ON THE ORIGIN OF TURBULENT MOTION

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Abstract

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ON THE ORIGIN OF TURBULENT MOTION

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One of the principal directions in the study of turbulent flows is the investigation of the process of transition from laminar flow to turbulent flow, with the aim of revealing the physical laws governing the formation of turbulent motion.

In the context of such work, an experimental investigation was carried out of the spectral functions of the longitudinal component of the velocity fluctuations of an air flow in a straight tube of circular cross section. Measurements were made at various Reynolds numbers. The latter were chosen in such a way that the experiment covered the laminar regime, the transition zone, and part of the region of developed turbulence. The Reynolds numbers were determined from the value of the mean velocity on the axis and the radius of the tube.

The air flow was produced by means of a fan installed at the outlet of a tube 800 cm long and 9.4 cm in diameter. The flow velocity on the tube axis could be varied from 10 to 1500 cm/sec. Measurements of the mean flow velocity and of the longitudinal component of the velocity fluctuations were made with a hot-wire anemometer at 13 points along the radius of the tube, at a distance of 100 radii from the inlet opening. Oscillations of the flow velocity (up to 40 Hz) were recorded in parallel on a loop oscillograph and on magnetic tape. The use of the method of frequency transposition made it possible to employ a standard SCh-1 spectrum analyzer for the spectral analysis of velocity oscillations in the infrasonic frequency range.

Four flow-velocity regimes are analyzed in the work, corresponding to Reynolds numbers 450, 1050, 1650, and 4800.

At Reynolds numbers 450 and 1050, low-frequency velocity oscillations, close to sinusoidal, are observed in the tube. The frequency spectrum of the longitudinal component of the velocity fluctuations has a sharp maximum in the frequency range 0.4–0.5 Hz.

In Fig. 1, 1 the spectral functions of the velocity fluctuations at Re = 1050 are presented. The spectral functions corresponding to different points of the tube cross section are combined in one figure. As is seen from the graph, the

Fig. 1

Figure 1: Fig. 1

shape of the spectrum in the core of the flow does not depend on the coordinates. In the immediate vicinity of the tube wall, on the spectral curve, in addition to the main maximum, there appears a second, considerably less pronounced maximum, located at frequencies of 7-10 Hz. The spectral functions of the velocity disturbances for the regime Re = 450 have an analogous form. However, the principal maximum in this case becomes still sharper, while the second maximum is detected at distances closer to the tube wall, and its relative magnitude is considerably smaller. The second maximum on the spectral curve of the velocity fluctuations, observed in the immediate vicinity of the wall at low Reynolds numbers, indicates the presence in the near-wall region of a zone of turbulent-energy generation, possibly due in its existence to the roughness spectrum on the tube wall.

In the transition region (Re = 1650) the relative energy associated with higher frequencies increases; the spectrum becomes broader, covering frequencies from 0.3 to 20 Hz (Fig. 1, 2).

The frequency spectrum of the velocity fluctuations has a series of maxima, and it cannot be regarded as independent of the coordinates: with increasing distance from the tube wall, the spectrum shifts into the region of higher frequencies.

In Fig. 1, 3 the spectral functions of the longitudinal component of the velocity fluctuations corresponding to developed turbulent flow are presented (Re = 4800). As in Fig. 1, 1, the curves corresponding to different points of the tube cross-section are combined in one drawing. In the region of developed turbulence the frequency spectrum of the velocity fluctuations again becomes stable, has a clearly expressed maximum, and does not depend on the coordinates. The fraction of energy falling on the low frequencies decreases. The width of the spectrum in turbulent flow increases, and its maximum falls at higher frequencies ($\sim$ 10 Hz at Re = 4800).

We have qualitatively interpreted the results obtained in the following way.

At low velocities, air may be regarded as a viscous incompressible fluid. In this case the velocity components obey the Navier–Stokes equation and the no-slip condition. This system of equations is still poorly investigated. Up to now it has not been possible to prove its solvability (solvability is meant in such a topological space where uniqueness holds) ([1]). We assume that uniqueness of the solution of the system of hydrodynamic equations under the prescribed initial and boundary conditions exists.

Fig. 1. Spectral function of the longitudinal component of the velocity fluctuations of an air flow in a straight tube of circular cross-section. Curve **1** was ob-

tained under the conditions of the laminar regime of motion (Re = 1050), $y/R =$ 0.01; 0.02; 0.03; 0.04 (a), $y/R = 0.05$; 0.06; 0.08; 0.09; 0.15; 0.26; 0.36 (b). (y is the vertical coordinate, R is the tube radius.) Curve **2** is the zone of intermittency (Re = 1650), $y/R = 0.05$. Curve **3** is developed turbulent flow (Re = 4800), $y/R = 0.01$; 0.02; 0.03; 0.04; 0.05; 0.06; 0.08; 0.09; 0.15; 0.26; 0.36.

It is known that the system of Navier–Stokes and no-slip equations at small Reynolds numbers has only one stationary solution, corresponding to laminar flow. With increasing Reynolds number, as shown in a series of works ([2], [3]), solutions of the equations of hydrodynamics begin to branch, so that for the given boundary conditions there may exist more than one stationary solution; moreover, if the original motion of the fluid is unstable with respect to small perturbations, these perturbations increase and tend toward a new state of motion.

The maxima on the spectral curves shown in Fig. 1, 1 and 2 precisely correspond, in our opinion, to secondary flows in the tube.

If the distance between the branching points in Reynolds number is small, i.e., if

$$|\mathrm{Re}_i - \mathrm{Re}_{i+1}| < \Delta v\, l/\nu$$

(where i is the number of the branching point, Δv is a fluctuation of velocity, l is a characteristic size, ν is the viscosity), then none of the stable flows $\mathbf{v}_i^{(1)}, \mathbf{v}_{i+1}^{(1)}$ can become established. We interpret this process as turbulent motion of the fluid. It should be noted that at large Reynolds numbers not two, but three or more stationary solutions may mix.

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Note: Figure translations are in progress. See original paper for figures.