PECULIARITIES IN RESEARCH OF THE TURBULENCE IN A SWIRLING FLOW BY THE LDA METHOD

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Introduction

The vortex axis precession may have a sufficient influence on the measured values of the swirling flow turbulence characteristics. It was shown in [1] that up to 80% of the measured value of the velocity fluctuation in a vortex chamber may be conditioned by the precession. A quasi-periodic low-frequency movement of the flow kernel is observed in different kinds of swirling flows. This may be the precession of the recirculation region in a flow with a strong swirl. For example, in a vortex combustion chamber [2], the swirling movement spiral occurs [3]. The quasi- periodical oscillation in vortex chamber were observed in our previous investigation [4]. It was shown that the mean flow field was not axi-symmetrical: the lines of equal velocity values had the elliptical form. For turbulence measurement in swirling flow, it is necessary to evaluate the contribution from quasi-periodical alteration of these parameters, since this may overestimate the measured velocity fluctuation. A similar problem appears during the measurement of turbulence in a boundary layer subjected to oscillation in the main flow [5].

The method of triple decomposition of the temporal rows of the velocity values may be adopted to analyze such kinds of flows:

$$u(x,t)=\overline{u}(x,t)+\widetilde{u}(x,t)+u'(x,t)\,,$$

where $\overline{u}(x,t)$ is the average value, $\widetilde{u}(x,t)$ is the periodical component of velocity in point x, and $u'(x,t)$ is the turbulent fluctuation. To make this triple decomposition, the method of ensemble average (phase average) is employed:

$$\langle u(x,t)\rangle=\lim_{N\to\infty}\frac{1}{N}\sum_{n=0}^{N-1}u(x,t+n\tau)\,,$$

where τ is the period of the cycle. Then the average velocity is:

$$\overline{u}(x,t)=\lim_{N\to\infty}\frac{1}{N}\sum_{n=0}^{N-1}u(x,t_0+n\Delta t)\,,$$

where $N\Delta t >> \tau$. Since $\langle u(x,t)\rangle$ and the turbulent component are uncorrelated in time, we obtain $\langle u(x,t)\rangle=\overline{u}(x,t)+\widetilde{u}(x,t)$, $u'(x,t)=u(x,t)-\langle u(x,t)\rangle$. The efficiency of such an estimate depends essentially upon knowledge of the period and the phase of the periodic cycle of the speed. The discrepancy in determination τ , its variation from a cycle to a cycle will be interpreted as the turbulence.

In [5], the filtering technique for triple decomposition was suggested which can be appled to a wide class of unsteady turbulent flow. The technique does not require an *a priory* information on the period and the phase of organized oscillations. In the present work the results of turbulence measurements for a swirling flow inside a vortex chamber are presented. For estimation of the precession influence, the method of spectral filtration [5] was fulfilled.

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Experimental installation

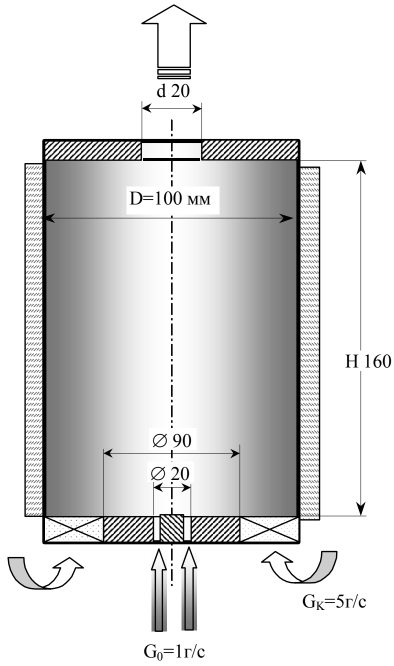

Fig. 1. The investigated vortex chamber.

The tests were carried out in the vortex chamber schematically shown in Fig. 1. The diameter of the chamber is 100 mm, and the height is 160 mm. A swirl flow was created using the directing device located on periphery of the bottom of chamber (36 splots with blades inclined to the bottom surface at 30°). The air from the chamber was released through the top hole with the diameter of 20 mm . Through the bottom of the chamber, an asymimmetric unswirl jet of air was injected through an annuler slot with the width of 1.5 mm and external diameter of 20 mm, or through the round nozzle with the diameter of 9 mm. Measurements of the two components of the speed (axial u_Z and tangential u_φ) were carried out by a two-component laser Doppler velocimeter. This optical method requires a flat optical window with the width of 27 mm made in the lateral surface of the chamber throughout the entire height. In our experiments we used a two- component back-scattering LDA "ABC" with adaptive optical channels. The light source was He-Ne laser LGN-503 with the operating power of 250-350 mW. The primary processing of the signal retrieved from the photoreceiver was made by the watching-filter processor "Flow-2". Particles of glycerin aerosol (diameter of 1-5 microns) were used for light scattering. The near-axis and peripheral flows were dusted separately: this provides a more uniform distribution of particles in the chamber volume. An analog signal from the output of the watching processor was digitized by a multichannel 12-digit AD converter "Lab-Master" with the frequency of 0.5-5.0 kHz, making the sampling for each of two channels with the volume up to 65536 readout.

The measuring system was tested on well-studied types of flows: a round flooded jet and a flat co-current jet. The metrologocal research gives us the requirements to operational conditions for the measurement system: the signal – noise ratio, the range of concentration for the light-scattering particles, parameters of the watching-filter processor providing reliable data on turbulence with the error less than 5%. The average characteristics of the flow were measured with accuracy < 0,5%.

Filtering Technique

The method of triple decomposition [5] does not require any information about the period of non-stationary movement; instead, the model of the power spectrum shape for turbulent pulsations is used. In the majority the researches devoted to non-stationary flows turbulence, the periodic change of parameters does not render an influence on the averaged field of turbulence. Except the cases, when the oscillation frequency coincides or close to the burst frequency of mean flow. In the method of triple decomposition, the model of the turbulent pulsation power spectrum is used as initial approximation. Then the estimation of turbulent power spectrum is calculated to find the estimates of the turbulent and periodical components with a minimum cross-correlation.

After deduction of the mean value of the speed in a point, we present the deviation from mean value as a sum of turbulent pulsation and periodic change of speed $w(t) = w'(t) + \widetilde{w}(t)$ After Fourier-transformation, in frequency space, it takes the form:

$$W(f) = W'(f) + \widetilde{W}(f) . \quad (1)$$

It is necessary to find the linear filter $\Phi(f)$, allowing to estimate the turbulent a component of the signal:

$$W'_{est}(f) = \Phi(f) \cdot W(f) . \quad (2)$$

The filter is searched as:

$$\Psi^{(k)}(f) = \left(\frac{S^{(k)}{}_{w'_{est} w'_{est}}(f)}{S_{ww}(f)} \right)^{1/2} .$$

In [4], the initial approximation is offered as an estimation of a power spectrum of velocity pulsations received from the measured row $w(t)$:

$$S^{(0)}{}_{w'_{est} w'_{est}}(f) = \frac{2(1 - R^2_{ww}(1))}{1 + R^2_{ww}(1) - 2R^2_{ww}(1)\cos(2\pi f / f_s)} ,$$

where $R^2_{ww}(1)$ is the measured value of the autocorrelation function for $w(t)$ delayed by one sampling interval, f_s is the is sampling frequency of the time series. After splitting the model turbulence power spectrum into, e.g., *M*= 100 elements, the quasi-Newton minimization method can be employed as the multi-dimensional procedure for finding the estimates w'_{est}, $\widetilde{w}_{est}$ with a minimal cross-correlation $\overline{\widetilde{w}_{est} w'_{est}} / \left(\overline{w'_{est} w'_{est}} \cdot \overline{\widetilde{w}_{est} \widetilde{w}_{est}} \right)^{1/2}$. That is, we find a_m, where $\Psi(f_m) = \left\{ \frac{a_m}{S_{ww}(f_m)} \right\}_{m=1}^{M}$:

$$\frac{2\sum\limits_{m}^{M-1} S_{ww}(f_m) \cdot \Psi_m (1 - \Psi_m) + S_{ww}(f_M) \cdot \Psi_M (1 - \Psi_M)}{\left[\left(2\sum\limits_{m=1}^{M-1} a_m + a_M \right) \left(2\sum\limits_{m}^{M-1} S_{ww}(f_m) \cdot (1 - \Psi_m)^2 + S_{ww}(f_M) \cdot (1 - \Psi_M)^2 \right) \right]^{1/2}} = \min . \quad (3)$$

As a rough estimate (about 10 percents accuracy for $\overline{w'w'}$), the first approach may be sufficient if the value of (3) is about 10^{-1}-10^{-2}. If there is a distinct individual peak in the spectrum of the measured signal (corresponding to organized movement), this method should result in a unique minimum (3) with the size of the order 10^{-11}. With the known function for the filter Ψ, and by applying the inverse Fourier transformation, it is possible to restore $w'_{est}(t)$, $\widetilde{w}_{est}(t)$.

Restrictions: the method does not work for the case when the intensity of turbulent pulsations is low (in comparison with the noise for the estimate of the organized movement); method is unsuited in transition or relaminarizing flows.

In [5], the results of method testing are presented for measurement of the turbulent boundary layer parameters with controlled periodic influence. This approach is compared with the method of conditional sampling. In the case when the period and phase of the organized movement are known, both techniques identical results (within the accuracy 2 %).

Measurements results

The analysis of power spectra of velocity pulsations in various points of flow demonstrated that the influence of precession on pulsation of a swirling and axial component of the speed is practically identical. The reduction of peak size (which is caused by organized movement) in the spectrum is appreciable along the chamber axis. For the investigated flow modes, the maximal effect of precession is achieved in the sections close to the bottom of the vortex chamber (at the height up to z ≈0.5H). The data corresponding to the maximal effect are plotted in Fig. 2. One can see that the method of spectral filtration allows to obtain the quasi-periodical component with the time character far from coherent (Fig. 3). The estimations of precession influence obtained with the method of spectral filtration have shown that, for the considered configuration, the measurement results for the intensity of turbulent pulsations can be overestimated ($\sqrt{\overline{w'w'}/\overline{w'_{est}w'_{est}}}$) by factor not more than 10-12%.

Distributions of Tu for various heights of the vortex chamber are shown in Fig. 4. The borders of the near-axis jet almost do not change with height of the chamber, approximately

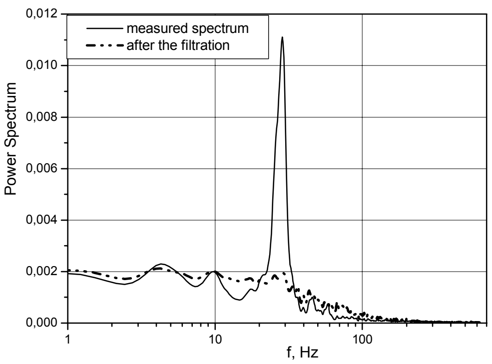

Fig. 2. Normalized power spectrum of velocity fluctuations.

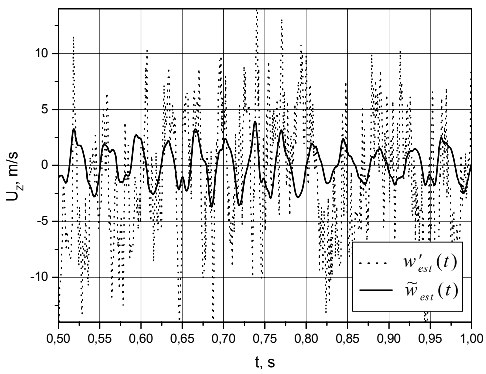

Fig. 3. The result of triple decomposition of velocity time series.

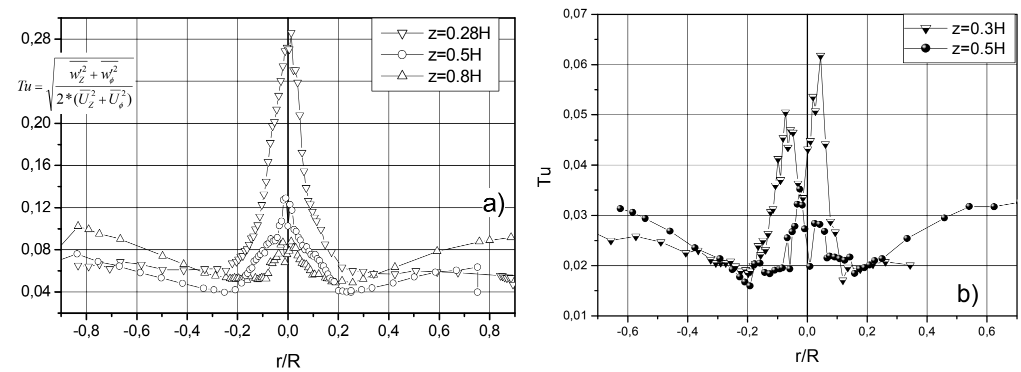

Fig. 4. The distributions of turbulence level in different cross-sections of the vortex chamber: injection of the air jet through the annular slot (a), and through the nozzle with d=9 mm (b).

corresponding to the diameter of the exit diaphragm. There are two different areas in the flow: the peripheral and near-axis area. These zones differ both in their turbulence levels and in the pattern of profile change over the chamber height. The turbulence level in the peripheral area (r/R > 0.2) grows towards the periphery from 3% up to ~ 10%. And, the level of turbulent pulsations in the cross-section $h/H = 0.8$ is much higher, than for the cross-section $h/H = 0.28$. In the near-axis area (corresponding to quasi-solid rotation law: $w_\varphi \sim r$), there exists a maximum in the turbulence distribution; its magnitude decreases upwards the flow. In this sense it is possible to speak about suppression of turbulent fluctuations in the field of centrifugal forces from 25 % up to 8%. The high level turbulence in the vicinity of the bottom of the vortex chamber is apparently caused by peculiarities of interaction between the injected non-swirl jet and the rotating peripheral flow near the edge of the annular slot. So, when the near-axis jet is formed up by the round nozzle with the diameter of 9 mm (Fig. 4b), the intensity of pulsations appears to be much lower. At z = 0.5H, in the center of the jet, a local minimum appears, connected with the observed fact that here the core of the non-swirled jet still exists. Thus, the character of turbulence evolution in the vortex chamber remains qualitatively the same.

Conclusion

The estimation of contribution from the precession into the measured velocity pulsations with the spectral filtration method demonstrated that the data on intensity of turbulence pulsations in the vortex chamber under consideration can be overestimated by factor less than 10-12%. The performed measurements for the flow field in the vortex chamber reveal two different areas, distinguishing in the turbulence level and evolution of pulsation intensity over the chamber height. For the near-axis jet zone, suppression of turbulence intensity is observed.

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