A STUDY OF THE SKIPPING-PASSED CHARACTERISTICS OF SOLID PARTICLES IN THE BOTTOM REGION OF A TURBULENT FLOW

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Development of up-to-date theories of the motion of sediment requires reliable observational data that can be used both to test adopted hypotheses and to bring out new details of the mechanism of the effect under study. Among the least understood characteristics are those of the initial segments of the paths of particles that have just been detached and the particle-acceleration characteristics, which play an important role in probabilistic theories of sediment motion [1, 2]. Experimental determination of these characteristics is the subject of the present paper, which is a further development of [1].

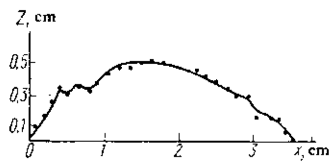

Fig. 1. Path of saltating particle.

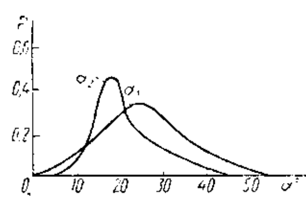

Fig. 2. Distribution of takeoff and landing angles α_1 and α_2 of saltating particles.

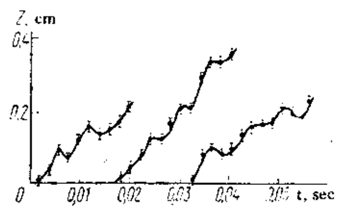

Fig. 3. Initial segments of saltating-particle paths.

The trajectory characteristics were determined by statistical processing of motion pictures taken with an SKS-1M camera at a speed of 500 frames per sec. We were aided in the design and performance of the experiment by G. A. Dmitrieva. Sixteen millimeter film was used. The motion of spherical particles 8 mm in diameter with a density of 1.4 g/cm^3 and a settling speed of 30 ± 3 cm/sec in the flow was recorded on the film. The experiment was carried out in a glass channel 7 m long and 20 cm wide. The average flow velocity was 27 cm/sec, the depth 9 cm, and the gradient 0.006. Plexiglas plates with polystyrene balls 5-7 mm in diameter bonded to them were placed on the bottom of the channel.

Determination of the particle coordinates is subject to errors due to the error of the method itself [3], the unsharp contours of the moving particle and the stationary landmark, and the imprecision of the instruments used to fix successive positions of the particle. In our case, the last two factors dominated; we may therefore say that the total error in the deviation of the measured coordinate value from the actual value is a random variable and, like all nonsystematic errors, has a normal distribution. To estimate the errors of coordinate measurements, we shall use the standard deviation σ_x of this distribution. The fiducial probability of the confidence interval is 0.68.

The experimentally determined standard deviations were different for the vertical (z) and horizontal (x) axes: $\sigma_z = 0.03$ cm, $\sigma_x = 0.04$ cm. This can be explained by the differences in the length and position of the measuring scales. (Obviously, numbers are read visually with greater care from the shorter vertical scale than from the long horizontal scale.) Another factor is the presence of the bottom on the frame, which permits more accurate determination of the particle's vertical coordinate.

We shall discuss the variation of the vertical coordinate below, since statistical processing of the film showed that the motion of the particle in the longitudinal direction can be regarded as uniform. The trajectories were worked up several times to reduce the error of particle-coordinate determination. In a given series of n measurements, the arithmetic mean $\bar{x}$ is a linear function of the results of a single measurement. Since the results of single measurements are independent random variables, we find from the theorem of the variance of a linear function of such variables that the measurement error is reduced by a factor $\sqrt{n}$ on n-fold projection. We projected the trajectories nine times. Thus, the error in determination of the successive particle positions on the path was reduced by two-thirds. In our case, the error will not exceed 0.01 cm at a 0.68 fiducial probability. Considering that the vertical particle displacement (Fig. 1) on the indicated time interval are 2-3 mm if we exclude the neighborhoods of the inflection points, the accuracy attained can be regarded as acceptable.

Statistical distribution curves of the particle takeoff and landing angles can be examined to obtain more complete description of the motion of a particle along its path. The takeoff angle is the angle formed by straight lines drawn from the center of the particle at the instant at which saltation begins. The first line runs parallel to the bottom in the downstream direction, while the second points to the center of the particle in the next particle position recorded on the screen. Similarly, the landing angle is the angle between the direction from the center of a particle that has just settled to the bottom to its center at the time preceding its contact with the bottom. The takeoff angles are nearly normally distributed (Fig. 2). The landing-angle curve is asymmetrical. The particle appears to be accelerated on a very short initial segment of its path, and thereafter its motion is governed in large part by random velocity fluctuations in the layers of the flow at the particle crosses. This may explain the dissimilarity between the takeoff- and landing-angle distribution curves: the particle "forgets" its takeoff angle during its flight.

To determine the acceleration of the particles immediately after separation from the bottom, the initial path segments were projected at the shortest possible interval ($\Delta t = 0.002$ sec), which was determined by the filming rate. The initial path segment is a stepped curve consisting of segments of parabolas with a positive parameter (Fig. 3). The parabolic shape of the climbing segments indicates that the operating acceleration is positive. Let us assumed that the acceleration is constant on each climbing segment, an assumption that is adequately justified by the shortness of the time intervals (0.006-0.008 sec); then the calculated values, with consideration of the errors, lie in the range $2.5 \cdot 10^3$ to $9.4 \cdot 10^3$ cm/sec^2. The results indicate that in the immediate vicinity of the bottom, a significant fraction of the energy in the turbulent-fluctuation spectrum falls into the high-frequency end of the spectrum (around 150-200 Hz). Estimating the eddy sizes in accordance with the "frozen-turbulence" theory, we obtain a value on the order of the roughness height, which tends to support the above hypothesis.

The following conclusions can be drawn on the basis of the work done.

At the instant of separation from the bottom of the flow, the particle experiences extremely brief (0.006-0.008 sec) positive accelerations that vary from $2.5 \cdot 10^3$ to $9.4 \cdot 10^3$ cm/sec^2.

In its skipping motion through the bottom region, a particle may be acted upon strongly by the turbulent flow. It may be assumed that in the immediate vicinity of the bottom, a substantial part of the energy in the turbulent velocity fluctuation spectrum is in its high-frequency range (at approximately 150-200 Hz).

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