DISTINCTIVE FEATURES OF THE DEVELOPMENT OF LARGE-SCALE DISTURBANCES IN VORTEX FLOWS

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A comparative study is made of the dimensions and periods of large-scale disturbances generated in laboratory and natural vortices.

Recent studies have focused considerable attention on the specific physical characteristics of the hydrodynamics of strongly nonlinear nonuniform vortex flows, in particular various kinds of large-scale vortex formations. The dynamics of these natural vortices in the category of tropical cyclones, tornadoes, etc., is determined in large measure by the way in which the turbulent fluctuations are related to the velocities of the mean motion [1]. The principal distinction of these interactions lies in the fact that energy is transferred along the spectrum from small-scale to large-scale components, but not vice versa, as implied by the notions of the cascade transfer mechanism [2]. In the present article we use an indirect procedure to analyze the behavior of macroscale turbulent disturbances in a physical model of an atmospheric vortex. We determine the specific features of the evolution of a turbulence scale corresponding to zero correlation radius in the axial and radial directions of the vortex.

To characterize the structure of the turbulent flows we introduce the integral scale [3]

$$L = v \int_0^\infty \frac{\overline{u'v'}}{\overline{(v')^2}}(t)\, dt, \tag{1}$$

where the integrand represents the correlation function and v is the velocity of the mean motion.

The integral turbulence scale computed with respect to zero correlation radius can be identified with the Prandtl mixing length l [4]. In the case of an axisymmetrical flow twisted about the vertical axis the length l is calculated according to the formula [5]

$$l = \frac{\sqrt{|\overline{u'v'}|}}{\left|\frac{\partial v}{\partial r} - \frac{v}{r}\right|}. \tag{2}$$

We use the following hypothesis. We assume that the components of the turbulent stress tensor are proportional to the product of the mean velocities of the motion [6, 7]. The proportionality factor in this case can be the square of the Kármán constant $\varkappa$ [8]:

$$|\overline{u'v'}| = \varkappa^2 |uv|. \tag{3}$$

The characteristic scales l of turbulence in vortices generated under laboratory conditions have been calculated according to the data of velocity measurements on equipment at the A. V. Lykov Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR and the M. V. Lomonosov Moscow State University [8, 9]. The vortex generator was a bladed-surface swirling unit rotating inside a deflector. The vortices were generated in the air between the underlying surface and the swirling unit. We propose to analyze the

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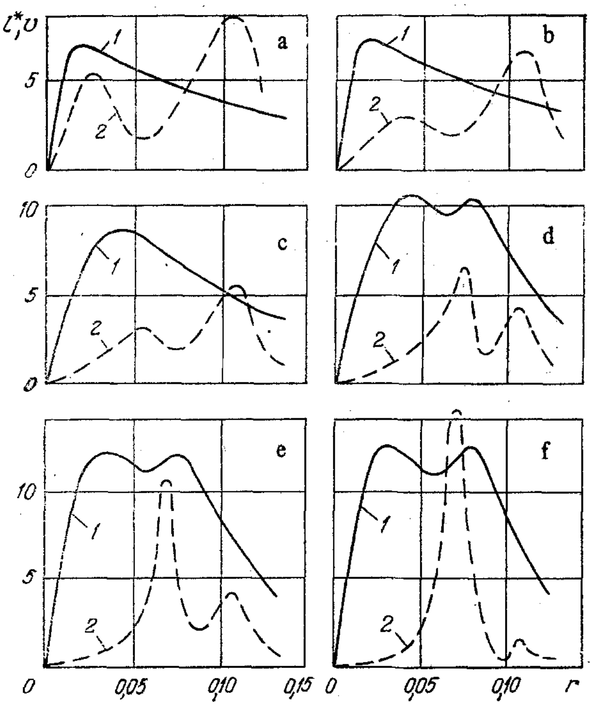

Fig. 1. Radial profiles of the tangential velocity v (m/sec) (curves 1) and scale of turbulent fluctuations l^*, 10^{-1} (curves 2) in a laboratory vortex model for various distances z (m) from the lower end of the vortex. a) z = 0.03; b) 0.05; c) 0.1; d) 0.13, e) 0.14; f) 0.19.

measurements carried out in vertical-axis vortices generated with the swirling unit spinning at 4000 rpm. The length of the vortices was 0.25 m, the radius of the swirling-unit blades was 0.059 m, and the diameter of the deflector was 0.21 m. The velocity vector was measured by means of a miniature spherical five-channel probe and Prandtl micromanometers [9] at the following distances measured from the lower end of the vortex: 0.03, 0.05, 0.1, 0.13, 0.14, 0.19 m. It is evident from Fig. 1 that the profiles v(r) have a second maximum near the deflector. It is induced by the anomalous transfer of turbulent momentum in the direction of the angular velocity gradient [10]. To calculate the value of the macroscale of turbulent disturbances at various points of the vortex according to Eqs. (2) and (3) we use the relation [8]

$$\varkappa = 8.3\left(\frac{\nu}{v_m r_m}\right)^{1/3}. \tag{4}$$

The values of the quantities v_m and r_m in (4) are chosen for the distance corresponding to the depth at which the flow enters the vortex [11]. In the experiments discussed here the inflow depth was 0.1 m. The speed of rotation of the vortex core was v_m = 8.5 m/sec, and the radius of the core was r_m = 0.045 m (Fig. 1c).

The fluctuation scale shown in Fig. 1 attains its maximum values at two points with a certain shift relative to the maxima of the tangential velocity. The largest turbulent disturbances are localized beyond the boundary of the vortex core and in the peripheral region. The size of these fluctuations corresponds to the inertial interval of space scales. Convection, turbulent diffusion, and energy transfer to smaller-scale components take place through such fluctuation disturbances. On closer approach to the swirling unit the curves v(r) acquire a second maximum, and a tendency toward growth of the scale of the turbulent disturbances is noted. Close to the swirling unit it attains values commensurate with the outer scale of the vortex flow (radius of the swirling unit). In particular, the maximum value of the scale normalized to $\varkappa r_m$ = 1.13 cm, i.e., $l^* = l/\varkappa r_m$, was equal to l^*_{max} = 7.3. The period $T = l/v_m$ of the large-scale disturbances for the investigated laboratory vortex model attained values equal to $7.3 \cdot 10^{-3}$ sec.

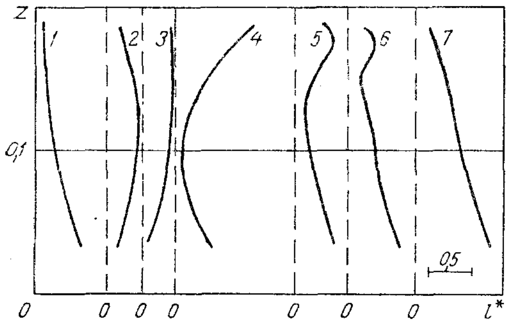

Fig. 2

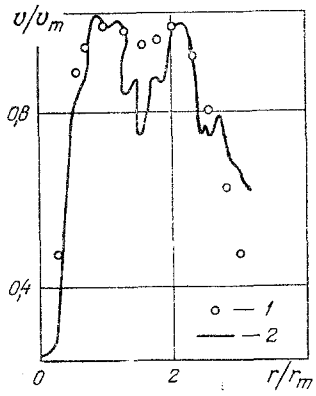

Fig. 3

Fig. 2. Distribution of the turbulence macroscale l^* for a laboratory vortex model along the vertical z (m) axis at various distances r (m) from the center of the vortex. 1) r = 0.03; 2) 0.05; 3) 0.06; 4) 0.07; 5) 0.08; 6) 0.085; 7) 0.1.

Fig. 3. Comparison of radial profiles of the tangential velocity in: 1) a laboratory vortex model (our measurements); 2) hurricane Frieda [12].

The nature of the development of large-scale disturbances along the vertical direction can be assessed from Fig. 2. It is seen that large-scale disturbances occur only at certain distances from the axis of the vortex in its upper region. The dimensions of the disturbances decrease on approaching the lower end of the vortex. Near the center of rotation and at the periphery of the vortex a different behavior is observed on the part of the fluctuation scales in the vertical direction: The scales of the turbulent disturbances decrease systematically with distance from the lower end of the vortex.

In the case of natural atmospheric vortices (such as tornadoes, tropical cyclones, typhoons, etc.) there are no data on the nature of the evolution of large-scale disturbances in the axial and radial directions. On the other hand, the existence of two maxima on the tangential-velocity profiles v(r) is reported. For comparison, Fig. 3 shows curves of the radial variation of the tangential velocity for hurricane Frieda (September 21, 1957) [12] and for our investigated laboratory vortex model, in dimensionless form. The rotational velocity of the core of the hurricane was v_m = 19 m/sec, and the radius of the core was r_m = 40 km. The corresponding quantities in the laboratory model were v_m = 11.2 m/sec and r_m = 0.04 m.

We have used the model data to estimate the possible period of the large-scale hurricane disturbances responsible for the transfer of energy from the fluctuations to the mean motion. The Kármán constant calculated according to (4) for the hurricane is $\varkappa = 2.26 \cdot 10^{-3}$, and the quantity $\varkappa r_m$ = 90.4 m. We assume that in the hurricane the normalized scale l^* of the disturbances inducing the second maximum of the curve v(r) is the same as in the model. Then the scale of the large-scale fluctuations in the hurricane is l = 660 m, and the lifetime is T = 35 sec. According to van Mieghem [13], turbulent fluctuations with such periods supply atmospheric circulation currents with energy.

In conclusion we note that the established features of the development of large-scale turbulent disturbances are a consequence of the nonlinear character of the processes both in physical models of vortices and in their natural atmospheric counterparts. Nonlinear interaction between systems of motion of different scales is what causes the local growth of turbulent disturbances in certain zones of vortex formations. The indicated average (steady) processes are mirrored in the characteristics calculated here. Rigorous estimates require more complete information about the systems of motion of all scales.

NOTATION

L, momentum scale of turbulence; l, mixing length; v, tangential velocity; $\varkappa$, Kármán constant; ν, kinematic viscosity coefficient; v_m, first maximum of tangential velocity at $r = r_m$; T, period of large-scale disturbances.

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UNIFORM AND NONUNIFORM FLUIDIZED BED REGIMES

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By analyzing jet flows in a fluidized bed the author has obtained a relation defining the boundary between uniform and nonuniform regimes.

In accordance with the conventional terminology (see, e.g., [1-3]) we shall call a fluidized bed regime uniform if the bed can continuously expand upon an increase of velocity of the gas or liquid, due to a uniform increase of the gaps between particles of the granular material. If, on the other hand, for velocities exceeding the bed start-up velocity, the gas or liquid moves through the bed in the form of bubbles, we shall call this regime nonuniform.

Several approaches have been taken toward an explanation of the differences between these regimes, and the most important results have been obtained from the concepts of a model of two mutually permeable continua, a two-phase model combined with extremal principles, and a model based on analysis of random motions of phases.

With the two continuous media model, described in detail in [1], one can formally show the instability of a uniform fluidized state relative to small perturbations by analyzing a linearized system of equations of continuity and motion of the two phases. A considerable defect of the model is that the roots obtained for the characteristic equation, which define the rate of growth of perturbations, depend on the pressure and the dynamic viscosity of the

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