Journal of Visualization, Vol. 6, No. 3 (2003) 303-311

Visualization of the Large–scale Vortex Structures in Excited Turbulent Jets

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Received 26 July 2002
Revised 6 October 2002

Abstract : The present work is a part of the more common research aimed at establishing the role of large-scale vortex structures in the mechanism of noise generation by subsonic turbulent jet. The work presents the results of photography and videography of fast non-stationary processes in a circular subsonic jet under lateral acoustic excitation by harmonical source located upstream in a stilling chamber. Jet velocity varied in the range of 40 – 200 m/s (M = 0.12 – 0.6).

Keywords : Turbulent subsonic jet, Large–scale vortex structures, Shear interferometer, Optical averaging technique.

1. Introduction

Investigations of the large-scale vortex structure role in turbulent jet dynamics (Crow and Champagne, 1971; Hussain, 1983; Ginevsky et al., 2001, etc.) and evaluation of their contribution into the noise radiated by the jet (Laufer et al., 1974; Moore, 1977; Tam, 1991, etc) have a long history and a broad references. However, attempts to more profoundly understand the sound generation nature in the jet are confronted by an exclusively complex character of dynamic turbulent processes in subsonic jets. At the same time the fact itself of coherent structure presence in the jet offers a possibility of separating different dynamic events and revealing their role in the noise generation processes. These events can be effective noise radiators or, on the contrary, slightly affect radiation. Thus a high-speed shooting (7000 frames/s) was used for revealing noise sources of subsonic jet, together with measurements in the acoustic near-field (Sarohia and Massier, 1977). Joint measurements permitted comparison between the burst in the acoustic near field of the jet and the merging process of large-scale vortical structures taking place in the jet. At the same time, the investigations of Bridges and Hussain (1992), which used the method of conditional sampling, have shown that sound radiation from the structure merge events in the far field takes place, but is rather insignificant in the total jet noise. It is important to consider some other events and to compare their significance with each other.

In the papers of Kopiev et al. it was shown that separate vortex rings can be noise sources in themselves (Kopiev, 2000). Therefore in accordance with the main idea, it is of interest to make an attempt at finding a real contribution of separate vortex rings into the overall jet noise. First it is necessary for this purpose, to establish the fact of vortex ring presence in the jet, locate their generation, life duration, stability of life etc. In this particular case, one can try to reveal a "footprint" of their radiation in the acoustic jet field.

2. Experimental facility

One of the traditional ways of obtaining some additional information on real processes and phenomena in turbulent flows is visualization. Several ways of coherent structure visualization is known (Bradshow et al., 1964; Crow and Champagne, 1971; Ahuja and Whiffen, 1972; Yule, 1978; etc.) for turbulent jets. All of them are based on shadowgraph or schlieren methods of visualization of gas flows. This work presents a system of visualization on the basis of shear interferometer operating according to an auto-collimation scheme with a spherical mirror of large diameter (d=500mm) and a strobe light source.

Photos and video-recording of a pure jet and a jet excited by harmonic acoustic signal were made in an unechoic acoustic chamber with dimensions of 10 × 5 × 4.7 m^3 (Fig. 1). A cold jet issuing from a conical nozzle with an exit diameter of D=4 cm at velocity V_0 of 40-200 m/s (M=0,12-0,6) was investigated. As a source of longitudinal acoustic excitation, a loudspeaker was used. It was placed at the stilling chamber inlet, at a distance of ≈ 2 m upstream from the nozzle exit plane. The acoustic excitation frequency f_{ex} varied in the range of 600-2500 Hz. The image recording was made with the help of the video-camera Sony CCD TR730E. For comparison with the visualization results, steady and pulsating characteristics of disturbed and non-disturbed jets were measured as well as sound pressure levels generated by an external acoustic source. The exciting signal level was measured in the nozzle exit section at the flow absence with the use of a 1/4-inch microphone, type 4133 of B&K. For measuring velocity fluctuations in the jet, a hot-wire system based on DISA Electronics anemometer 55M was used. The longitudinal component of the mean velocity was measured with Pitot tube.

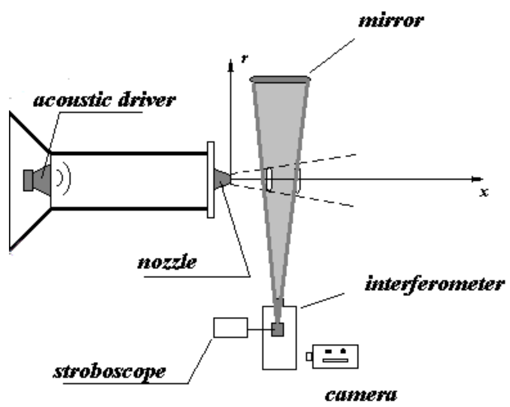

Fig. 1. Scheme of experimental set up.

To separate large-scale vortex structures on the background of non-correlated small-scale fluctuations in the jet, the method which can be called optical averaging technique was used. The jet image is repeatedly exposed on the same frame, so the repeating events are separated out and the random ones are smoothed out. Recording was made in the passing light with the use of shear interferometer (Zabelin, A. A., 1967). An important peculiarity of this device which permits a more complete research of the phenomenon is a possibility of varying the wave front shear: at the lateral shear the gradients of lateral optical non-uniformity (associated here with the non-uniformity of velocity field and density) are identified, i.e. gradients along the jet axis; and at the longitudinal shear the gradients of optical non-uniformity across the mean flow are separated out. As a source of illumination, a strobe light source was used, the light impulse frequency of which can be smoothly varied in the range of 0-300 Hz. The stroboscopic light impulse frequency $f_s = \frac{f_{ex}}{n}$ was taken to the maximum possible, so that the condition $f_s \leq 300$ Hz would be realized. At such a frequency the events periodically appearing at one and the same place of the jet (here they are vortex rings periodically generated in the initial jet part) are repeatedly exposed on one frame, and a slight shift between the stroboscope frequency and the radiation frequency permits achieving the high-frequency video-shooting effect in application to the repeating events. The presence of a similar effect was indicated by Raman, Taghavi (1995) for visualization of periodical processes in supersonic jet.

Thus, at the slight frequency shift between the stroboscope and the acoustic signal exciting the jet, the large-scale vortices slowly move in the vision field and their evolution from initiation to break-up can be traced in detail and recorded on video. The research shows that the combination of stroboscope and interferometer offers new possibilities of studying evolution of large-scale vortical formations in jets.

The system sensitivity appeared to be sufficient for obtaining a contrast image in the jet issue velocity range even without using especially sensitive films (in photo-recording) and without adding some visualizing means or jet heating. Thus, with the use of the above indicated method it appeared possible to obtain photos and video-fragments of subsonic circular jet and to trace the dynamics of large-scale vortices in the excited jet.

3. Results of Video-recording of the Excited Jet

As the experiment result, a video-film was made, in which unsteady dynamic processes in a subsonic turbulent jet at different combinations of jet issue velocity and amplitude/frequency of the exciting acoustic signal were systematically recorded. Visualization was realized over a wide velocity range (from 40 m/s to 200 m/s) and over a wide excitation frequency range f_{ex} (from 600 Hz to 2500 Hz) according to the following scheme: first, at the steady jet issue regime and given frequency of external acoustic excitation, a stroboscope frequency (limited by 300 flash per second) was selected and interferometer tuning was realized, so that in the vision field a stable picture of vortex rings was fixed (this frequency appeared to be equal exactly to $f_{ex}/n<300$, where n is an integer; only each nth ring is recorded). Then at the invariable irradiation frequency and the stroboscope frequency, the issue velocity increased smoothly up to the maximum value and then again decreased to the minimum. The stable picture of the vortex rings in the vision field appears to be invariable while jet velocity increases, hence the formation frequency of vortex rings is quite synchronized with exciting frequency. The jet velocity determined from manometer indications, which fixed the pressure in the stilling chamber, was said to the video-camera audio-channel. After this the excitation frequency was changed and the following series of experiments was realized. The effect of acoustic signal amplitude on the jet structure was investigated in a separate series.

Figure 2(a) shows video-frames of the excited jet at different issue velocities obtained at stroboscopic illumination and interferometer tuning to the horizontal shear of wave fronts. At such a shear the large-scale structures look like developed instability waves at the jet boundary that often encountered in the literature on visualization (Ahuja and Whiffen, 1972; Moore, 1977; Lilley, 1991; etc.). However at shear variations (Fig. 2(b)) and still more at fore-shortening shooting variations it becomes obvious that the non-linear formations are a stable train of 3-4 vortex rings in the initial jet part. Indeed, at ¾ fore-shortened video-shooting (Fig. 2(c)) the large-scale vortices of oval structure are clearly seen, and they are observed especially well at a distance of $1.5D$. At jet velocity increase, the vortex images become rather spread, and optically averaged picture seems to be not so characteristic. For the undisturbed jet, the picture of vortex ring “train” was not obtained at any stroboscope tuning frequency value. However, this can only mean the fact that due to a larger degree of chaos in ring formation in the undisturbed jet, their disagreement with the stroboscope frequency takes place and no

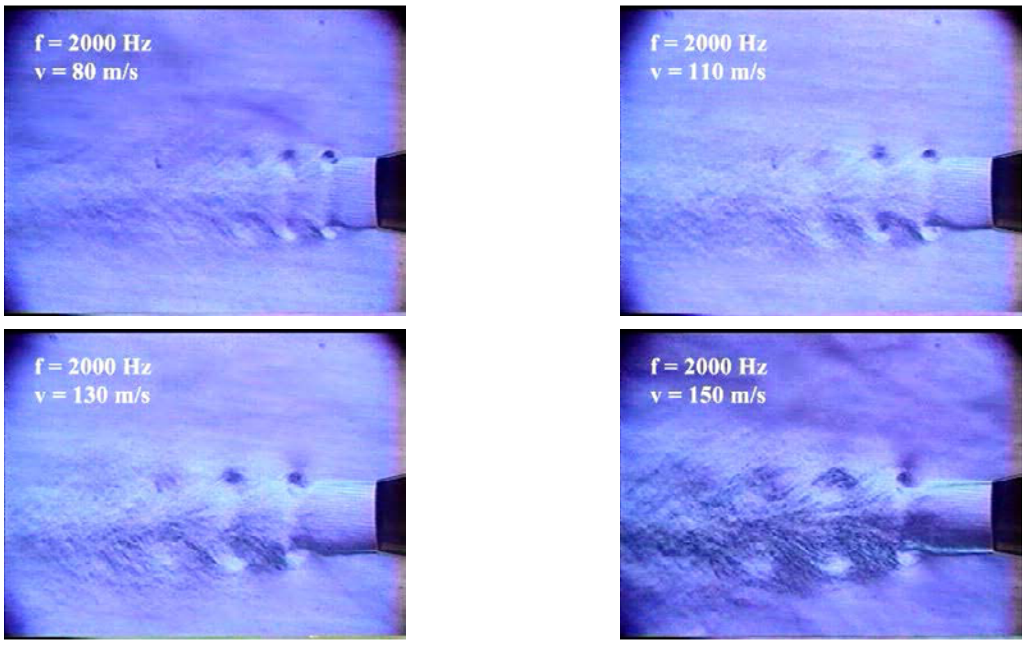

Fig. 2(a). Video-frames of excited turbulent jet (horizontal shear of wave fronts, a side view).

phase averaging of large-scale vortices occurs (Zaman and Hussain, 1984). An interesting flow peculiarity obtained while tuning the interferometer to the horizontal shear is the longitudinal vortex presence on a cylinder surface of the initial jet part. We see (Fig. 2(b)) that the vortex rings are slowly changing while moving. On the first stage after formation, the ring seems to have thin core (the first ring to the nozzle in the frame), then it becomes thicker and before disappearing it has a maximal core size. Since the circulation of core vorticity does not increase (in inviscid fluid it is a constant), the vorticity in the core will decrease while rings move. If we consider the acoustic output from such a system then the high frequency radiation will produce by the rings located near the nozzle exit and the lower frequency will radiate by the rings which are farther from the exit, because the vortex ring radiation frequency is determined by core vorticity value (Kopiev, 2000). Other reasons for the effect of the core visible to become thicker could be connected with increasing chaos in exact position of rings as the distance from the nozzle exit plane increases or with increasing of core disturbances amplitude due to instability.

Figure 3 presents excited jet structure at close Strouhal numbers ($St = f_{ex}\ D/V_0$) and different issue velocities. At jet velocity increase, the location of the first large regular vortex smoothly retreats from the nozzle edge. Large vortex ring is the result of merging of small-scale disturbances developed near the exit which are associated with instability waves. Due to their small-scale structure in axis direction, the increment δ of space instability could be approximated by simple 2D formula for Kelvin-Helmholtz instability waves $\frac{\delta}{Sh} \sim M_0 \sqrt{\sqrt{1+M_0^2} - (1+M_0^2/4)} \Big/ \left(\sqrt{1+M_0^2} - 1\right)$ (Miles, 1958). Since the increment decreases as Mach number M_0 increases, the disturbances for larger Mach number are developed slowly and the first stable vortex is created at larger distance from the nozzle exit plane (Fig.4). In this case, the acoustic excitation synchronizes not the reference waves of instability, but only modulates process of their merging.

This is also qualitatively confirmed by the effect of the exciting signal amplitude. At the smooth excitation amplitude increase, the vortex rings are clearly seen starting from some threshold value of amplitude. The following amplitude increase leads to decreasing of first stable vortex distance from the nozzle exit plane. At signal decrease, the vortex rings, at the same threshold amplitude, disappear from the vision field and the flow picture looks like that of undisturbed jet.

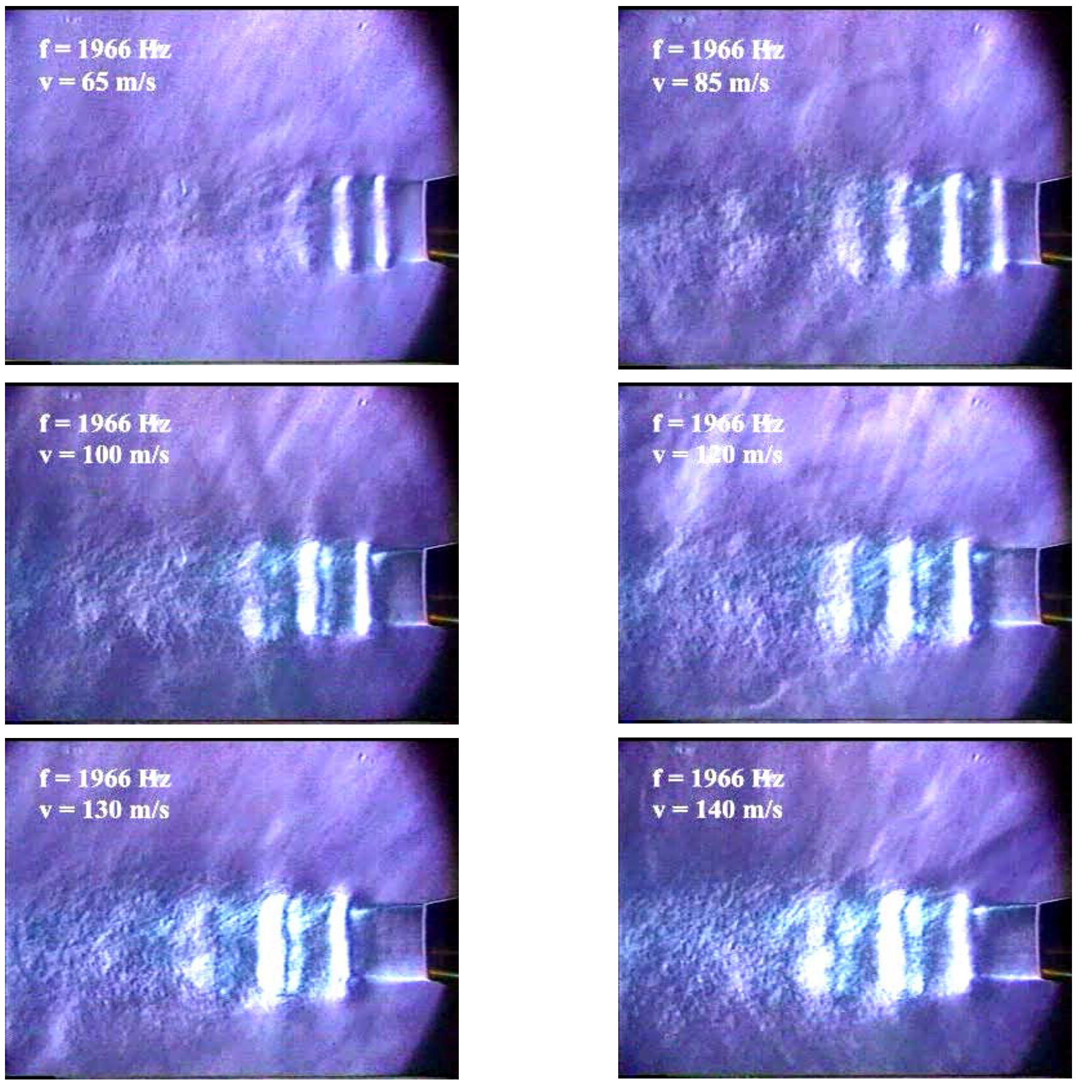

Fig. 2(b). Video-frames of excited turbulent jet (vertical shear of wave fronts, a side view).

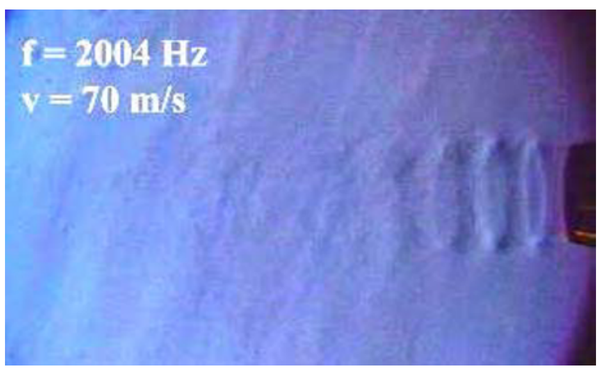

Fig. 2(c). Video-frames of excited turbulent jet (vertical shear of wave fronts, ¾ side view).

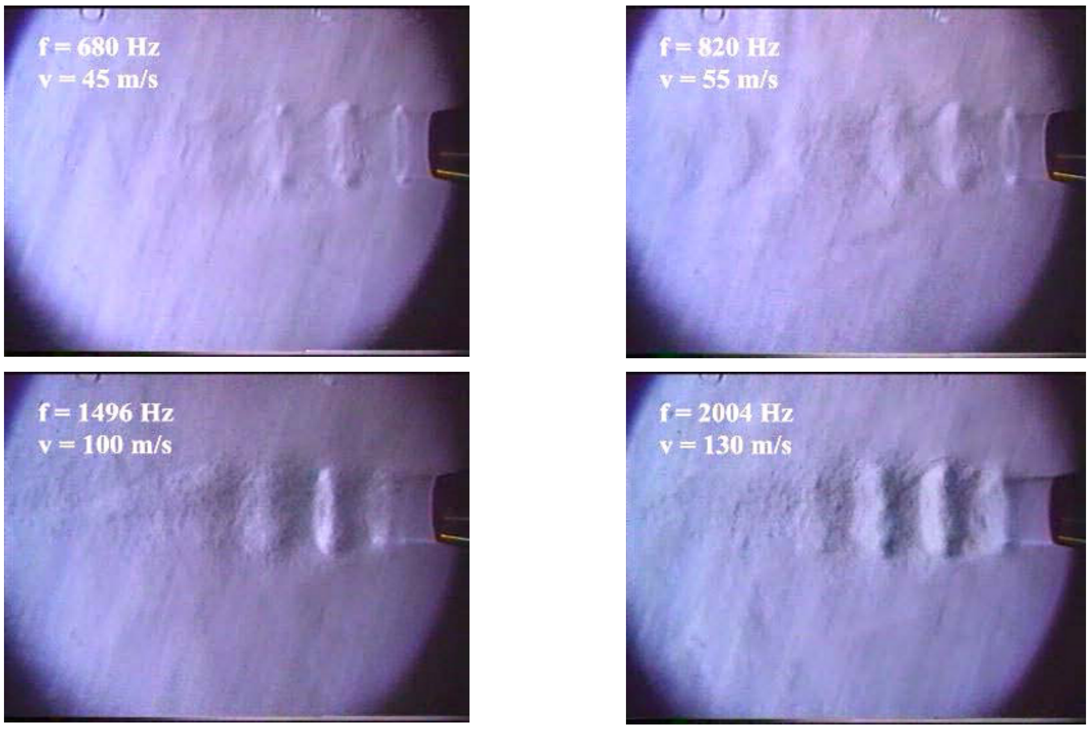

Fig. 3. Effect of jet issue velocity on flow structure under the fixed Strouhal number $St = f_{ex}D/V_0 \approx 0{,}6$.

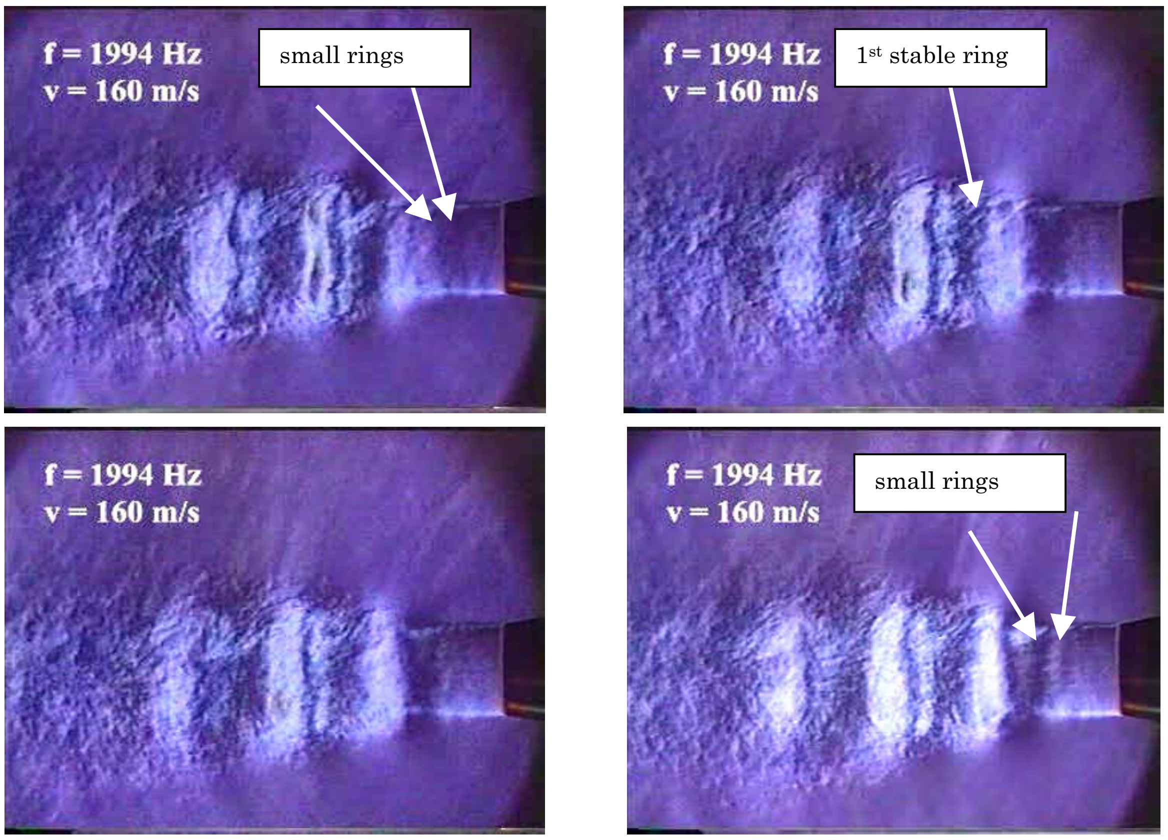

Fig. 4. Small vortex rings not synchronized by external acoustic excitation merge to form stable ring in the initial part of a round jet (four successive phases).

4. Vortex Ring Formation

Vortex ring formation close to the sharp nozzle edge can take place even without acoustic excitation of the edge. Fig. 5 presents the shadow photograph obtained by the authors who demonstrates a process of vortex ring formation at impulsive air jet issue from a circular nozzle of the same diameter that was in the above described experiments ($\mathrm{Re}_D = \frac{V_0 D}{\nu} \approx 10^5$). It is seen in Fig. 5 that initially the cylindrical shear layer subjected to Kelvin-Helmholtz instability, due to non-linear processes rolled into a non-linear spiral, forming the vortex ring core. Note that the shear layer forming the vortex ring core has already been broken into separate small vortex rings. Such a behavior seems to be typical for vortex sheet rolling up at $Re>>1$ and it was discussed by Held et al. (1995). Thus, vortex ring formation in the jet can be a consequence of non-linear evolution of the shear layer by itself without any acoustic excitation at the nozzle edge which nevertheless can substantially synchronize this process.

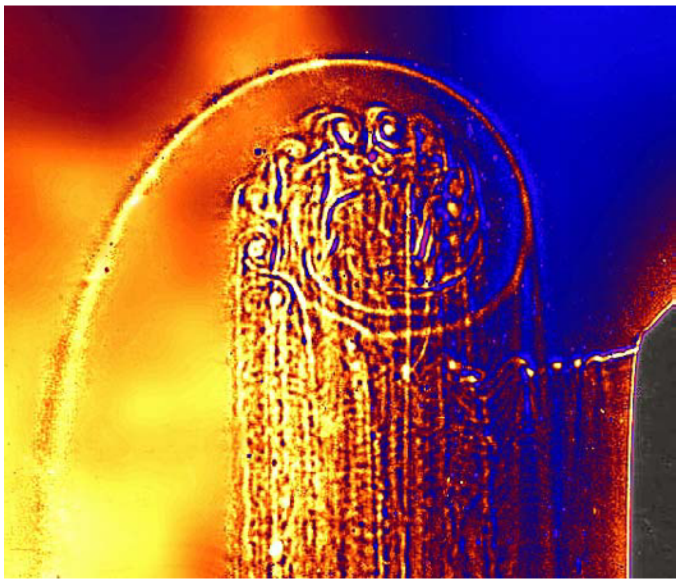

Fig. 5. Shadowgraph of vortex ring formation.

5. Conclusion

The procedure of visualization of periodical processes in the turbulent jet is perspective from the point of view of researching the mechanisms of sound generation by complex three-dimensional flows. The main qualitative conclusion which can be reached from the experiment carried out is that the initial part of the excited jet consists, over a wide range of Strouhal number variations (St=0.12÷2), of a train of regular vortex rings dominating in the main flow. Averaging of this anisotropic flow exactly gives a usual form of mean flow. Besides, the vortex rings well seen in photos are completely synchronized with the exciting field. This conclusion is not quite trivial – the large rings spoken about are formed as a result of merging the small rings shed from the nozzle edge. These small rings are not synchronized with the external field and are not quite regular. At neither frequency of the stroboscope (not necessarily multiple to the exciting signal) one can synchronize these disturbances. Nevertheless, their merging at given task parameters (Strouhal and Reynolds numbers) occurs at one and the same place and is exactly synchronized with the excitation frequency.

6. Acknowlegements

The work is realized with the support of Russian Foundation of Basic Research (02-01-00570) and INTAS (00-00232). The authors would like to thank to A.D. Frolova and V.I. Novikov for help in experiment conducting.

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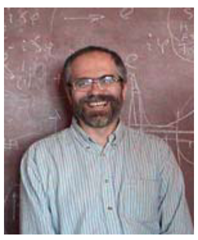
Authors Profile



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