TRANSITIONAL FLOW CONDITIONS ON A ROTATING DISK

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Transitional flow conditions on the surface of a freely rotating disk were investigated by cine-recording, acoustic, and visual methods.

Recently there has been a considerable upsurge of interest in the hydrodynamics of the transition from laminar to turbulent flow. This forms part of the problem of the appearance of turbulence and is also of great independent value, since the rotating disk is a necessary element of many widely used rotor devices, while the boundary layer close to the disk surface is among the simplest of three-dimensional boundary layers; there is great practical interest in establishing the transitional conditions on a rotating disk.

In one of the first studies [1], using the coalignment method, a series of tracks in the form of Archimedes spirals were observed on the surface of the rotating disk in the region $\mathrm{Re} = (1.9\text{–}3)\cdot 10^5$. It was suggested that the flow is laminar in the central part of the disk, but then becomes unstable and breaks down into a series of discrete stationary eddies (the region $\mathrm{Re} = 1.9\cdot 10^5\text{–}3\cdot 10^5$) rotating with the disk [2-4].

The theoretical investigation in [1], based on the simplified Orr—Sommerfeld equation, did not confirm the experimental data; when the experimentally observed value $\mathrm{Re}_{\mathrm{cr}} = 1.9\cdot 10^5$ is substituted into the calculational formula for the number of eddies

$$N = 0.262\sqrt{\mathrm{Re}_{\mathrm{cr}}}$$

the result is N = 112, instead of the observed value N = 30.

A theoretical analysis of the onset of instability for a three-dimensional boundary layer in [4] produced a value of $3.2\cdot 10^4$ for the critical Reynolds number $\mathrm{Re}_{\mathrm{cr}}$.

In the visual investigation of instability on a rotating disk in [5, 6], eddies with wavelength $22\sqrt{\nu/\omega}$ were observed, together with a parallel system of unstable eddies with wavelength $44\sqrt{\nu/\omega}$, which arose sporadically in rapid motion. In [7] it was shown by an electrochemical method that the transitional flow region is wider than previously assumed and extends over the range $\mathrm{Re} = 1.7\cdot 10^5\text{–}3.5\cdot 10^5$. It consists of a turbulent region ($\mathrm{Re} = 1.7\cdot 10^5\text{–}2.6\cdot 10^5$), in which the intensity of the stationary eddies increases with Re, and an intermediate turbulent region ($\mathrm{Re} = 2.6\cdot 10^5\text{–}3.5\cdot 10^5$) where the eddies break down to a smaller size.

A study of the stability of the three-dimensional boundary layer of dilute polymer solutions [8] showed that the number of eddies observed visually is in good agreement with the analytical data and agrees with the formula of [1].

In several investigations of the solution of metals in acids [9-12] spiral tracks formed on a rotating disk electrode; the tracks began at the center of the disk, which indicates the presence of perturbations in this region.

Thus, the data available in the literature do not give a clear picture of the transition from laminar to turbulent flow on a rotating disk.

The method used in the present investigation for visual examination of the flow on a rotational disk was approved and described in [14].

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TABLE 1. Characteristics of Transitional Flow Conditions

n, rpm	r_{cr}, mm	Re_{cr}	No. of eddies observed	ε	No. of eddies given by Stuart formula [1]	r_{per}, mm	Re_{per}	Notes
7000	26	$0,332 \cdot 10^5$	15	21°	48	—	—	Expt.
12000	24	$0,485 \cdot 10^5$	14	22°	58	—	—	—
19000	17	$0,386 \cdot 10^5$	15	19,5°	51	—	—	—
12000	27	$0,59 \cdot 10^5$	16	20°	61	54	$2,65 \cdot 10^5$	
3200	89	$1,9 \cdot 10^5$	32	13,7°	114	110,5	$2,82 \cdot 10^5$	From [1]

Special removeable steel disks, coated with naphthalene, were carefully ground (nonplanarity 0.6–0.8 μ over a radius of 80 mm) and set on a centrifuge rotor.

In the course of the experiment the surface temperature of the naphthalene coating and the rate of rotation of the disk were measured [15].

By means of a pulsed stroboscopic lamp, synchronized with the rotational frequency of the disk using a photoelectric pickup, processes occurring on the disk surface were directly observed and photographed throughout the experiment. Disks of diameter 100–200 mm were used in the experiment, and the rate of rotation of the disk was regulated within the limits $(5–25) \cdot 10^3$ rpm.

The results of the first series of experiments with a disk of diameter 100 mm are shown in Table 1.

Tracks in the form of Archimedes spirals could be clearly distinguished on the disk surface; the change from purely laminar flow to transitional flow, characterized by the presence of tracks, begins at a certain critical radius r_{cr_1}, and a corresponding critical value of the Reynolds number Re_{cr_1} (Fig. 1). At first sight, the presence of spiral tracks appears to confirm the results of [1]. In all the photographs obtained eddy formation began earlier than in [1], which confirms the theoretical calculation of [4] and the experimental results of [7]. Note that substituting the obtained value of Re_{cr_1} into the Stuart formula gives N = 50 instead of the N = 114 obtained in [1].

However, in all the experiments for various rates of rotation of the disk surface, 14–16 tracks were formed, whereas in the experiments of [1], 30–32 tracks were observed. In addition, the angle between the tangent at a given point of the spiral and the normal to the radius-vector was ε = 20° in our experiments, but did not exceed 13.7° in [3]. This cannot be explained by the change in viscosity due to the presence of naphthalene vapor in the boundary layer, since under the experimental conditions the viscosity changes by no more than 5%. These discrepancies imply that the eddies observed are not those described in [1].

Further experiments were carried out with disks of diameter 160 mm; in this case the effect of the edge of the disk was eliminated and completely developed turbulent conditions of flow were obtained in the peripheral region of the disk.

The relief formed on the disk is very complex (Fig. 2). The central zone of the disk is relatively smooth, and the tracks that are present are only weakly expressed. First appearing at the radius r = 8 mm ($Re = 5.6 \cdot 10^3$), the tracks become gradually more pronounced and extend out toward the periphery of the disk as far as $Re = 1.5 \cdot 10^5$. The tracks observed in this region, corresponding to eddies of type I (ε = 19°), number 14–16.

In the peripheral region of the disk ($Re = 2.6 \cdot 10^5$), there is a large number of fine tracks in the turbulent-flow region with ε = 12–14°. These will be called eddies of type III. It is not entirely clear in the photograph (Fig. 2a) that type-I eddies begin right at the center of the rotating disk, but examining an impression of the surface relief on paper (Fig. 2b) shows this to be the case. To obtain the impression, the surface of the disk was sprayed with a thin layer of paint.

The flow region in the range $Re = 1.5 \cdot 10^5 – 2.65 \cdot 10^5$ is of particular interest. In this region, tracks of type-I eddies and tracks corresponding to some other type of eddy appear simultaneously. It was assumed at first that these new tracks are formed by the splitting of type-I tracks in this region. However, careful analysis of a large number of impressions showed that the flow picture in this region somewhat resembles the interference pattern of surface waves traveling at different angles (ε = 12–14° and ε = 20°). It may be assumed that these tracks (N = 30, ε = 12.5°) are due to the eddies described in [1–3], which will be called eddies of type II.

Fig. 1

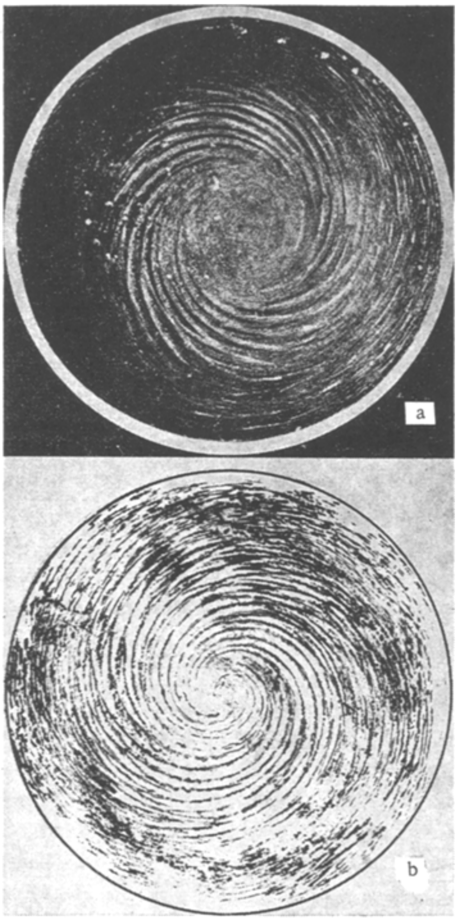

Fig. 2

Fig. 1. Relief of disk surface formed by steady eddies (R = 50 mm, Re = $3.19 \cdot 10^5$, D = 100 mm, $\omega = 2 \cdot 10^3$ sec^{-1}).

Fig. 2. Formation of spiral tracks on the surface of a freely rotating disk: a) photograph; b) impression; Re = $6.85 \cdot 10^5$; D = 160 mm; ω = 1680 sec^{-1}.

To verify and refine the results of visual investigation of the flow, experiments were carried out to study the pressure pulsations above the surface of the rotating disk. The pickup used was a Bruell and Kerr type-4138 condenser microphone of diameter 3.1 mm. The microphone has a linear frequency characteristic in the range 5 Hz to 160 kHz with sensitivity 1 mV/N/m^2. The equipment used in conjunction with the microphone allowed recording and analysis of the pulsation spectrum in the range 40-20,000 Hz, which completely satisfied the experimental requirements. The microphone mounting allowed it to be moved in the radial and axial directions over the surface of the disk. The spectrograms in Fig. 3 were obtained as the microphone moved over the radius of a disk rotating at 14,000 rpm; the microphone was 0.25 mm above the disk surface.

It is evident that in the central region (up to Re = $0.6 \cdot 10^5$), the only signals picked up by the microphone are the frequency of rotation of the disk (f = 232 Hz) and its first four harmonics. From Re = $0.6 \cdot 10^5$ onward, a peak begins to appear (at first very weak and then gradually growing stronger) at a frequency corresponding to 14-17 perturbations (f = 3-4 kHz). For Re = $1.8 \cdot 10^5$, and above, this peak diminishes somewhat and there appears, side by side with it at a frequency f = 6.3 kHz, a peak corresponding to 27-30 perturbations. Note that, from this point onward, the pulsation spectrum expands at both the high- and low-frequency ends, which indicates an increase in the intensity of turbulence. Moving further out along the radius, the intensity maximum of the spectrum shifts toward higher frequencies.

Thus, the visual and acoustic results obtained lead to the conclusion that there are three clearly expressed types of eddies on the surface of the rotating disk, each type appearing at a different height and at a different position over the radius.

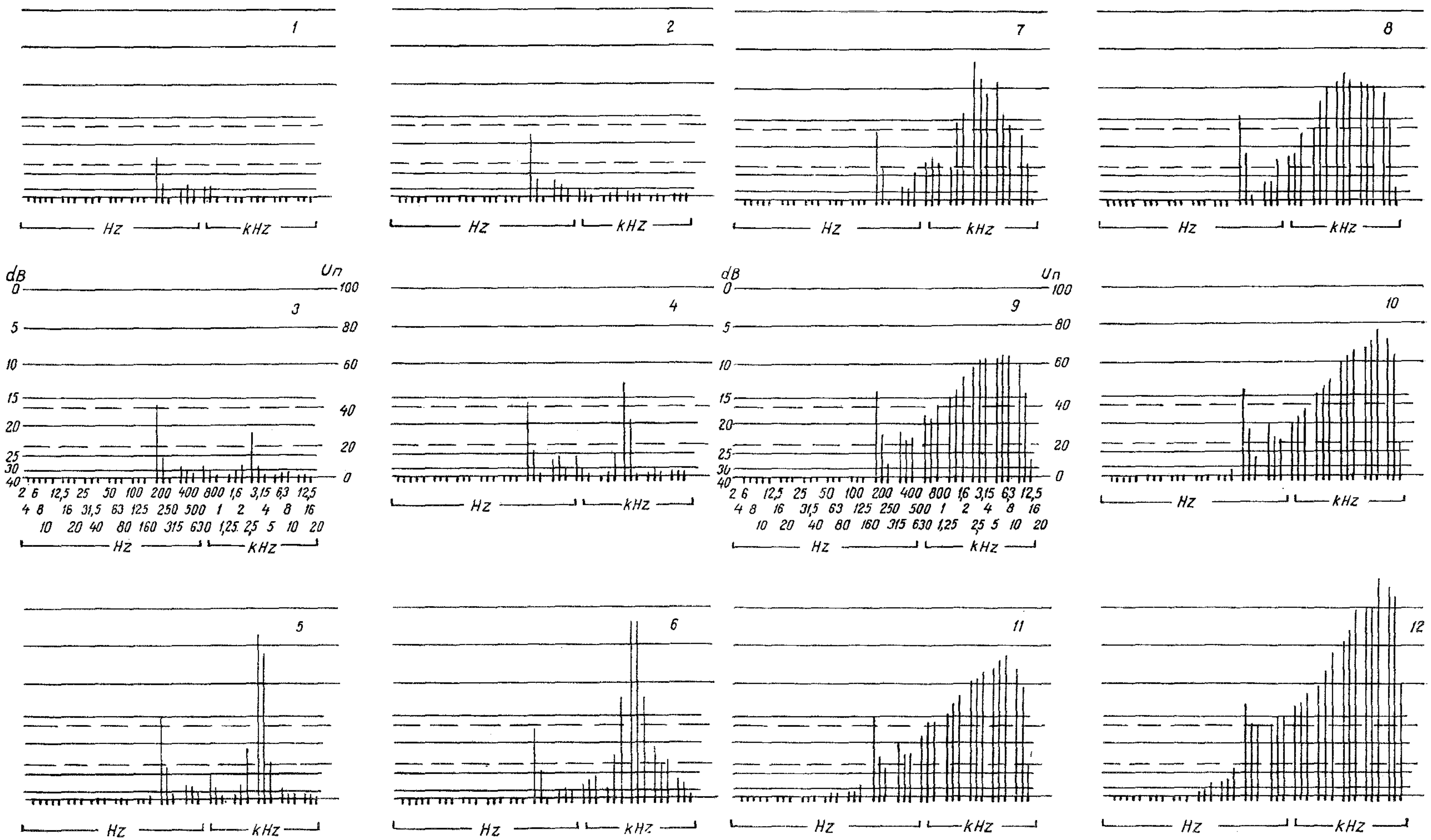

Fig. 3. Spectrograms of pressure pulsations over the surface of a rotating disk: 1) r = 0, Re = 0; 2) r = 25 mm, Re = $0.625 \cdot 10^5$; 3) r = 28, Re = $0.78 \cdot 10^5$; 4) r = 31, Re = $0.96 \cdot 10^5$; 5) r = 37, Re = $1.37 \cdot 10^5$; 6) r = 40, Re = $1.6 \cdot 10^5$; 7) r = 43, Re = $1.85 \cdot 10^5$; 8) r = 46, Re = $2.11 \cdot 10^5$; 9) r = 49, Re = $2.4 \cdot 10^5$; 10) r = 52, Re = $2.7 \cdot 10^5$; 11) r = 55, Re = $3.02 \cdot 10^5$; 12) r = 70, Re = $4.9 \cdot 10^{-5}$.

Fig. 4. Impression of relief of rotor surface in disk—disk system: $h = 1$ mm, $D = 160$ mm, $\omega = 1470$ sec^{-1}, $Re = 6 \cdot 10^5$.

To verify this assumption cinerecordings were made of the formation of the relief on a naphthalene surface. Frame-by-frame examination showed that initially relief corresponding to eddies of type II ($\varepsilon = 14°$) appears at the surface of the rotating disk.

Simultaneously a set of fine tracks is formed in the turbulent region. Then some of the tracks corresponding to type-II eddies become deeper and broader, and the remainder cannot be seen against this background. The result is the formation of 16 tracks with $\varepsilon = 20°$, which gradually appear also in the central region. Note that the remainder of the tracks from type-II eddies do not entirely disappear; they too become deeper, and are clearly visible on the photographs and impressions obtained (Fig. 2b). Tracks due to type-I eddies ($\varepsilon = 20°$) and type-II eddies ($\varepsilon = 14°$) overlap and form an interference pattern. Supposing that type-I eddies begin to be formed in the incoming flow, and lie above eddies of type II on the disk surface, then in the system of two plane-parallel disks, one of which is rotating while the other is at rest, a different picture should be observed.

In experiments in a system of disk—disk type, with a distance of 2 mm between the disks, it was possible to observe only two types of track on the surface of the rotating disk (Fig. 4): 38 tracks lying in the range $Re = 3.42 \cdot 10^5 – 9 \cdot 10^5$ with $\varepsilon = 20°$, and a set of fine tracks penetrating into the turbulent region with $\varepsilon = 10°$.

It is important to note that the number and structure of the eddies in the gap between the disk depend on the gap width.

Thus, the results obtained indicate that the structure of the flow on a rotating disk is considerably more complex than the classical model [1].

It is possible that similar phenomena may also be observed in other forms of flow.

Further investigations in this field would undoubtedly lead to a clearer picture of the general features of the transition from laminar to turbulent flow.

NOTATION

Re, Reynolds number, $Re = \omega r^2/\nu$; r, R, disk radius; D, disk diameter; ε, angle between the tangent to a given point of the spiral and the normal to the radius vector; N, number of eddies.

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INTERACTION OF DROPS WITH BOUNDARY LAYER ON ROTATING SURFACE

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The interaction of a drop with a boundary layer on the surface of a rotating disk is investigated experimentally.

Theoretical and experimental investigations of a two-phase current flowing around a fixed plate [1, 2] have shown that the boundary layer has a significant effect on the type of motion observed and the settling out of moisture.

The interaction of moisture with the boundary layer of a moving surface, although it is a subject of some importance, has yet to be adequately studied.

In the present paper, the interaction of a single drop with the boundary layer on the surface of a rotating disk is considered.

A diagram of the experimental apparatus is given in Fig. 1. Disk 1 is rotated by a dc motor about an axis perpendicular to its plane. A generator 2 feeds a series of drops (d_d = 0.3-4.0 mm; v_d = 0.1-10 m/sec) normally to the disk surface [4]. The processes of interaction of the drop with the boundary layer and the change in velocity and diameter of the drops were recorded using a fast-exposure SKS-1m-16 cine camera (Fig. 1a) and photography by a Zenit-3m camera (Fig. 1b). In the first case, the light source was a DPSh-250 mercury lamp, in the second case an ISSh-15 strobe lamp with a flash length of no more than 10^{-5} sec. The flash frequency could be varied in the range 5-500 Hz.

It is considerably simpler to study the interaction of a drop with a disk surface rotating in an infinite space, since in this case the Navier—Stokes equation for the boundary layer has an accurate solution [3]. Analysis of this solution shows that the axial velocity components in the boundary layer are small in comparison with the other components; the maximum value of the radial velocity component is an order of magnitude less than the azimuthal. Thus, the behavior of the drop in the boundary layer is determined mainly by the gradient of the azimuthal velocity component.

The upper part of Fig. 2 shows strobograms of the drop trajectory for collision with the surface of a disk rotating with frequency ω. It is evident that in the region of contact with the disk the drop is deformed and then immediately reflected at an angle α to the disk surface; the drop trajectory is close to parabolic. After reflection from the disk, the deformed drop begins to rotate with frequency ω_d.

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