On Measurement of Airy Waves by Tension Thread Flow Meter

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Abstract

This paper is concerned with measurement of Airy waves by Tension Thread Flow Meter.

The utility and potential of the Tension Thread Flow Meter to measure water particle velocity ranging from 0 to 100 mm/s in the periodic oscillatory gravity waves, have been successfully demonstrated. It is realized that Tension Thread Flow Meter can measure the velocity vector while the water particles are changing the direction from 0 to 360°. It is found that comparing with other existing flowmeters Tension Thread Flow Meter is quite suitable to measure flow velocity very close to solid boundary. It has been verified by measurements of waves with Tension Thread Flow Meter that the present data on waves show a good agreement with Airy wave theory. That is, it is inferred that both of Airy wave theory and the present flowmeter are reliable research means. It is suggested that these characteristic points together with the robustness of Tension Thread Flow Meter to be used both of laboratory and experiment are critical in the progress of flowmeter.

Keywords: Airy Wave, Flowmeter, Oscillating Flow, Velocity Measurement, Drag

1. Introduction

It is the technique measuring the flow velocity in accurate that plays a crucial role in development of physics in fluid mechanics (Alan 2001, Bean 1971, Baker 2016, and/or Miller 1996). Undoubtedly, Pitot tube invented by Henri Pitot in 1732 was the inaugural point of the quantitative measurement in flow velocity. It has, however, become clear that performance of Pitot tube is not sufficient to measure unsteady and three-dimensional flow velocities ranging near zero to more than sonic velocity, in periodic and oscillatory motion, near solid and/or free boundary. For these reasons, after Pitot's invention many other flowmeters based on different physical principle have been deployed in nature and laboratory. For examples, Robinson wind meter, hot wire (or film), propeller, electro-magnetic flowmeter, ultrasound flowmeter (Drost 1978), acoustic Doppler velocimetry(Chanson 2008), laser Doppler velocity meter(Adrian 1993), particle image velocity meter (PIV) and/or tension thread flow meter(Sharp 1964, Sleath 1969, Nakagawa 1983a, 1983b) have provided valuable data. Main purpose of the present study is to measure water particle velocities of intermediate waves in terms of a Tension Thread Flow Meter(referred to TTFM hereafter), which is useful for measuring velocity changing the direction from 0 to 360°, the magnitude ranging nearly 0 to 10 cm / s, and close to air-water and water-solid boundaries.

2. Tension Thread Flow Meter

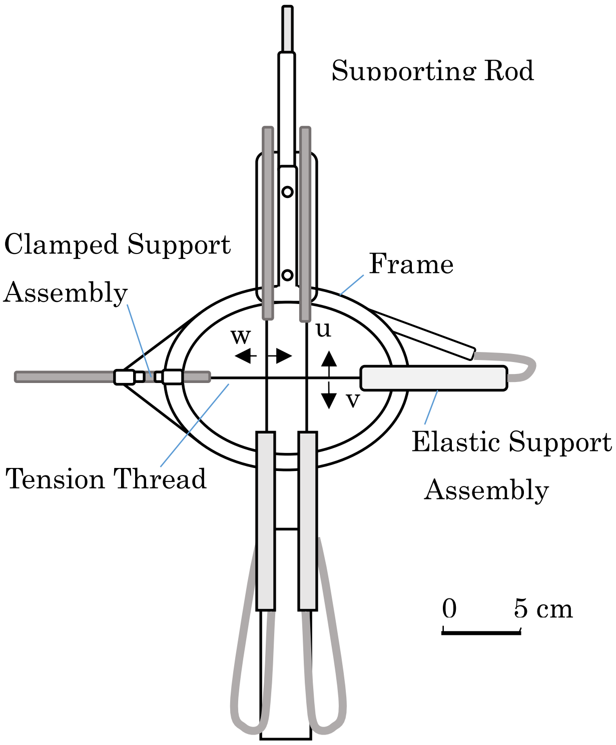


Fig.1 Present Tension Thread Flow Meter model.

The TTFM is a potential flowmeter based on a simple physical principle that "the drag exerting on a thread suspended in the flow depends on the velocity around it ". However, it is not easy to derive the analytical relation between the velocity around the body and the drag(Nakagawa & Nakagawa 2020a), so that in case of TTFM the drag is transformed into the electric signal produced in the Wheatstone bridge(Nakagawa & Nakagawa 2020b) via the strain in the cantilever, which supports one end of the thread. Hence, it is possible that once the drag force is calibrated by the velocity with a carriage in the laboratory, the velocity around the thread can be known.The present TTFM model as sketched in Fig. 1 can measure three velocity components concurrently, but in this study only two velocity components u and v have been measured, where u is the velocity component in the wave direction, and v is that in the vertical direction. One end of the thread is clamped rigidly, while the other is supported elastically at the tip of the cantilever of 60 mm long, 5 mm wide and 0.5 mm thick, respectively. A semi-conductor strain gauge of 120 Ω is glued with paste on each side of the cantilever made of brass, and these strain gauges form two registers within four registers in the Wheatstone bridge. The length and diameter of the cotton threads are 70 mm and 0.1 mm, respectively.Flow velocity at each the points has been measured by TTFM as follows: The flow drag normal to the plane of cantilever will be deflected at first. The deflection causes a strain at the place where the gauge is pasted, and then the magnitude is transformed into an electrical voltage via the potentiometer in

Wheatstone bridge. Then, the voltage is amplified by the dynamic amplifier and finally recorded on the tape or computer. It may be worth noting each of the threads can detect the velocity component normal to plane of the cantilever, respectively, for ratio of the width to thickness of the cantilever is designed so as to be sufficiently large value of 10. It may be already clear that the velocity measured by TTFM is the mean velocity integrated at a small space, where two threads are suspended, but in the experimental analyses the geometrical center of the two middle points of threads has been assumed as the measuring point.

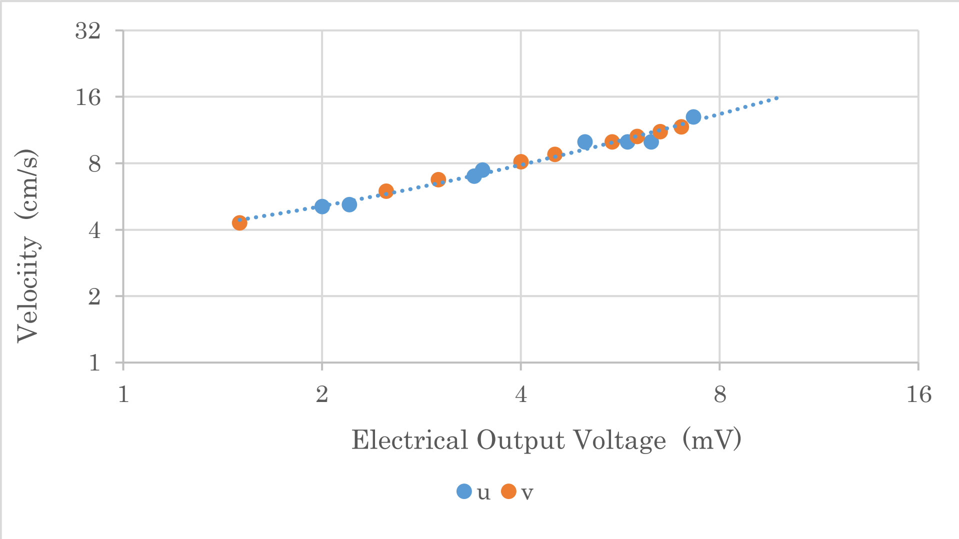


Fig.2 Velocity calibration curve for present Tension Thread Flow Meter.

Fig.2 shows velocity calibration curve for the present TTFM. It is realized that a single calibration curve is sufficient for the two velocity components u and v, as shown in this figure. The calibration has been done in a flume: The TTFM is towed by a carriage at a constant speed in a still water for each the threads, respectively, an output electrical voltage is recorded on the tape for each of runs. Repeating this procedure for different carriage velocities, the calibration curve of Fig.2 is obtained.

3. Experimental

The present experiment has been done Michell Laboratory, at University of Melbourne, named after A.G.M. Michell who invented the tilting pad thrust bearing.

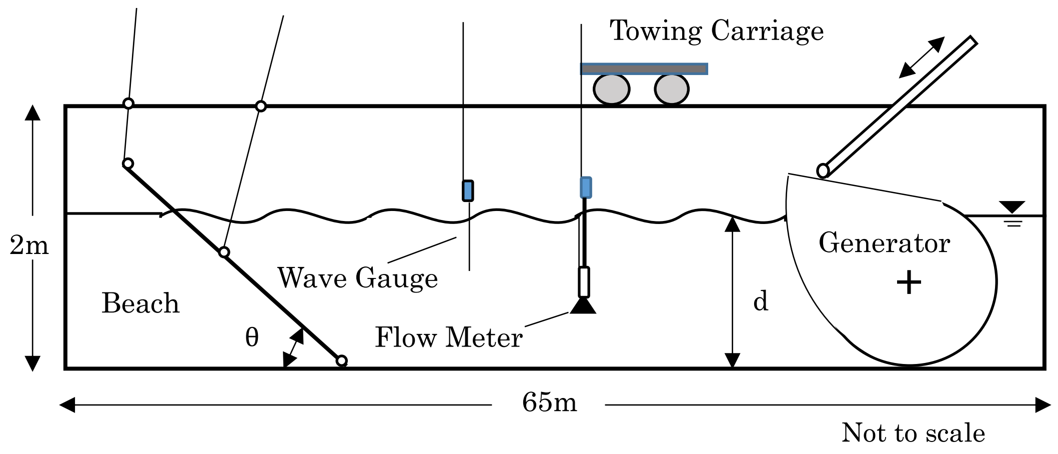


Fig.3 Schematic diagram for the present experiment.

Fig.3 shows a schematic diagram of the present experiment. The flume is of 65.0 m long, 2.03 m deep and 1.83 m wide, respectively. The wave generator is 'duck' type and has been designed for regular two-dimensional wave generation. The sloping beach is of 4.0 m long and 1.83 m wide, respectively. The beach consists of hollow square tube frames covered with 25 mm layer of plywood. The frame is hinged on the flume floor and two sets of the support arm at the middle and top ends allow the beach angle θ set to be varied between 8 and 20 degree. The plywood has 25 mm holes on 100 mm square grid pattern and is covered with a layer of nylon fiver, which itself is protected from breaking up by a layer of 12.5 mm square plastic mesh. It has been confirmed empirically that the wave reflection is 5 % at most.

In the experimental run, supporting rod of TTFM is mounted on the carriage which is capable of moving along the rails on the upper edge of flume. One end of the supporting rod is fixed to a point gauge mounted on the carriage. The vertical position of TTFM is, thus, adjustable by turning the point gauge knob, whereas the longitudinal and transverse positions are 30 m from the wave generator and on the center line of the flume, respectively.

During measurements of water particle velocity, waves have been measured concurrently with two capacitance type wave gauges, where one gauge is put at the same position at TTFM, while the other gauge is at 1 m behind TTFM.

4. Results and Discussion

In the experiment, two sinusoidal waves with small amplitude have been measured with TTFM in the flume. The wave parameters are summarized in Table 1, where the wavelength L is calculated with the dispersion relationship of Airy wave theory (1845),

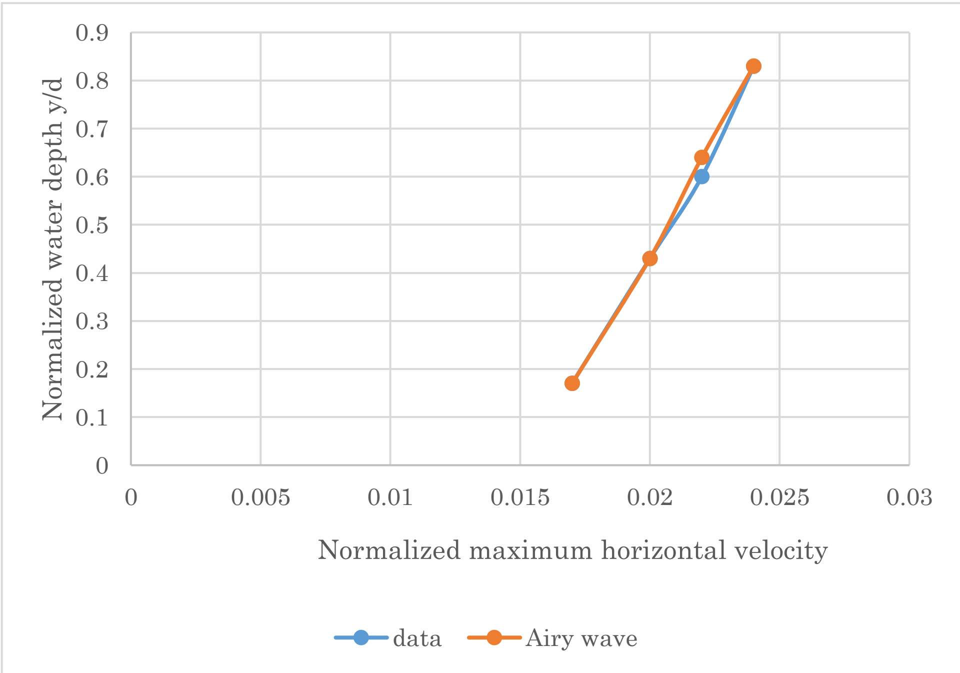
$$c = L / T = [(g / k) \tanh (dk)]^{1/2},$$

where c is the wave celerity, L wavelength, T wave period, g gravitational acceleration, k = 2π / L wave number, d water depth.

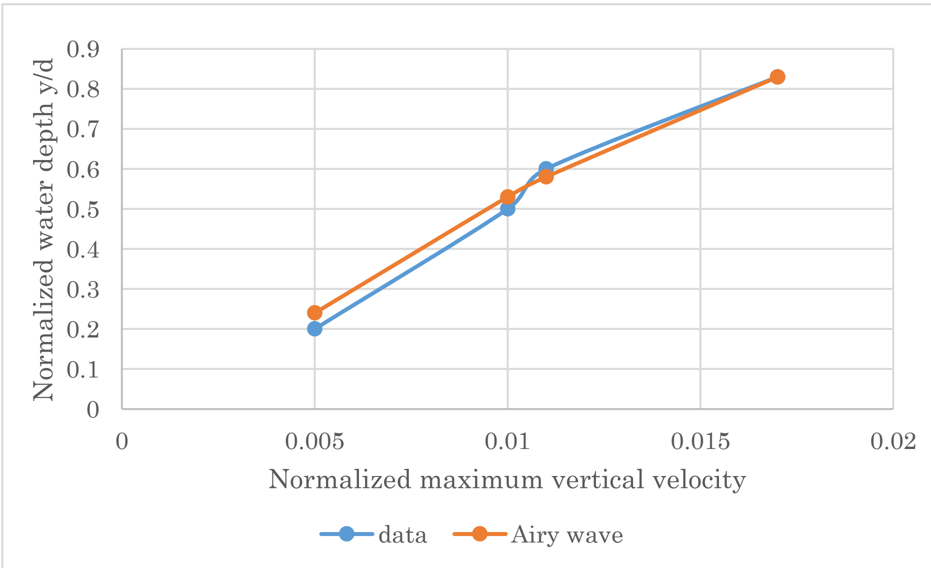
Table 1 Wave parameters of the present waves.

Wave	T(s)	H(cm)	L(cm)	d(cm)	H/L	d/L
1	2.21	5.182	631.6	110.0	0.0082	0.17
2	1.51	11.176	377.0	118.0	0.0296	0.31

Note: H is wave height. It is clear from Table 1 that the present waves are categorized as intermediate wave.



(a)



(b)

Fig.4 Vertical profile of the maximum water particle velocities for wave 1.

Fig.4 shows vertical profile of the maximum water particle velocity for wave 1. In this figure, (a) shows the relation between the normalized maximum horizontal water particle velocity $u / (gd)^{1/2}$ and normalized vertical coordinate y / d, where origin of the coordinate is at the flume bed, whereas (b) shows the relation between the normalized maximum vertical water particle velocity $v / (gd)^{1/2}$ and the normalized vertical coordinate y / d. In each of these figures, Airy wave curve is plotted concurrently for reference. It may be evident that present data show good agreement with the theory.

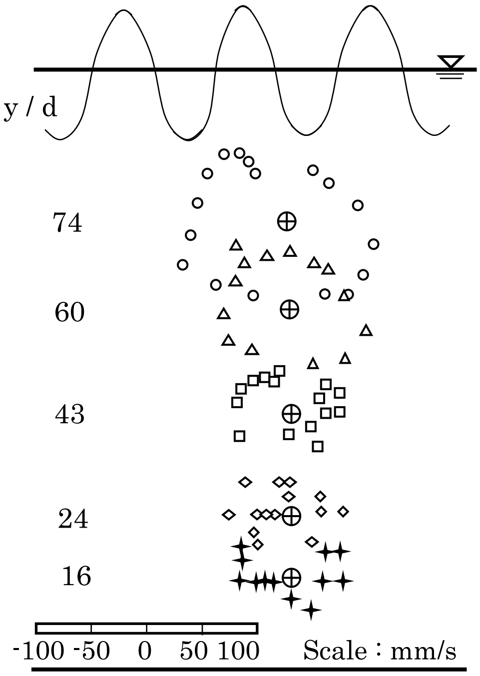


Fig.5 Time histories of the water particle velocity vector for wave 2 at each normalized vertical distances.

Fig.5 shows time histories of the water particle velocity vector for wave 2 at the normalized vertical distances y / d = 0.16, 0.24, 0.43, 0.60, and 0.74, respectively. It may be noted that near the water surface, at y / d = 0.74, locus of the water particle velocity vector is almost circle, but as approaching to the flume bed, it tends to be changed into a horizontal line via deformed ellipses. Hence, it has been confirmed empirically that near the water surface, magnitude of the water particle velocity is almost constant irrespective of the change of direction, but near the flume bed, magnitude of the vertical velocity component becomes small relative to that of the horizontal velocity component.

In Airy wave theory, it is assumed that the fluid is incompressible and inviscid, and that the wave amplitude and profile are small and sinusoidal, respectively. It seems to be generally believed that the incompressible and inviscid assumptions regarding to gravity waves appearing in the flume are reasonable. Hence, the agreement of the theory with data in Fig.4 might confirms that Airy wave theory is vigorous but also that the present flowmeter provides reliable data.

5. Conclusions

In this section, new knowledge and insights obtained through the present study have been summarized:

1. The utility and potential of the Tension Thread Flow Meter to measure water particle velocity ranging from 0 to 100 mm / s in the periodic oscillatory gravity waves, have been successfully demonstrated.
2. It is realized that Tension Thread Flow Meter can measure the velocity vector while the water particles are changing the direction from 0 to 360°, and has no limitation to the magnitude of velocity in principle.
3. It is found that comparing with other flowmeters the present Tension Thread Flow Meter is suitable to measure flow velocity very close to not only solid boundary but also free boundary.
4. It has been verified by measurements of waves with Tension Thread Flow Meter that the present data on waves show a good agreement with Airy wave theory. That is, it is considered that both of Airy wave theory and the present flowmeter are reliable research means.
5. It is suggested that the above characteristic points together with the robustness of Tension Thread Flow Meter to be used both of laboratory and experiment are critical in the progress of flowmeter.
6. Considering in the attractive potentials of TTFM as demonstrated in this study, it is strongly recommended for someone or company to develop flowmeters, which are commercially available.

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