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Laser Doppler Method for Measuring Oscillating Flow in Prismatic Tanks

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Abstract

THE flowfield inside a partially filled prismatic tank with a rectangular section which oscillates laterally has been analyzed using a laser Doppler velocimeter. The distribution of vertical velocity near the free surface, when the frequency of the acting force is equal to one of the natural frequencies of the liquid-tank system, shows that the maxima and the nodes are shifted toward the center of the tank in comparison with the positions computed using the linear theory. Considering the effective value of the horizontal velocity along a vertical line, it is possible to show a velocity out of phase at different points. This phenomenon is particularly noticeable for the vibration modes of higher order.

Contents

Experimental studies of the sloshing flow, which are needed essentially to determine the natural frequencies of the tank-liquid system, have been carried out by flow visualization or by measuring the free surface levels, the accelerations, and the pressures.[1] Few attempts have been made to analyze the velocity field instead. In fact, the particular characteristic that the velocity of the fluid motion oscillates near the zero value has made it difficult to analyze the fluid field experimentally. In the present paper good results are obtained using a laser Doppler velocimeter (LDV) to determine the velocity field inside the fluid in a tank laterally excited. The LDV method enables one to obtain very accurate velocity measurements with a good spatial resolution, without disturbing the field in any way.

The tests have been carried out using a Plexiglas rectangular tank (30×15 cm) rigidly fixed to the oscillating table which is excited by a sinusoidal force of given amplitude and frequency supplied by an electromagnetic vibrator; the height of the liquid at rest was kept at $h = 15$ cm. The vibrator is controlled through an amplifier by a signal generator with a 0.01-Hz sensitivity in the low-frequency band (Fig. 1).

The LDV is a one channel system and was used in the dual beam mode.[2,3] The transparent walls of the tank permit the use of the forward-scattering method. The two beams are then led in the tank and allowed to cross at the point of interest. The LDV apparatus consists essentially of an He-Ne laser of 5 mW power; an optical unit with a Bragg cell to shift the frequency, in order to measure negative velocities and those close to zero; a photomultiplier; a series of filters, in order to reduce the noise-signal ratio; and a tracker, in order to measure the Doppler frequency. The output signal from either the accelerometer amplifier or the trackers are sent to an rms voltmeter which measures the effective value of acceleration and velocity.

The vertical component of velocity is measured by the LDV at the point M which has been taken on the symmetry plane 2 cm away from the $x = 0$ plane (Fig. 2); the elevation of M has been taken as close as possible (2 cm) to the liquid free surface in order to be able to carry out the measurements with the LDV. From the shape of the curve of vertical velocity rms, $\bar{v}(f)$, as a function of the excitation frequency, it is possible to find the frequency of the system considered as a simple pendulum (A) and the frequencies characteristic of the natural modes of the liquid. The results are in good agreement with the values obtained analytically from the linear theory.[4,5]

If the acceleration of the tank motion is measured by an accelerometer glued over one of the two vertical walls perpendicular to the direction of the excitation force, it is possible to know only the peak related to the first three

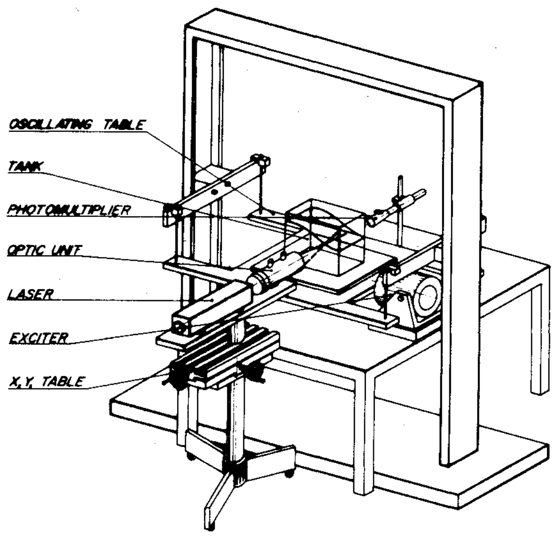

Fig. 1 Experimental apparatus.

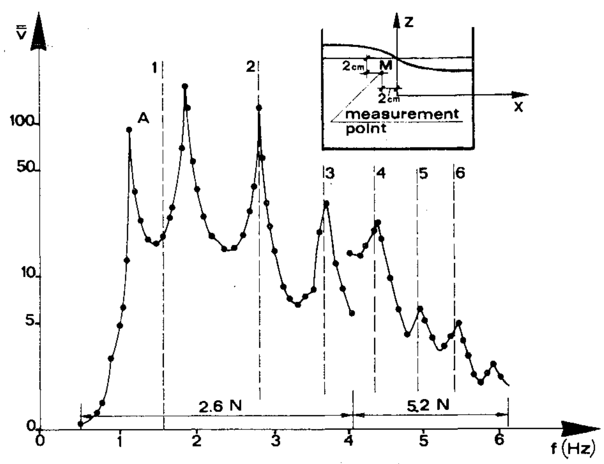

Fig. 2 Vertical velocity rms values $\bar{v}$ vs excitation frequency f; the dashed straight lines represent the natural frequencies given by linear theory.

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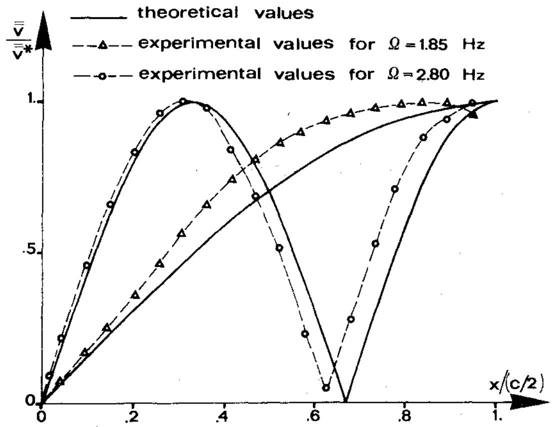

Fig. 3 Horizontal profiles of vertical velocity rms values $\bar{\bar{v}}$ for the first and the second vibration mode.

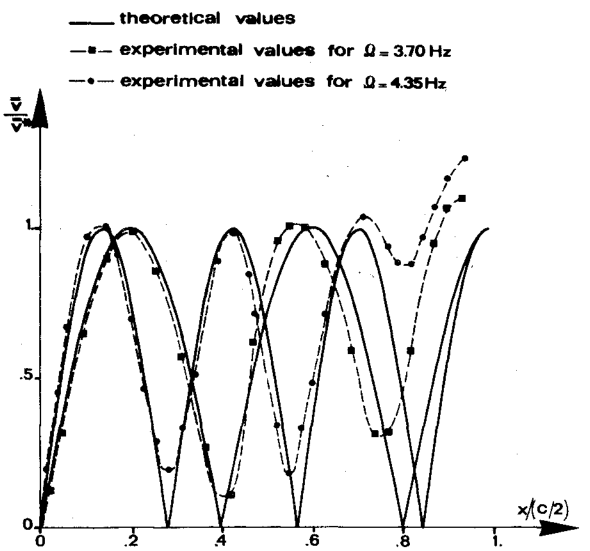

Fig. 4 Horizontal profiles of vertical velocity rms values $\bar{\bar{v}}$ for the third and the fourth vibration mode.

natural modes. Since the structure acts as a low-pass filter, natural frequencies larger than 4 Hz can not be found even for excitation forces up to 5.2 N.

The rms of vertical velocity as a function of x, measured at a depth of 2 cm from the free surface at rest, is shown in Fig. 3 for the first two modes and in Fig. 4 for the third and fourth modes. The values of $\bar{\bar{v}}(x)$ are normalized with respect to the first maximum value $\bar{\bar{v}}^*$. The experimental results seem to agree well with the results obtained from the linear theory (also shown in Figs. 3 and 4) except for two features.

1) The nodes and the maxima obtained experimentally tend to move toward the center of the tank as if the side of such a tank were smaller than that of the corresponding nonviscous fluid case.

2) The ratio $\bar{\bar{v}}/\bar{\bar{v}}^*$ does not take a zero value at the minima of the experimental curve and the maxima are greater than 1, especially for the third and fourth modes, and increase as x increases.

The first feature is due to the presence of the boundary layer near the vertical walls. The second feature can be explained assuming that there is a coupling between the different modes of oscillation and that, for any natural mode of

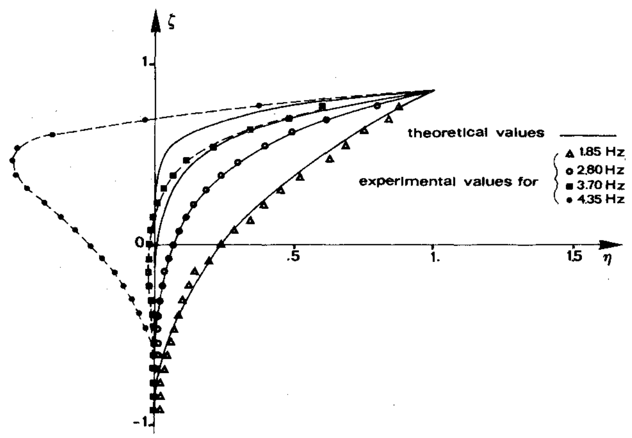

Fig. 5 Vertical profiles of η for the first four vibration modes.

oscillation j, the effects of the modes of order lower than j are larger than the effects of the modes of order greater than j.

Further experimental results have been obtained measuring the rms of the horizontal component of velocity u along the vertical direction. If $\bar{\bar{u}}_b$ and $\bar{\bar{u}}^*$ are, respectively, the rms of u at the bottom of the tank and at $z^* = 2$ cm below the free surface, from linear theory one obtains

$$\eta(\zeta) = \frac{\bar{\bar{u}} - \bar{\bar{u}}_b}{\bar{\bar{u}}^* - \bar{\bar{u}}_b} = \frac{\cosh[(2i+1)(\pi h/2c)(\zeta+1)] - 1}{\cosh[(2i+1)(\pi h/2c)(\zeta^*+1)] - 1}$$

where $\zeta = z/(h/2)$, $\zeta^* = z^*/(h/2)$ and c is the transversal width of the tank. Experimental and analytical values of $\eta(\zeta)$ are plotted in Fig. 5 for the first four modes of oscillation. For the first two modes there is good agreement between the two sets of values but for the third and even more for the fourth mode there is a zone where the experimental results show negative values of $\eta(\zeta)$. In such zone, therefore, the rms of u are lower than at the bottom of the tank.

The effective values of the horizontal component of velocity can be considered the sum of three terms. The first term represents the motion of the tank. The second term represents the jth isolated mode which is $\pi/2$ out of phase with respect to the tank motion and is an exponential function of z. The third term represents the coupling between the jth mode and the other oscillation modes and it adds further increments out of phase with respect to the tank motion. It is then possible that, when the first term is of the same order of magnitude of the sum of all the other remaining terms, the effective value of the fluid horizontal velocity may be smaller than the effective value of the tank velocity. Such a phenomenon becomes more evident for the third and the fourth oscillation modes and this fact confirms that any given mode is affected more by smaller order modes than by the higher-order modes. Obviously such a phenomenon could not be modeled by a nonviscous theory.

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