Water Discharge From An Opening In Ships

S. M. Calisal[1], M. J. Rudman[2], A. Akinturk[1], A. Wong[1] and B. Tasevski[1]

Abstract

Water trapped on ship decks can play an important role in the safety of ships in terms of stability. The goal of this study is to understand the governing factors and to model the discharge mechanism of water from an opening e.g. freeing-ports onboard of ships. This paper presents the initial results obtained by experimental and numerical studies done at the University of British Columbia and Melbourne University, respectively.

In the formulation of the discharge flow from a flooded deck two major problems exist. One is the form and location of the free surface, the other discharge rate and how it is connected to the rest of the form of the free surface. In the study of water-on-deck flows without freeing ports, only the form of the water-on-deck is of interest. The problem of water-on-deck with discharge can be reduced to a water-on-deck without freeing ports if a relationship between the discharge rate and the free surface form can be established. This is the starting point of this research. The proposed method and approach consists of both the numerical and the experimental study of water discharge from the open deck of a ferry or a fishing vessel through permanently open freeing ports or freeing ports with a flap cover. A two-dimensional model of the discharge was built during the summer of 1997 to visualize the free surface and to measure the flow discharge from a flat bottom. The model has four different lengths corresponding to the width of the ship and the initial water height used before the discharge was changed in order to determine the importance of the level of accumulated water on deck. The discharge flow pattern and free surface form were recorded with a digital camera. The frames were captured on a computer and the location and the form of the free surface established. From knowledge of the free surface the change in volume, discharge rate velocity at the freeing port and various parameters of the discharge kinematics were calculated. The experimental results will be studied to generate numerical algorithms that can be used to calculate the discharge rates from freeing ports.

Numerical modelling and preliminary results are also given in this paper. Initial results suggest a very good agreement between the experimental and numerical results.

[1] University of British Columbia, Department of Mechanical Engineering, Canada
[2] Melbourne University, Advanced Fluid Dynamics Laboratory, Australia

1. Introduction

Some Canadian ferries operating in British Columbia in relatively sheltered areas have open car decks. Water could possibly collect on deck of these ferries by the scooping action in waves, or as a result of an accident thus causing loss of stability by a process which is generally known as the "free surface" effect. Various researchers in Canada have studied the possibility of water on deck and its drainage from freeing ports. The authors participated in the experimental study of water accumulation on a ferry model in head seas, Roddan et al. (1995). In this study the model was in moderate waves and a procedure was developed to estimate the minimum freeboard required to avoid water accumulation on deck for a given sea state, Calisal et al. (1997). This procedure consists of experimental and numerical results. During the summers of 1997 and 1998, discharge from a two-dimensional model of a section of a ferry was experimentally studied. The model, initially full of water was drained by instantaneously opening a freeing port. The measurement of the form of the water surface on board and the discharge rates were the primary objectives of this preliminary study. This preliminary experimental study allowed us to measure and document the variation of the free surface and discharge rates of water from the freeing ports during the draining phase. An optical measurement system was developed for this purpose, which uses a video camera, a frame grabber and specialized software developed in-house to calculate the location of the free surface during draining. The data collected are currently under study. This paper presents some of the preliminary results and comparison of the experimental results with the numerical predictions. The visualization showed that in addition to the expected gradual drop in the free surface, some traveling waves are also present on deck. The objective of this study is to develop a numerical procedure for calculating the water collection and discharge rates from the open deck of a ferry or a fishing vessel. The numerical procedures will be validated in experimental work and suitable design procedures and algorithms will be developed for the time-domain calculations of ship stability. The requirement of an estimate of the discharge rate is essential for the numerical calculations, and the use of such an algorithm permits the definition of the boundary conditions necessary for the application of numerical methods such as Boundary Element Method. The defining of a boundary condition supported by experimental work is expected to increase the numerical accuracy of the computed flow field, therefore of the critical discharge time. This in turn is expected to permit relatively fast evaluation of damaged stability of open deck vessels in time domain.

Another important objective is the establishment of a "closure" relationship for the completion of the potential flow formulation. That is, knowledge of the discharge rates for unsteady flow is necessary in order to assign the normal velocity boundary condition for the potential flow formulation (BEM). Work done on steady waterfalls suggests that the depth-Froude number of the flow should be equal to one ($Fr = 1$). However, our recent experimental work with a constant model length but with various initial water heights suggests that the Froude number of the flow discharging from the decks is time dependent and starts at a value of zero. The Froude number then increases to a value of approx. 0.7 and then starts to decrease continuously back to zero. We will study various model lengths and model roll frequencies to establish if numerical algorithms can be developed to predict the discharge velocity from knowledge of the instantaneous water height. Of course, the form of the water surface will remain an unknown and will be calculated by a numerical procedure. The overall objectives can be listed as:

- Establishment of a relationship between water height and discharge speed.
- We expect to find a time domain expression for the Froude number for unsteady free-surface flows. This algorithm is expected to improve the performance of existing codes on water deck flows as it will permit a relatively easy and accurate calculation of the discharge rates.
- This result will also be important for the understanding of free-surface flows such as waterfalls, where for steady conditions, the depth-Froude number is usually assumed to be equal to one.

  The development of a numerical code to establish water accumulation and discharge volume rates for different ship conditions such as rolling, and stationary, and with and without

list, will permit the study of the dynamic stability of damar :̣ feri
The study will give uւsign criteria for the minimum free board necessary for open-deck ferries, as this height determines the amount of water which will accumulated on deck for a given wave height condition. As this rate must be smaller than the discharge rate for the number of available freeing ports, a design procedure based on a design wave height, freeboard height and number and size of freeing ports will result from this study.

2. Experiments

The experimental apparatus consisted mainly of the following items: water discharge tank, data acquisition devices including a high speed camera, VCR, and data analysis devices including video frame grabber, imaging software, and a surface scanner program.

A discharge tank was constructed with 1/2' clear Plexiglas (see Figure 1). The inner dimensions of the tank are 6 feet long by 1.5 feet tall by 1 feet wide, or 72 x 18 x 12 inches respectively. The tank is closed on one end and water is only allowed to drain out of the other end. A height adjustable gate was installed on the open end such that the opening area of discharge port can be changed between 0 and 12 inches. An elastic cord mousetrap like device was used to open the piano hinged door to start the discharge very quickly.

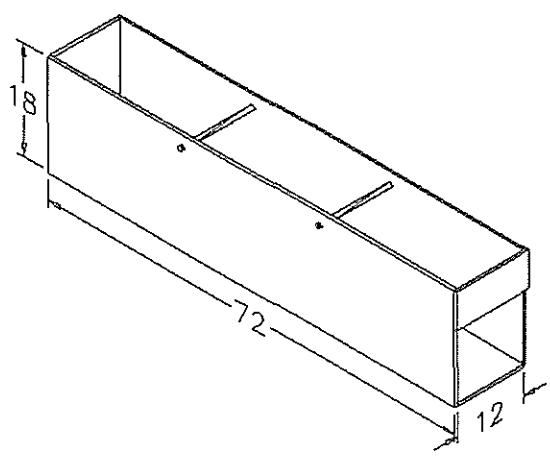

Figure 1. Plexiglas discharge vessel dimensions

A dexion table with four height adjustable feet was also constructed to support the tank. The adjustable feet allowed us to properly adjust the height such that the tank could be perfectly level.

For experiments where shorter tank length was required, a piece of 1/2-inch removable Plexiglas divider was placed at the desired location (see Figure 2). The divider was supported by an angle plate and a 2 x 6 lumber to prevent it from sliding back when the other side was filled with water. A non-permanent rubber gasket tape was also added at the edges to prevent leakage.

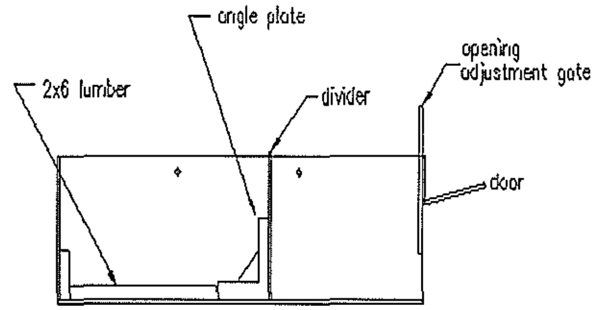

Figure 2. Side-view of discharge vessel

2.1 Data Acquisition Devices

The Optikon MotionScope High Speed Video System was used to capture the discharging water profile near the opening of the gate (see Figure 3). The system is a simple to "point" and "shoot" device, with a built-in 5" monochrome CRT video display and a separate video camera. The system has the capability to capture 60, 120, 180, 250, 300, 400, and 500 frames per second. The electronic shutter is also user adjustable and can be set from 1X to 20X of the set recording rate. The images captured were stored temporary in the system's buffer, with a capacity to store up to 2,048 full frames.

The lens which came with the MotionScope was removed and a Cosmicar CCTV 1/2-inch manual-iris c-mount lens was used as a replacement (see Figure 4). This lens was used because the software that was used to analyze the captured data had previously been calibrated for distortion with this particular lens. With the irregularity of the MotionScope's camera however, some problems were encountered with the lens geometrical specifications. For one, the Cosmicar lens was located too closely to the CCD of the camera, which caused the lens to provide a very large field of view (FOV) which cannot be focused properly. A 5mm CS to C mount adapter ring, which was supplied with the MotionScope, must be installed onto the lens mount of the sensor head assembly before the c-mount lens could be mounted. However, with the use of the adapter ring, the lens was moved too far away from the CCD which gave us a very small FOV (5.64 degrees). Nonetheless, this set up was used because no other options were available if the MotionScope was to be used. The small FOV was compensated for by moving the camera further away from our water tank.

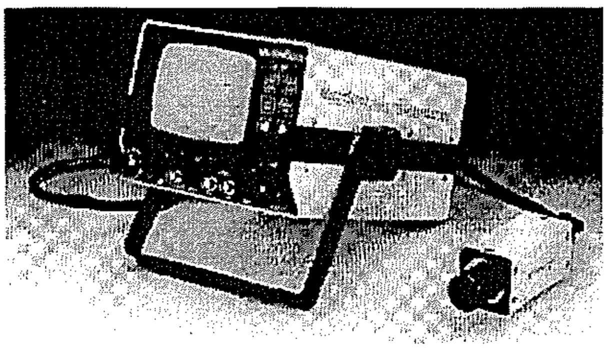

Figure 3. Optikon MotionScope High Speed Video System

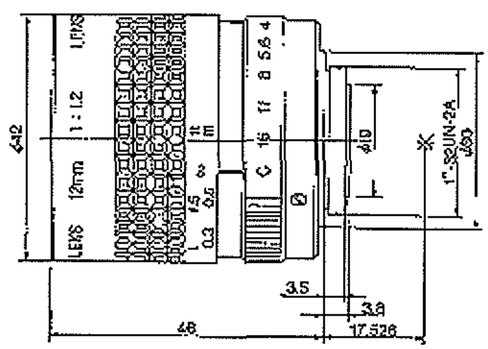

Figure 4. Cosmicar CCTV 1/2inch manual-iris c-mount lens

2.2.1 TV and VCR

A TV and VCR combo was required due to the lack of permanent storage on the MotionScope. The data from the MotionScope was played back through it's RS-170 (NTSC compatible) video output and recorded onto a videocassette in the VCR. If a PC computer with a frame-grabbing card was available, then the TV and VCR would not be required as we could directly save the MotionScope playback images as a bitmap on the computer.

A schematic of the experimental setup is shown in Figure 5. The camera was placed in such a way that the line passing through the center of the lens and its focal point is perpendicular to the side of the disharge tank. With the current distance (S), it was able to capture the floaded length of the discharge tank.

In this initial study, there were three parameters that were planned to change, t, height of the opening, h, initialwater height in the tank and l, floaded length of the tank. For the results presented in this paper, only initial water height was varied as 6, 10 and 14 inches. The floaded length was 2 feet and height of the opening for water discharge was 4 inches.

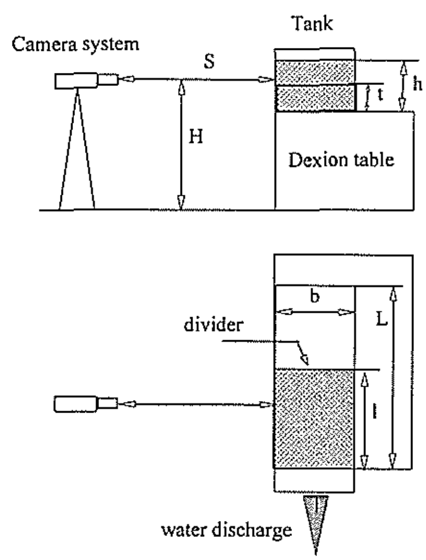

Figure 5: Experimental setup

3. Numerical Method

The numerical method used to simulate the flow of water through the dam sluice gate is the volume tracking method of Rudman (1998). The method is based on the Volume-of-Fluid (VOF) method introduced by Hirt and Nichols (1981) and improved by Youngs (1982). A brief overview of the method is given here, but details of the implementation are beyond the scope of this paper and may be found in Rudman (1998).

The gas-liquid system is treated numerically as a single incompressible fluid whose density and viscosity vary rapidly in the vicinity of physical interfaces. The incompressible Navier-Stokes equations for a variable density fluid are written:

$$\frac{\partial (\rho U)}{\partial t} + \nabla\cdot(\rho\ UU) = -\nabla P + \rho\, g + F_S + \nabla\cdot \mathrm{T} \qquad (1)$$

$$\nabla\cdot U = 0 \qquad (2)$$

$$\frac{\partial C}{\partial t} + \nabla\cdot(U C) = 0 \qquad (3)$$

where ρ is the density, U is the velocity vector, P is the pressure, g is the gravity vector, F_S is the surface tension force and $\mathbf{T}$ is the stress tensor defined as:

$$\mathbf{T}_{ij} = \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \qquad (4)$$

The fractional volume function C is a function that takes a value of one inside the liquid and zero inside the gaseous phase. In computational cells through which the interface passes, the value of C varies between 0 and 1. Local densities are calculated from C using:

$$\rho = C\rho_G + (1-C)\rho_L \qquad (5)$$

And local values of the dynamic viscosity μ are determined in a similar manner. The equations are discretised on a rectangular Cartesian mesh.

The numerical method is second order in time and space. It uses the Flux-Corrected Transport (FCT) ideas of Zalesak (1979) to calculate the advective terms in the momentum equations and a multigrid pressure solver based on the Galerkin coarse grid approach of Wesseling (1992) to solve for pressure and enforce incompressibility. Accurate determination of surface tension forces is often an important part of the solution of free surface flow problems and is achieved here using a kernel-based variant of the Continuum Surface Force (CSF) method of Brackbill et al. (1992). In this method, a continuously varying body force approximates the exact discontinuous surface force over a thin transition region near the interface. Volume tracking (Eqn 3) is undertaken using a Volume-of-Fluid method based on that of Youngs (1982). VOF methods are designed to maintain very thin numerical interfaces, with the transition from gas to liquid occurring across just one mesh cell in most instances. The advantage of VOF methods over more common approaches for interface problems (such as Boundary Integral Methods) is the ability to accurately simulate arbitrarily complicated problems of fluid coalescence and fragmentation without the need of purpose-built algorithms. In the code used here, the only difference to the method discussed in Rudman (1998) is the inclusion of obstacle cells that allow arbitarily complex internal boundaries to be included in a computation. These obstacle cells are included in the same way as in the original Marker and Cell (MAC) method of Welch et al. (1965)

The basic first-order in time algorithm on which the second-order method is based is as follows:

1. Estimarte new values of C:

$$C^{n+1} \doteq C^n - \delta t(\nabla\cdot U^n C^n)$$

2. Estimate new densities and viscosities, ρ^{n+1}, ρ^{n+1}, using Eqn 5.
3. Estimate new velocities using old timestep velocities and pressures:

$$\rho^{n+1} U^* = \rho^n U^n + \delta t\,(-\nabla\cdot\rho^n U^n U^n - \nabla P^n + \rho^n g + F_S^n + \nabla\cdot \mathrm{T}^n)$$

Calculate the pressure correction ρP required to enforce incompressibility:

$$\nabla\cdot\left(\frac{1}{\rho}\nabla\delta P\right) = \frac{1}{\delta t}\nabla\cdot U^*$$

4. Adjust velocities and pressure:

$$U^{n+1} = U^* - \frac{1}{\rho^{n+1}}\nabla\delta P$$

$$P^{n+1} = P^n + \delta P$$

The second-order in time algorithm used in this study performs two passes of steps 1-5. On the first pass, steps 1-5 are performed using a half timestep. In the second pass, steps 1-5 are performed again with a full timestep, the only other difference being that the pressures and velocities on the right-hand side of step 5 are replaced by the half time estimates calculated in the first pass.

The computational domain was discretised on a uniform mesh of 256 × 192 grid cells with physical dimensions 1000mm × 750mm. The holding tank (dimensions 601mm × 425mm) was then numerically `constructed' by placing a horizontal row of obstacles cells at a height of 200mm above the domain bottom (forming the tank base) and a vertical row 601mm from the left wall of the domain (forming the tank wall). The additional part of the domain outside the tank was required in order to allow the fluid to drain from the tank in a natural way without enforcing arbitrary (and possibly incorrect) boundary conditions on the draining process. The initial condition had the tank filled to a depth of 356mm. The initial velocities were zero and the pressure was set to be equal to the hydrostatic pressure equilibrium that would exist if the tank gate were closed. At zero time, the gate is instantaneously removed and the water flows out of the opening under gravity.

4. Results

As mentioned earlier, after the discharge gate opens, a travelling wave is observed as the free surface level drops gradually. Figure 6 shows the drop in the free surface level and the formation of the travelling wave as the time progresses. The discharge end of tank corresponds to the location around 0.6 meters in the figure. Numerical results are shown as lines. "x" marks the experimental results in the figure. Generally, there is a very good agreement between the two results. In both of the results travelling wave phenamonon was apparent.

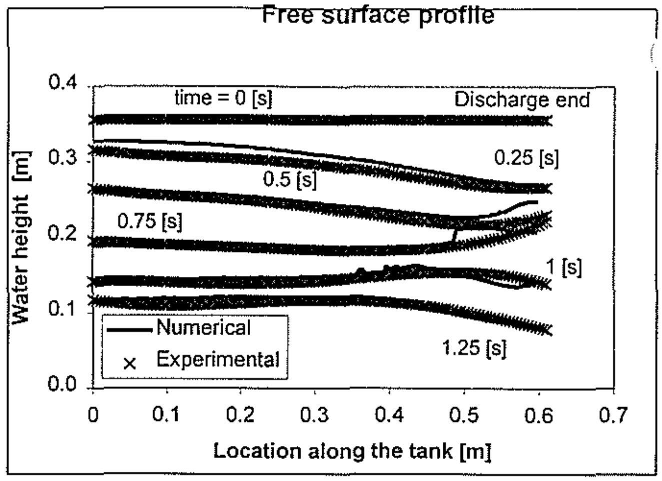

Figure 6: Comparison of the free surface profiles inside the discharge tank at different times

In Figure 7 discharged volumes for both numerical and experimental study are compared. Initially, the agreement is very good between the numerical and experimental volume data. However, as the free surface level decreases considerably, there appaers to be some differences between the two cases (see Figure 7).

Figure 8 shows the effects of initial water height on the Froude number (Fn). The definition of Fn is as follows:

$$Fn = {(Q/A)}\Big/{\sqrt{g * Hr}}$$

Where Q is the discharged volume per unit time, A is the exit cross sectional area, g is the gravitational acceleration and Hr is the water height at the rear end of the floaded section. As shown in the figure, Froude number initially starts from 0, increases to a certain value (less than 1) and drops to zero as the amount of water reduced in the discharge tank. From the figure, it seems that as the initial water level in the tank increases so as the maximum Froude number for each experiment. Maximum Froude numbers for the experiments with 14, 10 and 6 inches of initial water heights are approximately 0.7, 0.6 and 0.3 respectively.

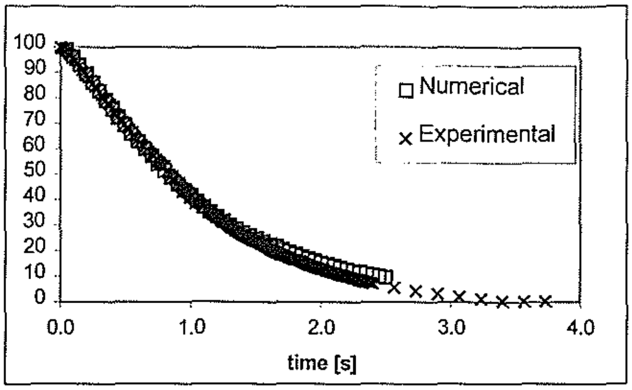

Figure 7: Remaining volume in the discharge tank as the percentage of the initial water volume

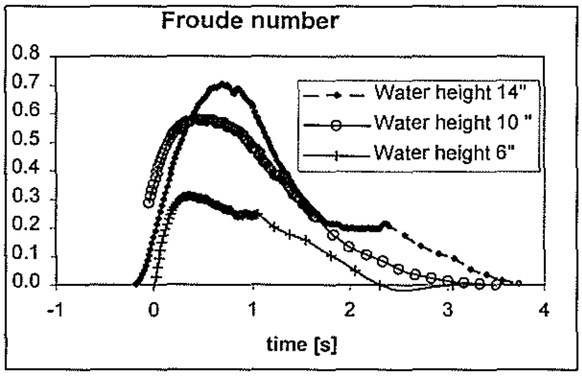

Figure 8: The effects of initial water height on the Froude number

5. Summary

Up to now two model lengths (length of the floaded section in the discharge tank) have been used and discharge data for them at various initial water heights stored. However, the results presented in this paper correspond to 60.96 cm model length only. The discharge tank was filled with water at a prescribed level and the discharge gate was opened to simulate the freeing ports with a flap cover. The discharge flow pattern and free surface form were recorded with a digital camera. The frames were captured on a computer and the location and the form of the free surface established. From knowledge of the free surface the change in volume, discharge rate velocity at the freeing port and various parameters of the discharge kinematics were calculated. In addition to using horizontal bottom conditions we intend to study discharge from listing and periodically rolling decks both with permanently open freeing ports and with freeing ports that have flapped covers. The experimental results will be studied to generate numerical algorithms that can be used to calculate the discharge rates from freeing ports. Time domain results will also be used to validate the numerical studies.

Initial numerical calculations done by Rudman showed that a very good representation of flow can be predicted by his formulation including wave formation by the opening of the gate. This type of wave formation was observed during the experiments and was successfully predicted using this code.

After completion of the two- dimensional studies we intend to model symmetric, three- dimensional flows and study them experimentally and numerically.

6. References

Brackbill JU; Kothe DB; Zemach C (1992) A continuum method for modelling surface tension. *J. Comput Phys*. **100**: 335–354

Hirt CW; Nichols BD (1981) Volume of Fluid (VOF) Methods for the dynamics of free boundaries. *J. Comput. Phys.* **39**: 201–225

Rudman, M (1998) A Volume-tracking method for simulating multi-fluid flows with large density variations. *Int. J. Numer. Methods Fluids* **28** 357-378.

Welch, JE, Harlow, FH, Shannon, JP and Daly, BJ (1965) The MAC method: A computing technique for solving viscous, incompressible, transient fluid-flow problems with free surfaces, Los Alamos Scientific Laboratory Report LA-3425.

Wesseling P (1992) *An introduction to multigrid methods.* John Wiley and Sons. Chichester U.K.

Youngs DL (1982) Time-dependent multi-material flow with large fluid distortion, in *Numerical methods for fluid dynamics*. Morton and Baines (eds), Academic Press, New York: 273-285

Zalesak ST (1979) Fully multi-dimensional Flux Corrected Transport algorithms for fluid flow. *J. Comput. Phys.* **31**: 335–362