Instability Wave Control in Turbulent Jet by Acoustical and Plasma Actuators

Victor F. Kopiev, Ivan V. Belyaev, Georgy A. Faranosov, Vladimir A. Kopiev, Mikhail Yu. Zaitsev
Central Aerohydrodynamics Institute (TsAGI)
105005 Moscow, Radio str. 17, Russia

This paper presents experimental investigations of control possibility of instability waves in jet shear layer. Principal possibility of hydrodynamics instability wave suppression in turbulent jet by external affecting, which was predicted theoretically, is demonstrated in experiment. This result may be used on creation of active control system of jet noise.

I. Introduction

The paper deals with the problem of instability wave control in turbulent jets. The noise of a turbulent jet issuing from jet engine nozzle still remains an important community noise source of civil aircrafts. One of the promising ways in reducing jet noise is the development of active noise control techniques [1-3]. The main problems of this idea are related to the absence of understanding of jet noise generation mechanisms which is clear enough for the realization of the active closed loop control system. The most worked out from the standpoint of theoretical description, and hence the most convenient for building active noise control system, is the mechanism of sound radiation by instability waves which is realized in high-speed jets [4-8].

Though the instability waves are present in low-speed jets, they do not radiate a sound directly. Nevertheless, instability wave development at initial part of the shear layer is essentially identical for low- and high-speed (including supersonic) jets. This implies that successful realization of instability waves control in low-speed jets, which are more convenient for experimental investigation, will mean the possibility of noise control in jets of technological interest. Notice that the shear layer instability is stronger for low-speed jets where instability waves normally come to nonlinear regime.

In [9-10] the fundamental possibility of the realization of active instability waves control concept was justified within the framework of relatively simple model problems. It was shown that the instability wave excited by time-harmonic action can be suppressed by a plane acoustic wave, the amplitude and phase of the latter being selected in a proper way. It was shown that the instability wave excited by time-harmonic action with frequency ω can be suppressed by a plane acoustic wave, the amplitude and phase of the latter being selected in a proper way.

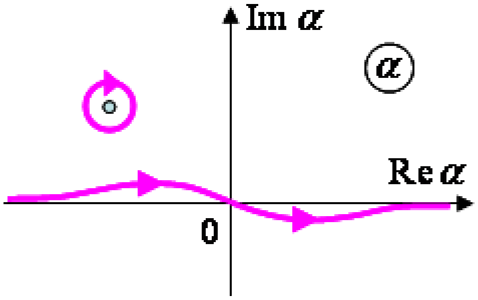


Fig. 1. Integration contour on the complex plane α.

Indeed, from the mathematical point of view instability wave excited in the jet by any kind of (small) time harmonic action (e.g. acoustic excitation) corresponds to the complex instability wavenumber pole α_0, say, of the dispersion relation of the system (mean flow). For any type of time-harmonic action with the same frequency ω the solution for the jet response to the action will contain two different parts: diffraction part related to the integral over real wavenumbers (in terms of inverse Fourier transform) and hydrodynamic part – instability wave – related to the residue in the instability pole (Fig. 1), the spatial structure of the latter being independent on the way of excitation. Therefore if instability wave is excited it could be suppressed by any other type of excitation, (for example plasma actuator Fig.2), therefore the idea of instability wave control seems to be quite realizable in theory.

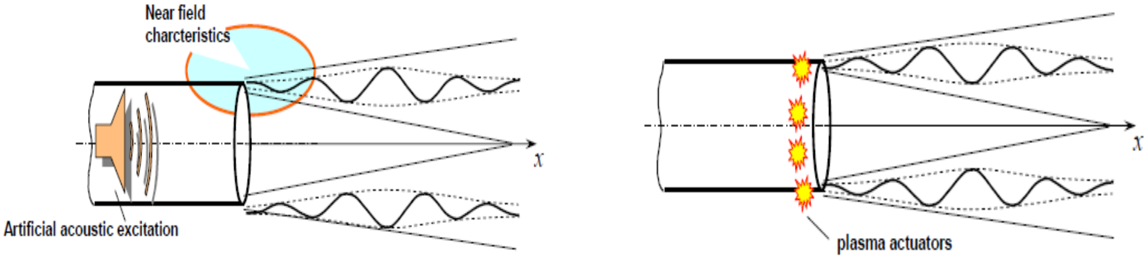


Fig. 2. a) Artificial instability wave generated by acoustic sound driver located in the stilling chamber, b) Plasma actuators generating the instability wave in the opposite phase.

The present paper is devoted to experimental investigation of the possibility of the suppression of artificial excited instability wave by means of acoustic as well as plasma actuators. It should be noted that the case in point is the suppression of the hydrodynamic (instability) part of the field, the remaining acoustic part being, in general, unsuppressed and representing just a linear combination of the two different diffracted acoustic fields.

II. Experimental set-up.

All experiments were carried out in TsAGI's anechoic chamber with flow AC-2. The main experimental tool for instability wave diagnostics in excited jet was Time-resolved Particle Image Velocimeter (TR PIV) with the integrated software-hardware system FlowMaster HS-PIV by LaVision©. This measurement complex can provide accurate quantitative measurements of the instantaneous flow velocity field of turbulent flows with high spatial and temporal (up to 10 kHz) resolution. The main components and measuring possibilities of FlowMaster are as follows:

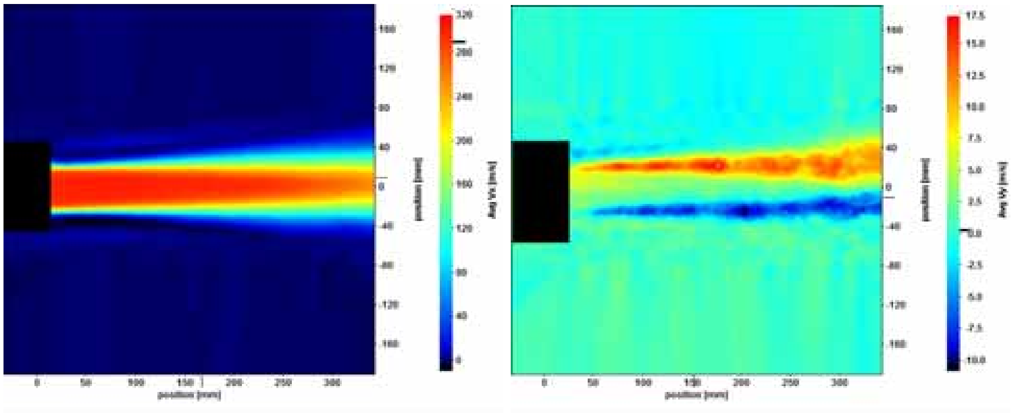
- Nd:YAG double-cavity Laser: wavelength 532 nm, pulse energy: 2x22.5 mJ at 1000 Hz , max. pulse frequency - 2x10 kHz
- Digital camera HighSpeedStar 8 with CMOS matrix 1024 x 1024, sampling frequency 7500 fps-full resolution, 12 bit digital, memory - 8 Gb, Gigabit Ethernet
- Synchronization module HSC Controller with pulse generator for PIV
- Light sheet optics with light-guide manipulator Laser Guiding Arm
- 2-D PIV Software package: DaVis 8, 2D PIV, High Speed, Data Analysis.
- Large Seeding Device (40 jets, for high mass flow rates). Seeding liquid - DEHS
- GPU (Graphics Processing Unit) for acceleration of PIV post-processing.

A. Instability wave identification for an acoustically forced jet with TR PIV

For quantitative diagnostics of artificially excited coherent structures/instability waves in jets, phase-locked PIV has been used. The method is similar to stroboscopic PIV utilized by Schram et al [11] for investigation of sound field generated by vortex pairing in a subsonic jet. The principal idea of phased-locked PIV consists in averaging the PIV results over a sequence of images with the same phase shift relative to the excitation signal. This allows us to separate a periodic (in time) component of velocity field from the uncorrelated pulsations. For the purposes of coherent structure identification, a specific value of this phase shift is of no interest because it is well known from schlieren visualization [12].that at the stroboscopic visualization with the frequency multiple to the excitation signal frequency, the "frozen" picture of coherent structures in a jet is obtained for any arbitrary phase shift due to the effect of optical averaging. Thus, PIV measurements have been performed without using the triggering signal from the acoustic excitation; the only requirement was a coincidence of the excitation frequency and the TR PIV frame rate.

The TR PIV technique has been used to conduct an experimental investigation of high-speed turbulent jet issuing with the velocity of 300 m/s from a conical nozzle with the diameter of 40mm. An artificially excited instability wave was generated by a loudspeaker working at a tone frequency and located at ~1.5m upstream the nozzle exit. The stability of excitation frequency has been controlled with 0.5"-microphone B&K 4189C in the far-field and the data acquisition and analyzing system Pulse 3560D with the accuracy 1 Hz.

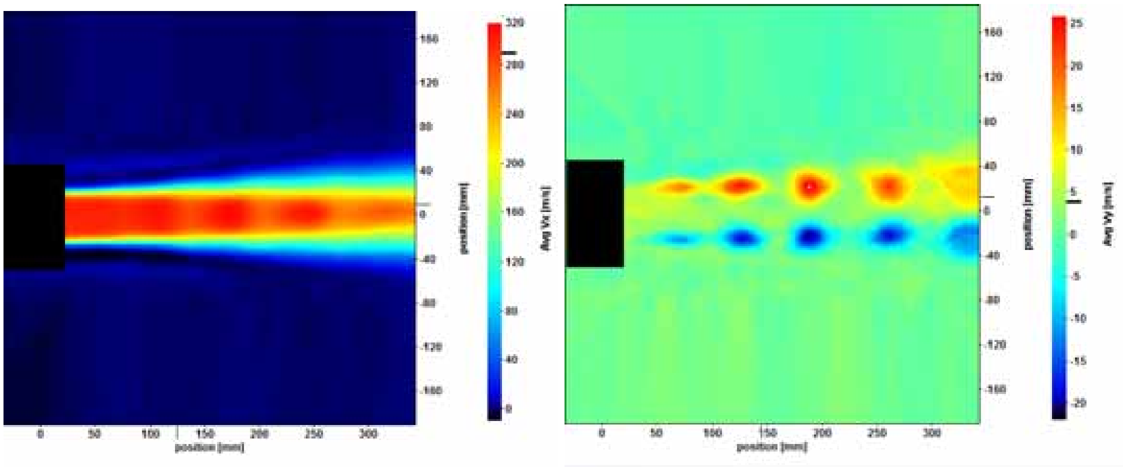
The typical scalar fields of Vx (velocity component along the jet direction) and Vy (velocity component normal to the jet direction) obtained in the longitudinal cross-section of the jet by averaging the sequence of 300 instantaneous maps are presented in Fig. 3.



a b

Fig. 3. a - average Vx velocity field and b - average Vy velocity field for the unforced jet. The black geometrical mask is larger than the nozzle, which exit is located at x = 0 mm.

Results of phase-locked PIV presented in Fig. 4 demonstrate the appearance of periodic spatial structure (especially in Vy field, Fig. 4b) which can be associated with the most excited instability wave for high-speed jet in consideration.



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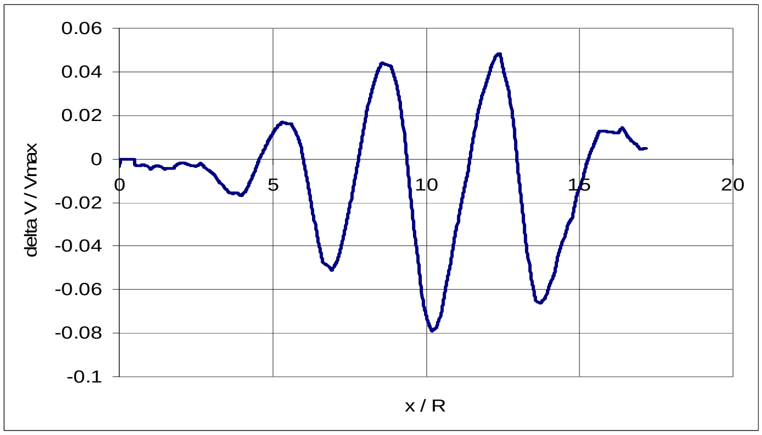

c

Fig. 4. a - Vx velocity field and b - Vy velocity field for the jet, acoustically forced at the frequency 3000 Hz. Sampling rate is also 3000 fps. c - – PIV measured wave pocket.

In the case of mismatch between acoustical excitation frequency (3 kHz) and PIV sampling frequency (3.72 kHz) the orderly structure of velocity field disappears and the flow picture looks like for the unforced jet.Thus, these experiments provides an experimental technique and database on acoustically forced and unforced turbulent jets, which can be used for identification and analyses of instability waves.

III. Experimental verification of the possibility of control over artificially exited instability wave by external acoustic action

The main goal of the experiment described below was to clearly demonstrate the possibility of control over artificially excited instability waves in turbulent jet. The diagnostic technique described in the previous section was successfully used in the experiments.

The idea of the experiment was based on the theory of acoustic instability wave control presented in [13]. In the mentioned report instability wave was excited by plane acoustic wave coming from semi-infinite cylindrical nozzle, and then this instability wave was cancelled by the external acoustic wave, the amplitude and phase of the letter being specially adjusted according to the analytical solution of the control problem. The main result of the developed theory consisted in the justification of the possibility of the effective control over artificially created instability wave by means of external action with the amplitude of the same order as the internal one. It should be emphasized here that it is fundamentally important that we considered inner and outer excitations of the jet since otherwise, e.g. in case of inner-inner excitation, the problem reduced to trivial acoustic cancellation in the duct, whereas in the former case we do not cancel acoustic fields but we cancel hydrodynamic instability which is not the same.

In order to test experimentally the possibility of shear layer instability control which was shown to be realizable theoretically, we first should provide axisymmetric external and internal acoustic excitations of the jet in order to create mainly axisymmetric instability (zero mode) and to obtain the situation close to the model problem considered theoretically. Axisymmetric internal excitation was created by a loudspeaker located in the settling chamber at a distance about 1.5m upstream from the nozzle exit, the diameter of the nozzle was 52mm. Such configuration was tested to provide azimuthally uniform near and far field at a frequency of excitation with the error less than ±0.5dB. Excitation of axisymmetric external acoustic wave near the nozzle exit with the amplitude comparable to the internal one turned out to be more complicated problem. The solution was to use metal truncated cone located in alignment with the jet axis and formed a quasi-annular duct around the main nozzle (Fig.4). The back surface of the cone was closed by a special ring cover with 2 loudspeakers inserted in it. The exit plane of the cone was coplanar to the main nozzle exit. This system of external excitation provided azimuthal uniformity of the near field with the error about ±0.9dB. Azimuthal structure of the field was measured by 6 microphones located symmetrically near the front edge of the cone. These microphones were removed during the main measurements performed with 50m/s jet excited at 1kHz (Sh=1.04).

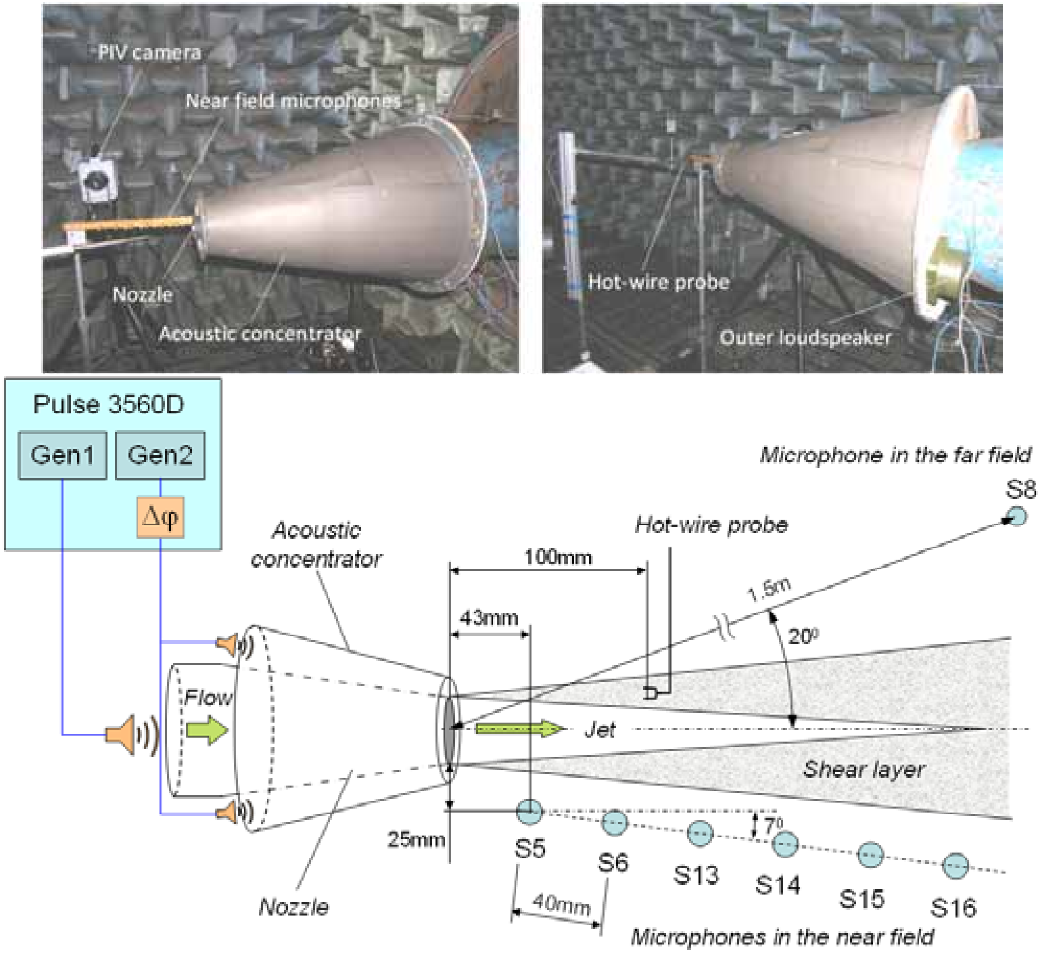

Fig. 5. Experimental set-up. Top – photo in AC-2, bottom – sketch of the set-up.

The measurements were conducted in two stages. During the first stage 7 microphones and one hotwire probe were used (Fig. 5). Six ¼’’ 4935 Bruel&Kjaer microphones were located in the near field along the jet outer boundary, one ½’’ 4189C Bruel&Kjaer microphone was placed in the far field at a distance of 1.5m from the nozzle exit center at an angle 200 to the jet axis, and one Dantec 55P01 hotwire probe was inserted approximately in the middle of the shear layer 100mm downstream from the nozzle exit plane. During the second stage PIV measurements of the excited jet were performed.

The microphones and hotwire measurements showed that given the internal and external excitations adjusted in proper way, one can effectively amplify or attenuate hydrodynamic coherent structures in the jet at hand just by varying phase shift between the sources of excitation.

Though the microphones and hotwire measurements was all-sufficient, but they became more convincing when they was supplemented by the results of phase-lock PIV measurements. These measurements were performed at the excitation frequency of 1kHz, the PIV sampling frequency being the same (1 kHz) in accordance with the procedure described in Section A. The microphones were removed. The sources amplitudes were adjusted by means of hotwire measurements, then the hotwire was also removed from the jet and phase-lock PIV measurements were carried out for different phase shifts between the internal and external sources. The evolution of coherent structures observed after PIV measurements postrpocessing is presented in Fig. 6, where one can see radial velocity field for the phase shift corresponding to maximal amplification and maximal attenuation of the instability waves.

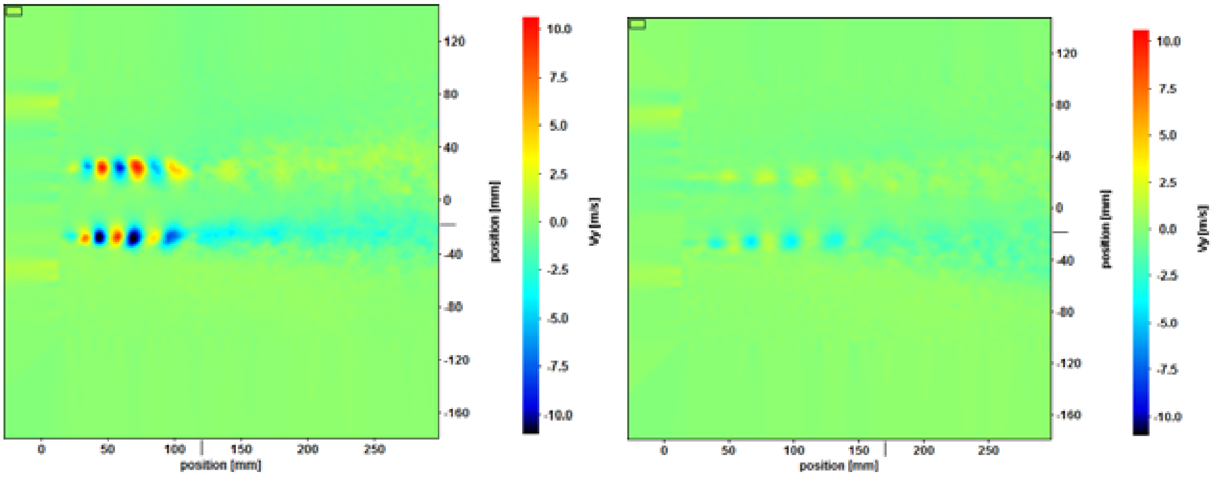

Fig. 6. Radial velocity field for the phase shift corresponding to maximal amplification (left) and maximal attenuation (right) of the instability in the jet shear layer.

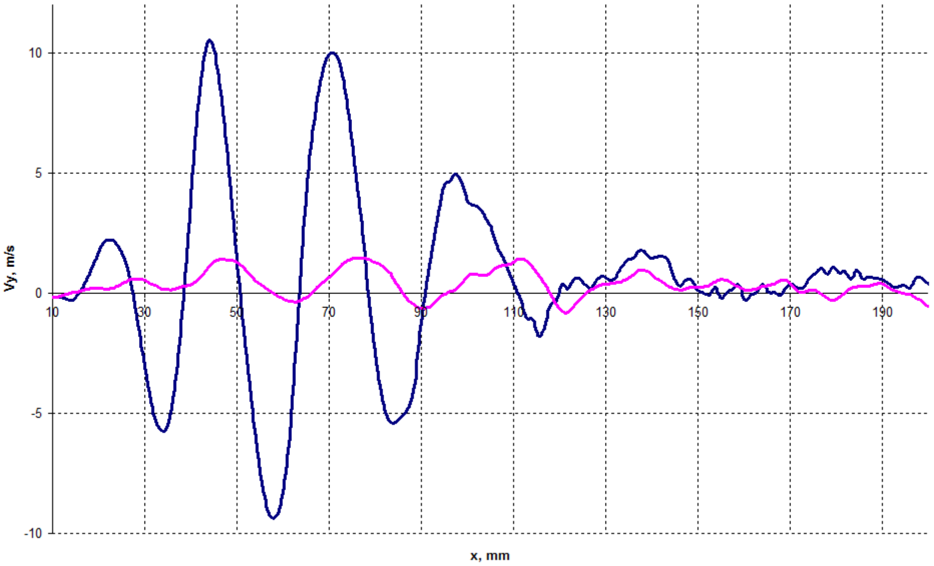

Fig. 7. Radial velocity profiles along the lip-line for the regimes presented in Fig. 6.

In Fig. 7 one can see the profiles of the radial velocity along the lip-line for the regimes presented in Fig. 6. It is clearly seen from Fig. 6 that in the conducted experiment fivefold variation in the shear layer instability amplitude was reached. It should be emphasize here that it doesn't really matter by what particular action the control instability is created. In the described experiment it was created by an acoustic excitation, but equally well it could be produced by any other actuator.

Preliminary conclusions and additional work for full-paper

In this work acoustic control over artificial instability wave excited by preset acoustical source is realized, i.e. it is experimentally confirmed theoretical conclusion that the time harmonious instability wave can be cancelled by means of an external acoustic action under condition of a correct choice of its amplitude and phase. PIV measurements have shown, that for the jet considered the proper choice of the amplitude and phase of the control action made on basis of hot-wire measurements leads to a considerable (five times) decreasing of instability waves amplitude in the whole shear layer.

The results for plasma actuators will be presented in the full paper. Realization of this effect in high-speed jet where instability waves can directly radiate sound, will allow creating active close-loop system of jet noise suppression.

Acknowledgements

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