FLOODED VOLUME BY CALCULATION: AN EXAMPLE

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ABSTRACT

The International Maritime Organization 2000 High Speed Craft Code specifies that the amount of accumulated water needs to be determined to assess the residual stability of a damaged ship. This paper presents a methodology used to determine the volume by calculation from relative water levels within the model. The method uses multiple water level probes to determine the flooded volume of volume cells in the model. The paper discusses the calculation of volume cells, calibration, measurement, and uncertainty of the method. Model test data indicate the method is valid and can capture transient flooding events.

KEYWORDS damaged stability, flooded volume

INTRODUCTION

This paper details the measurement of flooded water in an experimental investigation of the damage stability performance done in May 2000 (Thomas and Bachman 2000). The purpose of the model test was to investigate the behavior of the hull subject to flooding at a critical location in calm water, waves, and during maneuvers. Additional goals of the test were the collection of data for the validation of theoretical damage stability predictions as well as the identification of basic sloshing behaviors.

The testing was performed in the Maneuvering and Seakeeping Basin (MASK) of the Naval Surface Warfare Center, Carderock Division (NSWCCD) by the Seakeeping Division, Code 5500.The model was 6.1 meters in length with a hole on the starboard side, allowing for flooding of 3 compartments. The model was radio controlled with data transmitted to shore. Wave data were collected on a separate computer located on the MASK carriage.

There were four model configurations tested – three hole sizes and two metacentric heights (GM) at the largest hole size. The model was equipped with a remote controlled, pneumatically actuated, poly-carbonate panel (door) that covered the hole. This door ran in rails up alongside the hull and over the deck. The door was heavily greased with silicon grease to ensure watertight integrity and ease of movement. The door was connected to the pneumatic ram by steel wires. This arrangement allowed for very rapid hole opening. There were two door sizes. The first door covered hole 1, while the second door covered hole 2 and then hole 3. Holes 1, 2, and 3 had equivalent full-scale areas of 50, 84.1, and 138.3 m^2, respectively. A section of the starboard bilge keel was removed for holes 2 and 3 to accommodate the larger holes.

Additionally, the instrumentation and ballasting changed between testing with holes 1 and 2. The major change in instrumentation was replacing the yaw gyroscope and roll and pitch potentiometers with a KEARFOTT^{tm} T16 Miniature Integrated Land Navigation System (MILNAV^{tm}). Data were collected at 20 Hz.

IMO RO-RO GUIDELINES HSC CODE

The International Maritime Organization (IMO) High 2000 Speed Craft (HSC) Code specifies that the amount of accumulated water needs to be determined to assess the residual stability of a damaged ship. The HSC Code is aimed at high speed ferries and Roll-On/Roll-Off ships to ensure their safety if damaged and flooded. There are two methods outlined in the Interim Guidelines for Model Testing Annex to measure accumulated water. The first, is to measure the amount of water after each run by emptying the model, measuring the extracted water, and then replacing the water for the next run. The second method is to calculate the amount of flooded water by use of multiple water height probes in the flooded compartments. The HSC Code gives specific guidelines on number of probes and probe locations.

The applicable sections are 5.4.3 and 5.4.4 of the Annex. Section 5.4.3 describes the two methods and defines steady state volume. Section 5.4.4 gives details on calculating the amount of flooded volume.

The HSC Guidelines call for 15 probes arranged in 5 rows of 3 probes in the vehicle space. The rows are 10%, 30%, and 50% from the bow and aft watertight boundaries of the vehicle space. Transversely, the probes are port, centerline, and starboard. The volume is then calculated based on the given formula, vehicle space plan area, and mean heights of water at these locations.

Measuring the water after each run is certainly the simplest method. The water can be vacuumed out very quickly and thoroughly. Still there is always some water that remains in the model, vacuum, or sponge that remains unmeasured. Additionally, stopping every run to measure the accumulated may increase the test time by an unacceptable amount.

Calculating the amount of water in the model using wave probes requires more effort in model construction, probe calibration, and uncertainty control. The advantage of calculating the amount of water is the measurement of transient effects, such as initial flooding and sloshing.

Both methods are acceptable. This report deals with the second method, calculation of flooded water, though the test did not follow HSC guidelines on probes or locations. Still the methodology used is applicable to HSC damaged stability testing.

FLOODED COMPARTMENT SET UP

Determination of the flooded water levels in the scaled model begins with defining the compartments in the full-scale ship. The damaged test condition of the ship was that which had the most severe impact on static stability caused by a single hull penetration. The worse case scenario tested addressed the stability requirement that a U.S. Navy ship longer than 300 feet must withstand a hole 15% the length of the waterline (DDS079 1976). This length encompasses the breaching of the two transverse watertight bulkheads. Damaged stability was evaluated using the Ship Hull Characteristics Program (SHCP) (SHCP 1976) to determine which flooded compartments yielded the worst static stability condition.

The damaged compartments were fully open, with the exception of the counter-flooding compartments that communicate with the open spaces via cross-flooding or up/down-flooding ducts. This was to simplify the software modeling.

The damaged volume comprised 3 compartments and was divided into 16 separate volume cells. Dividing the compartments into cells distributed throughout the floodable spaces provided the means to determine water level in the compartment. The compartments are designated A, B, and C. Each volume cell had a capacitance probe associated with it, as seen in Figure 1. Each probe measured the level (sounding) of the water column in its immediate vicinity. Not all probes are the same height. Probes are numbered within each compartment, e.g., A3. The cells, representing cross-sections of the water columns, can be seen by the dashed lines in Figure 1. The number of probes is similar to the number specified by HSC Code.

Compartment A represents part of the main engine room. Compartment B is the rest of the main engine room with some crew space. Compartment B is the largest compartment. Compartment C is crew, recreation, and library space with many cross flow ducts.

Foam blocks were added to the model to match the compartment permeability to that of the ship. The middle compartment (B) permeability matched quite well between the model and ship without modifications. Blocks were added to compartment A. The model's aft compartment (C) permeability was less than the ship's, so the foam block representing Module-B in compartment C was narrowed appropriately to match the ship permeability.

Damage to model bulkheads was modeled by removing sections from the centerline to the starboard side between the base to just below the damage control deck. The two damage bulkheads would be located at the forward and aft edges of the damage hole shown, extending athwartships to the port hull. The intact compartments are crosshatched in Figure 1.

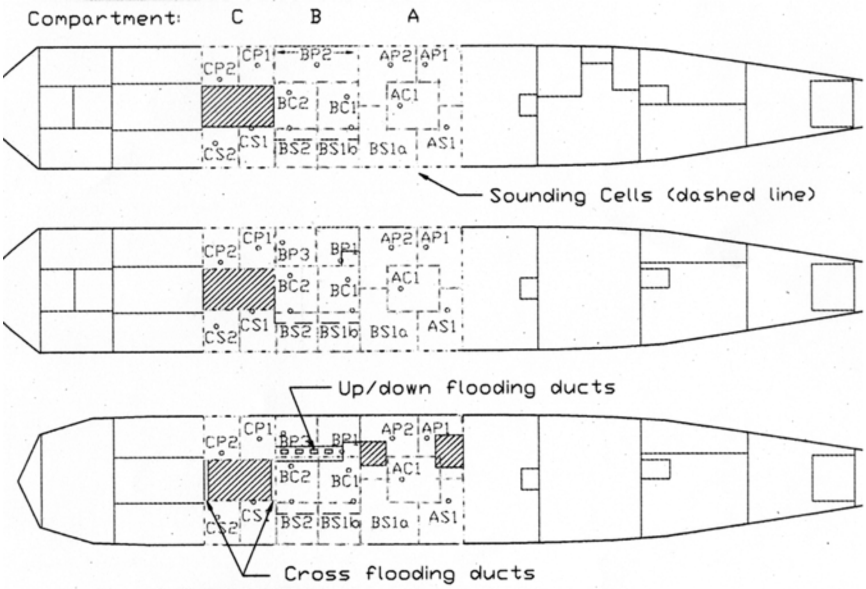

Figure 1. Damaged compartment and volume cell locations by waterline.

Table 1. Maximum volume cell capacities.

Volume cell	Model scale (ltrs)	Full scale (m3)
AP1	17.34	265.25
AP2	24.63	376.76
AS1	21.81	333.70
AC1	22.18	339.35
BP1	5.48	83.86
BP2	11.76	179.88
BP3	5.48	83.90
BS1	16.54	253.07
BS1A	29.43	450.20
BS2	20.35	311.32
BC1	25.77	394.25
BC2	25.43	388.99
CP1	9.68	148.02
CP2	9.05	138.51
CS1	12.85	196.61
CS2	9.75	149.10

DETERMINATION OF WATER LEVELS

The water level for each cell was measured using a capacitance probe sensor. Measuring the time history of water levels provides not only the water levels, but also flow rates and volumes. The distribution of the probes required providing a degree of separation between the probes to minimize electromagnetic interference from each other. Shielding the probes with perforated aluminum tubes additionally mitigated interference.

The SHCP program was used to establish virtual compartments representing the volume cells, and to determine the soundings of each of the virtual compartments. The cells have a consistent cross-section throughout the elevation, with the exception of cells BC1, BC2, AP1, and AP2 at the lowest levels. Cells BC1 and BC2 are slightly expanded to the port. Cells AP1 and AP2 are reduced in the lower half of Compartment A, due to machinery volumes. SHCP uses a generic permeability that is evenly distributed throughout the space. However, in the case of Compartment A, the generally distributed SHCP permeability was concentrated into machinery volume.

All but three of the probes extend from the intact damage control deck down to an intact bottom tank. Three of the probes, BP1, BP2, and BP3, measure more limited elevations than the others. BP1 and BP3 measure the water levels at the crew space. These two probes are isolated from the water external to these decks because the aluminum tubes were perforated only in the span of interest. BP2 measures the water level only in the uppermost exposed deck of Compartment B.

The soundings were at 0.39 m increments full scale, beginning and ending at the appropriate elevation. When combined, the flooded levels of each of these cells yielded the total volume, i.e., capacity, of water in the actual flooded compartments. The capacities of each of the three compartments (A, B, and C) and their associated cells are presented in Table 1.

The cell capacities versus soundings for zero trim and zero heel were plotted and 4-6th order polynomial curves determined. The elevations and capacities were converted to model scale for application to the capacitance probes.

FLOODING CALIBRATIONS

With the model assembled, the calibration of the wire probes was the next step. Calibration of the probes outside of the model was not successful to electronic sensitivities in the capacitance probes. The probes were calibrated by pouring water into the sealed model and estimating water depth at each probe and measuring the probe output. Water depth could be estimated by counting the number of perforation holes. The output from the capacitance probes was volts, which was converted to data counts by the analog-to-digital board.

The total volume flooded regardless of hole size or GM is 156 liters model scale. The lost of buoyancy due to flooding is the same for the different loading conditions. The smaller restoring moment for GM#2 results in more heel, as shown by the data.

Three attempts were made to calibrate the wire probes, though none were perfect. The first attempt, DSCAL01, recorded water depth by tube hole, water volume by tank, and data counts; however, not all probes were recorded. The second attempt, DSCAL03, recorded water depth by hole and data counts, but not water volume. The final attempt, runs DSTAB102-104, recorded total water volume and data counts, but not tube hole. Furthermore, probe 5 (BS1) was not working during the last attempt. The probe calibration coefficients were not the same between DSCAL01 and DSCAL03.

Initially, the model test used wire probe calibrations based on a linear fit to DSCAL03 data, converting holes to engineering units. Using these values resulted in a large difference in total volume from the measured total volume of 156 liters model scale. Using quadratic fits to the DSCAL03 data resulted in total volumes on the order of 126 liters total, i.e.30 liters too little.

The post processed data used a new set of calibration numbers based on the final volume check, DSTAB102-104. Because the probe locations are known, it is possible to calculate relative water levels at each probe based on geometry, heel, and trim. An iterative solver calculated absolute water levels and cell volumes based on matching total volume, using the cell volume curves. These, combined with the measured counts, provided the data for calibration coefficients.

The exception was probe 5 (BS1), which was malfunctioning intermittently. Probe 5 (BS1) was one of the largest volume cells and required to determine the flooded volume. The following method was used to compensate when necessary. The data counts for zero and full flooded volume are known from other zero runs. The BS1 calibration curve is the same shape as BS2 (probe 6) between these end points. The total volumes using these calibration coefficients and BS2 water level for BS1, matched the measured volumes to within 2.76%. These new probe calibration coefficients are a combination of quadratic and cubic fits, see Table 2. As some port side probes were not wet, i.e., their cells were not flooded, DSCAL03 data were used where needed.

The calculated flooded volume for all the flooded zeros for holes 2 and 3 is 156.3±10 liters for GM#1; and 155.7±2 liters for GM#2. For GM#1, 10 probes had standard deviations in volume of over a half liter. Probe BS1 had over 4 liters. For GM#2, all probes had standard deviations less that a half liter, except BS1 which was 1.5 liters.

Figure 2. Zero speed transient flooding in 1/20 slope regular waves for hole #2, GM#1.

An alternative method would be to pour in water while maintaining zero trim and zero heel. This would have flooded the higher, port probe volume cells.

UNCERTAINTY ANALYSIS

The uncertainty of the flooded volume is the combination of wire probe and cell volume uncertainty. The average standard error of the 16 probes was 7.1mm. This number is the error associated with the calibration curve fit to the calibration data. The 7.1mm error corresponds to a error of 68.14 tonnes full scale for total volume.

The average standard error associated with the curve fit of the cell volume to water depth is 8.21 tonnes full scale. The combined error of the flooded mass due to probe calibration and cell volume is 68.63 tonnes full scale. While the standard error for the cell volume curve fit is a small contributor to the combined error, it can be reduced to negligible amounts by the use of more significant digits for the curve coefficients. This is especially true for higher order polynomial fits.

Probe 5, for cell BS1, was electronically unstable and would record obviously erroneous data. This was compensated for by using BS2 as mentioned in the CALIBRATION section. For GM#1, 11 of the probes had standard deviations greater than 1.27 cm; with BS1 being 2.97 cm. A 2.5 cm change in water level can result in a 20-liter volume change for the entire flooded compartment. Also the probes were removed and replaced between holes 1 and 2, without re-calibration.

The mean roll angle for hole 1-GM#1 is –13.58±0.52deg; for holes 2 & 3-GM#1 –13.55±1.51 deg; and for hole 3-GM#2 –25.90±0.46 degrees. The large standard deviation for holes 2 & 3 result from four runs whose heel was near –16.4 degrees. It is uncertain why those runs were different, but ignoring them results in a heel angle of –12.55±0.67 degrees.

Trim angle for hole 1 was –0.60±0.028 deg, and -2.40±0.11 degrees for the other holes. So flooding the compartments results in a small change in trim as well as heel.

FLOODED ZERO CONFIRMATION

The flooded zeros provided a good check for the wire probe calibrations and flooding calculations. The zeros were repeatable throughout the entire test, except for runs DSTAB029-32. Runs DSTAB029-032 have a 16-degree mean heel rather than 13 degrees with flooded volumes being similar. Given the probe water levels are comparable to other GM#1 conditions, it is uncertain why these runs had more heel. The test log notes that the door popped off right before the heel angle increased. The flooded heel angles returned to their more expected values the next day.

EQUILIBRIUM FLOODING

Equilibrium flooding runs evaluated the model motions in the damaged condition, with the door open in waves. This is the IMO HSC and ITTC scenario of a damaged ship, dead in the water, in a seaway.

The model was allowed to drift without rudder or speed control during the test. During regular wave runs, an attempt was made to obtain 24 cycles of data, realizing that some of the later data may be corrupted by reflection from the beach. Typically, only 10 cycles are necessary for harmonic analysis, but more data provides a smaller margin of error. The irregular sea data were collected in six to eight minute runs. The minimum time for a condition was six minutes, but if conditions permitted, more data were collected. The runs were stopped when the model drifted away from the center of the wave train or when the possibility of collision with a wave probe existed. The data collection start and stop times were synchronized between the carriage and shore collection computers.

Collected data show the effect of inflow and outflow due to wave action as oscillations in total volume. Examining the changing volume of the different cells shows the effect of sloshing within the compartment. See Figure 2 for an example of equilibrium flooding in waves following transient flooding.

TRANSIENT FLOODING

Transient flooding cases modeled the sudden flooding of a compartment and subsequent dynamic response. It was of interest to determine if a quickly moving mass of water could provide an overturning moment, in an otherwise stable position. This model test did not have any instances of capsizing due to transient flooding. The model did heel quickly, with some overshoot, but the motion soon reached stable equilibrium.

The sudden flooding was accomplished by opening the remote controlled pneumatic door on the starboard side of the model. The hole was located with the centriod at the waterline for hole 1 and 0.76m below the waterline for holes 2 & 3.

There was an attempt to maximize the force of the water entering the hull by timing the opening with the wave crest. This was marginally successful. Therefore, the results should not necessarily be considered the “worst case”.

DATA FILTERING

The flooding data are smoothed using Savitzky-Golay window over 21 points (Press et. al. 1992). The smoothing eliminates the noise in the signal. The volume data are smoothed and numerically differentiated to get flooding rates. The flooding rate data are smoothed a second time with the same window. This produces a relatively clean volume and volume rate curve. The Savitzky-Golay window reduces the flattening effect of smoothing. Press et.al. recommend digital filtering with Fast Fourier Transforms.

Using the Savitzky-Golay window preserves much of the sloshing oscillations during flooding, but eliminates high frequency noise. These oscillations can be large and pose a problem in determining the duration of flooding. Examining roll angle or volume flooded and looking for a constant steady state will not work for the flooding-in-waves cases. Flooding velocity is a good channel to examine because it should be near zero after flooding regardless of waves.

To determine the duration of flooding, a square window was used to smooth the data. Using the Savitzky-Golay window resulted in very short flooding times as the sloshing oscillations can be large. The square window eliminated most of the sloshing oscillations, resulting in an easier to evaluate initial peak. The square window times are consistent with the time to attain flooded volume and heel equilibrium. Therefore, the square window was used for flooding duration, and Savitzky-Golay window for all other data.

FLOODING RATE

Flooding is considered to have started when the flooding acceleration is above a noise threshold. The flooding duration time is the time duration of the first big peak in the flooding rate time history. The start time is the first time the slope is positive and greater than 150. The ending time is the first time, after the start time, that the slope is negative, and the value is less than 6% of the maximum flooding rate peak.

The average flooding rate is the final mean volume divided by the flooding duration time. Time to equilibrium is the time from when flooding starts until a 10-point running average of the flooded mass is within a standard deviation of the average final value. These limits, while somewhat arbitrary, match visual inspection of the test cases well.

Visual observation indicates a more rapid flooding consistent with using the maximum flooding rate as the average rate. This would give flooding durations on the order of 2 seconds model scale. Most of the times using the Savitzky-Golay window are of this order.

CALM WATER

Calm water transient flooding runs provide flooding data without wave excitation. This gives a clearer picture of what is happening during a flooding event. See Figure 3 for an example of calm water flooding at zero speed.

During a flooding event, the door opens, and water rapidly floods the compartment. The videos show the water entering as almost a jet. The model begins to heel immediately. The flow rate reaches a maximum when the flooded mass is 75-80% of the maximum value. Compartments A and C begin flooding after Compartment B as expected. After the compartment is flooded, there is some sloshing as indicated by oscillations in the flooded mass and rate data. The model then experiences damped motion until equilibrium.

Roll tends to over shoot, reaching a maximum when the compartment is completely flooded. The equilibrium roll angle is less than the maximum by ~3 degrees.

CONCLUSIONS

The 2000 High Speed Craft damaged stability code calls for the assessment of flooded water in a seaway. Two methods are outlined, direct measurement of the flooded water after each run or calculation of flooded water based on water elevation probes.

Calculating the flooded water based on water elevation probes can be done with acceptable accuracy by using enough probes and ensuring an calibration procedure.

The probe calibration is best done by measuring known amounts of water in the compartment in an upright position. Then measuring known amounts of water allowing the model to heel and trim freely. This ensures the end points of the calibration curves are correct and accounts model trim and heel.

Noisy signals may require digital filtering to obtain useful data. The digital filter should not remove wanted phenomena in the data.

Calculating the flooded water level allows for the determination of transient effects such as rapid flooding, flooding rate, and sloshing, as well as, gradual flooding. Using water elevation probes and calculating flooded water should be seriously considered when conducting damaged stability tests.

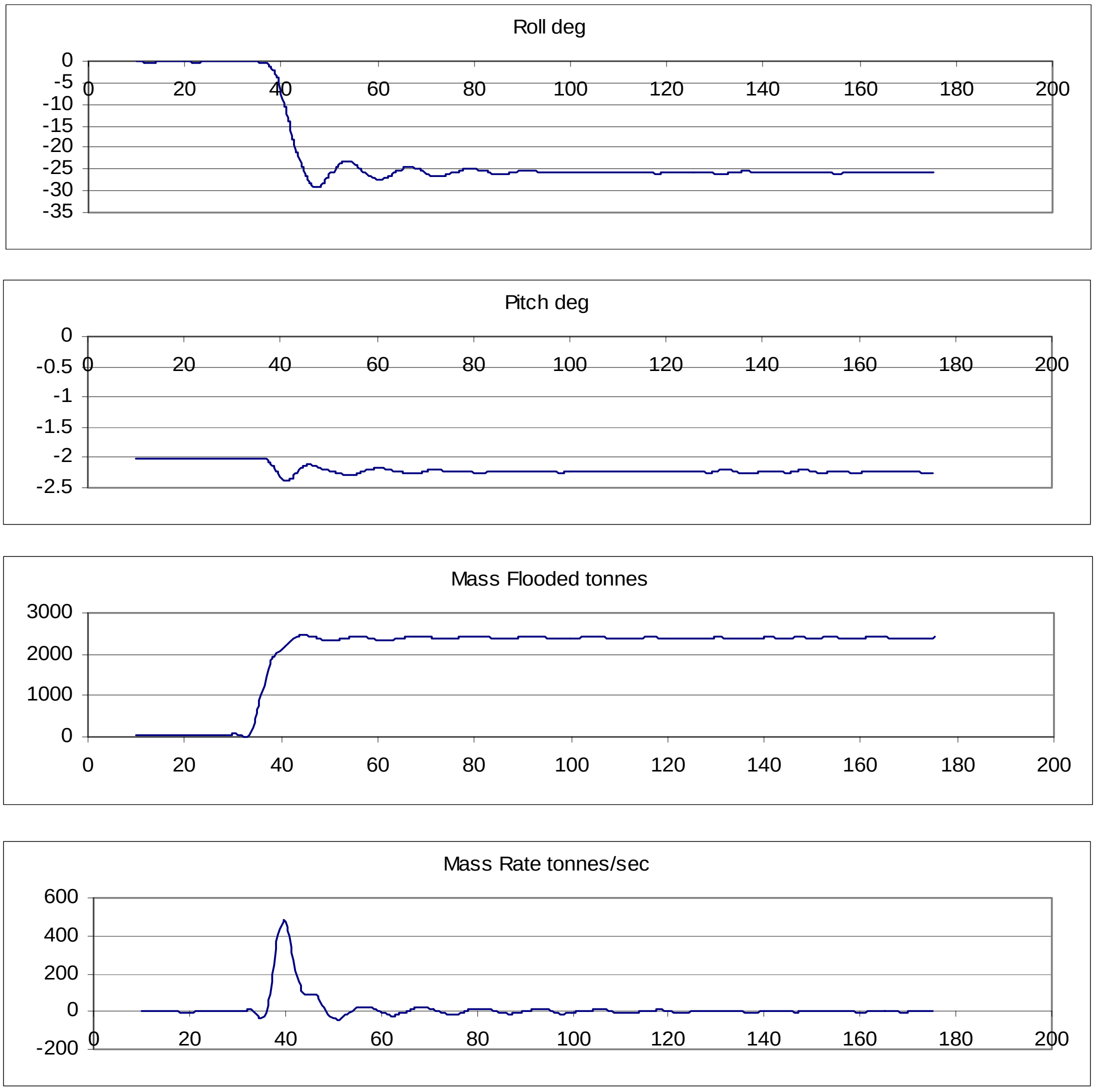

Figure 3. Zero speed calm water transient flooding for hole #3, GM#2

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