Dynamic hydraulic jumps in oscillating containers

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Abstract

When the liquid in a tank undergoes sudden movement, as in the case of a fuel tank in an aircraft or in a marine vessel, it may be subjected to as many as 6 degrees of freedom. Three of these are in rotation; yaw, pitch and roll, and three in translation; sway, surge, and heave. Work is currently being conducted on simulating the effects of the liquid motion under roll conditions in a rectangular tank of dimensions 1.9 x 0.94 x 1.2 m^3 located on a 6 degree of freedom simulator capable of mimicking the movements typical of an aircrafts performance. At present, water is being used to investigate the fluid motion when subjected to oscillating roll frequency of 0.35 Hz and oscillation amplitudes of 2.42^0, 3.50^0, and 4.71^0 for different liquid depths. It has been found that under such motions, typical of those obtained within the flight envelope of military, private and commercial aircraft, a dynamic hydraulic jump can occur. This jump is out of phase with the roll motion and is produced as the fluid abruptly changes direction within the tank. As the tank reaches its lowest rotational position in the roll manoeuvre the fluid level at this point of the tank increases rapidly against the end wall causing splashing, resulting in bubble formation and a fine spray. This change in direction increases the fluid depth and this has to move against the residual oncoming fluid that is at a much lower depth, resulting in a very dynamic, moving, wave that breaks and forms into a hydraulic jump comprised of air and liquid mixing. This preliminary investigation into the characterization of this phenomenon using water shows that the spatial characteristics of the hydraulic jump and the dynamic range of the resultant spray are affected by the amplitude of the tank oscillation.
Keywords: hydraulic jump, multiphase flow, particle image velocimetry.

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1 Introduction

Liquid dynamics in moving containers is of special interest to air, marine and ground vehicles due to the movement of the liquid, or slosh, in the container and the resulting impact forces it produces on the walls of the container. The role that liquid dynamics play in the stability of an aircraft has been extensively examined by several researchers. Slosh can influence the stability and control systems of air vehicles and care must be taken when designing a tank so that the sloshing impact forces can be controlled, [1, 2]. Furthermore, sloshing in partially filled liquid containers can significantly alter the motion of cargo ships [4, 5]. Each of these studies notes the formation of a non-linear, multiphase event, characterized by an air/liquid turbulent region, when the vessel is oscillated at the resonance frequency of the liquid in the container. This phenomenon is known as a hydraulic jump.

Hydraulic jumps are of special interest in dynamic container flows because they represent a transition between two flow states: subcritical and supercritical. Waves travelling faster than the wave celerity of the liquid depth must dissipate energy in the form of a hydraulic jump. The jump is characterized by a rapid change in liquid depth with a turbulent region between the two depths. These jumps can be stationary or moving, [6]. Previous research conducted by Chanson [7] has shown distinct flow regimes and spray regions for stationary hydraulic jumps in channel flows. His research showed that typical hydraulic jumps are comprised of an entrained air shear layer that forms at the base of the jump. Above this shear layer are multiple recirculation regions with air bubble entrainment. At the top of the jump, three distinct spray regions are produced: an aerosol/fog region, a spray/mist region, and large droplet region. However, the research of Chanson [7] utilized intrusive measurements which are not practical for dynamic environments.

The goal of the present research is to investigate the characteristics of dynamic hydraulic jumps that form under near resonance conditions. The spatial characteristics of the jump will be explored. Furthermore, a preliminary study of using optically based techniques to measure the spray distribution formed by the jump will be performed. This will provide insight into this multiphase phenomenon.

2 Theory

Two coordinate systems were setup to provide a theoretical basis for characterizing the liquid free surface in the tank coupled with the motion of the test fixture. These coordinate systems will also be referred to when discussing shallow water flow theory. The coordinate systems, shown in figure 1, contains the stationary coordinate system of $O - x_0\, y_0$ and the moving coordinate system of $G - x\ y$, which rotates about the origin O. The moving coordinate system moves with the tank with its origin, G, located at the center point on the base of the tank. The incline angle of the tank is given as θ, the wave height normal to the bottom of the tank and measured from the rest depth of the liquid is represented as η. The rest height of the bottom of the tank as H, and the rest height of the liquid is denoted by h_0.

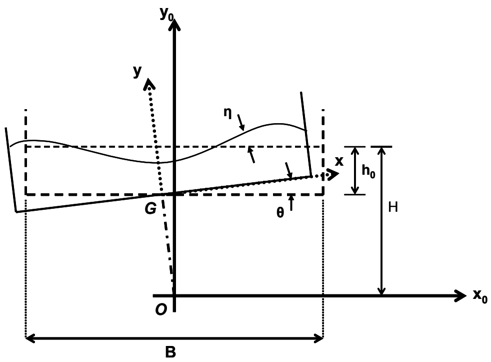

Figure 1: Coordinate system of dynamic tank.

The liquid dynamics within an oscillating tank have been extensively studied and modelled [3, 4, 9, 10]. It has been shown in these references that the resonance frequencies for a rectangular tank experiencing roll oscillations are given as:

$$f_n = \frac{1}{2\pi}\left[\frac{g\pi n}{B}\tanh\left(\frac{n\pi \quad h_0}{B}\right)\right]^{1/2} \quad n = 1,\ 2,\ldots,\infty \tag{1}$$

For shallow liquid depths, the fundamental resonance frequency (n = 1) can occur under small perturbations such as turbulence for aircraft or general water waves for marine vessels. As a result, an out of phase hydraulic jump is observed to travel back and forth between the end walls of the tank [8, 10]. According to a linearized theory called "shallow water wave theory" [11], the theoretical phase difference between the tank oscillation and hydraulic jump formation approaches 90° as the tank oscillation approaches the resonance frequency of the liquid depth. This implies that the jump forms at the centre of the tank for liquid depths where $h_0 << B$ [10].

3 Methods and materials

A testing facility at Wright-Patterson Air Force Base was utilized for an investigation on the effect of low frequency, small amplitude roll oscillations on the liquid dynamics in a rectangular tank. The test facility consisted of a state-of-the-art motion simulator and a clear, rectangular tank.

To replicate generic roll aircraft dynamics, a hydraulically activated Sarnicola Hexad AIES Six-Degree-of-Freedom motion simulator was employed. This simulator has base dimensions of 3.28 m (129'') x 2.03 m (80'') at a rest height of 1.73 m (68''), and it is capable of carrying an 11,364 kg (25,000 lb) payload. This motion simulator has 6 degrees of freedom provided by six hydraulic cylinders or actuators and is controlled through proprietary computer software called HexTest. The hydraulic cylinders are arranged in a hexapod configuration that allows for maximum rotational excursions.

A clear tank provides optical access to three spatial planes through the top, side, and front of the tank by means of 25.4 mm (1'') thick walls of Lexan with the other walls fabricated from 6.35 mm (0.25'') thick steel. An interior steel frame was constructed to provide additional reinforcement for the Lexan sides. The clear tank frame supports a tank with overall internal dimensions of 1.9 m (73'') x 1.2 m (48'') x 0.94 m (37''), yielding a maximum capacity of 2.1 m^3 (563 gal), and will provide a larger scale study than any previous experiments discussed in the previous section. Lexan walls with a thickness of 12.7 mm (0.5'') were added on the outside of the open sides of the tank shell to provide optical access in each spatial plane. The steel sides of the frame provided the internal tank walls for the remaining sides. The generic tank was positioned inside of the steel shell constructed of 6.35 mm (0.25 in) thick steel tubing and placed on the motion simulator. Steel tubing located on the top and two steel bars along the clear side of the tank provide additional support for the Lexan walls. The total motion simulator and tank setup is shown in figure 2.

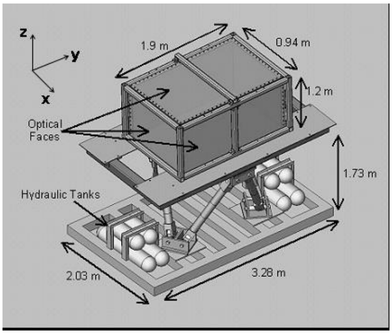

Figure 2: Overall simulator and slosh tank setup.

3.1 Data acquisition

A high-speed digital Nanosense XS-3 CMOS camera from IDT with a resolution of 1280 x 1024 pixels was utilized to capture the full field liquid dynamics within the generic clear tank. The camera was positioned on a tripod at a height of 1.93 m (76'') at a distance of 2.24 m (88'') from the front wall of the tank fixture. A 20 mm Nikon lens was attached to the camera and captured the full field of view of the test apparatus. The digital imaging system acquired video at 75 Hz for a total of 15 seconds at the start of the oscillation. All images were stored in the onboard camera memory and then transferred to the computer via the USB 2.0 connection upon completion of each test for analysis. The full field visualization setup is shown in figure 3.

To investigate the spray region above the hydraulic jump suggested by Chanson [7], a particle image velocimetry (PIV) system was used. The system is composed of a two-dimensional light fan created from a Nd:YAG laser and a high speed digital imaging system. An XS-4 camera with a 512 x 512 pixel resolution and attached 60 mm Nikon lens was used to image the spray region. This resulted in a field of view of 167 mm x 167 mm. The camera and laser are synchronized by a personal computer (PC) to pulse simultaneously. Several images of the spray above the hydraulic jump region were captured and downloaded to the PC for image analysis. The PIV system setup is diagrammatically shown in figure 4.

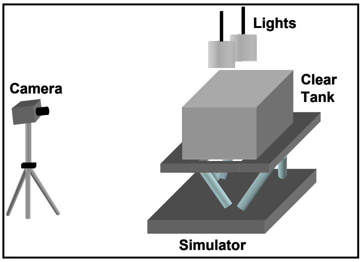

Figure 3: Full field setup.

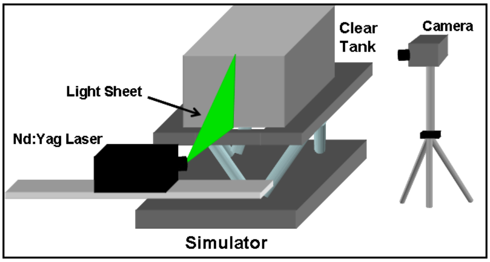

Figure 4: PIV setup.

3.2 Testing conditions

A liquid depth of 0.265 m (approximately 25% of the volume of the tank) was selected for the examination of multiphase flows in oscillating containers. This depth has a characteristic resonance frequency of 0.42 Hz based on eqn (1). The tank was oscillated at a near resonance frequency of 0.35 Hz and oscillation amplitudes of 2.42^0, 3.50^0, and 4.71^0 according to the expression in eqn (2). A slight offset, *A*, had to be introduced due to a bias in the motion simulator when the centre of gravity (CG) is shifted from its manufactured position. The asymmetry of the materials of each tank wall caused this shift in the CG.

$$\theta(t) = \theta_0 \sin(\omega t - \phi) + A \tag{2}$$

3.3 Data analysis

All post processing analysis was performed in the X-Vision software from IDT for the full field digital videos. The software was utilized to time stamp and measure spatial characteristics of the hydraulic jump formation. Each event was enlarged and its significant pixel locations noted. Also, the pixel locations of the bottom corners of the tank were recorded to provide insight into the angle of the tank as well as relative jump location with respect to the bottom and sides of the tank. A calibrated scale was positioned on the tank to determine a calibration coefficient, which was used to calculate the physical dimensions and locations of the hydraulic jump from the pixel locations determined previously.

For the PIV images of the spray region, the image analysis was performed in the Flowmanager software from Dantec Dynamics. This software implements a method termed "shadow sizing" to measure the equivalent diameter of the droplets. The equivalent diameter is the spherical diameter of a droplet that gives similar geometric and optical properties for the examined droplet. This method assumes each particle reflects light with a Gaussian intensity distribution with the greatest light intensity at the center of the droplet. A light intensity threshold is set by the user and employed by the software to find the edges of individual droplets.

4 Results

Each 15 second video was analyzed for hydraulic jump formations and the spatial characteristics of each jump were measured. A typical hydraulic jump in the 0.265 m depth is shown in figure 5 below. This phenomenon is characterized by the multiphase, turbulent region of air/water mixing coupled with a rapid change in liquid depth as evident in the encircled region in the figure.

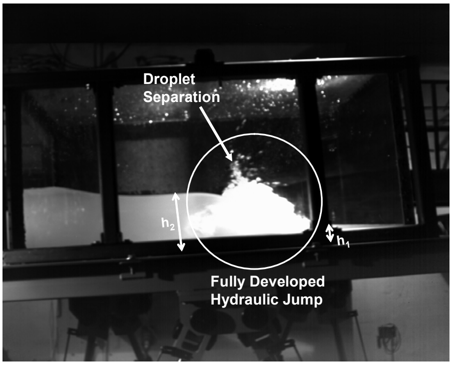

Figure 5: Fully developed hydraulic jump.

4.1 Hydraulic jump formation

The formation of each hydraulic jump was recorded and the tank angle at which the jump occurred was measured. The hydraulic jump formation points are presented below in figure 6. The data points represent the observation of a hydraulic jump and the solid and dashed lines represent the calculated tank angle based on eqn (2). Figure 6 shows the hydraulic jump formation for all three oscillation amplitudes at the 0.35 Hz oscillation frequency. Left to right hydraulic jumps formed at lower tank angles than right to left travelling hydraulic jumps. Each of these jumps formed at the frequency of the simulator.

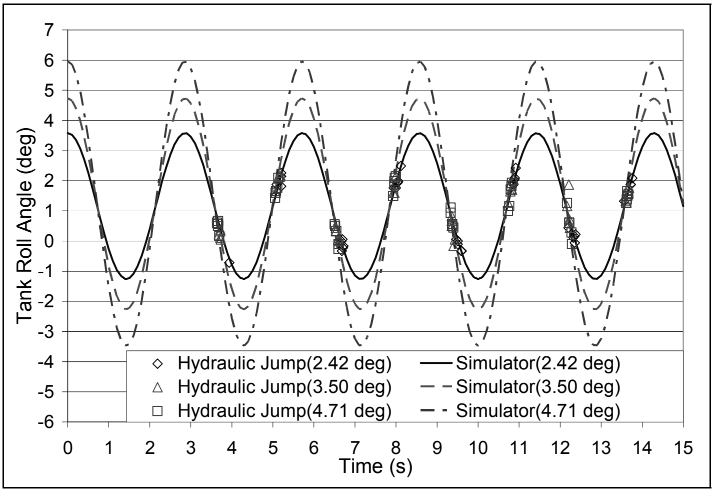

Figure 6: Hydraulic jump formation for three amplitudes.

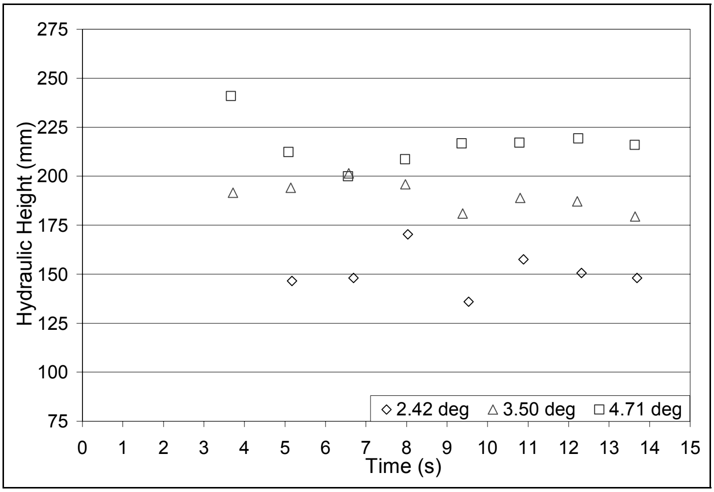

Figure 7: Hydraulic height for 0.265 m at 0.35 Hz.

4.2 Hydraulic height

To provide insight into the physical nature of each of the hydraulic jumps throughout the oscillation, the height of each jump at the time of formation was measured. Increased hydraulic height suggests greater energy dissipation and an increased amount of spray from an end wall impact. Furthermore, larger jumps suggest greater wave speeds and near resonance conditions. In figure 7, the hydraulic height variation of each observed jump throughout the oscillation is plotted. Increasing the amplitude of the tank oscillation increased the height of the hydraulic jump due to the greater gravitational force. The height changes with time due to the spray from the previous hydraulic jump impacting the end wall. Therefore, a tank oscillation produces a range of hydraulic heights throughout the oscillation.

4.3 Spray formation

The PIV system was used to image the spray region that forms above the hydraulic jump for the three oscillation amplitude conditions. Each image was processed by the acquisition software for the droplet size distribution in the image. These results are part of a preliminary investigation on the feasibility of using the PIV system to characterize the spray region. A typical PIV image from the 3.50° configuration is shown in figure 8.

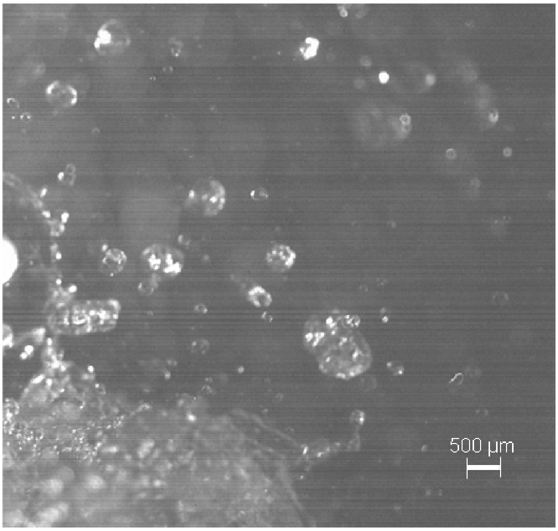

Figure 8: Typical PIV image.

Each image was analysed by the PIV software and a distribution of droplet sizes directly above the hydraulic jump for each oscillation amplitude was produced. Figure 9 shows the typical distributions for a given image at each of the oscillation amplitudes. The 3.50° and 4.71° amplitude appeared to produce a large amount of droplets compared to the 2.42° amplitude. Furthermore, the distribution shifted to larger droplets as the oscillation amplitude increased.

5 Conclusions

The spatial properties of multiphase flows in an oscillating tank environment have been examined. It has been shown that near resonance conditions, the formation of a hydraulic jump characterized by liquid/air mixing is observed.

The formation location of this event is dependent on the frequency of the tank oscillation. Furthermore, the angle of the tank at which the hydraulic jump formed appeared to be independent of the oscillation amplitude of the tank.

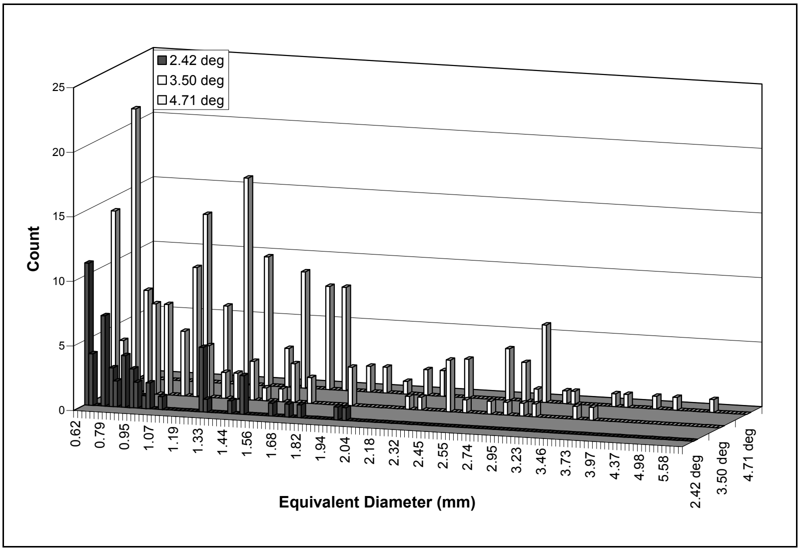

Figure 9: Equivalent diameter distribution.

The height of the hydraulic jump for the tested frequency is affected by the amplitude of the oscillation and the spray from the previous jump impact on the end wall. It is suggested that the increased gravitational force due to the greater incline angle of the tank increases the speed of the wave. As a result, a larger jump forms to dissipate the increased energy. All oscillation amplitudes of the tank exhibited a range of hydraulic heights produced throughout the oscillation.

Droplet separation was observed using the PIV system and preliminary results suggest that increased oscillation amplitude increases the size of the droplets produced. It is believed that the increased amplitude delivers additional kinetic energy to the hydraulic jump, allowing larger droplets to be ejected from the surface. Difficulties with the intensity threshold were noted and future tests are expected to provide a characterization of the droplet dynamic range as a function of height above the hydraulic jump.

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