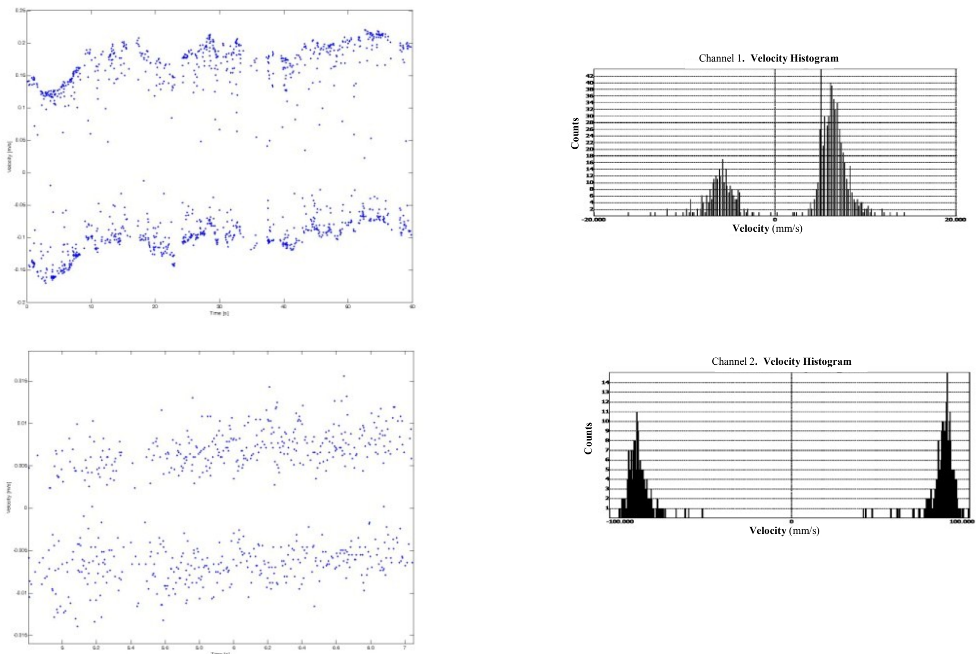

Figure 2: Examples of non-homogeneously sampled time waveforms and histograms of LDV measurement data

An application of Laser Doppler Velocimetry to visualize the acoustic flows and mixed flows at low velocities and quite high acoustic frequencies requires some other methods of signal processing and data analysis. The main problem with the acquisition of acoustic signal with standard LDV hardware processor is the assumption, that the observed particle traverses the probe volume with constant velocity and direction. For acoustic particles velocity measurement this assumption is not always valid. It is because the acoustic particle movement trajectory has got at ordinary sound levels (below 120 dB SPL) and frequencies of hundreds Hz, the size of the same or lower range than probe volume. So the Doppler shift frequency in LDV signal originating from one particle varies during the single burst.

The frequency is modulated and the way of modulation may be a source of information about behaviour of the particle in the measurement volume. In the figure 3 (left) an example of bursts registered in acoustic field is presented. If we apply the classical FFT analysis to that type of data the spectrum becomes more blurry and thus it disables this approach of determining the movement parameters. Moreover, Standard LDV hardware and software recognize such bursts as corrupted by noise and do not accept them as valid measurement data (shown in fig. 3 right)

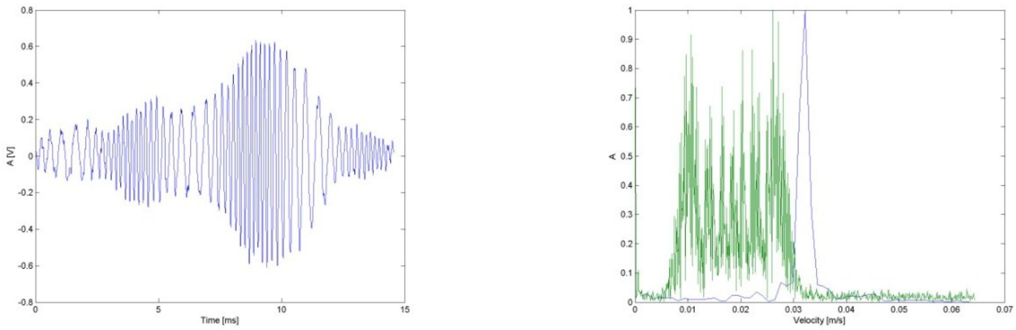

Figure 3: Sample of acoustic burst(left) and its long term spectrum (right,green) compared to spectrum of constant mass flow burst (right,blue)

OVERVIEW OF LDV ACOUSTIC SIGNAL

In order to get some reasonable data which describes the variable movement the burst cannot be treated as a single unit of data. The measurement system should enable to estimate the frequency with higher resolution than only one value for each burst.

Many sophisticated methods have been developed for last 10 years to deal with acoustic flow visualization using LDV. The main aim of present research is to evaluate the usefulness of selected methods applied to the real data and to propose some modifications allowing better results resolution and presentation.

In presented experiments the ARTIUM Technologies Inc. stereo-LDV system model TR-200 is used (Fig.1). It uses green (532 nm) and yellow (561 nm) lasers with 505 mm focal length transceiver optics. The interference fringe spacing is 4,53 and 4,84 μm respectively. The LDV transceiver was coupled with 3D positioning system. This allows to scan the interesting volume.

As the source a loudspeaker was used, in front of which was placed a ventilator. Into the space between the loudspeaker and the ventilator the seeding particle (DEHS) was delivered. The source of acoustic and mass excitation was placed at the end of a round waveguide of 15 cm diameter and length of 100 cm. For this paper the data was collected at one spot at the end of the waveguide in three basic cases: acoustic excitation, mass excitation and mixed acoustic excitation with mass flow.

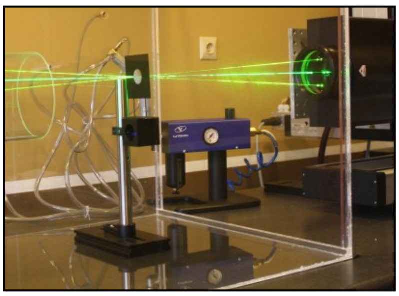

Figure 4: Experimental setup at WUT Laboratory in Szczecin

The AIMS software originally provided with the ARTIUM LDV system provide basic tools to proceed the experiment (calibrations, positioning system control and synchronization), to collect the data and visualize them in the form of histograms. These abilities are convenient and sufficient for precise evaluation of the mass flow. To apply some advanced signal processing techniques for acoustic component evaluation, the demodulated burst signals were acquired with the auxiliary system based on Agilent MSO 3014 digital oscilloscope. On the following figures some chosen examples of modulation of bursts were shown.

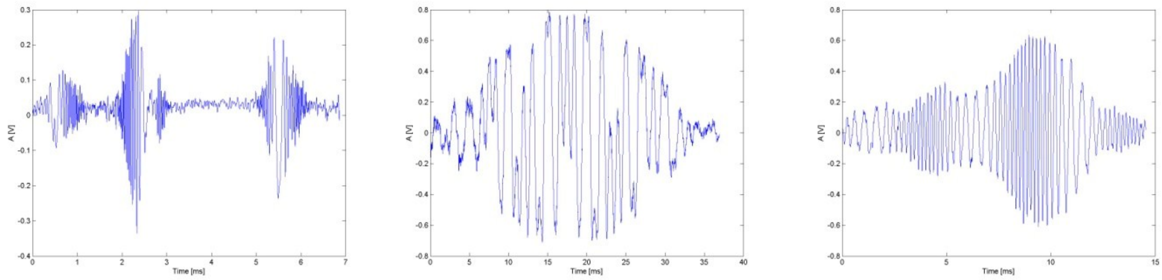

Figure 5: Modulated acoustic LDV bursts

As it was described previously it's possible to classify the bursts to different categories depending on the environment they were registered. Symmetric bursts are generated by a particle which trajectory is parallel to the main axis of the measurement volume. Acoustic bursts are not constant in terms of frequency. If the particle which appears in the measurement volume has the maximum velocity there will be almost no frequency modulation and the burst will be accepted by the original system. Bursts with specific frequency discontinuity are generated by a particle which enters the fringe but during its stay inside changes the orientation of the movement. Bursts which were generated by the mass flow with acoustic excitation can be observed in the figure 5(right). The discontinuity which is typical for acoustic bursts is not symmetric in case of mixed source bursts. It's due to the fact that the mean flow is constant and pushes constantly the particle thought the measurement volume.

TIME-FREQUENCY ANALYSIS OF LDV ACOUSTIC BURSTS

Time frequency analysis of the signal consists of representation with a sum of base signals $g_k(t)$ as it was shown below.

$$x(t) = \sum_k a_k g_k(t)$$

where

$$a_k = \int x(t)\gamma_k^*(t)dt$$

Signal $\gamma_k(t)$ is a dual signal to $g_k(t)$. For the non-stationary signals the base functions should be non-stationary impulse oscillations. Exist many time-frequency representations of signals (e.g. short time Fourier transform, Gabor transform, wavelet transform, etc.) (Zieliński, 2007). In order to assess the applicability and robustness of the selected methods some sample real data was analysed. The results are shown below. Taking as the reference the methodology shown in (Valiere, 2000) where Cross-Wigner-Ville detector (CWV) and time-frequency synchronous detector (TFSD) according to classic wavelet decomposition and short time Fourier transform (STFT) methods were presented, in the figure 6 we show results of the comparison of applying STFT() and the Gabor transform to estimate the frequency and phase of the acoustic velocity measured in mixed flow. During the experiment the data was sampled with 4MS/s, in both cases the Gaussian window was used of 2^{14} samples in case of STFT and 2^{16} in case of Gabor. Presented results confirm the usefulness especially of the Gabor Transform.

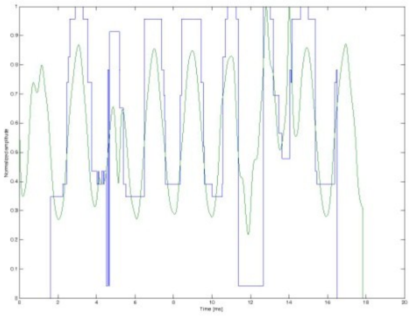

Figure 6: STFT and Gabor transform of LDV signal

CONCLUSIONS

It has been demonstrated in the paper that LDV measurement technique can be useful to obtain detailed insights into the complex mechanisms within aeroacoustic sound field (Acoustic-LDV). The observation of the mean flow (as in previous papers of other authors, e.g. (Paal G. et al., 2006) showed the large complexness of the flow dynamics which is very different from that obtained by simplified models. The advanced signal processing methods allows to obtain not only the mean part of the flow velocity, but also the pulsating part connected with other energy flow.

On this stage of our research so far we are not able to precisely reconstruct time evolution of the acoustic velocity components, but presented methods (especially Gabor transform) are sufficient for amplitude, frequency and phase estimation of sinusoidal components. It can be used together with pressure measurements to get sound intensity vector, where essential is the information about phase shift between pressure and velocity signals in time domain.

The evaluated methods have different robustness, but it is still difficult to judge experimentally, which method will always perform in the best way. It shall be also the goal of further research. Another important issue is to evaluate the metrological precision of amplitude, frequency and phase estimation.

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