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Hydromechanics Department Report

POROUS HULL RESEARCH - PHASE 1

by

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High speed planing craft suffer repetitive and intense shock loads from wave impacts that injure or fatigue personnel and damage equipment. A porous hull concept is tested for reducing the impact loads and spreading their energy over a longer time. The concept is essentially an outer hull with holes and an inner hull for watertight integrity, and bladders and foams are used between the hulls to expel water between impacts. A drop-box apparatus is used to test this concept with two bottom dead rise angles and a variety of hole shapes and porosities. Significant impact reduction is measured, and these reductions are shown to be in frequency ranges that affect human comfort and performance.

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ABSTRACT

High speed planing craft suffer repetitive and intense shock loads from wave impacts that injure or fatigue personnel and damage equipment. A porous hull concept is tested for reducing the impact loads and spreading their energy over a longer time. The concept is essentially an outer hull with holes and an inner hull for watertight integrity, and bladders and foams are used between the hulls to expel water between impacts. A drop-box apparatus is used to test this concept with two bottom dead rise angles and a variety of hole shapes and porosities. Significant impact reduction is measured, and these reductions are shown to be in frequency ranges that affect human comfort and performance.

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Combatant Craft Division (Code 2350) and the Hydrodynamics Department (Code 50) at the Naval Warfare Center, Carderock Division (NWCCD). This effort was funded by the Independent Applied Research (IAR) program at Carderock, a funding category 6.2 component of the Office of Naval Research Discovery and Invention program. Work was completed under Work Request N0001406WX20231/AA, Program Element 0602123N, Job Order Number 06-1-0021-001-02.

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INTRODUCTION

The Combatant Craft Division (CCD) and the Hydromechanics Department of the Naval Warfare Center Carderock were awarded funds under Carderock's Independent Applied Research Program to investigate the feasibility of mitigating wave slamming shock loads of high-performance combatant craft with a porous hull concept.

This report describes the testing and evaluation performed during the first year effort. Drop tests were performed with a test apparatus in the 140 ft Towing Basin at Carderock in Bethesda, Maryland. These tests demonstrated impact reductions using a porous outer hull, and various hole patterns and porosities were tested on two dead rise angle hull sections. Methods for expelling the water from inside the porous cavity were also tested.

BACKGROUND

Small, special-forces combatant craft suffer harsh, repetitive mechanical shock caused by random and repetitive wave 'slamming'. Mission requirements force these craft to operate at speeds and sea-states that impose extreme physical requirements on the boat crew. Craft accelerations in excess of 7 to 10 g's over 200 milliseconds have been reported at high sea states, and laboratory tests of slamming ship models show acceleration levels from 4 to 6 g's. Figure 1 below shows an 11-meter RIB that has launched off of a wave, and a solid hull slam is imminent. The acceleration-time history is evidence of the repetitive slamming nature associated with such craft and their typical operations.

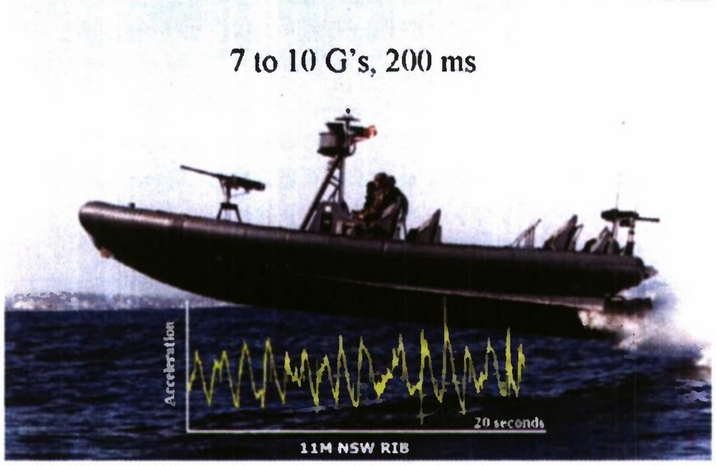


Figure 1. Common Slamming Event

These extreme shock levels, transferred to personnel while in transit or during mission operation, can reduce operational effectiveness of the craft by limiting craft speed and compromising the effectiveness of personnel. These impacts cause repetitive trauma with acute injury of the lower back, knees, and neck, resulting in tremendous injury rates. Figure 2 shows a typical beach landing and the variety and frequency of injuries imposed on personnel from wave slamming. Equipment attached to the craft or carried along for the mission also suffers shock and requires special mounting or protective padding.

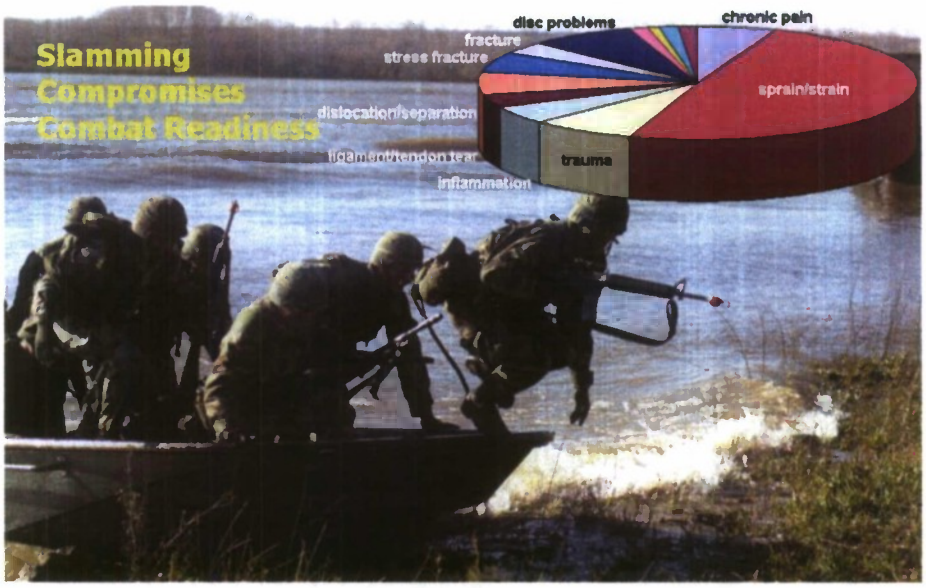


Figure 2. Storming the Beach with Mission Readiness in Mind

Effective shock mitigation is required so that personnel can train and perform their duties without injury and still operate the boat up to its intended design limits. To date, shock-mitigating systems have limitations based on space, mission requirements, and modes of operation. Furthermore, systems designed to satisfy specific mission constraints may not be applicable, appropriate, or safe on all platforms. That is why shock mitigation must begin with the hull. Numerous studies over the last four decades have documented the hydrodynamic loading as the cause for hull slamming [1-4].

Heller and Jasper [1] first documented this in 1960 when they published a method for designing planning craft structures. The response of a hull to wave impacts is correlated more closely with low pressures acting on large sections of the hull than the local, high peak pressures which act on much smaller areas. A typical computer prediction of impact pressures at an instant of time is shown in Figure 3 [from Ref 2].

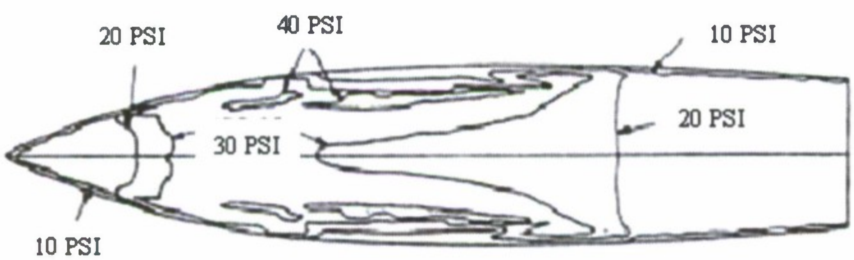


Figure 3. Common Pressure Profile for Deep-V Monohull

In 1966, Chuang [3, 4] published the results of his hull slamming studies which consisted of a series of drop-tests with varying degrees of deadrise. He correlated maximum impact pressures with deadrise angle, for different drop-heights and impact velocities.

The resulting plot, provided in Figure 4 below, shows that as the deadrise increases from 0° (flat bottom hull) to a small angle (3-5 degrees), the pressure rises, then falls off rapidly at higher deadrise angles. The reduced impact pressures for angles less than 5 degrees is thought to be caused by air compressibility. Chaung's setup used side walls to create a two-dimensional hull section impact, and this may have limited thc ability of the air to move out of the way. The plot shows that air compressibility effects for deadrise angles larger than about 5 degrees is negligible.

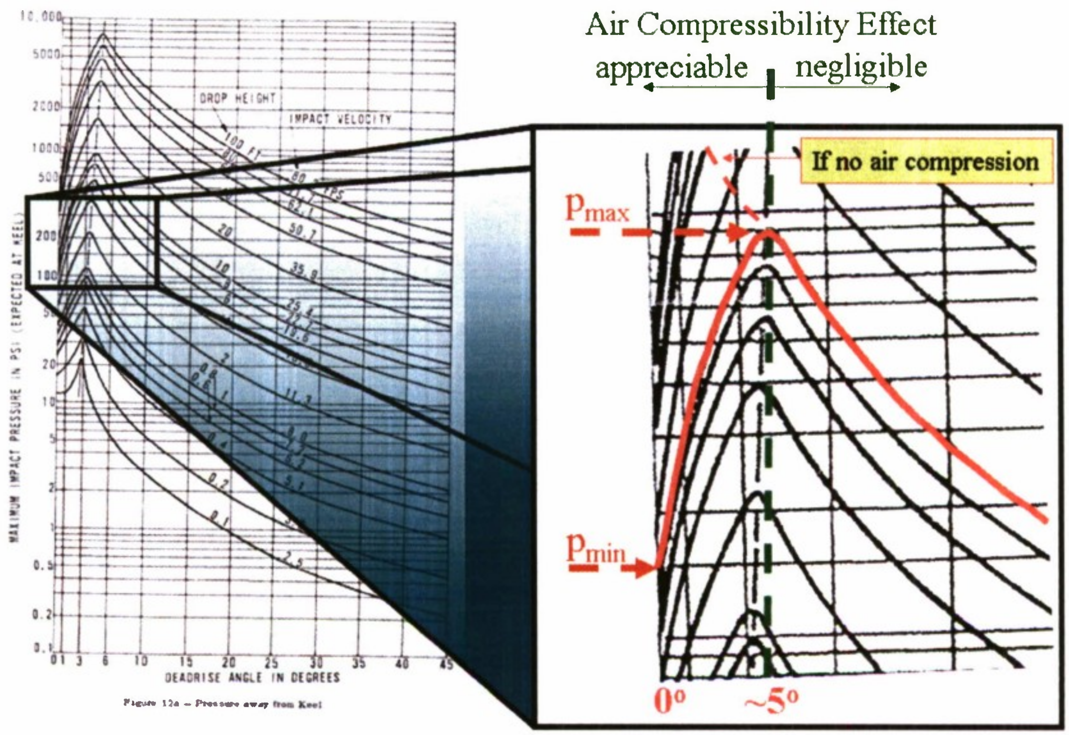


Figure 4. Impact Pressure as a Function of Deadrise and Drop Height

Allen and Jones [2] published a method to predict hull pressure magnitudes and distributions for high-speed craft. The method focused on providing input to structural analysis methods for Naval Architects. They noted that the magnitude and shape of the pressure distribution during impact is mostly dependent on trim, deadrise angle, and velocity – these dictate the severity of the impact. Furthermore, they observed from the results of their computational predictions that "during an impact the maximum impact pressures act over relatively small areas of the hull, thus constituting a small portion of the total impact load. Conversely, lower pressures were evident over a greater portion of the hull surface area and represented a higher percentage of the load". This is illustrated in Figure 5 below and means that any attempt to modify the hull to absorb impact energy will have to consider a significant section of the slamming area and not just the peak pressure points.

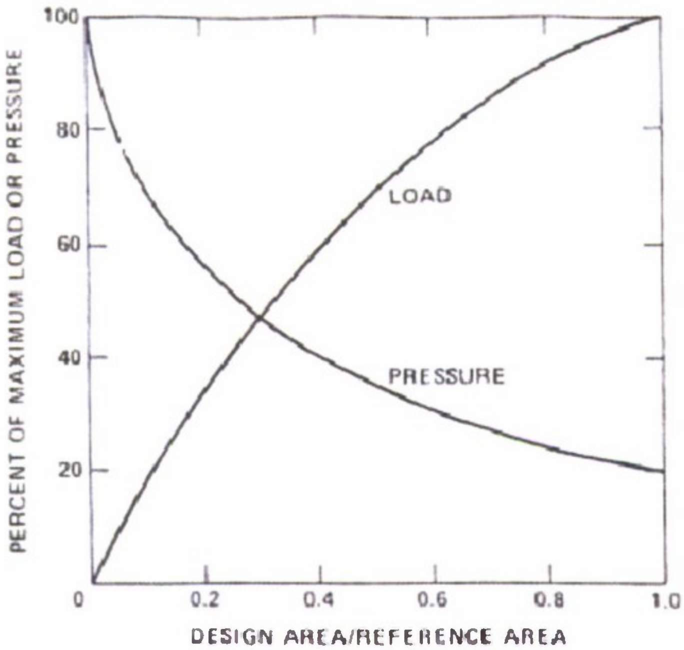


Figure 5. Load and Pressure as a Function of Area

Hence the efforts to develop shock mitigating technologies such as ride control systems, suspended decks, and shock-absorbing seats, address only the symptoms of shock, whereas using an advanced hull technology addresses the cause of the problem – hydrodynamic loading. Using this approach, a porous hull concept was proposed in June 2005 to absorb the energy from slamming and therefore reduce the loads transferred to the deck and personnel. This concept is similar to perforated, permeable, or irregular walls used on coastal breakwaters to protect harbors from sea waves and reduce their impact. Similar to the boat-wave slamming problem, the concept is to replace the sections of the hull that contact a wave with a porous surface, making it behave like a breakwater. Because the wave impact pressure will typically occur in the forward part of the craft, only this portion needs to be made of a porous surface, and a complete hull re-design is not required. This proposal was funded for the first year to quantify energy reduction of porous plates using simple drop tests, and to demonstrate method(s) for water expulsion from the porous cavity to enable shock reduction with multiple slam events and reduce drag. These tests would determine if the concept had merit for further study.

Subsequent development of this concept is to perform hydrodynamic experiments with porous plates on a small craft model to quantify energy absorption and resulting craft accelerations as a function of porosity; test the water displacement system to expel hull infiltration and maintain buoyancy, and measure drag effects. The final objective is a prototype demonstration with a full-scale craft. The text herein focuses only on the energy absorption and water displacement demonstrated with simple drop tests, similar in fashion to the tests performed by Chuang [2].

CONCEPT

Figure 6 shows a conceptual porous hull surface to absorb the energy from a slamming event. The deck plate is watertight to preserve buoyancy and maintain watertight integrity, and the porous section is made of holes or slots in the outer hull shape. Only the section of the hull that is exposed to the greatest slamming pressures needs to be made porous. Based on test data and model predictions, one can make initial estimates on where the peak pressures should occur. Figure 3 above is representative of such a pressure profile.

Figure 6. Porous Hull Arrangement

Figure 7 shows cut away view of the porous cavity, with the porous surface being the outer hull. A bladder has been placed between the porous plate and the deck plate. The bladder may be filled via an air tube with air or other gas to improve the boat performance in any of three ways:

> The bladder may be pressurized to effectively seal off the porous plate and return the outer hull shape to a relatively smooth condition when the surface is calm and the porous section is not needed.
>
> The bladder may provide additional energy absorption to reduce deck accelerations. The pressure can be varied over a range of values for optimal impact absorption.
>
> Bladder inflation recovers the buoyancy lost in the porous compartment by displacing the water.

Other considerations for bladders are deformable, lightweight and high-energy dissipation materials or foams to absorb impact.

PHYSICS

The impact load on a rigid hull is an integration of surface pressure on the boat's outer surface and is a function of the wetted surface area and an impact coefficient relating the dynamic pressure to the instantaneous impact load. Figure 7 illustrates the forces in detail. The waves first impact the porous surface. Assuming a porosity of 50%, the porous surface is half of the rigid area and will result in an impact nominally one-half of the original load. Because of three-dimensional effects (pressure relief by local flow acceleration through the holes), the impact will be less than this value. Therefore, the first impact load F1 will be less than 50% of the original impact load on the rigid hull.

The second wave impact (F2) will transmit to the deck plate. As the flow passes through the porous openings and onto the bladder (or damping materials), the flow loses energy, making it less than half of the original load. Therefore the total impact load on the porous and inner surfaces (the sum of F1 and F2) is less than the impact load on a smooth and continuous rigid hull surface.

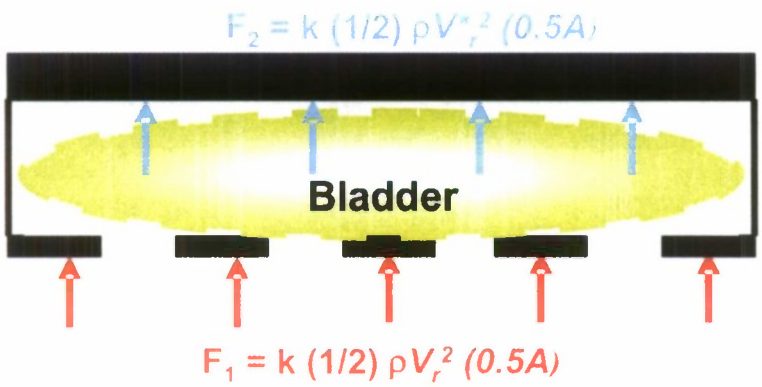


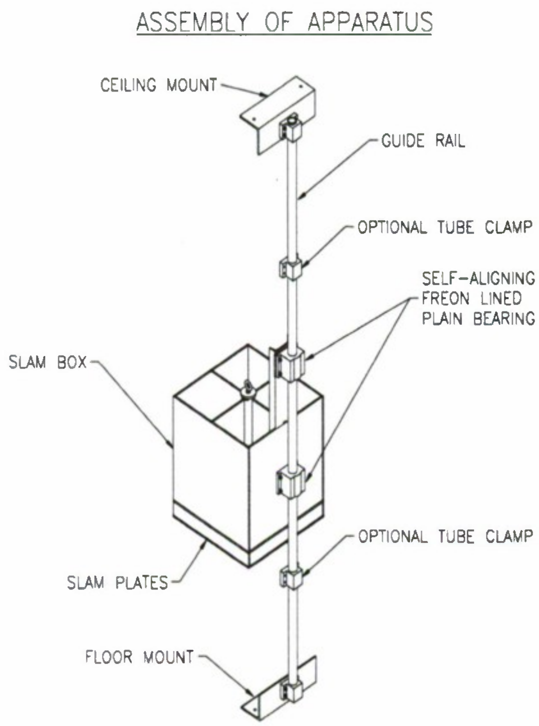
Figure 7. Slamming Forces Modified by a Porous Hull

An important feature of this concept is the gap between the hull surface and the deck plate. The impact load F2 will occur at a time delay after F1, spreading the forces over a longer time interval and reducing acceleration. The singular impact F that would occur with a rigid hull is split into two impacts separated by a time interval that prevents their summation to a single value. The net impact load can thus be greatly mitigated.

APPROACH AND TEST APPARATUS

The effort reported herein was to quantify energy reduction of porous plates using simple drop-tests and determine if the concept had merit for further study, and to investigate passive methods for expelling the water out of the porous cavities. Figure 8 shows the test apparatus used in this first year effort. The 'slam box' is a 2-foot by 2-foot aluminum box intended to mimic the hull section. The box is built of 3/8 thick aluminum plate welded together with internal stiffening plates and a hollow tube in the center for rigidity.

The design was intended to make the box stiff and rigid for impact studies while avoiding structural bending modes and low resonant frequencies. Attached to the bottom of the box is a 3 inch deep section divided into four chambers or quadrants, and the porous outer plates attach to the side walls of the section. The chamber and porous plates are assembled with screws and machined surfaces to insure solid contact. A smooth, round guide rail keeps the model aligned during the drop; and self-aligning bearings provide smooth motion with no 'chatter'. Threaded into the bottom of the box were accelerometers and dynamic pressure gages, and similar pressure gages were threaded into the porous plates as well. The layout is shown in Figure 9. An electric hoist and snatch block release mechanism provided lifting control, and an electric trigger attached to the guide rail provided signal input for synchronizing the data collection.



- *2 ft x 2 ft aluminum "slam box" mimics hull section*
  - *Vertical drop into basin, 1 to 3 feet*
  - *Rail keeps model aligned*
  - *Bottom assembles for different porous hull plate configurations*
  - *Accelerometers, dynamic pressure transducers, velocity transducer instrumentation*

Figure 8. Apparatus for Drop-Test Experiments

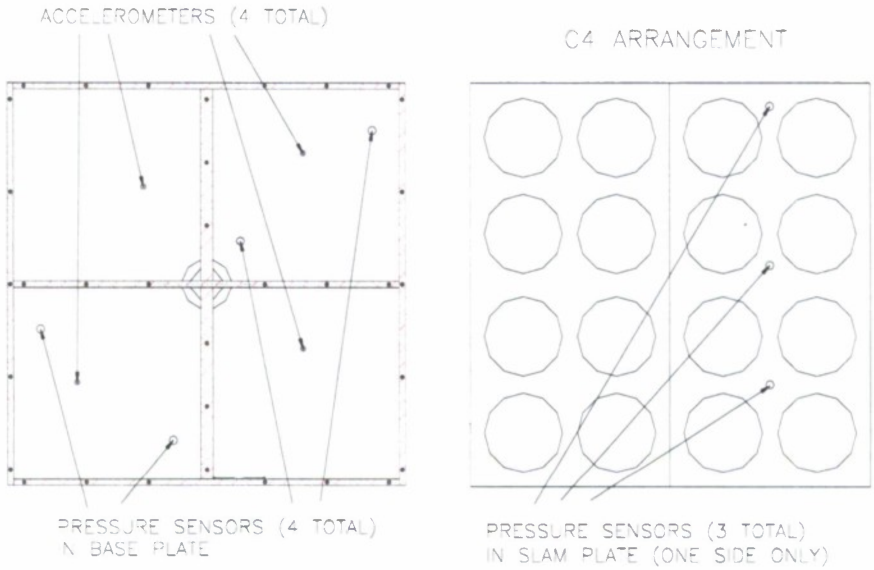


Figure 9. Pressure Transducer and Accelerometer Mounting Locations

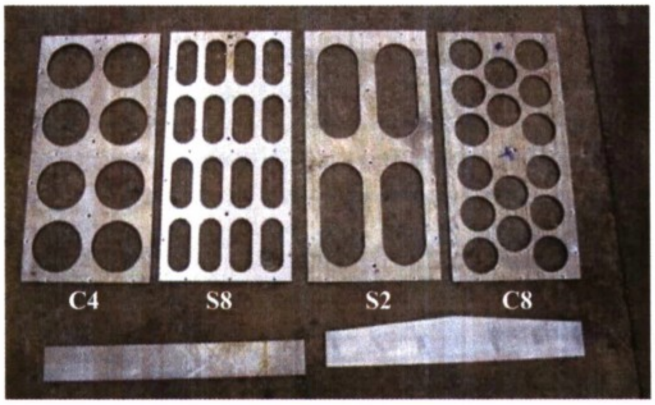
A variety of porous plates with different hole shapes and sizes were tested. Shown below are most of the plates, all with 50% porosity. The plates were designated with the letter 'C' or 'S' to indicate if the hole shape was a circle or slot, respectively, followed by a number indicating how many holes were in each quadrant of the empty chamber. A 'C4' designation meant that there were 4 circular holes in each The quadrant size is constant so as the number of holes increascs, the holes/slots become smaller to maintain 50% porosity. The porous plate data were compared to the data of the baseline solid plate to quantify shock absorption. Some of the philosophical thoughts concerning the tested hole patterns were:

If the edges of the flow that pass through the holes dissipate energy, slots should show more shock absorption than circles for the same area because slots have more edge length.

For thc samc rcason, a greatcr number of holes should show morc absorption than a smaller number of holes of similar shape.

Different holc patterns may offer advantages for commercial availability or manufacturing

Different hole patterns may offer advantages for decreased flow resistance.



- *3/8 " thick aluminum plates screw onto side support plates*
- *50% porosity should "split" impact pressure*
- *Make smaller porosity patterns by covering holes w/ sheet metal*
- *Smaller holes have greater losses (edge/area ratio)*
- *Shape factor (long slots vs. round holes*

Figure 10. Porous Patterns

Two deadrise angles were tested, 0 degs and 5 degs (Figure 11). The 0 deg angle represents the flat bottom condition, and the 5 deg angle represents the angle of maximum pressures, according to Chaung (Figure 4). The intent of the project at this phase was to demonstrate and quantify the porous hull concept, so deadrise angles more representative of combatant craft were not tested at this time. More angles would have been difficult to test because of the added manufacturing costs and tests times.

The slam plates and box were instrumented as shown in Figure 11; and the instrumentation details are shown in Table 1. Data were collected at 2 kHz with 500 Hz low pass filters to prevent aliasing. The A/D sample rate of 200 kHz limited the data skew to less than 60 μs. A dual channel FFT analyzer was also used to examine the signals during testing and insure the data being collected were free of artifacts that sometimes occur when performing numerous repetitive tests, especially loose or malfunctioning sensors.

While the accelerometers were all mounted to the inside of the box base plate, the pressure transducers were mounted both to the base and to the outer porous plates. The transducers mounted to the inside were positioned such that their sensors were not blocked by the outer porous panels for any of the hole patterns tested, except the solid bottom. Figure 10 shows these locations.

Table 1. Test Instrumentation.

Instrument	Manufacturer	Model No.	Range	Frequency Response	Sensitivity
Accelerometer	PCB	353B16	500 g	1 Hz – 10 kHz	10 mV/g
Pressure Transducer	PCB	101A06	500 psi	0.01 Hz - 20 kHz	10 mV/psi
Signal Conditioner	PCB	442C04 4-channel ICP conditioner, gain x1, x10, x100			
Filter	Ithaco	Model 4111 8 pole Butterworth Low Pass AC Filters			

The elapsed time for the box to fall and hit the water was measured from the time history of the trigger signal and the leading edge of the accelerometer peak. These times were 1% to 3% more than the kinematic estimate, hence it was decided to use kinematics to predict the impact speeds instead of creating a separate speed sensor. These speeds were 3 to 10 fps for the drop heights tested. The depth of water below the box was typically 3 ft.

The focus of the tests was the shock absorption of the porous plates. The secondary tests for water exclusion from the cavity included inflatable bladders and foam, and some tests were run with these configurations using a smaller selection of porous patterns. The last test parameter was variation of the plate porosity. This was achieved by covering various numbers of holes with shim stock and tape to seal them off.

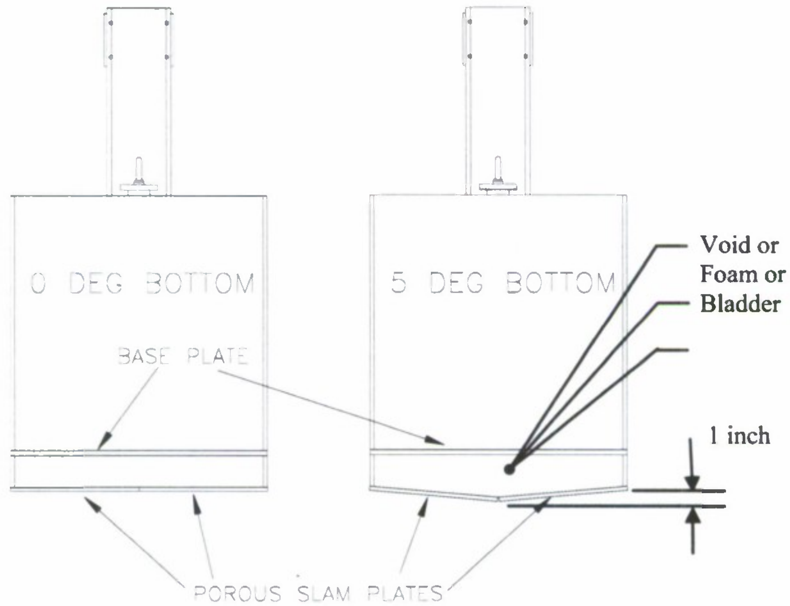


Figure 11. Slam Box Comparing Flat and 5° Bottom Configurations

TEST PROCEDURES

The drop box tests were performed at the south end of the 140 ft Towing Basin at Carderock. This basin has a 10 ft wide by 5 ft deep section into which the box was dropped. An aluminum block with a trigger switch was mounted to the guide pole at the desired drop height. The box was raised to the stop with a snatch block release hook, closing the switch. After manually starting the data collection routine, the release lanyard was yanked to drop the box into the basin. The switch release, vertical drop, box impact, and subsequent bobbing motion time histories were captured in the laptop using LabView. Figure 12 shows the box in the release position, and Figure 13 shows the box at impact.

Typically three drops were performed for each drop height; and three to five heights were tested for each configuration. Tests with porosity variations, bladder pressures, and foam were typically run from a single drop height.

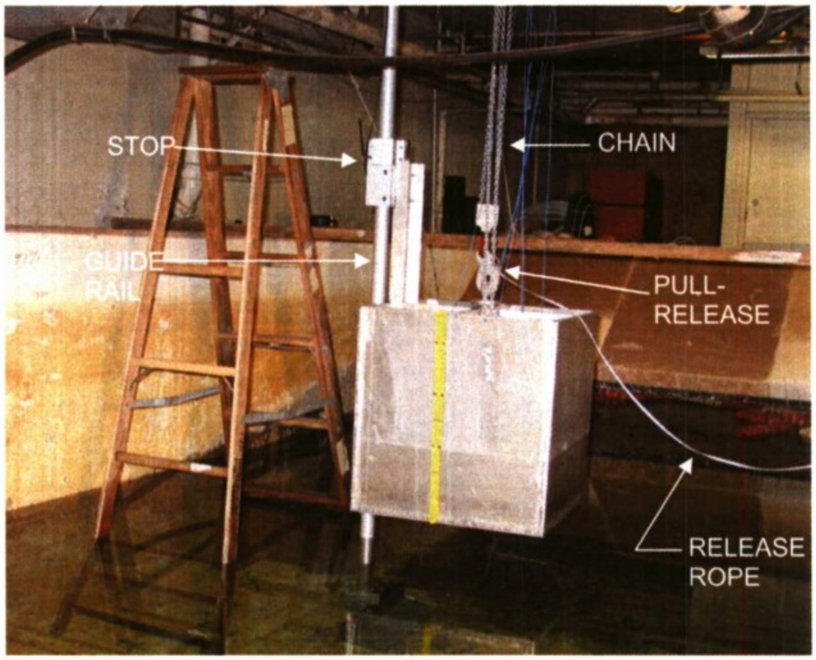


Figure 12. Drop-Test Apparatus in Place for Drop

Figure 13. Drop-Test Apparatus During a Drop

RESULTS AND DISCUSSION

SHOCK AND PRESSURE TIME HISTORIES

Figure 14 and Figure 15 show typical time histories of the accelerometers and pressure transducers, respectively, for the solid flat bottom configuration, at a drop height of 10 inches. When the trigger signal rises from zero is when the box is released. The next 0.23 secs is the time when the box is falling, and the accelerometers show about -1 G's. The right-hand figures show the impacts in more detail. The rise time of the acceleration peak is about 3 ms, and the accelerometer and pressure traces are very similar. Figure 16 and Figure 17 show equivalent time histories for the 5 deg deadrise configuration. The rise times are similar to the flat bottom test, but the amplitudes are smaller and the lengths of the acceleration pulses are longer. The length of the accelerometer peaks for the 5 deg case were the same as the length of time for the 5 deg bottom to penetrate from keel to edge through the water surface at the terminal drop speed. For example, the 10" drop tests showed accelerometer peak widths of about 11 ms, the same as the time required for the 5 deg bottom to travel from initial keel contact to edge contact (1 inch) at a terminal speed of 7.3 fps.

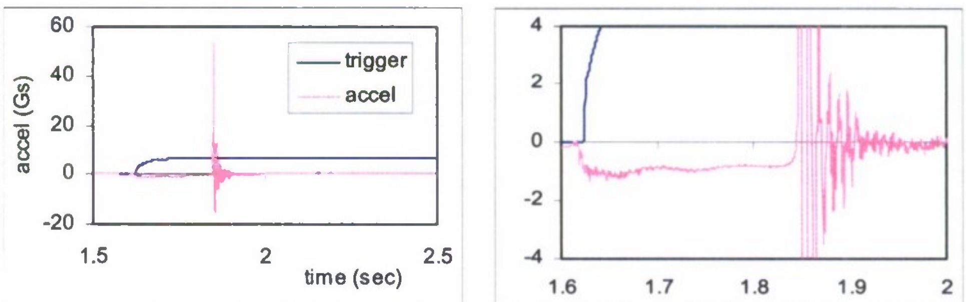


Figure 14. Accel Time History for Flat Bottom

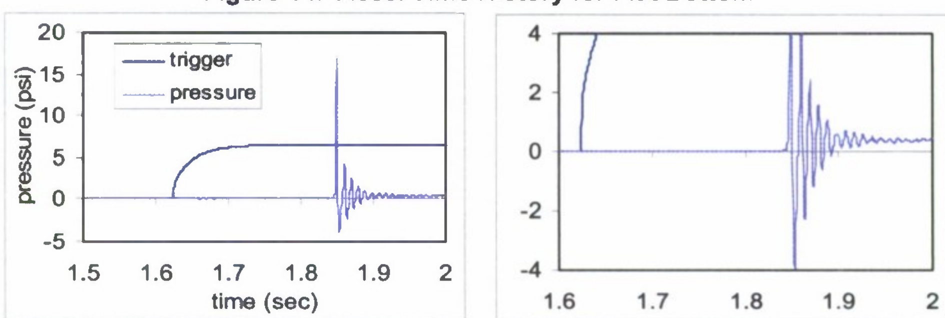


Figure 15. Pressure Time History for Flat Bottom

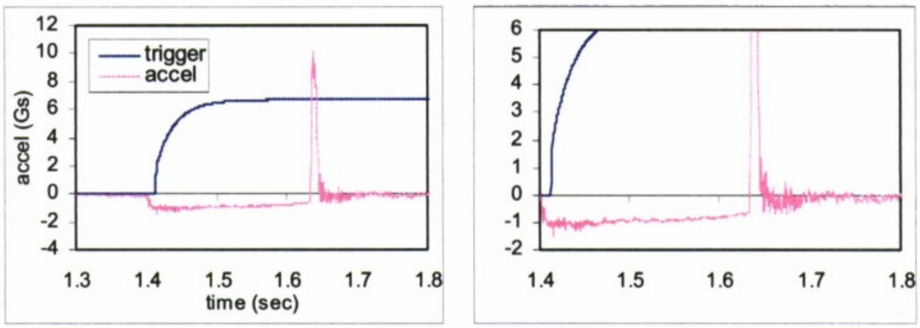


Figure 16. Accel Time History for 5 Deg Bottom

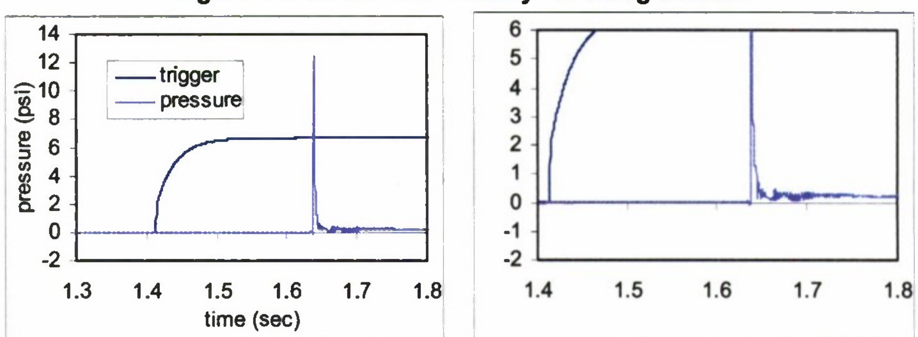


Figure 17. Pressure Time History for 5 Deg Bottom

Figure 18 compares the pressure and time histories from the C4 and C8 porous plates to the solid plate with the flat bottom configuration (10" drop height). The time histories have been synchronized on the rise of the acceleration peaks. Equivalent traces are shown in Figure 19 for the 5 deg case. Note that the amplitude of the acceleration peaks are significantly reduced in both bottom configurations, and the lengths of the peaks are much longer. For the 10" drop height with the porous plates, a second impact should be seen 40 ms to 50 ms after the first impact if the box continued to fall unimpeded, but a well-defined, second impact peak is not observed. These results were typical of all the porous patterns tested.

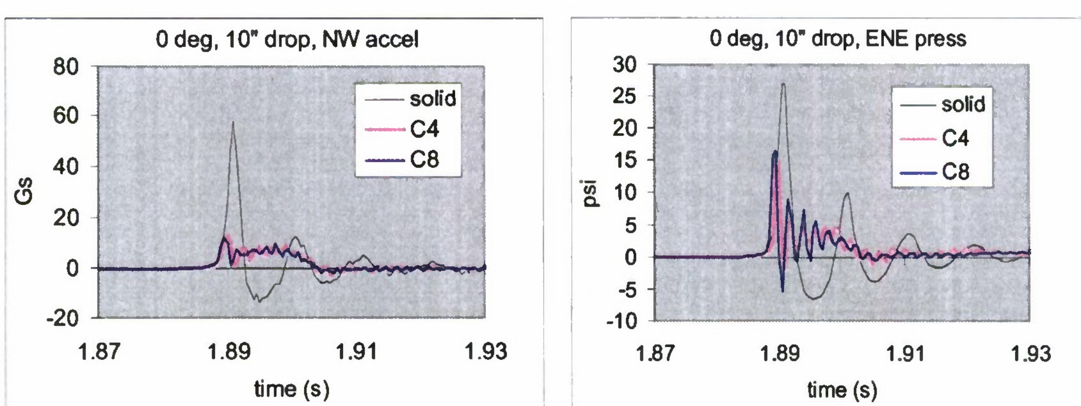


Figure 18. Accel and Pressure Time Histories for Flat Bottom

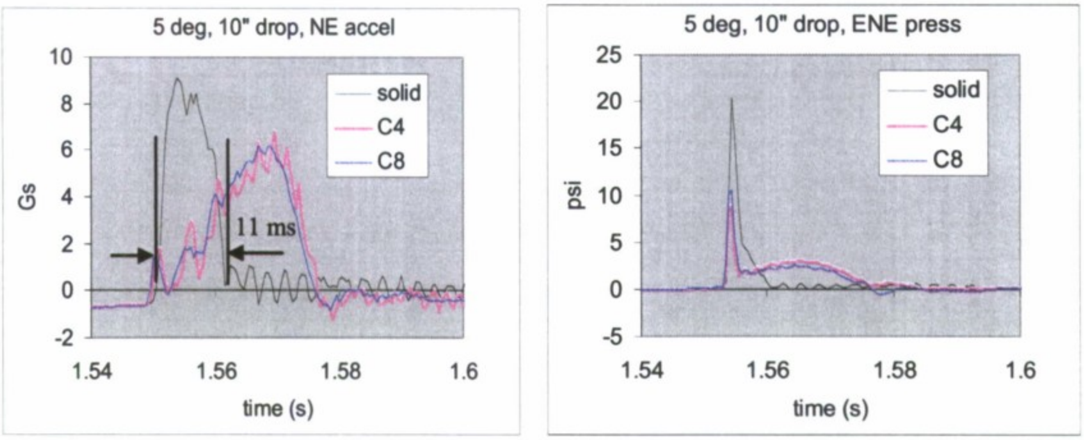


Figure 19. Accel and Pressure Time Histories for 5 Deg Bottom

PEAK LEVELS

Drop height effects

Figure 20 shows the variation of average shock and pressure level with drop height, respectively, for the flat bottom box. Figure 21 show the equivalent data for the 5 deg configuration.

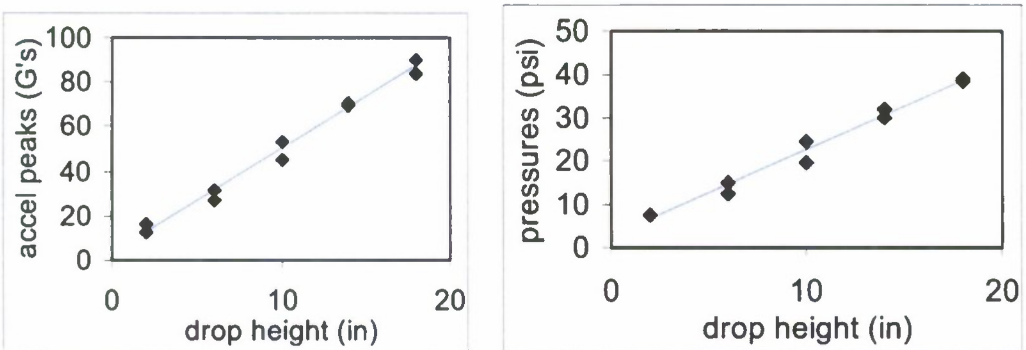


Figure 20. Peak Accel and Pressure Levels for the Flat Bottom.

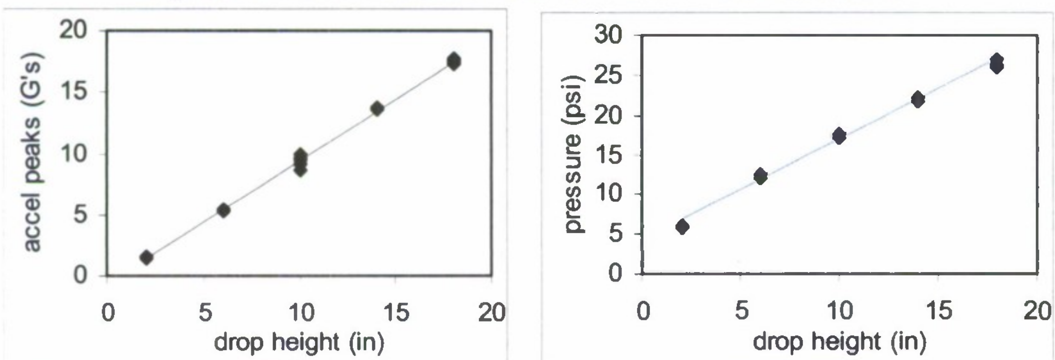


Figure 21. Peak Accel and Pressure Levels for the 5 deg Bottom

Both cases show linear variation of the shock or pressure with height, which is proportional to dynamic pressure or velocity squared. Although the peak shock levels decrease substantially with the 5 deg bottom from the flat bottom levels, the peak pressures are not reduced as much. These data are in contrast to Chuang's which show maximum pressure peak levels at 5 degs and reduced levels for the flat bottom case. Chuang's data for the flat bottom case may have suffered air compressibility effects because his model was shielded by walls on two sides to make a 2-D section. The present model was open on four sides and allowed the air to easily escape from underneath.

Hole pattern effects

Figure 22 shows the hole patterns tested. Each pattern was replicated on both sides of the bottom plates i.e. the S2 pattern had 8 slots total in the bottom.

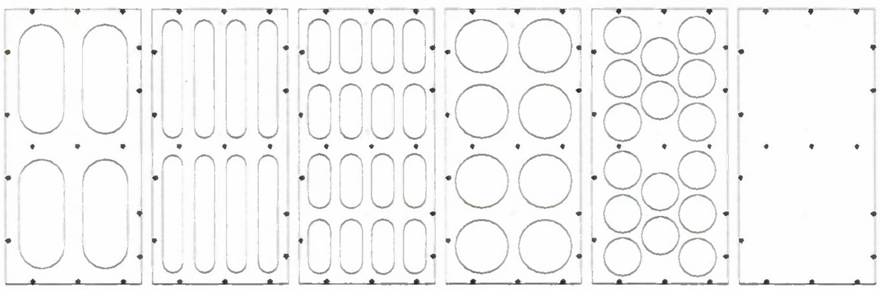


Figure 22. Three Slot Patterns, Two Circular Patterns, and Solid Baseline Plates

To compare the reduction effect of the different hole patterns within a reasonable time, they were compared by performing two to here drops at a constant height of 10 inches with the flat bottom configuration. The C22 and C76 hole patterns (shown in Figure 23) only had one pressure transducer installed between the holes. The other patterns had three transducers installed between the holes in the same locations as the solid plate. The averages of the accelerometer peaks and external pressure peaks are shown in Figure 24. The pressure data are difficult to compare for different hole patterns because the pressures should vary considerably between holes, but the pressures for all the hole patterns are lower than those for the solid plate.

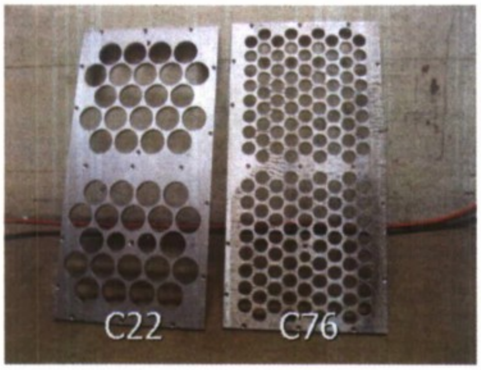


Figure 23. 50% Porosity with 2-Inch and 1-Inch Holes

The accelerometer data do not vary considerably among the hole patterns but they are lower than the solid plate case. Comparing the effect of hole shape (circle vs slot) on shock reduction for similar area holes, there is a trend for the slot shape to show more reduction than the circle shape (S4 vs C4, S8 vs C8). But comparing the effect of hole size for the same shape (C4 vs C8 vs C22 vs C76) or (S2 vs S4 vs S8), there is no clear trend for smaller holes to show more reduction. This result is surprising. Therefore, the concept of achieving more reduction via greater hole edge length for the same area is not proven.

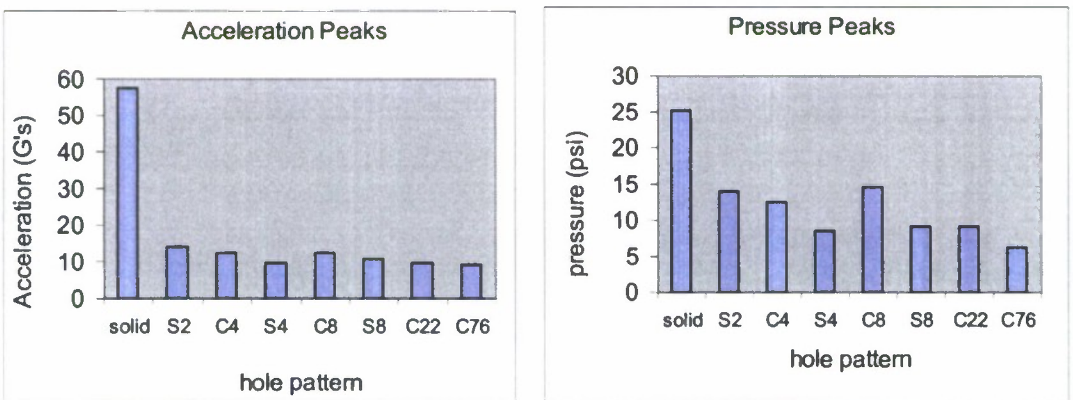


Figure 24. Acceleration and Pressure Comparisons for Different Hole Patterns

Height effects on reductions

The shock and pressure reductions were compared for different drop heights to see if there was any effect. The S4, C4, C22, and C76 hole pattern results were compared for the 0 deg and 5 deg bottom configurations, and the C8 pattern was also tested for the 5 deg configuration over a range of drop heights. The plots in Figure 25 and Figure 26 show that the drop height was not significant in the reductions except for shock reduction with the 5 deg bottom. Interestingly, the shock loads were higher for the 2" drop tests by 50%. The data were re-examined and nothing different could be discerned for those tests. The average of the pressure signals did not follow this trend.

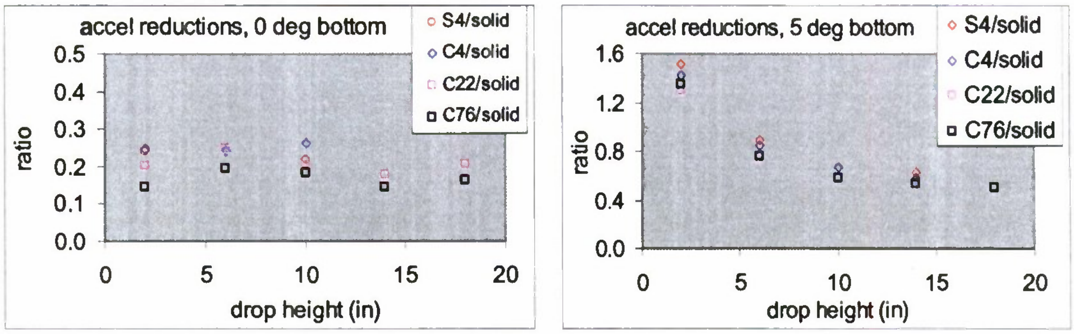


Figure 25. Drop-Height Comparisons for Accelerations

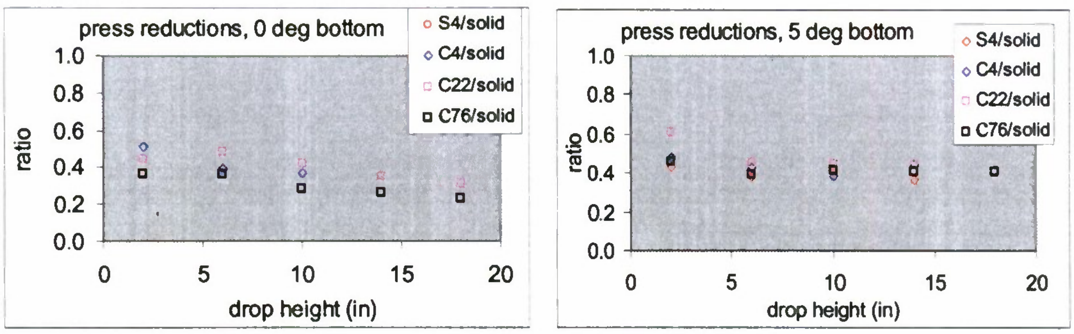


Figure 26. Drop-Height Comparisons for Pressure

Porosity effects

An investigation of the effect of porosity was performed to understand its influence on energy absorption. The S8 panel was chosen and slots were covered with shim stock to provide the porous variations shown in Figure 27 below. The plates were also removed completely to represent 100% porosity. In this case there were no porous plates but the side plates provided a 2 inch deep recess in the bottom (Figure 28). The results shown in Figure 29 suggest that porosity effectiveness is convergent at 50%, and with this in mind, the work herein remained focused on tests with 50% porosity.

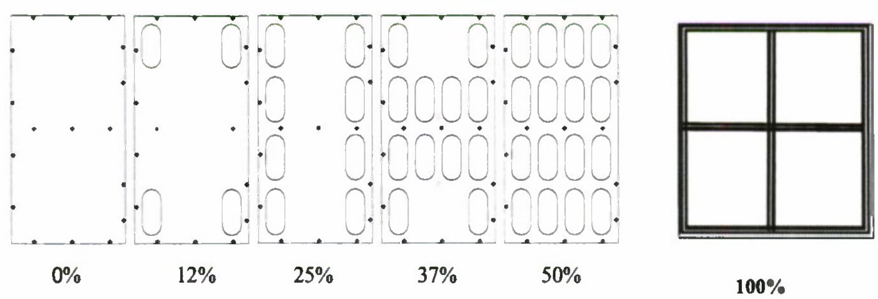


Figure 27. Porosity Variations Tested

Figure 28. 100% Porosity (Underwater View at Impact)

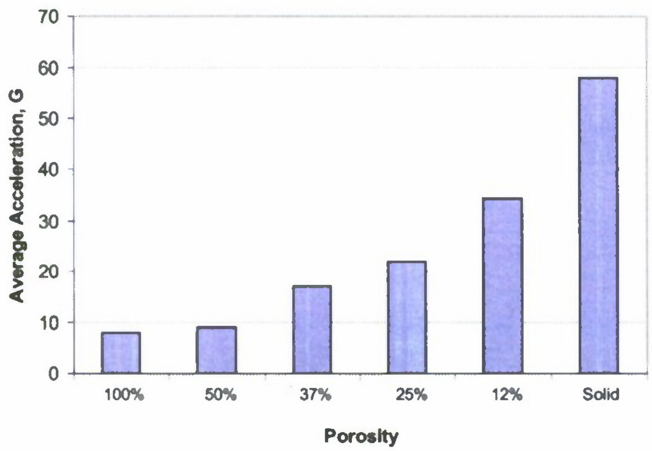


Figure 29. Porosity Effects on Peak Magnitudes

SPECTRAL CHARACTERISTICS

For the energy reduction of the porous hull to be relevant for personnel, it must be in frequency ranges sensible to humans. Reductions in frequency ranges that interact with mechanical systems are also important but are outside of the scope of this report. Figure 30 shows the frequency ranges and acceleration levels of reduced performance for personnel standing in a boat [5]. The vertical axis and plots show the vibration levels and endurance limits. The most problematic frequencies are the ones with the minimum acceleration levels and are highlighted in the figure.

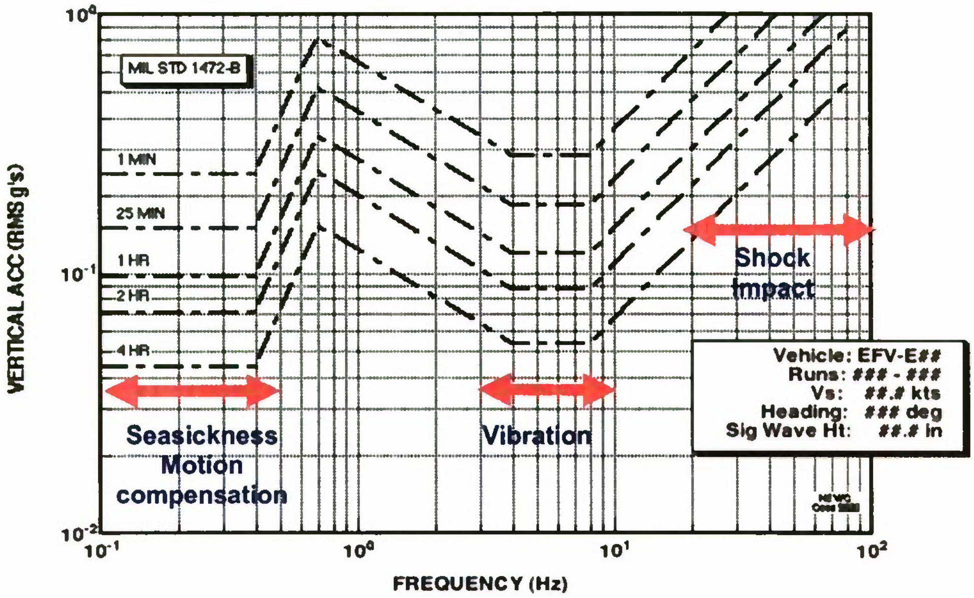
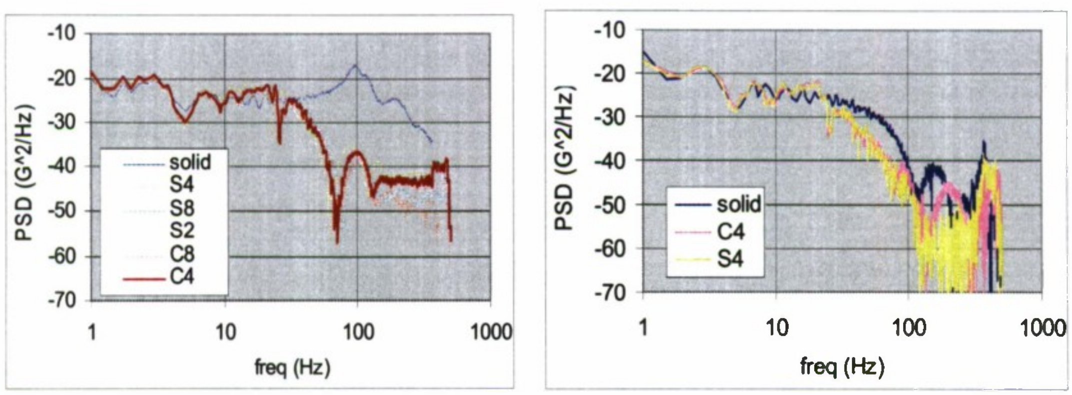


Figure 30. Acceleration Effects on Standing Humans

Figure 31 shows the spectral characteristics of the 0 deg (flat) and 5 deg bottom tests, and the effect of the S4 and C4 hole patterns. Both setups have similar baseline acceleration levels from 1 Hz to 30 Hz. For the solid plate, flat bottom impacts have much more energy from 30 Hz to 500 Hz than the 5 deg impacts, hence the higher shock levels for flat bottom impacts are from high frequency contributions. The porous holes reduce the energy as much as 20 dB for the flat bottom box, and the reductions extend to about the limit of the data collection, 500 Hz. The spectra are similar regardless of the hole shapes, but there is a trend for more reduction with higher hole numbers in the higher frequency range. The 5 deg case shows reductions from 30 Hz to about 90 Hz, then from 110 Hz to 200 Hz. The 5 deg tests did not include the S2, S8, and C8 hole shapes.



0 deg Bottom　　　　5 deg Bottom

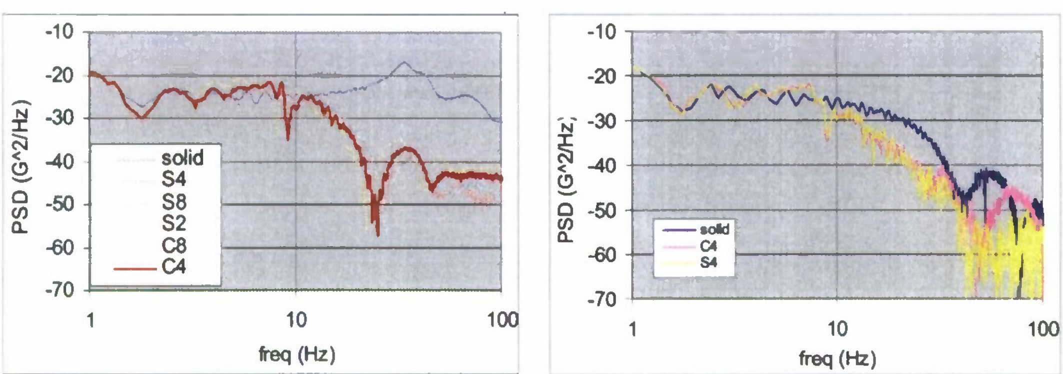
Figure 31. Spectra of Accelerometer Signals with Porous Patterns

Scaling the frequency trends of the model results to full scale depends on the physical mechanism involved in the shock reduction. For the 5 deg configuration, the time scales of the initial impulses of the accelerometer signals roughly equal the time for the bottom plates to move through the water a distance equal to their deadrise height (keel to outer edge). For the flat bottom configuration, the accelerometer signals' initial impulses are much shorter. This indicates that the impact depends on the mass of the water being accelerated by the box, and the time scale of the impact depends on the interaction time of the bottom plates with the water (deadrise height divided by the impact velocity). Froude scaling dictates that the velocities scale as the square root of the geometric ratio λ and the length scales as λ directly. The time scale and frequency scales then become:

$$V_{FS} = \sqrt{\lambda}\, V_{MS},\quad L_{FS} = \lambda\, L_{MS},\quad t_{FS} = L_{FS}/V_{FS},\ \text{and}\ f_{FS} = 1/t_{FS} = V_{FS}/L_{FS}$$

$$\text{hence}\quad f_{FS} = f_{MS}\left(V_{FS}/V_{MS} \bullet L_{MS}/L_{FS} \right) = f_{MS}\left(1/\sqrt{\lambda} \right)$$

in which f_{FS} and f_{MS} are the frequencies in full-scale and model-scale, respectively, and λ is the geometric scale ratio. The drop box device is not a model of any vessel, but it can be imagined to be representative of the forward portion of a combatant craft hull. For example, the width of the PTF-3 (*NASTY*) class planning boat is 21 ft, a Mk V is 17 ft wide, and an 11 m RHIB is 12 ft wide. Relative to these boats, the scale ratio of the drop box is then 1/6 to 1/10. The corresponding full-scale frequencies would then be 0.3 to 0.4 of model scale. Figure 32 shows the model results scaled to full scale at an average scale ratio of 8. Comparing Figure 30 and Figure 32, the impact reductions fall in the frequency range of shock/impact. The flat bottom case shows reduction from 10 Hz to more than 100 Hz. The 5 deg bottom shows reductions from 10 Hz to about 40 Hz, then a subsequent reduction range from 40 Hz to 80 Hz. The shock reductions in the tested models encompass frequencies that are significant for improving personnel performance.



0 deg Bottom 5 deg Bottom

Figure 32. Spectra Results Scaled to Full Scale

WATER ENTRAINMENT AND EXPULSION STUDIES

Other measurements were made to examine potential problems with a porous outer-hull and void cavity arrangement. The data shown in Figure 33 reveals a 5 to 7 percent increase in plunge depth with porous plates versus a solid bottom. This is only an indication of how porous plates might exacerbate the problem with drag. For a typical planing monohull, drag is reduced substantially when the boat passes the hump-speed and planing is achieved. In rough seas this craft will experience multiple and repetitive slamming events as the hull repeatedly rises and falls coming in contact with oncoming waves. Replacing that hull with a porous one that allows water to become entrained in the void cavity, the hull may plunge into the waves 7 percent more than before. This data points to the importance of providing a mechanism to both reduce the entrainment of water into the empty cavities and help purge the cavities to be ready for subsequent wave impacts.

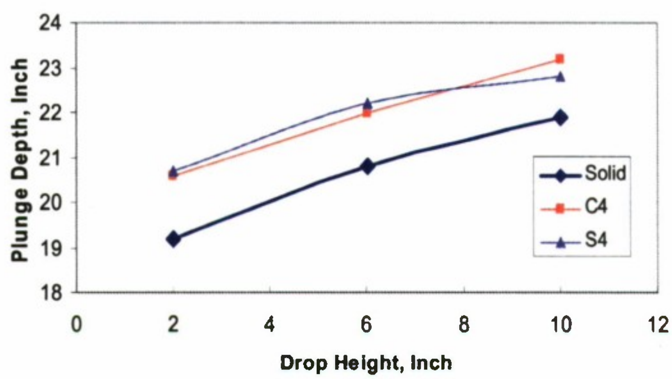


Figure 33. Plunge Depth of Slam Box with Void Cavity Arrangement.

As a means of purging water out of the void or sealing the holes to reduce drag in calm water, air-bladders and foams were considered and investigated. An energy absorbing foam was inserted into the 5 deg C4 configuration, and softer foam with bubble wrap was placed in the flat bottom C4 configuration. Results are shown in Figure 34 for 10"drops. While the soft foam showed no additional energy absorption, the hard foam reduced the energy absorption of the C4 holes. Because of this, the foams were abandoned in favor of bladders for sealing of the holes and water expulsion.

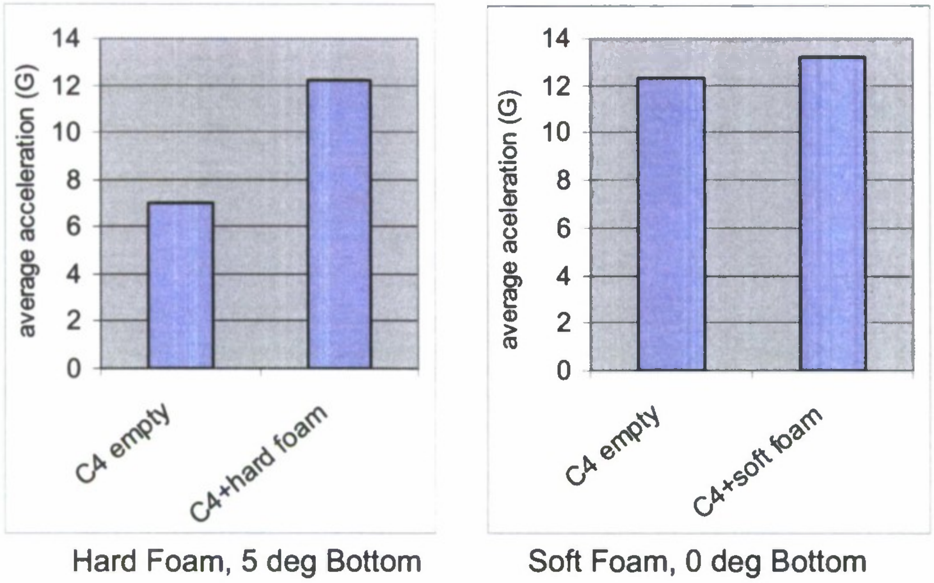


Figure 34. Foam Results with C4 Porous Hole Pattern

The foam was then replaced with an air bladder shown on the left of Figure 35. The intent of the air bladder was to seal the holes to reduce drag and expel water quickly. The bladder material is visible through the holes of the porous plate in the picture on the right in Figure 35. The picture shown was taken from a frame of the underwater video one second after impact. Earlier frames in the video are obscured by foam and splashing, but the bladder appears to expel the water in less than one second. This is sufficiently fast for repetitive wave impacts.

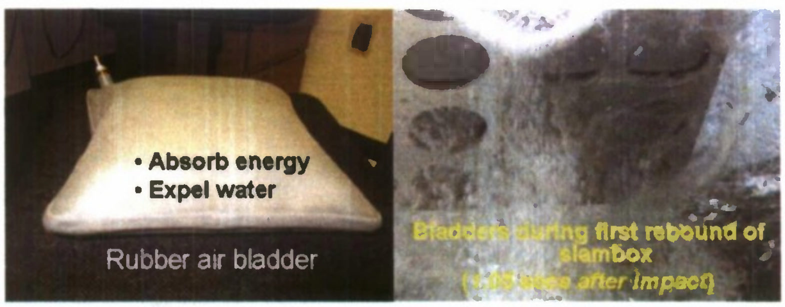


Figure 35. Rubber Air Bladder Installed in Porous Cavity

SHOCK REDUCTIONS WITH BLADDERS

With video and pictures supporting the effectiveness of the air-bladder to expel water, the remaining questions concerned energy absorption, bladder pressures, and hole-size effects. The maximum bladder pressure and hole size are related, as shown in Figure 36 with the bladder protruding out of the 2 inch holes (pattern C22) at 10 psi.

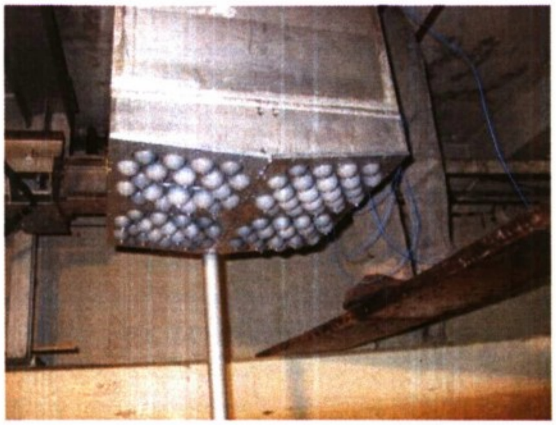


Figure 36. Bladder Protruding Out of the 2-inch Holes at 10 psi

The bladder protruded out of the holes at 2 psi, 10 psi, and 15 psi, for the C4, C22 (2 in.), and C76 (1 in.) holes, respectively. Figure 37 shows the variation of the accelerometer signals with bladder pressure for the 0 deg and 5 deg configurations. The accelerometer signals increase with bladder pressure. For the 0 deg case, the shock reduction is reduced from about 80% to 50% at the highest pressure. For the 5 deg case, the shock reductions are actually eliminated, and the resulting impacts are *increased* at the higher pressures. This result was not expected. Clearly, the minimum bladder pressure should be used for water expulsion and sealing of the holes. The bladder pressure in Figure 35 was less than 2 psi. Higher pressures may have to be considered for impact loads at higher speeds. For example, an actual hull traveling at a speed of 32 knots may see dynamic pressures exceeding 20 psi. That does not mean the static air pressure in the bladder must exceed 20 psi, but certainly higher pressures may need to be investigated. The maximum pressure is limited by the stresses on the fasteners used for the porous plate connections and the pressure at which the bladder protrudes out of the holes. The drag associated with an actual porous hull should be lower using smaller holes.

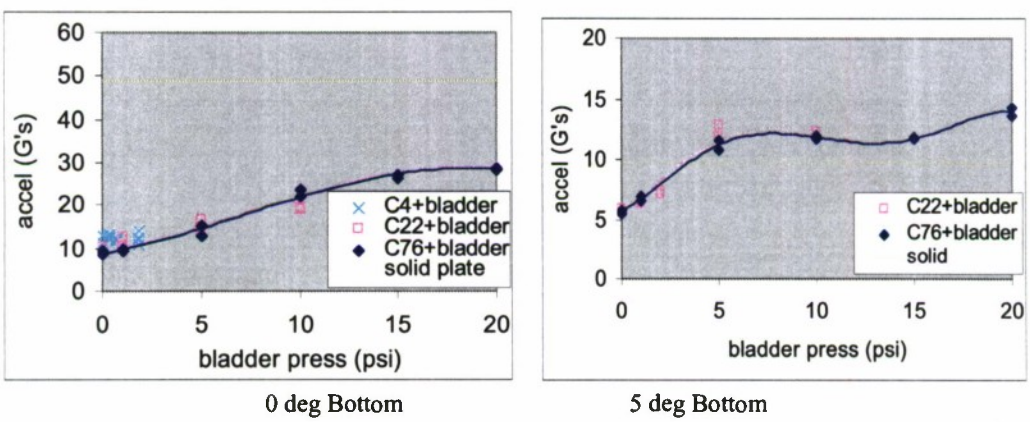
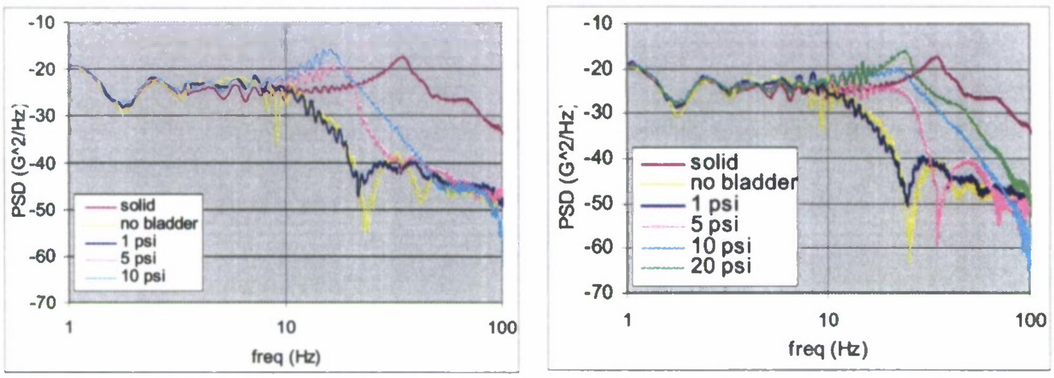


Figure 37. Bladder Results with 0 deg and 5 deg Bottoms

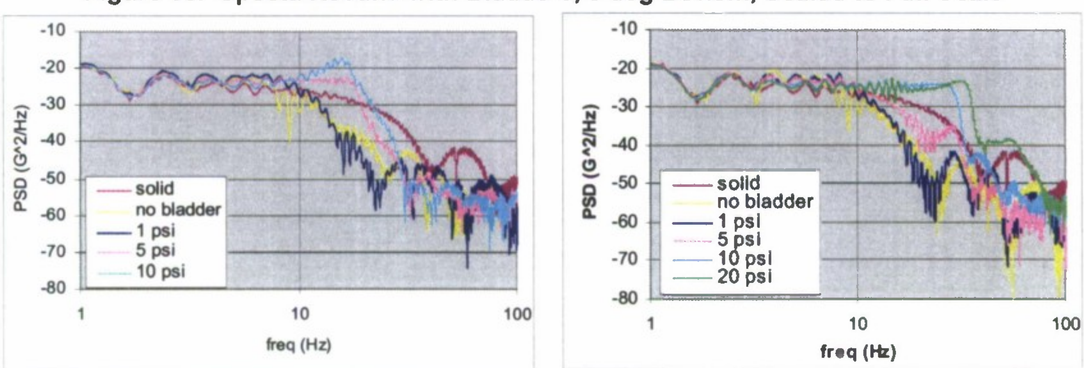
SPECTRAL EFFECTS WITH BLADDERS

Tests with the bladders showed increasing energy with increasing bladder pressure, or higher pressures reduce shock absorption. This same trend is seen in the accelerometer spectra shown in Figure 38 and Figure 39. Increasing pressures of 5 – 20 psi show energy increases in frequencies between 50 Hz to 75 Hz, corresponding to full-scale frequencies of 18 Hz to 25 Hz, for the flat bottom tests with 2 in. and 1 in. holes. For the 5 deg case, the increased bladder pressures cause energy increases from 50 Hz to 95 Hz, corresponding to full-scale frequencies of 18 Hz to 35 Hz. However, the 10 psi and 20 psi bladder conditions show energy levels *greater* than the solid plate. This same trend is apparent in the peak data shown in the right side of Figure 37. The best method for using bladders to purge the holes of water is to pressurize them at as low a pressure as possible.



2 in. Holes 1 in. Holes

Figure 38. Specta Results with Bladders, 0 deg Bottom, Scaled to Full Scale



2 in. Holes 1 in. Holes

Figure 39. Specta Results with Bladders, 5 deg Bottom, Scaled to Full Scale

CONCLUDING REMARKS

A porous hull can significantly reduce the impact of slamming for flat and shallow-rise hull bottoms. For a flat bottom hull, the impacts can be reduced as much as 80% of their original value independent of the drop height leading to the impact. For a hull with a shallow deadrise, the impacts are reduced provided that the impact heights are large (> 2 in.). Point pressure measurements shows peak pressure reduction trends that are very close to the impact reductions sensed by the accelerometers. The shape of the holes is not critical, but the impact reduction depends directly on the porosity, with a maximum reduction at 50%. Two types of foam were tested for additional energy absorption, but no additional impact absorption benefit was shown. Bladders inserted into the porous hull void space worked well at expelling the water quickly, at a rate fast enough to enable subsequent wave impact absorption in sea states. The pressure in the bladder affects the impact absorption, with higher pressures leading the higher impact levels. For a shallow deadrise hull fitted with a porous hull and bladders, the impact reduction of the porous hull can be negated entirely.

ACKNOWLEDGEMENTS

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