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EXPERIMENTAL MODEL OF A TORNADO

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In this work results are presented for an experimental study of movement of a fluid filling a cylindrical vessel moving with constant angular velocity, part of the surface of which oscillates in a prescribed way. It has been established that under certain conditions a system of vortices forms in the fluid. The main properties of these vortices are the oscillating nature of fluid movement in them, and the high level of vorticity markedly exceeding double the angular velocity of vessel rotation. In arranging experiments considerable use was made of data in [1, 2] where in a linear approximation information is given about actual oscillations of a solidly rotating cylindrical column of fluid. It was found that the properties of laboratory vortices are similar to those known for natural atmospheric vortices, i.e., tornadoes. The analogy established makes it possible to explain numerous facts caused by the occurrence of a tornado.

1. Experiments were carried out in a device whose diagram is given in Fig. 1. A transparent cylindrical vessel 1, in which the fluid was placed, rotated with constant angular velocity ω. Movement of the initially solidly rotating fluid was disturbed by means of generator 2, consisting of a disk, or a ring, or of a disk and a ring. The fluid surface 3 between disks, rings, and the side surface of the vessel is free. Disks and rings rotate together with the vessel, and in the vicinity of the free fluid surface they complete harmonic vertical oscillations with frequency $\omega_h = \omega$. By this method axisymmetrical inertial waves (zero harmonic for the amplitude coordinate) were created in the fluid. A resonance regime for wave excitation was used which made it possible to isolate the required mode and made it possible to obtain waves of considerable amplitude. In order to provide resonance the level of fluid in the vessel was chosen so that with a prescribed oscillation frequency for the generator the height of the fluid column equalled a whole number N of half-waves for the test mode. The edges of generator disks and rings moved over cylindrical surfaces, where vertical velocity v_z in the exciting wave, calculated by linear theory [1], returned to zero (see Fig. 1).

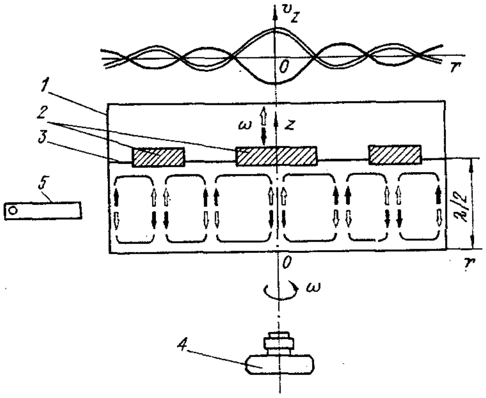

Fig. 1

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TABLE 1

Mode	Disk diameter, cm	Ring internal and external diameter, cm	
I	1,55		
II	—	6,3;	14,5
III	4,36	10;	15,65

In tests the first three axisymmetrical modes were excited corresponding to wavelengths $\lambda = 26.2$, 14.4, and 9.9 cm with vessel diameter $2R = 18.4$ cm. Angular rotation velocity ω for the vessel was selected from the range 2-6 $\sec^{-1}$; the prescribed value of ω was maintained accurate to within 0.5%. Amplitude a of the generator vibration equaled 0.125, 0.25, 0.5, and 1 cm; $N = 1, 2, 3, 4$. Dimensions of the disks and generator rings are given in Table 1. Aqueous solutions of sodium chloride and glycerol were used as the fluid. Reynolds number $\mathrm{Re} = \omega R^2/\nu$ (ν is kinematic viscosity of the fluid) varied from 10^3 to $6\cdot 10^4$.

In order to study the internal structure flow was made visible by means of dyes and polymer spheres 0.5-1 mm in diameter with a density $\rho = 1.05$ g/cm^3. Flow pictures were recorded on photographic film. Exposure in the direction of the axis of rotation was carried out with a camera 4 (see Fig. 1) fastened in the rotating vessel. The field of flow was illuminated by a flat light beam 5 perpendicular to the axis of rotation.

It should be noted that in order to excite periodic axisymmetrical inertial waves along the vertical coordinate, the value of ω_h according to [1] may be selected from any of the range $0 < \omega_h < 2\omega$.

2. With these experimental conditions in a few periods $T = 2\pi/\omega$ after switching on the generator, flow is created in the fluid in which the required mode (the basic wave) is predominant. In the initial stage of its development it has a structure in good agreement with that predicted by linear theory. In the plane of a rectangle $0 \leq r \leq R$, $0 \leq z \leq \lambda/2$ flow is a collection of oscillating cells with closed flow lines whose number coincides with that of the excited mode (see Fig. 1, in which a diagram of flow is given for the third axisymmetric mode with $N = 1$; shaded and open arrows indicate the direction of fluid flow with movement of the generator down and up, respectively). Flow pictures for the initial stage with observation from the side conform with those given in [3]. With passage of time the amplitude of the basic wave increases and on a background of it azimuthal waves of higher harmonics occur. With a further increase and breakdown of these waves a system of vortices forms in the fluid which has quite a complex space—time structure and they exhibit the following main properties:

1) vortices form in regions of maximum absolute values of vertical velocity v_z, forming an annular belt of vortices;

2) vortices propagate to the whole depth of the fluid and they are parallel to the axis of rotation of the vessel;

3) axial flow velocity in a vortex and vortex intensity at a point fixed relative to it experience oscillations with a frequency mainly equal to that of the generator frequency; in each observation period the axial velocity changes sign;

4) on average over a period and over the whole length of a vortex angular rotation velocity Ω in the vortex relative to its axis in a coordinate system connected with the vessel may be positive (cyclonic vortices) and negative (anticyclonic vortices); as a rule annular belts with cyclonic and anticyclonic vortices alternate;

5) both types of vortex in the vicinity of levels $z = 0, \lambda/2, \lambda, \ldots$ may have sections with a relative angular velocity of opposite sign.

Given in Fig. 2 are pictures of the transverse section of flow at level $z = \lambda/4$. Systems of vortices presented in them were obtained with excitation of the first three axisymmetric modes for $a = 0.5$, 0.25, 0.25, and 0.5 cm, respectively (mode number is indicated on the photographs). In these tests fluid density was selected equal to particle density, and the exposure time was 0.5 sec, $\omega = 4$ $\sec^{-1}$, $\mathrm{Re} = 4\cdot 10^4$, $N = 1$. Rotation directions for the vessel and fluid movement in anticyclonic vortices are shown by arrows.

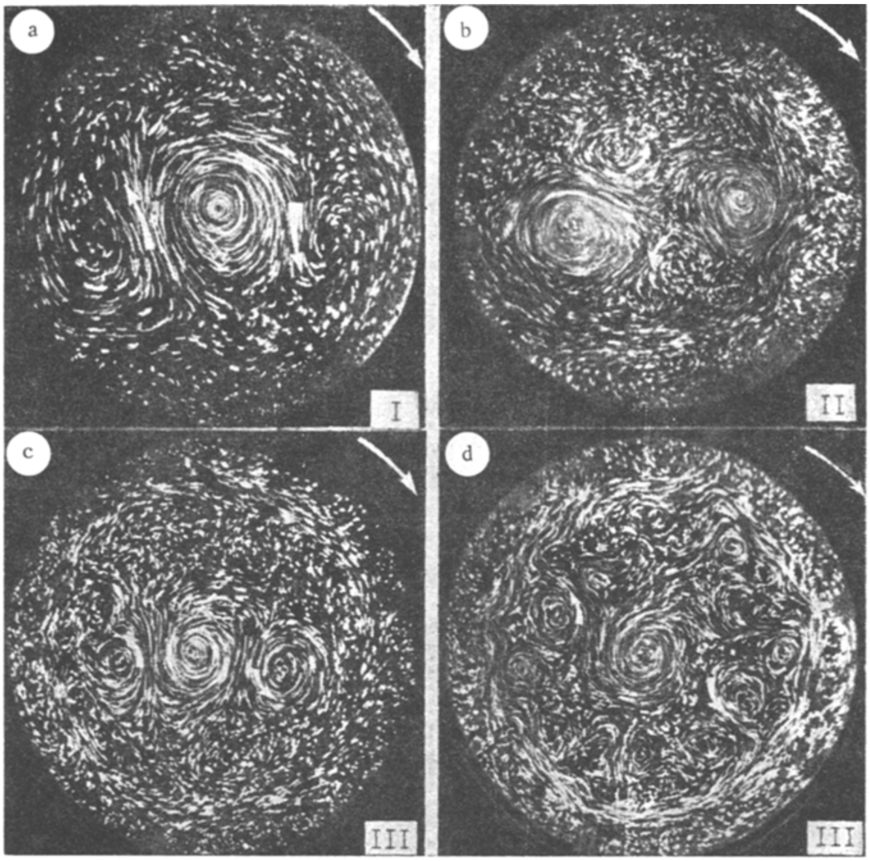

Fig. 2

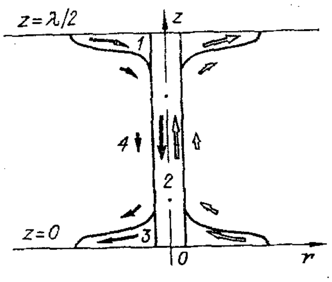

Fig. 3

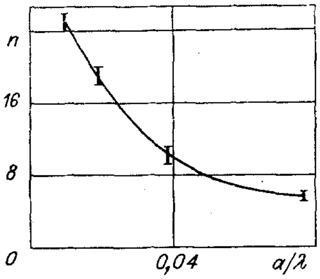

Fig. 4

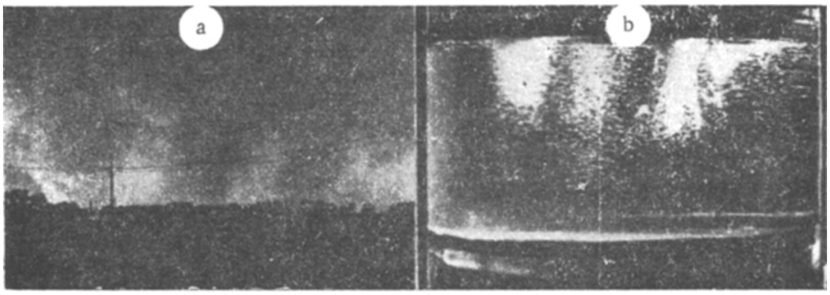

Fig. 5

Vortices move together with the fluid with an angular velocity differing little from ω. The number of vortices increases with an increase in mode number. Formation of belts of vortices more distant from the center cannot occur with a low generator vibration amplitude. The number of vortex annular belts and the number of vortices in an individual belt increase with an increase in generator vibration amplitude, which is illustrated in Fig. 2c,

d. The maximum number of vortex belts observed exceeds by one the number of annular oscillating cells.

In individual tests within a cyclonic vortex located along the vessel axis a system of several small active vortices was observed within which the fluid also has movement of an oscillating nature.

For a clear idea of the structure of a cyclonic vortex we present the flow scheme in the region near the axis occurring with excitation of the first axisymmetrical mode, for $N = 1$ (Fig. 3). In this flow it is possible to separate four typical zones: 1, 3) annular regions of high radial velocity; 2) a region of high axial velocity and high relative angular rotation velocity; 4) a region of moderate radial and axial velocities.

With movement of the generator from top to bottom fluid from region 1 flows into region 2 and from 2 into 3. In this way, due to retention of circulation, the rotation velocity of fluid flowing from region 1 into region 2 increases, and toward the instant when the generator is stopped the maximum relative angular rotation velocity is achieved in the vortex axis at level $z = \lambda/2$. For this region with flow of fluid from 2 into 3 its rotation velocity decreases, and at level $z = 0$ at the instant when the generator stops in a certain angular region the minimum relative angular rotation velocity is achieved. With reverse movement of the generator the flow picture changes with time in the reverse direction. In any oscillation phase the direction of fluid rotation remains cyclonic in the greater part of region 2 (with the exception of the vicinity of levels $z = 0, \lambda/2$).

For $N = 2$ the flow system may be obtained by adding to Fig. 3 its mirror reflection relative to plane $z = 0$. The flow scheme for larger N is constructed in a similar way.

Now we introduce some quantitative characteristics for a cyclonic vortex formed with excitation of the first axisymmetrical mode. In order to estimate its radius and angular rotation velocity use is made of particle tracks recorded in pictures with $N = 2$. By means of them it was established that the average vortex radius $r_0 \approx R/20$. The maximum relative angular rotation velocity $\Omega \approx 50\omega$ in the vortex was fixed at level $z = \lambda/2$. In this level after oscillation half-period (π/ω) the minimum $\Omega \approx -0.1\omega$ was reached. At the level $z = \lambda/4$ at both instants of time $\Omega \approx 20\omega$. The maximum circumferential velocity in a vortex corresponding to $\Omega \approx 50\omega$ exceeded ωR by a factor of 2.5. In one oscillation half-period particles traveled in the vertical direction a distance equal to the length of the half-wave, which for the axial velocity of a fluid particle gives an estimate $\langle \max |v_z| \rangle = \lambda/T$ $(T = 2\pi/\omega)$.

The number of periods n of generator vibrations in which flow emerges into a steady regime depends on its vibration amplitude. This dependence, indicating a reduction in n with an increase in a, is shown in Fig. 4 ($Re = 4 \cdot 10^4$, $N = 1$). With an increase in ν the time for emergence of flow into a steady regime increases (e.g., with $Re = 10^3$, $N = 1$, $a/\lambda = 0.076$, $n = 50$). The qualitative picture of flow does not change, and there is only a reduction in vortex intensity.

Anticyclonic vortices observed in experiments did not exhibit high intensity. A value of $\Omega \approx -0.5\omega$ $(z = \lambda/4)$ was recorded in them.

3. Intense vortices observed in experiments may serve as an experimental model of natural atmospheric vortices, i.e., tornadoes, since properties of the laboratory vortices in question are similar to those known for tornadoes.

1) It is well known [4] that tornadoes form in a mesocyclone, i.e., an atmospheric vortex with a vertical axis which in essence is a natural analog of a rotating column of fluid in an experiment. Often there are cases when one mesocyclone generates simultaneously several tornadoes [4] (Fig. 5a). Shown in Fig. 5b is a family of four vortices obtained with excitation of the third axisymmetrical mode. Vortices are visible due to floating particles, initially at the free surface of the fluid.

2) For a tornado marked oscillations of its intensity at the earth's surface are typical. This is indicated by the "punctuated" band of destruction, i.e., along the path of tornado movement, apart from areas of active destruction, there are areas where destruction, there are areas where destruction is generally absent [5]. In the early stages of tornado development there are often clearly noticeable vertical oscillations of its funnel [5]. These facts point to the oscillatory nature of air movement in a tornado. In fact, this

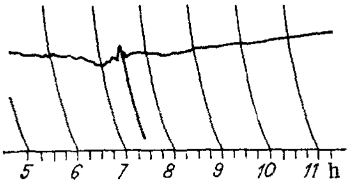

Fig. 6

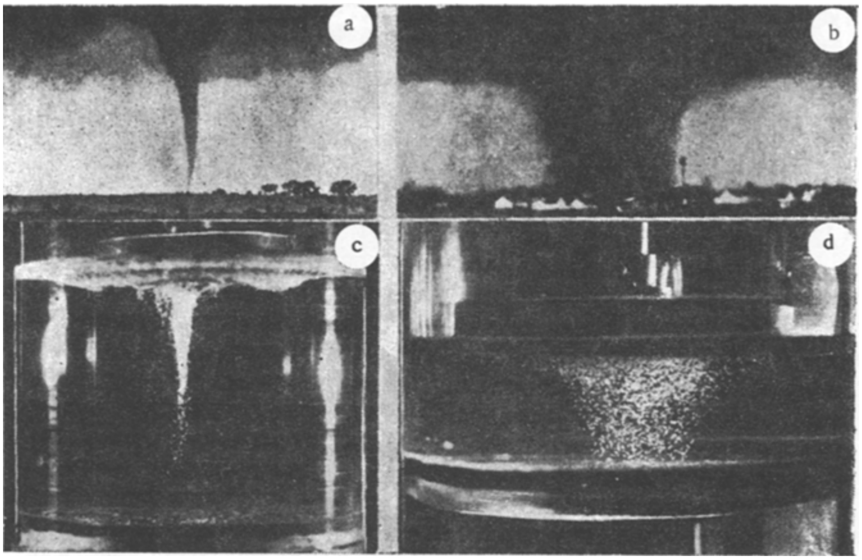

Fig. 7

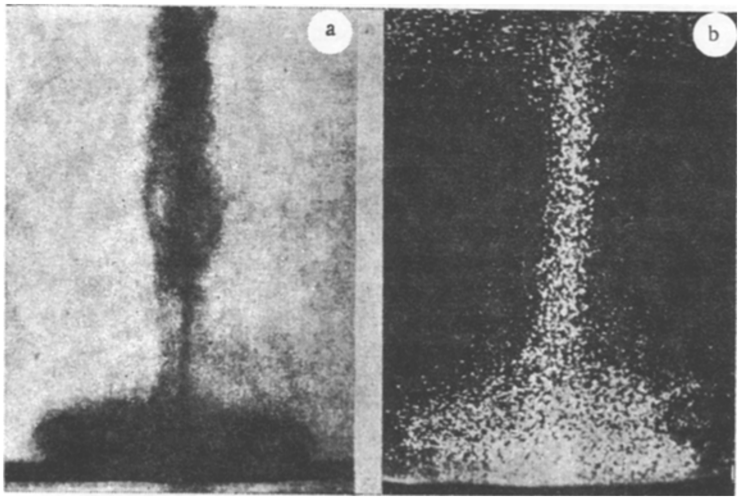

Fig. 8

nature of movement is present in a laboratory vortex. As in nature, it develops in particular in strong oscillations of rotation intensity at levels $z = 0$ (bottom of the vessel) and $\lambda/2$ where, depending on the phase, $\Omega \approx 50\omega$ and -0.1ω.

3) The pressure profile recorded with passage of a tornado (Fig. 6) indicates that close to the tornado there are local pressure maxima [5]. This indicates presence around the tornado of regions with a negative vorticity relative to the mesocyclone. Similar regions in an experiment are shown in Fig. 3a, c: two anticyclonic vortices are located alongside the central cyclonic vortex.

4) Within a tornado smaller vortices of greater intensity have been recorded which leave cycloidal traces of severe destruction [6]. As already mentioned, in laboratory tests within the central cyclonic vortex a system of secondary finer vortices was also observed.

5) Tornado funnels have different shapes. During the life of a tornado the shape of the funnel may change repeatedly. For different stages of tornado development a long narrow trunk-shaped funnel is most typical, presented in Fig. 7a [4]. As the tornado strengthens the funnel expands, and in individual cases it takes the form of a thick column (Fig. 7b) [5]. Shown in Fig. 7c is a laboratory vortex in the stage of increasing oscillations. The visible "trunk" consists of floating particles collected at the free surface of the fluid, and it approximately reflects the axial jet of a vortex (region 2, Fig. 3). As oscillations increase, particles in the vortex are carried from regions 1, 2, and 3 into region 4, and the transverse dimension of the visible "trunk" increases. In a steady oscillation regime the vortex has the form shown in Fig. 7d.

6) One of the noticeable features of a tornado is a cascade (a cloud consisting of dust or water droplets). Cascades are very different in shape and they are part of the visible funnel of the tornado. Unusually low cascades develop [5] whose horizontal dimension significantly exceeds the diameter of the funnel. Observers note that this cascade forms with impact of the funnel over the earth. A photograph of a low cascade is given in Fig. 8a [5]. Shown in Fig. 8b is the cascade of a laboratory vortex obtained with impact of an axial flow containing particles (Fig. 7c) over the bottom of the vessel.

By relying on data from laboratory experiments and using average parameters for a rotating atmospheric column of air, i.e., a mesocyclone (its height and diameter is 5-10 km, the maximum circumferential velocity of the wind is 15-25 m/sec, and angular rotation velocity $3 \cdot 10^{-3}$-10^{-2} sec^{-1} [7]), we make an estimate of the main quantitative characteristics of tornadoes.

1. It was established by laboratory experiments that the oscillation period of a vortex (including the oscillation period of its intensity at the bottom of the vessel) is governed by the oscillation period for the wave, and it is roughly estimated by the period of rotation for the fluid column $T = 2\pi/\omega$. This estimate for the oscillation period of tornado intensity at the earth's surface ($T = 2\pi/\omega$, $\omega = 3 \cdot 10^{-3}$-10^{-2} sec^{-1}) gives 10-30 min. In this way the length of sections of active destruction along the tornado path taking account of the velocity of its displacement (mostly 15-20 m/sec [5]) may reach tens of kilometers, which corresponds to data of observations [5, 6].

2. It has been established by laboratory experiments that the ratio of rotating column of fluid diameter to that of a vortex is approximately twenty. By using this ratio and the diameter of a mesocyclone (5-10 km) we obtain a typical value of 250-500 m for the diameter of a tornado [5, 6].

3. From the data of laboratory experiments, the ratio of maximum circumferential velocities in a vortex and a rotating column of fluid is 2.5. An estimate of the maximum circumferential velocity of the wind in a tornado based on this ratio and the maximum circumferential velocity of wind in a mesocyclone (15-25 m/sec) gives 40-60 m/sec, and taking account of the velocity of tornado displacement (15-20 m/sec) gives 55-80 m/sec. These velocities are typical for the majority of destructive tornadoes [6]. Taking account of the presence within the main tornado of a system of smaller vortices these figures may be increased markedly. It is well known [6] that tornadoes having a multivortex structure cause the most severe destruction.

Results of laboratory experiments make it possible to explain differences appearing at first glance to be astonishing and enigmatic cases connected with passage of a tornado. Formation of packed paths of crushed bushes and various articles beaten into the ground [5] may occur in the stage of tornado oscillation (or its secondary vortices) corresponding to the descending axial flow. The low wind velocity with passage of a tornado above the heads of observers [5] may be caused by phase oscillation, with which the rotation velocity in it at the surface of the earth is close to zero. Destruction in the absence of a visible funnel [5] may be caused by a rapidly developing tornado in the oscillation stage corresponding to an ascending axial flow. The reason for anomalous local damage, such as half-plucked chickens [5], may be small secondary vortices in a tornado similar to intense secondary vortices in a laboratory cyclonic vortex.

The conformity established between laboratory and natural vortices indicates that they are of the same nature, and formation of tornadoes proceeds with disturbance of a mesocyclone.

Sources of these disturbances may be, for example, wave movements in the atmosphere occurring in shear flows and flow around barriers [8], or unevenness of the earth's surface with which a moving mesocyclone reacts.

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