Influence of vibration in the horizontal plane on discharge of liquid from a cylindrical tank

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In this paper, the influence of vibration in the horizontal plane on the phenomenon of vortexing during draining of liquid from a cylindrical container is described. The studies are carried out when vibration is imparted without and with initial rotation. Flow visualisation results are presented which give a visual picture of the phenomenon. The investigation brings out that the vortexing phenomenon can be quite different from the case when the vibration occurs in the vertical plane.

During draining of liquid from a circular tank through an axisymmetrically placed circular orifice (drain), a vortex with an air core forms, as the free surface level reaches a critical height, \( H_c \). The vortex extends to the bottom port, reducing the effective cross sectional area of the drain outlet and consequently the flow rate. Initial disturbances like rotational motion and vibration due to environmental disturbances can augment the vortex formation\(^1\)-\(^5\). This phenomenon has practical relevance in fuel feed systems in space vehicles and rockets. During flight of space vehicles and rockets, such vortexing can affect the outflow from liquid propellant tank to the engines.

In a recent study\(^6\), the influence of rotation and vibration in the vertical plane on the discharge of liquid from cylindrical tanks has been systematically investigated. In the present investigation, the influence of vibration in the horizontal plane is studied. Results are obtained when both frequency and amplitude are varied systematically.

Experimental Procedure

The experimental set-up for controlled horizontal vibration of the draining tank is designed and fabricated as shown in Figs 1 and 2. An acrylic tank of 92 mm inside diameter (D) and 460 mm height with a drain hole of diameter (d) equal to 6 mm is used. The cylindrical tank is bolted to an 8 mm thick MS plate through a wooden packing. The MS plate is connected to two square shaped brass sliding blocks of length 95 mm (Figs 1 and 2). In case of vibratory motion, these two brass blocks slide through two stainless steel rods of diameter 10 mm and length 220 mm. The stainless steel rods are bolted to two angle sections which in turn are bolted to another MS base plate. The MS base plate bolted to a concrete foundation bed (specially made for the purpose), forms a platform for the sliding blocks to execute their to and fro motion. Helical springs are wound, two each to the stainless steel rods, on either side of the sliding block as shown in Fig.1. A rubber stopper is provided to control the outflow. A draining passage is provided in the concrete foundation bed to collect the discharge. The cylindrical tank and its accessories are connected to the vibrating table of the horizontal exciter using a MS rod of 8 mm diameter and 380 mm length. The exciter is mounted on a wooden block for proper alignment of the system. Both frequency and amplitude of vibration are varied using a waveform generator and power amplifier. An accelerometer is fixed to the cylindrical container and is connected to the FFT analyser through a charge amplifier. The container motion is measured by the accelerometer and the FFT analyser. Fig.2 shows the cross sectional view of horizontal vibration set-up.

The influence of vibration in the horizontal plane is studied without and with initial rotation, as the latter has considerable augmenting influence on vortex formation\(^6\). The quantification of the initial rotation imparted is done by controlled stirring of
the liquid in the tank (with the drain port closed by the rubber stopper, Fig.2). Further details of the procedure adopted are given elsewhere. In each of the figures where the results are presented, error bars are shown which indicate the uncertainty level in the measurements. All the results have been obtained with an initial height of the liquid column, $H_i$ equal to 300 mm. It is known from previous studies that initial height does not influence the vortex formation. The initial height of 300 mm was chosen so that the critical height $H_c$ and the time of draining could be conveniently measured. The liquid used is water at room temperature.

**Results and Discussion**

Experiments are carried out to study the influence...
of the vibration in the horizontal plane when frequency and amplitude are varied in a systematic way. It is found that when the cylindrical tank partially filled with liquid ($H_i = 300$ mm) is subjected to vibration in the horizontal plane and draining started, a vortex is formed, unlike in the case of vibration in the vertical plane. The detailed influence of the frequency and amplitude on this phenomenon is investigated. In the present study the results are presented for different values of frequency: 3.6 Hz (natural frequency of free surface oscillation in the horizontal plane), 7.2 Hz, 10.8 Hz, 14.4 Hz (multiples of natural frequency), 5 Hz and 9 Hz (two arbitrary frequencies) and at various amplitude of vibration. Experiments are also conducted at a subharmonic frequency of 1.8 Hz. However, it is observed that at this frequency there is no vortex formation.

Draining with vibration only (no rotation)—As reported in the previous study, when draining is
The natural frequency of the free surface oscillation of liquid in the tank was first determined and is equal to 3.6 Hz. This is done by finely tuning the frequency of vibration by using the waveform generator and finding the resonance condition. When the container is vibrated at this frequency, i.e., 3.6 Hz at various amplitudes and draining is started, it was observed that a vortex is formed when the amplitude is above 5.8 mm. This is shown in Fig.3a. However, the value of $H_c/H_i$ is around 0.5 unlike for the case with rotation where $H_c/H_i \approx 0.85^6$. It is very interesting to note that the vibration in the horizontal plane by itself can give rise to vortexcings unlike that in the vertical plane. The photographs (Figs 4a to d) show this phenomenon at four different instants of time while draining is taking place. In Fig.4a the vortex has just started forming and in other figures it is extending up to the drain hole.

The reason for this is probably due to strong sloshing that occurs in the azimuthal direction (Fig.5) which results in the displacement of the liquid column. Simultaneously, the entire liquid column appears to rotate about the vertical axis which can be made out by the different orientation of the liquid surface seen in Fig.5. In Fig.5a the peak of the displaced liquid surface is at the left end of the container. This peak has moved in an anti-clockwise (azimuthal) direction in Figs 5b and c due to the rotary motion. This 'apparent rotation' of the liquid about the vertical axis of symmetry of the tank, superimposed on normal sloshing motion
appears to be responsible for the formation of the vortex during draining. Such phenomenon is also reported at frequencies very close to the natural frequency of surface vibrations.

Similar experiments are conducted at other frequencies also. Vortex formation is not observed at these frequencies as shown in Fig. 3b. However, at 7.2 and 10.8 Hz, over a small range of amplitude (around 2 mm), a weak vortex is seen. The experiments at $f=14.4$ Hz are conducted due to the hump seen at 10.8 Hz. It was to check whether this phenomenon persists at higher harmonics also. As is seen, there is no vortex formation over the entire range of amplitude at $f=14.4$ Hz.

The draining time with only vibration in the horizontal plane ($t_v$) is also determined at various frequencies and the results are shown in Figs 6a and b. The correspondence between the Figs 3 and 6 can be clearly seen. At $f=3.6$ Hz, as long as the amplitude of vibration is smaller than 5.8 mm, the vortex is not formed; $t_v/t_0 \approx 1.0$. However, when the vortex is formed (amplitude greater than 5.8 mm) $t_v/t_0$ is nearly equal to 1.5. At frequencies other than 3.6 Hz, $t_v/t_0 \approx 1.0$ except for $f=7.2$ Hz and 10.8 Hz (Fig. 6b).

**Draining with vibration and initial rotation**—Initial rotation is found to augment the vortex formation as described. It is also seen that, horizontal vibration at the natural frequency of free surface oscillation (i.e. $f=3.6$ Hz) by itself can give rise to vortex formation. Hence, the question arises whether there will be further augmentation of vortex when both initial rotation and vibration are imparted. This becomes all the more relevant in the
light of studies with vibrations in the vertical plane where there is suppression of vortex. The procedure adopted is similar to that followed in the case of experiments with vibration in the vertical plane. After imparting the necessary initial rotation, the flow is allowed to take place from the container. Due to the presence of rotation, vortex is formed within a very short period of time. Immediately, the container is vibrated utilising the arrangement and the instruments shown in Fig.1.

At the frequency of \( f = 3.6 \) Hz, it is observed that the vortex is not suppressed when vibrated at various amplitudes. The photographs in Figs.7a to e demonstrate this fact. The vortex formed (Fig.7a) continues to exist during the entire period of draining (Figs. 7b to e). At the same time, it is found that the vibrations at this frequency do not augment or strengthen the vortex as reflected in the time of draining which is presented later.

However, at frequencies other than 3.6 Hz, the vibrations in the horizontal plane have the same effect as in the case of vibrations in the vertical plane, i.e., the vortex is suppressed or 'killed'. The detailed results at \( f = 5.0, 7.2, 9.0 \) and 10.8 Hz are shown in Figs 8a to d. The general features observed at these frequencies are that there is a minimum amplitude above which only the vortex is suppressed and this minimum amplitude reduces with increase in frequency. The typical variation (at any frequency) seen with amplitude is that there is an initial limb where the variation is steep and then, more or less a constant value of \( H_k/H_1 \) is observed. The steepness of the initial limb increases with increase in frequency and there is only a small difference between the results at rpm 94 and 143.

The minimum amplitude required (\( A_{\text{min}} \)) for vortex suppression at different frequencies is shown in Fig.9. It is seen that the variation is nearly asymptotic with increase in frequency.

As mentioned earlier and shown in Figs 7a to e, the vortex was not suppressed at \( f = 3.6 \) Hz. At other frequencies, it is possible to suppress the vortex formation. However, the vortex could be suppressed only as long as the vibration is maintained similar to the case with vertical vibrations. When vibrations are stopped, within a short period, the vortex reappears. Introducing the vibrations at this stage, the vortex can be suppressed and the process continues. These features are brought out in Figs 10a to h. The photographs with WV indicate results with vibration. In Fig.10a, the vortex has formed while draining due to rotation imparted (94 rpm). Then horizontal vibration is imparted due to which the vortex starts breaking up (Figs 10b and c) and eventually is completely suppressed (Fig. 10d). However, if the vibration is stopped and draining continued, the vortex reappears (Fig.10e). This vortex is also suppressed if the vibrations are reintroduced as seen in Figs 10f to h.

The draining time with initial rotation and vibration at various frequencies is determined and
shown in the set of Figs 11a to e. Considering Fig. 11a, i.e. at $f = 3.6$ Hz, it is seen that with increasing amplitude of vibration, $t_{rv}/t_o$ initially decreases reaching a minimum and then once again increases. This type of variation is not seen at other frequencies (Figs 11b to e). Though it is difficult to give the exact physical reason for the observed behaviour, it could be attributed to the non-linear interaction between the sloshing phenomenon and the vortexing. It is interesting to note that the vortex is not augmented or strengthened by the horizontal vibrations. This is borne out by the fact that $t_{rv}/t_o$ (Fig.11a) is always less than those with rotation and without vibration.

Considering the variation of $t_{rv}/t_o$ at other frequencies (Figs 11b to e) in conjunction with Figs 8a to d the following interesting features are seen. 1. Even before the vortex is completely suppressed, the time of draining starts decreasing. For example, at $f = 5$ Hz, the vortex is not suppressed for $a < 2.8$ mm (Fig.8a). However, at $a = 2.8$ mm for $D/d = 92/6$, $t_{rv}/t_o = 1.3$ i.e. there is nearly a reduction of 23 per
cent in the draining time compared to the value of \( t/t_0 \) without vibration. This indicates that the encroachment of the drain port by the vortex is reduced even before the vortex is completely suppressed by the vibration. The above feature is seen at other frequencies also (Figs 11b to e). 2. The influence of the magnitude of the rpm appears to be stronger on the draining time compared to the phenomenon of vortex suppression by vibration.

Similar to the case of vibration in the vertical plane, it is found that at any particular frequency (except at \( f = 3.6 \) Hz), a particular amplitude of vibration has to be maintained for a finite period of time to completely suppress the vortex. The results at various frequencies are shown in Figs 12a to d. From these figures, it is seen that there is an initial region of high amplitudes where the period over which the vibration is to be maintained, is nearly constant and small; with decreasing amplitude, much larger periods of time are required. The duration in the initial region of high amplitudes is around 5 s for \( f = 5.0 \) Hz (Fig. 12a) and it is around 2
at other frequencies (Figs 12b to d). There are very little differences between the results for 94 and 143 rpm.

Conclusion:
Vibrations in the horizontal plane can on their own (i.e. without initial rotation) induce vortexing unlike in the case of vertical vibrations. This occurs only at the natural frequency of the free surface oscillation and not at other frequencies. However, even at the natural frequency, with initial rotation there is no additional augmentation of the vortex. At frequencies other than the natural frequency, the vortex formed due to initial rotation is suppressed by the horizontal vibrations very similar to that observed for the vertical vibrations. However, the vortex is not suppressed at the natural frequency.

Fig. 12—Duration for vortex suppression (Hor. plane) (a to d)

References


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<tr>
<th>Nomenclature</th>
<th>Equation</th>
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<td>Diameter of the container</td>
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<td>Diameter of the drain port</td>
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<td>Frequency of vibration</td>
<td>( f )</td>
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<td>Height at which the air core is suppressed</td>
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