VELOCITY MEASUREMENTS IN A VORTEX MODEL

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A procedure is described for measuring the velocity in precessing vortex filaments which appear during convection of air from a hot surface.

Another method has during the past decade been made available for aerodynamic measurements, namely laser Doppler anemometry [1]. The possibilities and the limitations of this method have been realistically assessed in many studies [2, 3]. However, procedural problems of LDA (laser Doppler anemometry) measurements in vortical nonsteady streams still remain unresolved. One ought to consider the difficulties associated with the selection of criteria for velocity sampling on the basis of LDA signals. It has been shown in one study [4] what errors can arise when the conventional method of averaging the probability density curves is used for LDA measurements in nonsteady vortices behind a cylinder. No analysis of these procedural problems has yet been made as applied to the use of the LDA method for velocity measurements in nonsteady streams twisted around some vertical axis. This study will consider the conditions of velocity sampling from probability density curves for LDA signals, and the analysis will be based on the "convective vortex filament" model.

Vortex filaments were generated in a cylindrical vortex chamber (Fig. 1). Its diameter was 20 cm and its height was 20 cm. Sixteen tangential windows were installed in the lateral surface. The lower base was heated electrically with a wire coil at a power of 600 W. In the supply circuit for this heater coil was installed a relay for maintaining a given temperature within 1°C. Air was drawn inside by the temperature drop between chamber and ambient space. While passing through the windows, the air acquired an angular momentum. The latter was trans to the ascending air streams generated by natural convection. The angle at which the tangential windows had been installed could be varied.

The model of convective vortex generated in the vortex chamber of this type has been studied before [5]. These measurements were made with a laser anemometer. Details and the measurement procedure have not been described. It was only pointed out that the vortex consistently deviated from the geometrical center, which made measurements difficult. The velocity was determined as the time average of signals over a 15 min period.

The laser anemometer for this study was constructed according to the differential scheme [6]. The beam convergence angle was made 3.7° and the field of the interference pattern occupied a space of $0.73 \cdot 10^{-6}$ cm^3. The recording equipment included a frequency meter (model ChZ-38) and a computer (model 15VSM-5). As the light scatterers served particles resulting from evaporation of diffusive oil off the hot surface. A mist concentration was produced which would ensure the possibility of single-frequency Doppler count. In our LDA scheme not the frequency but the Doppler period was measured, namely on the basis of zero-crossovers of the signal. The period was read on the frequency meter and stored in the memory of the model 15VSM-5 minicomputer. The data processing program was started, after acquisition of the necessary data array. From the output data, obtained by processing the measurement data, were determined the probability density curves for velocities (histograms of Doppler signals).

Probability density curves are usually Gaussian in form, and the stream velocity is determined as an average value. Our systematic measurements in the given vortex have revealed two peaks along the probability density curves. To simplify the terminology, we will call this pattern "bimodality of histograms."

Visual observations have revealed that the vortex filament is not at rest, but in a periodic motion around some vertical axis. This motion resembles precession of a gyroscope, and the bimodality of histograms can be explained on the basis of that analogy.

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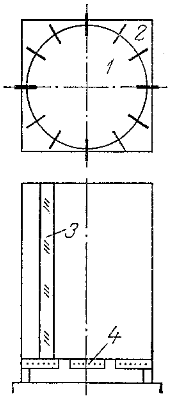

Fig. 1.

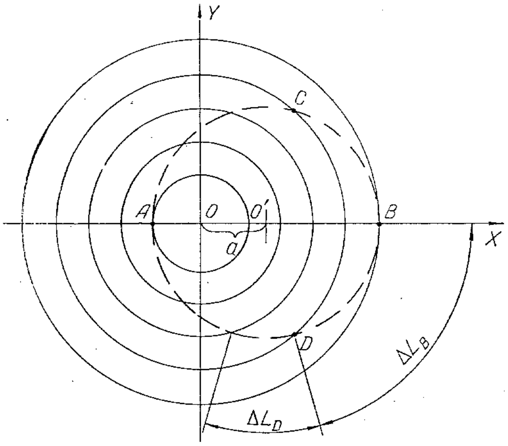

Fig. 2.

Fig. 1. Schematic diagram of vortex generator: bottom of chamber 1, base plate 2, tangential windows 3, heater elements 4.

Fig. 2. Schematic representation of vortex in moving system of coordinates XOY: dash line represent circle around which the observation point moves, dash lines represent circles around which the tangential velocities are constant, 0 is center of the vortex, 0' is center of contour around which the observation point moves, ΔL_B and ΔL_D are the lengths of arc of trajectories along which the observation point moves near points B and D, respectively.

We consider the simplest model. It will be convenient here to change from the laboratory system of coordinates, where the observation point remains stationary and the vortex precesses, to a system of coordinates tied to the vortex center. In this new system of coordinates the vortex will be stationary, while the observation point will perform a circular motion (dash line in Fig. 2). The lines of equal tangential velocities form a family of concentric circles (solid lines in Fig. 2). The probability of one or another velocity being found is proportional to the length of time the observation point dwells in the constant-velocity regions of the vortex. It is evident from the diagram in Fig. 2 that the observation point dwells much of the time within the constant-velocity annuli near points A and B. The observation point is, moreover, either farthest from or closest to the vortex center. In the indicated positions of the observation point its trajectory almost coincides with the circle around which the velocity of the vortex is constant. Near points C and D the dwell time of the observation point is shortest.

In this way, measurements with a laser anemometer in a processing vortex were made not from any one point but from points within an annulus of a width equal to double the precession radius. Most likely were found to be the velocities within the regions near the inner and outer boundaries of that annulus. These two likely velocities are responsible for the two peaks on the histograms.

The pattern of bimodal histograms and an analysis of their dynamics, based on measurements at various distances from the vortex axis, suggest a certain tentative velocity sampling from the histogram. We will examine a possible variant of such a tentative sampling from histograms, namely the example of processing a data array on the tangential velocity.

Characteristic points at which velocities can be tentatively sampled from histograms are shown in Fig. 3. The histograms have been plotted on the basis of measurements made at various distances from the vortex axis. This sampling yields two real radial profiles of tangential velocity (curves 1 and 2 in Fig. 3) shifted from each other by a distance equal to the precession diameter. From these profiles we determine the median curve. Calculations have revealed that this curve coincides completely with the experimental velocity curve plotted on the basis of conventional averaging of histograms. This correspondence suggests

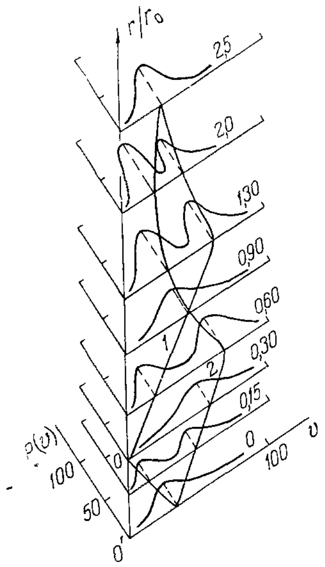

Fig. 3.

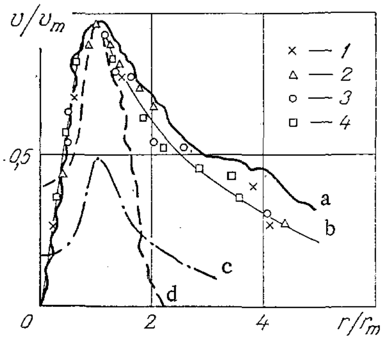

Fig. 4.

Fig. 3. Dynamics of histograms of tangential velocities measured at some distance from axis of precessing vortex. v, cm/sec; P(v), %.

Fig. 4. Radial profiles of tangential velocity (curves *a*, b) and of axial velocity (c, d): (*a*) measured in dust storm [7]; (b) based on measurements by these authors in convective vortex: 1) θ = 45° and T = 209°C, 2) θ = 80° and T = 191°C, 3) θ = 80° and T = 130°C, 4) θ = 79° and T = 72°C; (c) readings taken by these authors in convective vortex; (d) data for dust storm [7].

that the proposed method of tentative velocity sampling from bimodal histograms can be used for determining the instantaneous velocities in precessing vortices.

Let us estimate the errors incurred when bimodality of the histograms is not taken into account. The data in Table 1 include values of tangential velocities obtained by the conventional method of histogram averaging and by the method of tentative velocity sampling with precession taken into account. The velocities obtained by the conventional method do not become zero at the vortex axis, although some velocity drop occurs after the maximum has been reached at the core boundary. Instead of the indicated values, in Table 1 are given the values of velocities formally extrapolated to zero at the vortex center. The differences between velocities obtained by the methods of averaging and tentative sampling respectively are largest at the boundary of the vortex core. The instrument error of the LDA used for velocity measurements in this study was 1%. Averaging the histograms without accounting for their bimodality can evidently lead to large errors.

The preceding analysis was applied to processing of histograms of tangential velocities. The proposed method of tentative velocity sampling from bimodal histograms is equally applicable to determination of other velocity components.

TABLE 1. Comparison of Results of Processing the Histograms of Doppler Signals

r, cm	Tangential velocity, cm/sec		$\frac{\Delta v}{v}$, %	r, cm	Tangential velocity, cm/sec		$\frac{\Delta v}{v}$, %
	method of averaging	tentative sampling method			method of averaging	tentative sampling method	
0,5	35	30	14	3,5	53	63	19
1,0	62	60	3	4,0	48	56	17
1,5	68	86	27	5,0	41	45	10
2,0	72	95	28	7,5	26	30	15
2,5	66	82	25	10	22	23	5
3,0	56	71	27				

The method of tentative velocity sampling was used for processing of measurement data on the tangential velocity at various surface temperatures T and various angles θ of window setting. Radial profiles of the tangential velocity measured in the given vortex are shown in Fig. 4. Here are also shown data on velocity measurements in a dust storm [7]. All velocities are referred to velocity v_m at the boundary of the vortex core. As boundary of the vortex core is regarded the surface at the distance from the vortex axis where the velocity v reaches its maximum. Distances from the axis are given here in dimensionless values.

Measurements in the convective vortex model were made at one particular distance from the hot surface. Visual observations revealed a built up vortex flow at that location. The velocity field in the dust storm was measured at an altitude of 2.13 m. The radius of the storm eye was $r_m = 10$ m, the maximum wind velocity was $v_m = 10$ m/sec.

A comparison of velocity readings in the vortex model and in the dust storm indicates that the tangential velocities are nearly the same in both. The axial velocities are also close. There is an ascending flow in both, but in dust storms the maximum axial velocity is close to the maximum tangential velocity. In a laboratory model it is possible to attain a maximum axial velocity equal to only half the maximum tangential velocity.

For convective vortices analogous to vortices of the dust storm kind it is thus possible, under conditions of velocity sampling from the variation of the LDA signal in time, to obtain velocities close to the real ones.

NOTATION

Here v_m is the tangential velocity at the boundary of the vortex core; r_m, dimension of the vortex core; a, precession radius of the vortex; θ, setting angle of tangential windows; T, temperature of the underlying surface; P(v) is the probability density of velocity; and v, instantaneous velocity.

LITERATURE CITED

1. T. Dyurani and K. Greitid, Laser Systems for Hydrodynamic Measurements [in Russian], Énergiya, Moscow (1978), pp. 14-19.
2. G. L. Grozdovskii (ed.), Laser-Doppler Measurement of Liquid and Gas Stream Velocities (Review, Central Institute of Aerohydrodynamics) [in Russian], Moscow (1976), pp. 3-80.
3. R. I. Soloukhin et al. (eds.), Laser Methods of Diagnosing One-Phase and Multiphase Streams (Proc. Internat'l Study-Seminar) [in Russian], Izd. Inst. Teplo-Masso Obmena imeni A. V. Lykova, Akad. Nauk BSSR, Minsk (1978), pp. 3-73.
4. F. K. Owen and D. A. Johnson, "Measurement of unsteady vortex flow fields," AJAA Paper No. 18 (1978), pp. 1-9.
5. D. E. Fitzjarrald, "Laboratory simulation of convective vortices," J. Atmosph. Sci., 30, 894-902 (1973).
6. P. A. Baranov and A. A. Solov'ev, "Measurements with laser anemometer and probe in laboratory tornado models," Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana, No. 6, 656-660 (1980).
7. P. Sinclair, "General characteristics of dust devils," J. Appl. Meteorology, 8, 34-45 (1969).