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ON VELOCITY MEASUREMENTS IN HYDRAULIC JUMPS USING LDV, SMALL PROPELLER AND PITOT TUBE

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ABSTRACT

This paper is concerned with velocity measurements within a hydraulic jump in a horizontal rectangular flume(9 m long, 30 cm wide, and 40 cm deep), using laser Doppler anemometry (LDA), small both-ways propeller(3 mm diameter), and Pitot tube(2 mm inner diameter). Velocity data measured with these instruments based on completely different principles have been compared with each other. It is found that as far as longitudinal velocity component along the flume axis the present three instruments provide the same results within the experimental error of about 5 %. In general LDA is superior to the others, for it can measure an instantaneous velocity without disturbing the flow, but it is almost useless to measure velocities in the surface roller accompanying air bubbles, near the free surface, and near the flume bed. It is realized that the small both-ways propeller is an excellent means to measure the velocities in the surface roller as well as the recirculation flow region near the flume corners. The Pitot tube though it is classical,is a simple but extremely efficient instrument to measure *mean* velocity in the entire flow field including near the free surface, and near the flume bed. It is, therefore, inferred that no single instrument is sufficient to elucidate complex flow motions such as hydraulic jumps, or vortices.

INTRODUCTION

Hydraulic jump accompanying numeral air bubbles was described by Leonardo da Vinci(Rouse and Simon 1957) for the first time about five centuries ago. Since then, many researchers and engineers have been attracted by the hydraulic jump owing to its scientific interest and practical importance. The first scientific investigation, however, dates away back only to 1818(Bidone 1818), and a decade later Bélanger (1828) wrote an essay, in which he had derived the so-called Bélanger equation. Then, a very large number of investigation has been carried out on both the macroscopic and internal structure of hydraulic jumps, but most of these studies have been directed to the macroscopic features. There are several reasons for studying the internal flow hydraulic jumps. Foremost may be the problem of scaling-up physical model data to predict prototype behaviour. Major contributions to this subject were reviewed critically by Chow(1959), Rajaratnam(1967) and more recently by McCorquodale(1988).

Hydraulic jumps in a rectangular open channel are several distinct types. According to studies of the U.S. Bureau of Reclamation(1955) these types can be conveniently classified by the supercritical Froude number Fr as follows; undular jump(Fr=1 to 1.7), weak jump(Fr=1.7 to 2.5), oscillating jump(Fr=2.5 to 4.5), steady jump(Fr=4.5 to 9.0), and strong jump(Fr=9.0 and larger). It must be, however, noted that ranges of the supercritical Froude number given above for the various types of hydraulic jumps are not clear-cut, but overlap to a certain extent depending on local conditions.

In despite of the considerable research effort which has gone to study hydraulic jumps, their detailed flow structures do not seem to have been completely elucidated: Upon closer scrutiny of relevant research records it becomes clear that the flow data are limited essentially to those using Pitot tubes. In other words, no full confirmation of the velocity data measured with Pitot tubes has been made, using more advanced flowmeter such as laser Doppler anemometry or magnetic flowmeter, which is now readily available. This indeed prompts the present study.

The main purpose of this study is to compare with velocity data measured with laser Doppler anemometry, small both-ways propeller, and Pitot tube each other.

EXPERIMENT

Fig. 1 shows a schematic diagram of the present experiment. The experiment is conducted in a horizontal rectangular flume 9 m long, 30 cm wide, and 40 cm deep. The right-handed coordinate system is adopted, and the origin is set on the centre line of the flume bed and at the toe of jump.

The flow velocities are measured by means of a two-dimensional laser Doppler anemometry(Kanomax, GLS3260J), small propeller-type flowmeter (Shinozuka, SV-3W) with 3 mm external diameter, and Pitot tube(inner diameter 2 mm, outer diameter 3 mm).

An undular jump has been chosen for this study, where the supercritical Froude number $Fr=U_0/\sqrt{gz_0}$ is 1.56, U_0 the supercritical velocity g the gravitational acceleration, and z_0 the water depth at the toe of jump. The velocity distributions in the vertical planes at $y/b=0$, $\pm$ 0.27, $\pm$ 0.53, and $\pm$0.8, respectively, have been measured, where b is one half of the flume width. In the x direction, measuring points range from $x/z_0=-6$ to 50 at proper intervals, whereas in the z direction, measuring points range from z=1.5 mm close to the water surface, where in the supercritical flow region, the velocity is measured at 2 mm intervals, while in the subcritical flow region it is measured at 5 mm intervals.

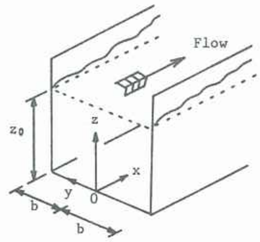
The surface height of the hydraulic jumps varies with time. Therefore, using a point gauge the mean surface height at each position is determined by averaging at least 10 data recorded during 60 seconds. The surface profile is drawn using the surface heights thus obtained at 10 mm intervals along the x coordinate.

RESULT AND DISCUSSION

Figs. 2 and 3 show the side-, and plan-views of an undular jump at Fr=1.56, respectively. These photographs may well illustrate how hydraulic jumps are complex phenomena. That is, the surface profile of the jump is completely three-dimensional, and a considerable amount of air is entrained by the supercritical flow through the air-water interface and then transported into the jump region. This phenomena are characterized by two oblique jumps originating from the left and right side walls, respectively. The oblique jumps are superimposed each other over the flume axis. As the result, the first swelling is formed at the first cross point. Then, the left jump proceeds and is reflected from the right side wall. On the other hand, the right jump is reflected from the left side wall. After the reflection, These two jumps are superimposed each other again over the flume axis, so that the second swelling is formed at the second cross point. It is evident that the first depression is at the middle point between the first and second swellings over the flume axis. These processes are repeated in many times, and thus a series of swelling/depression sequences is formed along the flume axis.

Fig. 4 illustrates a comparison among the longitudinal velocity profiles with respect to the vertical coordinate measured in terms of the laser Doppler anemometry(LDA), small both-ways propeller, and Pitot tube at x/z_0= 12.2 and y/b=0.27, where the abscissa is the normalized longitudinal velocity, and the ordinate the normalized vertical coordinate z/z_0. It may be evident from this figure that all of the three profiles indicate a good agreement with each other: When it is supposed that the laser Doppler anemometry resluts in a true velocity, the expected error in the velocities measured with the small both-ways propeller, and Pitot tube is about 5 % at most. This fact is quite encourageous for practical hydrodynamists due to the following two aspects. Firstly, a Pitot tube has given them a fairly negative impression on quality of the data, but this is not the case. Secondly, one could use these three instruments concurrently to investigate into complex flows such as hydraulic jump or vortex in such a way that one puts the right instrument in the right place in the flow field: In general, the laser Doppler anemometry is superior to the others, but it is almost useless to measure velocities in the surface roller accompanying air bubbles within a hydraulic jump, near the free surface, and near the flume bed. It is, however, realized that the small both-ways propeller is an excellent means to measure the velocities in the surface roller as well as the recirculation flow region near the flume corners. Moreover, the Pitot tube is a simple but extreamely efficient instrument to measure mean velocity in the entire flow field including near the free surface, and near the flume bed.

Fig. 5 shows the longitudinal velocity profiles within a vertical plane through the normalized transverse coordinate y/b=0.80 measured with the laser Doppler anemometry(LDA) against the vertical coordinate at each longitudinal position, where the abscissa is the normalized



Coordinate system

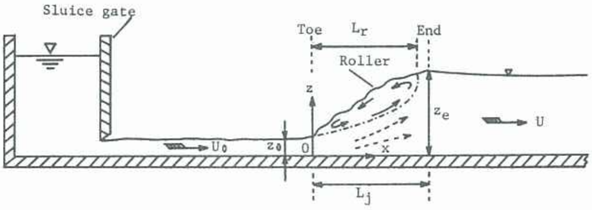


Fig. 1 Schematic diagram of the experiment.

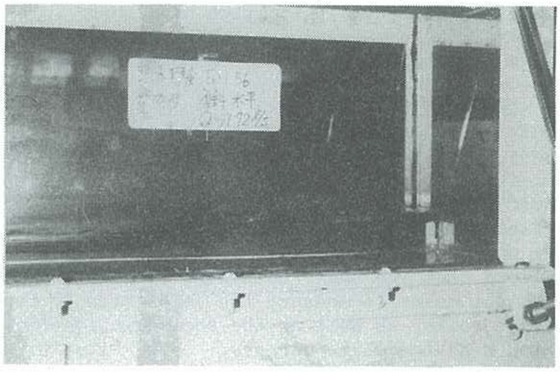


Fig.2 Side-view of an undular jump at Fr=1.56. Flow direction is from left to right.

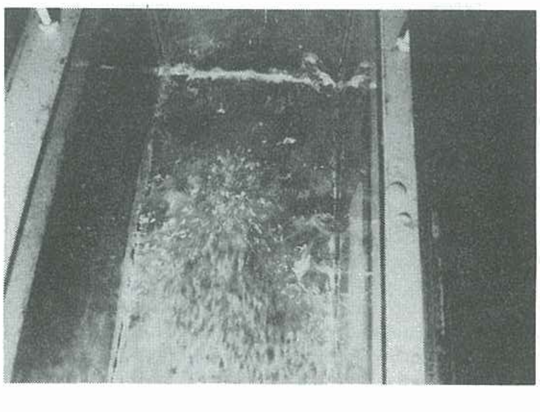


Fig. 3 Plan-view of an undular jump at Fr=1.56. Flow direction is from bottom to top.

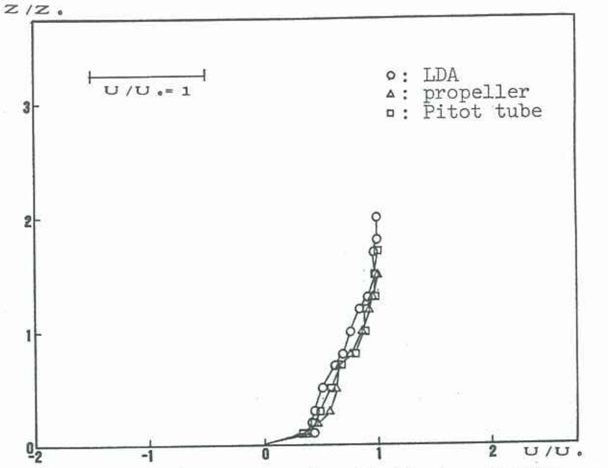


Fig.4 A comparison among longitudinal velocity profiles with respect to vertical coordinate measured by LDA, propeller, and Pitot tube at $x/z_0=12.2$ and $y/b=0.27$.

longitudinal coordinate x/z_0, and the ordinate is the normalized vertical coordinate z/z_0. In this figure, the velocity profiles at each x/z_0 are shown together with the mean surface profile and the normalized longitudinal velocity scale U/U_0.

Fig. 6 shows the longitudinal velocity profiles within a vertical plane through the normalized transverse coordinate $y/b=0.80$ measured with the small both-ways propeller against the vertical coordinate at each longitudinal position, where the abscissa is the normalized longitudinal coordinate x/z_0, and the ordinate is the normalized vertical coordinate z/z_0.

Fig. 7 shows the longitudinal velocity profiles within a vertical plane through the normalized transverse coordinate $y/b=0.80$ measured with the Pitot tube against the vertical coordinate at each longitudinal position, where the abscissa is the normalized longitudinal coordinate x/z_0, and the ordinate is the normalized vertical coordinate z/z_0.

Now, results presented in Figs. 5-7 will be discussed concurrently, for apart from flowmeter experimental conditions are similar to each other. Thus, it is considered that such a comparison makes it possible to extract effects of flowmeter on the velocity profile. It is important to note here the fact that no hydraulic jump is steady, so that the velocity profiles must vary with time. Nonetheless, all of the three velocity profiles at each the longitudinal position x/z_0 indicates a reasonable agreement. Degree of the agreement is improved with increasing x/z_0, or with increasing the distance from the jump region, for degree of unsteadiness in the flow is decreased with increasing x/z_0.

Variation of the surface profiles in Figs. 5-7 also suggests how the hydraulic jump is unsteady. It is realized that even the jump position changes with time during the measurement. This is, indeed, the reason why origin of the coordinate is chosen at the toe of jump.

CONCLUSION

It is found that as far as longitudinal velocity component along the flume axis the present three instruments, viz., laser Doppler anemometry(LDA), small both-ways propeller, and Pitot tube, provide the same results within the experimental error of about 5 %. In general, laser Doppler anemometry is superior to the others, for it can measure an instantaneous velocity, which may be devided into the mean and turbulence components, without disturbing the flow, but it is almost useless to measure velocities in the surface roller accompanying air bubbles, near the free surface, and near the flume bed. It is realized that the small both-ways propeller is an excellent means to measure the velocities in the surface roller as well as the recirculation flow region near the flume corners. The Pitot tube, though it is a classical flowmeter, is a simple but extreamly efficient instrument to measure mean velocity in the whole flow field including near the free surface, and near the flume bed. It is inferred that there is no last flowmeter in this world.

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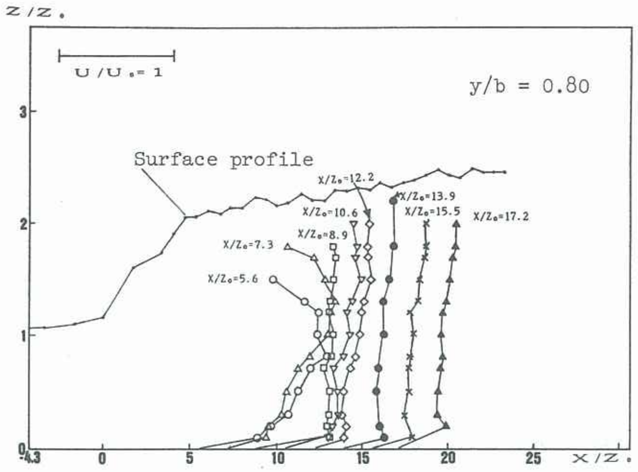

Fig. 5 Longitudinal velocity profiles measured by LDA against vertical coordinate at each longitudinal position.

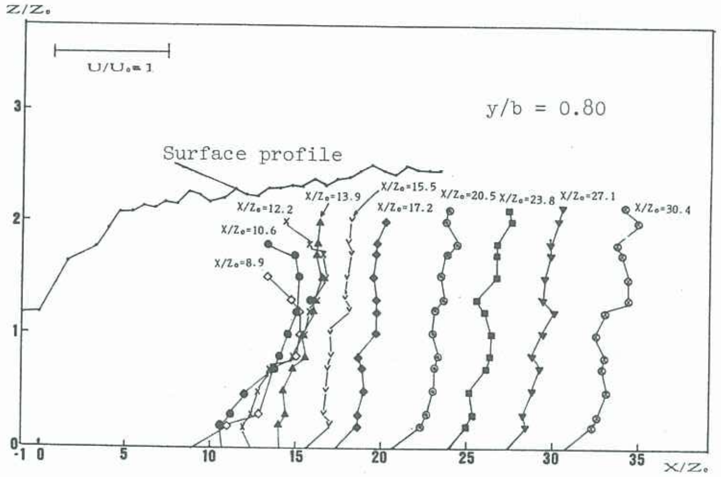

Fig. 6 Longitudinal velocity profiles measured by propeller against vertical coordinate at each longitudinal position.

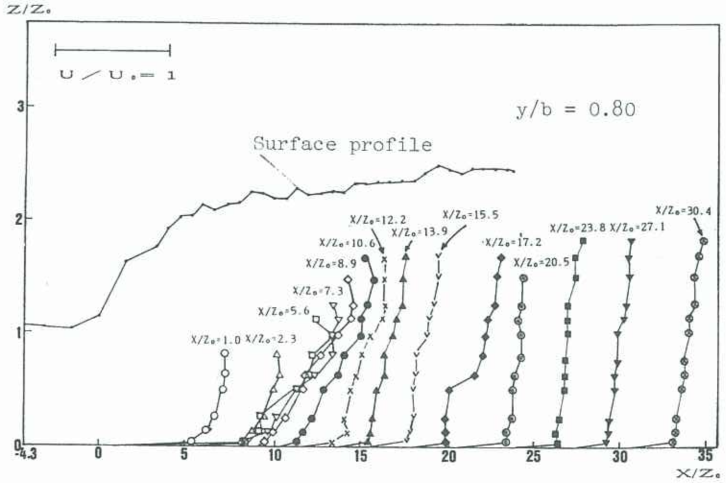

Fig. 7 Longitudinal velocity profiles measured by Pitot tube against vertical coordinate at each longitudinal position.