

MSC/Circular.616 – Evaluation of Free-Fall Lifeboat Launch Performance – (22 June 1993) – Circular

Circular

1. At its sixty-second session (24 to 28 May), the Maritime Safety Committee approved for circulation to Member Governments the guidance on evaluation on free-fall lifeboat launch performance, given at annex.

2. Member Governments, surveyors and manufacturers are invited to take into account this guidance in the testing evaluation and certification of free-fall lifeboats .

Section 1 – Introduction

1.1. The free-fall lifeboat is quickly becoming a common lifesaving appliance on seagoing vessels and offshore facilities. It represents an apparent improvement in safety over conventional lifeboat systems. Because of the apparent increase in safety, most maritime regulatory authorities have accepted the free-fall concept and have prepared design and certification criteria for these lifeboats.

1.2. Many life threatening accidents have occurred with conventional lifeboat systems. A majority of the accidents occurred during launch and after lowering into rough seas and high wind. During launch, the lifeboat may impact the sides of the distressed vessel, become severely damaged, and the occupants may fall into the sea suffering injury and even death. Launching the lifeboats may be impossible if the parent vessel is listing significantly or if the falls become tangled. After the lifeboat is in the water, it may be unable to move away from the distressed vessel because high seas and wind continually return the lifeboat to the vessel or because of a malfunction in the propulsion system. This situation is even more dangerous during a fire or when the potential for an explosion exists.

1.3. The risks with conventional lifeboat systems have been substantially reduced by the free-fall concept which allows the lifeboat to fall freely into the sea. The free-fall provides kinetic energy used to propel the lifeboat away from the distressed vessel during and after water entry. The lifeboat moves away from danger even if the engine does not operate.

1.4. Today, free-fall lifeboats are manufactured in several countries by many manufacturers. The materials used in the manufacture of the lifeboats include fiberglass, steel, and aluminum. These lifeboats are being actively marketed and are quickly gaining universal acceptance. Currently, free-fall lifeboats are in use on cargo ships, tankers, semi-submersible drilling platforms, and fixed production platforms. The heights of free fall range from approximately six meters on smaller ships to over 30 meters on drilling platform. Although a free-fall lifeboat has never been used in a maritime evacuation, over 15,000 people have been launched in free-fall lifeboats during training exercises. There has not been a reported injury during these training exercises. A free-fall lifeboat has been used in two separate maritime incidents. In one case, the free-fall lifeboat was used to rescue a crewman who had fallen overboard. In the other incident, a free-fall lifeboat was used to rescue the crew of a capsized fishing vessel. The free-fall lifeboats were successfully launched and recovered in a seaway in both of these incidents (Hatecke, 1991).

1.5. The purpose of this report is to provide a conceptual understanding of the launch behavior of free-fall lifeboats and of the methods used to evaluate the launch behavior. Mathematical formulations have been included, where appropriate, to show the basis and limitations of the analysis procedures as well as to provide some insight into the fundamental behavior of the lifeboat. In general, mathematics is used in the discussion only to the extent necessary to explain a physical concept or the limitations of an analysis procedure. All pertinent results are summarized in tables or are reduced to easily used equations. As such, a complete understanding of the mathematics involved is not necessary for this circular to be understandable.

1.6. It is intended that this document be a reference for maritime authorities and manufacturers when questions regarding launch behavior arise. Presented in Section 2 is a discussion of issues pertinent to the certification of free-fall lifeboats. A general discussion of the launch behavior of free-fall lifeboats is presented in Section 3. Because scale models are often used to evaluate lifeboat performance, criteria for developing properly scale models are presented in Section 4. Presented in Section 5 is a general discussion of considerations during the measurement of acceleration forces in lifeboats. Various methods that can be used to infer occupant safety during the launch of a free-fall lifeboat are discussed in Section 6. Included in appendices to this report are a suggested free-fall lifeboat prototype test program and a sample summary evaluation form that inspectors can use during free-fall lifeboat prototype tests.

2.1 Free-Fall Lifeboat Certification Issues

2.1.1. Most of the prototype tests required for certification of free-fall lifeboats are the same as those required for conventional davit launched lifeboats, e.g., the speed and self-righting tests. Other tests, e.g., the free-fall tests, are peculiar to and only conducted with free-fall lifeboats. Through these special free-fall lifeboat tests, several considerations which are unique to such lifeboats can be verified. In general, these considerations are:

- .1. The lifeboat must have adequate reserve strength. This is demonstrated during the overheight drop test .
- . 2. The lifeboat must have adequate strength for repeated use. This is demonstrated during the free-fall tests .
- . 3. The lifeboat must make positive headway after water entry. This is also demonstrated during the free-fall tests .
- . 4. The occupants must be protected from injury during the free-fall and water entry. This is demonstrated through acceleration forces measured during the free-fall tests.

2.1.2. Even though much can be learned about the performance of a free-fall lifeboat through use of models - the use of models to infer performance is definitely encouraged - there are some tests that can only be conducted with full-scale boats. It is not always economically feasible to conduct all these tests before the prototype certification trials are conducted. The free-fall tests are typical of such tests because special equipment and towers are often required for the evaluation. There will always be unknowns when a boat is tested the first time and failures may result. Such failures should not be interpreted negatively. They are not necessarily indicative of an inferior lifeboat or of carelessness on the part of a manufacturer. Often, more can be learned from a failure than from a success. Regardless, modifications can be made and the failed tests are usually successful the second time.

2.1.3. Following is a brief discussion of the intent of the special free-fall lifeboat tests that are conducted and considerations during those tests. More thorough discussions about the behavior of free-fall lifeboats and the bases of methods used to evaluate that behavior are presented in other sections of this circular.

2.2 Demonstration of Reserve Strength

2.2.1. A requirement of good design is that a system has reserve strength beyond that required to withstand anticipated loadings. The reserve strength in free-fall lifeboats is demonstrated by launching the lifeboat from a height greater than that for which it is to be certified. As such, this test is often referred to as the overheight test. The lifeboat will probably never experience a launch from this height during its service life. The purpose of the test is to demonstrate that the lifeboat has some reserve strength so that it can survive unexpected events. The actual reserve strength should be higher than that demonstrated.

2.2.2. During this test, the primary structural and watertight components of the boat should not be rendered ineffective. The test should be considered successful if the structural and watertight integrity of the lifeboat is maintained regardless of any cracks and delamination that may have occurred as a result of the test. The lifeboat does not need to be in such a condition that it can be launched again but it must still be able to serve as an effective lifesaving appliance. In this regard there are two issues. First, what are the primary structural and watertight components? Second, how much damage can be tolerated? These issues are best addressed separately.

2.2.3. Because there is much variation in lifeboats produced by different manufacturers, each boat must be evaluated separately to determine which components are the primary structural components. As a minimum, the primary structural components are the outer hull and canopy. The inner liners could be primary structural components if they were designed to work with the hull and canopy to resist load. The watertight components are the hatches, windows, and other closures. These components keep water and weather out of the lifeboat during operations.

2.2.4. Although it is always desirable that the lifeboat is not damaged during the reserve strength test, the occurrence of damage is not necessarily cause to reject the lifeboat. The amount of damage permitted will always be a subjective issue. In general, though, cracking of the gel coat during the reserve strength test is not serious, especially if the cracks do not penetrate the underlying material. At corners and sharp contours, the gel coat will almost always show some signs of cracking. These cracks are caused by the natural flexibility of the boat and are only cosmetic; it is virtually impossible to prevent these cracks from occurring.

2.2.5. Cracks which penetrate beyond the gel coat or delamination of the hull and canopy may be indicative of more serious problems. Such cracks and delaminations are often observed at corners and sharp contours. Cracks and delaminations that do not provide a path for water ingress, and do not render the lifeboat ineffective as a lifesaving appliance, probably are acceptable because there is no requirement that the boat be in such a condition that it can be launched again. It is only required that the boat continue to be a usable lifesaving appliance. However, if the cracks and delamination are extensive, some remedial action may be required.

2.3 Strength for Repeated Use

2.3.1. During the free-fall tests, the boat is launched from the free-fall certification height a number of times. The purpose of these tests is to evaluate the strength of the lifeboat during repeated launches as well its performance and safety under different load conditions and angles of roll and pitch. The demonstration of strength for repeated launches from the certification height is necessary because during its life the boat would be dropped many times from this height for training and lifeboat drills. It is imperative that the boat be fully operational and that no major flaws develop after repeated launches. Also, because the free-fall certification height is considered a normal operating height, there should be no damage to items that are primarily non-structural (inner-liners, handrails, etc.). Ancillary equipment such as compasses and searchlights (and their mountings) should also remain intact and fully operational. If the reserve strength test was conducted prior to this test, damage to structural and non-structural components that may have occurred during the reserve strength test probably should be repaired to the original condition. This would provide the best basis for evaluating the lifeboat during the free-fall tests.

2.3.2. At the judgement of the inspector, some minor damage may be permitted during the free-fall tests. Regardless, laminate cracking, delamination, and permanent deformation would usually not be considered acceptable. The extent of damage, if any, that occurs can be evaluated in many different ways. A visual inspection should always be conducted. Permanent deformation is almost always indicative of serious damage. Depending upon the damage observed, other evaluations may be required. Ultra-sonic testing and infra-red cameras are non-destructive methods that can be used to determine the existence and extent of delamination in FRP lifeboats. At the location of cracks, the lifeboat could be cored. These cores can be examined to evaluate the depth of observed cracks and, to a more limited extent, the existence of delamination. Another way in which possible delamination in FRP boats can be observed is through the use of unpigmented gel coats when the lifeboat is manufactured. When such a gel coat is used, the hull or canopy appears to be cloudy at areas in which delamination has occurred. Normally the hull and canopy would be translucent when such a gel coat is used.

2.4 Free-Fall Launch Performance

2.4.1. Another of the objective of the free-fall tests is to evaluate the performance of the free-fall lifeboat during and after the launch. The primary safety advantage of a free-fall lifeboat is that it can move away from danger during and immediately after the launch even if the engine does not operate. As such, the boat should enter the water in such a manner that the hull is the first part of the lifeboat to contact the water and it should make positive headway immediately after it is launched. It should be considered unacceptable for the lifeboat to enter the water inverted or, if after water entry, it does not initially move away from the launch platform.

2.4.2. In the context of free-fall performance, the launching appliance and the lifeboat need to be viewed as a system. As will be discussed in Section Two, characteristics of the launch ramp as well as characteristics of the lifeboat affect the launch performance of the boat. It is recognized that often the same manufacturer does not build both the lifeboat and the launching appliance, that a lifeboat can be used with more than one launching appliance, and that a boat may be used with a different appliance at some time in the future. Nevertheless, acceptable performance should be achieved with whatever launching appliance is used with the boat. However, if a different appliance is used in the future, the prototype tests do not need to be repeated. Instead, acceptable performance can be demonstrated during the required installation tests.

2.4.3. Another aspect of free-fall performance is the stability of the lifeboat in the launch cradle prior to launch. It is important that the lifeboat be properly supported so that it does not exhibit a tendency to tip when it is being loaded. In the case of a ramp launched free-fall lifeboat, stability is easily accomplished if the launch rail on the boat extends forward of the most forward location of the CG a distance no smaller than the roller spacing. Other means of support will need to be provided for vertically launched free-fall boats.

2.5 Occupant Safety During Launch

2.5.1. The final objective of the free-fall tests is the evaluation of occupant safety during launches from the free-fall certification height. Safe transportation of the occupants during the free-fall and subsequent water entry is a primary design consideration. When the lifeboat enters the water, the acceleration forces exerted upon the occupants are significant. Through proper design, water entry attitude, and seat orientation, the magnitude of these forces can be limited so that they are not injurious to the occupants.

2.5.2. The allowable limits for acceleration forces experienced by the occupants are presented in Resolution A.689(17) of the International Maritime Organization. These limits represent the acceleration forces that a human can tolerate with minimum potential for suffering adverse effects. If these limits are greatly exceeded, the occupant could become disoriented, lose consciousness, or suffer other physiological damage. Along with protection of the occupant from injury is an implicit requirement that all objects in the cabin must be well secured. If an object were to become loose during the free-fall and water entry, it could impact an occupant and potentially cause serious injury.

2.5.3. Included with occupant safety is the strength of the seats in the lifeboat. For the occupant to be protected, the seat must be strong enough to support a person with a reasonable margin of safety. A margin of safety is demonstrated by overloading critical seats when conducting the free-fall strength test. During this test, the overloaded seats should not break away from the supports or become fractured. Seat flexibility is acceptable unless it causes fittings to become loose and fly around the cabin during water entry, causes a loaded seat to impact an occupant in another seat, or causes excessive acceleration forces on the occupants.

2.5.4. Another consideration of occupant safety is the harness assembly at each seat location. The harness should be easy to use. It should be of adequate strength and design to fully restrain a person during free-fall and water entry. In this sense, the lap belt portion of the assembly should fit low across the abdomen and should not "ride up" as the shoulder harness is tightened. The harness assembly should be adjustable so that persons of varying size and weight can use it with efficacy.

2.6 Human Factors Engineering Considerations

2.6.1. It must always be remembered that every system is designed to be operated by or to serve human beings. Consequently, the man-machine interface is of paramount importance. The human being is very complex and has both physical and mental capabilities and limitations. Human beings are of varying shape and size and respond differently to external stimuli, especially under stressful conditions. It is probably impossible to design a system that will be suited to every person who will ever use it, but it can at least be designed for the expected user population.

2.6.2. Physical differences in human beings such as height, reach, weight, and strength are relatively easy to take into account during design. Numerous charts and tables have been published in which limiting body dimensions for a range of a given population are presented. These dimensions typically are tabulated as 5th and 95th percentile values. For any body dimension, a 5th percentile value is equal to or larger than the smallest five percent of the population. That particular dimension is exceeded by 95 percent of the population. Similarly, a 95th percentile value is equal to or larger than 95 percent of the population; it is exceeded by only five percent of the population. Therefore, if a system is designed to accommodate 5th and 95th percentile dimensions, 90 percent of the user population will theoretically be able to operate the system.

2.6.3. Inspectors should satisfy themselves that the lifeboat has been designed to allow access within the boat and to controls and equipment for the largest expected users (probably the 95th percentile male). At the same time the system should be designed to allow the smallest expected users (possibly the 5th percentile female) to reach all controls, lift any required weights, and have adequate visibility from their stations. Other design considerations may include the ability to operate valves, switches, or other controls while wearing gloves, immersion suits, or suitable lifejackets and the ability to read a label or observe an indicator light from the normal operating or seating position.

2.6.4. Accounting for cognitive and perceptual differences between people when designing a system is much more difficult and is the subject of continuous research. However, some basic principles can be followed easily. These include clear and unambiguous instructions inscribed on placards that are posted at eye-level, color coding of lights and displays so that the indications are intuitively obvious, fail-safe design features, and interlocks in release systems to prevent a dangerous situation from developing. Another design feature essential to safe operation is that the system must provide automatic feedback to the operator indicating whether an operation was successful. For instance, a click can indicate if a hatch is properly closed (audio feedback), a green light can be illuminated to indicate that all tasks required prior to release have been accomplished (visual feedback), and a steering control can become progressively harder to turn as the rate of turn is increased (tactile feedback).

2.6.5. This discussion has not been intended to be a comprehensive guide to human engineering. Rather, its intent is to inform the lifeboat designer, manufacturer, and inspector about the types of issues that are important and that should be noted during prototype certification tests so that a free-fall lifeboat system can be as safe as possible.

Section 3 ĩ Launch Behavior of Free-Fall Lifeboats

3.1 Introduction

3.1.1. The configuration of a free-fall lifeboat at the beginning of a launch is shown in figure 3.1. The free-fall height is measured from the water surface to the lowest point on the lifeboat when the lifeboat is in its launch position. The primary factors that affect the launch performance of a free-fall lifeboat are its mass and mass distribution, the length and angle of the launch ramp, and the free-fall height. These parameters interact to affect the orientation and velocity of the lifeboat at the time of water impact, the acceleration forces experienced by the occupants, and the headway of the lifeboat immediately after water entry.

3.1.2. The launch of a free-fall lifeboat can be divided into four distinct phases. These are the ramp phase, the rotation phase, the free-fall phase, and the water entry phase. The ramp phase

is that part of the launch when the lifeboat is sliding along the launch ramp. The ramp phase ends when the center-of-gravity (CG) passes the end of launch ramp and the lifeboat begins to rotate; this rotation marks the beginning of the rotation phase. The rotation phase ends when the lifeboat is no longer in contact with the launch ramp. This is the beginning of the free-fall phase; the lifeboat is falling freely through the air. The water entry phase begins when the lifeboat first contacts the surface of the water and continues until the lifeboat has returned to the surface and is behaving as a boat.

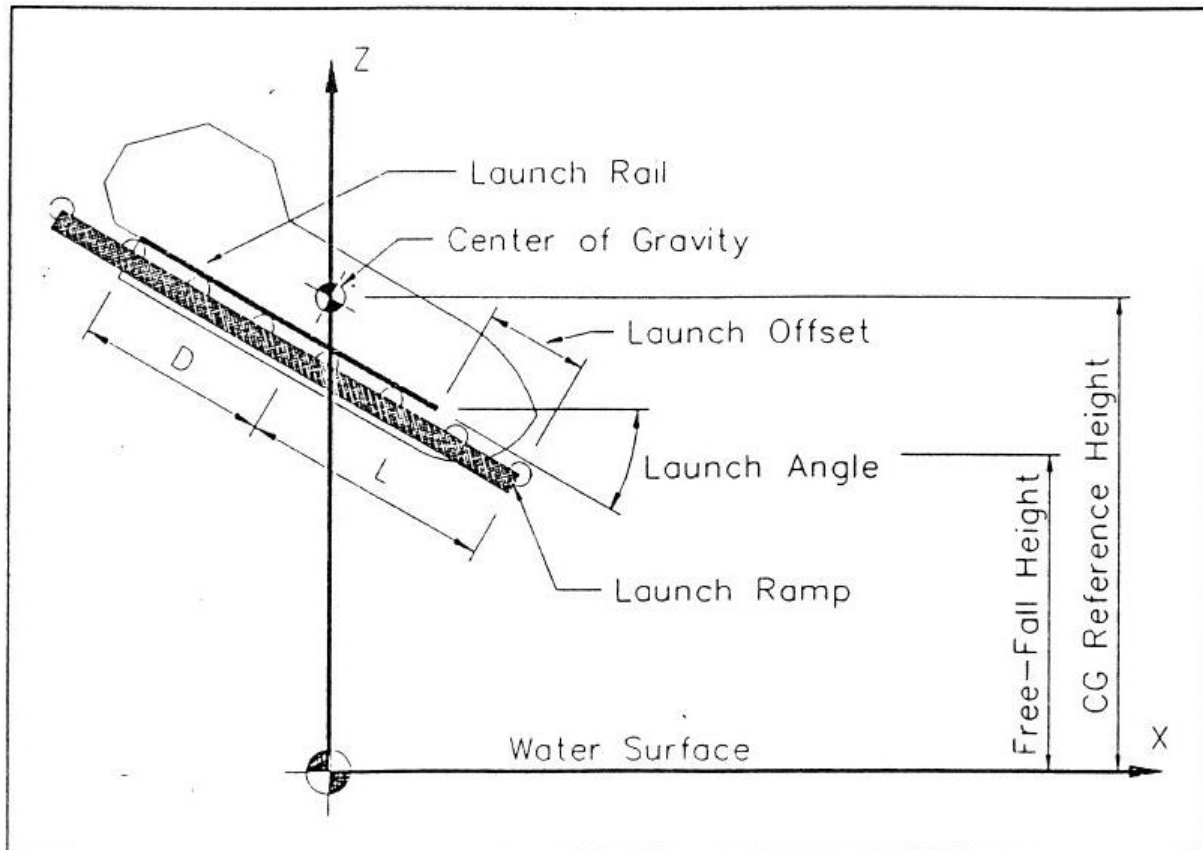


Figure 3.1 Parameters of a Free-Fall Launch with the Lifeboat in the Launch Configuration

3.2 Ramp Phase

3.2.1. During the ramp phase of a free-fall launch, the forces acting on the lifeboat are the weight of the boat, the normal force between the launch rail and the launch ramp, and the frictional force between the launch rail and the launch ramp. These forces are shown in figure 3.2 After the boat is released, it accelerates down the ramp under the influence of these forces. The equations of motion that govern the behavior of the lifeboat as it slides along the launch ramp are:

$$\ddot{X} = g(\cos \theta \sin \theta - \mu \cos^2 \theta) \quad (3.1)$$

$$\ddot{Z} = g(\cos^2 \theta + \mu \cos \theta \sin \theta) \quad (3.2)$$

$$\ddot{\theta} = 0 \quad (3.3)$$

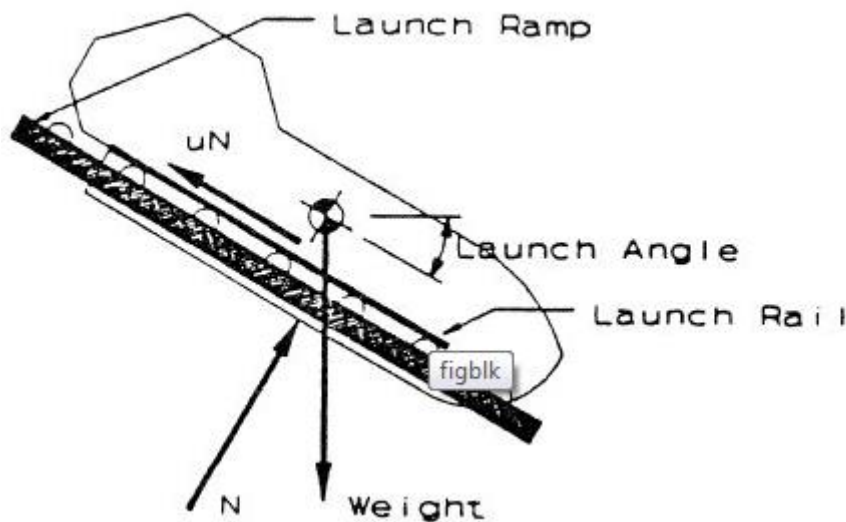


Figure 3.2 Forces Acting on the Lifeboat During the Ramp Phase

. Equations 3.1, 3.2, and 3.3 represent the acceleration in the X direction, the Z direction, and the rotational acceleration, respectively. The term θ is the launch angle, μ is the coefficient of friction between the launch ramp and the launch rail, and g is gravitational acceleration.

. From Equations 3.1 and 3.2 it can be seen that the acceleration of the lifeboat along the ramp is constant, and from Equation 3.3 it can be seen that the lifeboat does not rotate. The motion of the lifeboat is independent of its mass (all of the forces acting on the lifeboat and its acceleration are a function of its mass which appears on both sides of the equations and, as such, cancels). The only parameters affecting the motion of the boat as it slides along the ramp are the coefficient of friction, the angle of the launch ramp, and gravity. The location of the CG only affects the duration of the ramp phase, i.e., the time during which the lifeboat accelerates along the ramp. As previously stated, the ramp phase ends when the CG is directly over the end of the launch ramp.

3.2.2. The angle at which the lifeboat enters the water and its behavior after water entry are affected, in part, by the velocity of the lifeboat at the beginning of the rotation phase. This velocity is dependent upon the duration of the ramp phase which in turn is dependent upon the distance from the CG to the launch ramp. From the equations of motion, the velocity of the lifeboat along the ramp at the end of the ramp phase can be found to be:

$$V_r = \sqrt{2Lg(\sin \theta - \mu \cos \theta)} \quad (3.4)$$

3.2.3. From examination of Equation 3.4 it is evident that the magnitude of the coefficient of friction cannot exceed $\tan \theta$ if the lifeboat is to move along the ramp. Also from examination of Equation 3.4 it is apparent that the velocity increases as the length of the ramp increases and as the angle of the launch ramp increases.

3.2.4. Friction does not have a significant affect on the velocity along the ramp. Shown in figure 3.3 is V_r as a function of ramp length for three values of the coefficient of friction. These data were computed with a launch angle of 35° . The coefficient of friction in most free-fall lifeboats ranges from 0.02 to about 0.05 (the middle curve in figure 3.3). The difference between the top and middle curve or between the middle and bottom curve is slightly less than four per cent. This ratio does not change with ramp length

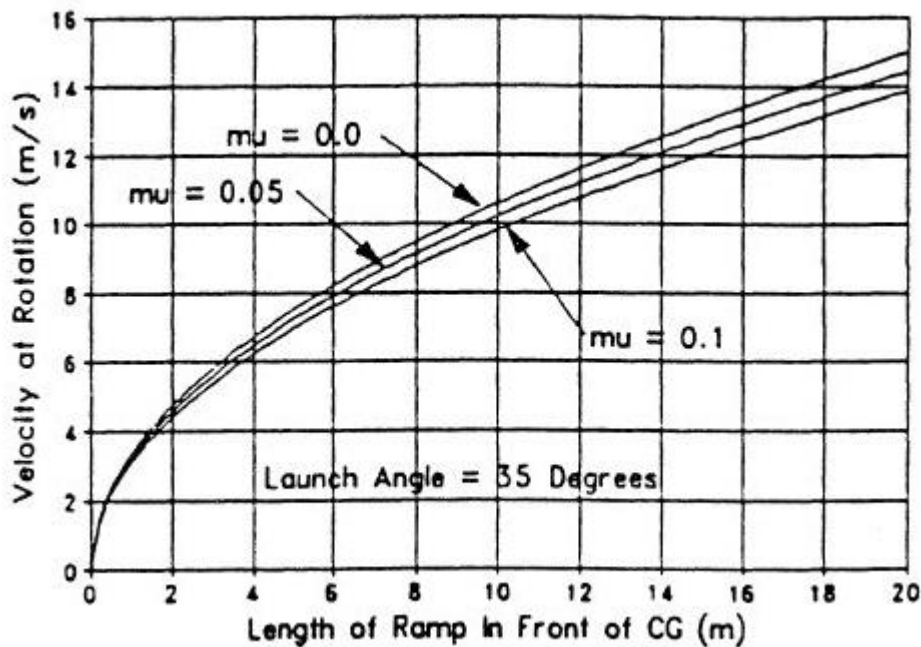


Figure 3.3 Variation of Velocity With Ramp Length for Three Coefficients of Friction

3.2.5. The two significant parameters affecting the velocity of the lifeboat at the beginning of the rotation phase are the length of the launch ramp in front of the CG at the time the boat is released and the angle of the launch ramp. The distance between the CG and the front of the launch ramp is the distance L shown on figure 3.1. Presented in figure 3.4 is the velocity of the lifeboat along the ramp at the beginning of rotation as a function of the length L . Data have been presented for a launch angle of 35° and a coefficient of friction of 0.05. The launch angles of 25° and 45° represent a trim of $\pm 10^\circ$ as required by SOLAS (IMO, 1986, 1990). Most free-fall lifeboats currently produced are launched at an angle of about 30° - 35° measured from the horizontal.

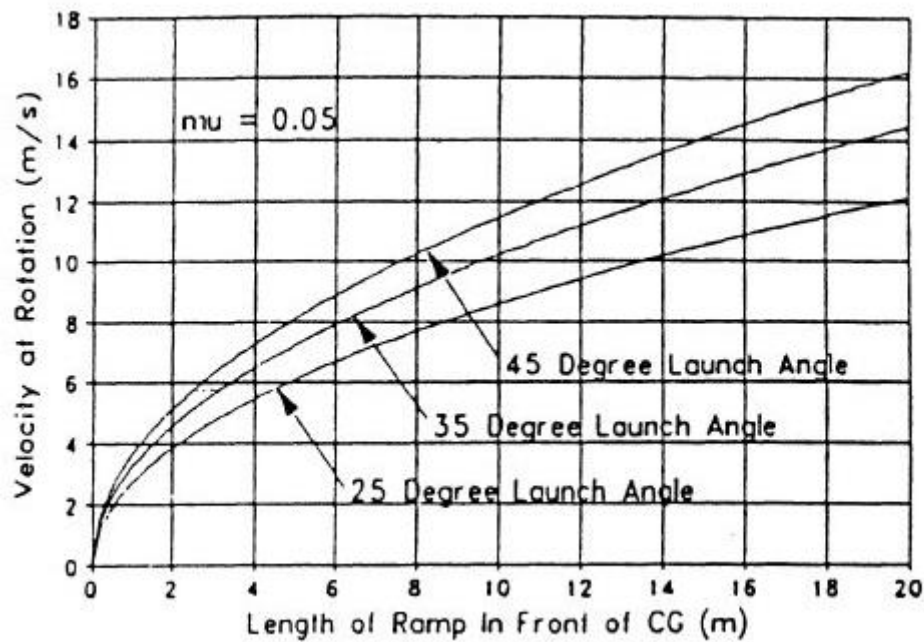


Figure 3.4 Variation of Velocity for Three Launch Angles

3.2.6. Presented in figure 3.5 is rate at which the velocity at rotation changes as a function of the distance from the CG to the end of the ramp. As can be seen from figures 3.4 and 3.5, the most significant increases in velocity occur during the first two to three meters that the lifeboat slides along the ramp. After that the rate of change becomes more linear and is in the order of 0.5 to 0.6 meters per second per meter of length.

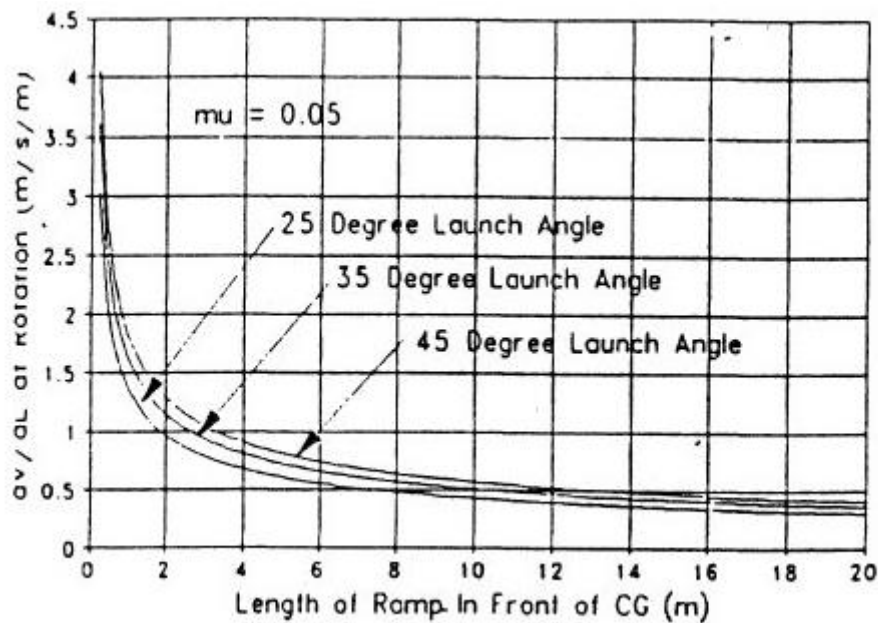


Figure 3.5 Rate of Change of Velocity with Respect to Ramp Length

3.3 Rotation Phase

3.3.1. The geometry of a free-fall lifeboat as it rotates at the end of the launch ramp is shown in figure 3.6. After the CG has moved past the end of the launch ramp, the lifeboat begins to rotate. The primary factors affecting rotational behavior are the velocity of the lifeboat, the mass and mass distribution of the lifeboat, and the distance from the CG to the end of launch rail. The equations of motion describing the behavior of the lifeboat during the rotation phase are (Nelson, et. al., 1991):

$$\frac{W}{g} \ddot{X} = \frac{N}{\cos \phi} \sin(\theta - \phi) \quad (3.5)$$

$$\frac{W}{g} \ddot{Z} = \frac{N}{\cos \phi} \cos(\theta - \phi) - W \quad (3.6)$$

$$I \ddot{\theta} = \frac{N}{\cos \phi} [\Delta X \cos(\theta - \phi) - \Delta \sin(\theta - \phi)] \quad (3.7)$$

where $\bar{u}$ is the friction angle which is equal to $\tan^{-1} \epsilon$. In addition to these three equations, an equation for the compatibility of displacements is required. This equation is:

$$\Delta X \sin \phi + \Delta Z \cos \phi = h \quad (3.8)$$

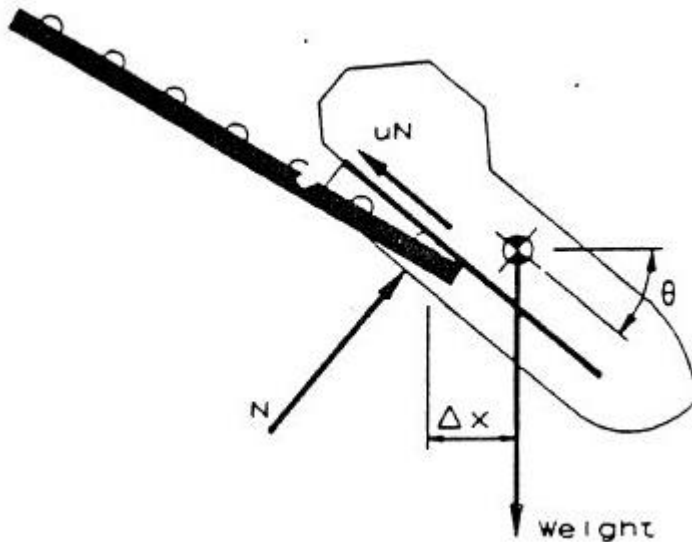


Figure 3.6 Geometry of a Free-Fall Lifeboat As It Rotates Off the End of the Launch Ramp

3.3.2. As implied in Equation 3.7, rotation is caused by a couple formed by the reaction force between the ramp and the lifeboat and the weight of the lifeboat. This couple imparts angular momentum to the lifeboat. The momentum increases during the rotation phase and then remains constant during the free-fall phase.

3.3.3. Presented in figure 3.7 is the angular momentum of a lifeboat versus ramp length for three launch angles (Nelson, 1992). The lifeboat for which these data were computed is about

10 meters long and weighs about 125,000 N. The end of the launch rail is at the stern and the CG is 3.85 meters forward of the stern.

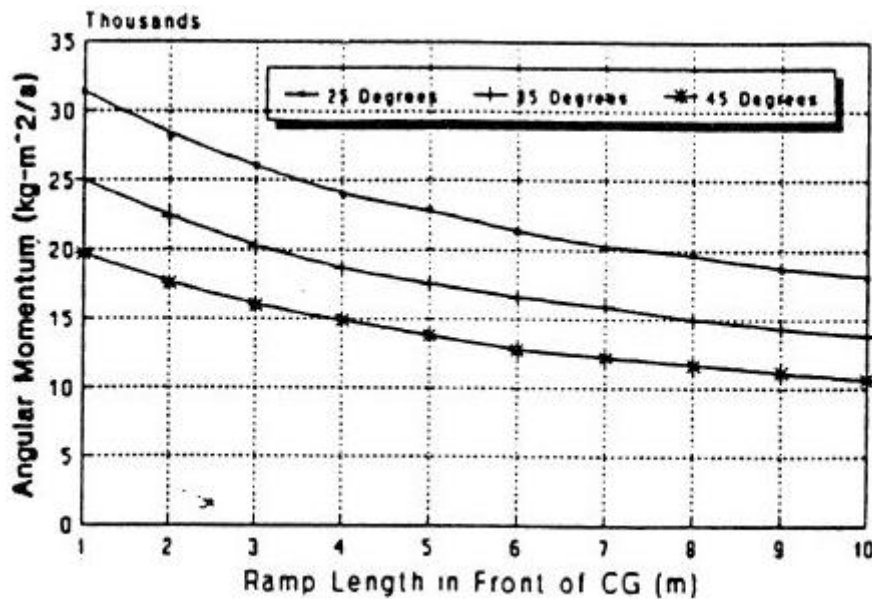


Figure 3.7 Variation of Angular Momentum at End of Rotation Phase

3.3.4. The angular momentum imparted to the lifeboat during rotation decreases as the distance L increases. This occurs because the velocity of the lifeboat at the beginning of the rotation phase increases as the distance to the end of the ramp increases. As such, the time during which it rotates, the time during which the couple acts, decreases as L increases. Because the time of rotation is reduced, the time during which the forces act, and therefore the angular momentum imparted to the lifeboat, is reduced. Likewise, the duration of the rotation, and therefore the angular momentum, increases as the distance to the end of the launch rail increases. The angular momentum increases until the time at which the lifeboat is no longer in contact with the launch ramp. After leaving the launch ramp, the lifeboat continues to rotate at constant angular velocity until it impacts the water.

3.3.5. The differences in the time during which the lifeboat rotates are evident from the force data presented in figure 3.8 (Nelson, et. al., 1992). The relative values of L and D were changed by moving the CG forward and aft. The data, which were computed for a typical free-fall lifeboat that was launched from a ramp at an angle of 30 degrees, were normalized by dividing by the boat weight. Until the rotation phase begins, the force between the boat and the ramp is constant. This force, which is about 87 per cent of the lifeboat weight in this case, decreases during the rotation phase and becomes zero at the end of the rotation.

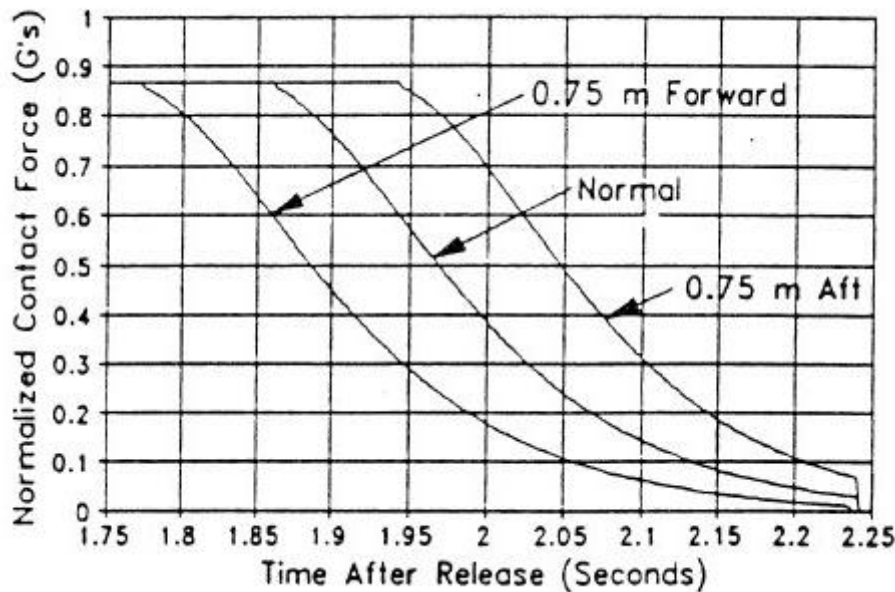


Figure 3.8 Typical Forces Acting on a Free-Fall Lifeboat During Ramp and Rotation Phases for Three Locations of the CG

3.3.6. For the three locations of the CG presented, the rotation phase ends at approximately the same time. The time at which rotation begins, however, changes with the location of the CG. When the CG is in the forward location, the boat begins to rotate about 1.75 seconds after it is released whereas rotation begins about 1.95 seconds after release when the CG is moved aft. Although this difference in time is small; the difference in the resulting rate of rotation during free-fall is significant. Presented in figure 3.9 is the angular velocity from a time just before the boat begins to rotate until shortly after the free-fall phase begins. As can be seen from this figure, the rate of rotation increases during the rotation phase. At any time during the rotation phase, the rate of rotation is higher when the CG is located forward than it is when the CG is located aft. The constant angular velocity at the right side of the curves is the rate at which lifeboat is rotating as it is falling through the air. For the lifeboat represented by these data, there is about a 20 per cent change in the angular velocity during free-fall as the CG is moved from an aft location to a forward location.

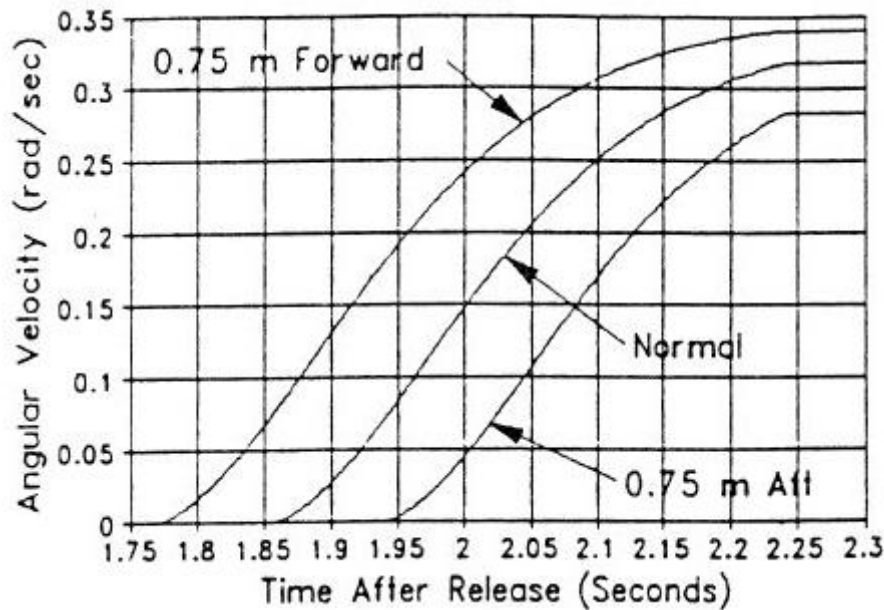


Figure 3.9 Angular Velocity During Rotation for Three Locations of the CG

3.4 Free-Fall Phase

3.4.1. Presented in figure 3.10 is the angular velocity during free-fall as a function of different launch angles. These data were computed for a lifeboat that is about 11 meters long and is normally launched from a ramp at an angle of 35°. During free-fall, the angular velocity is constant; it does not change with height. As the launch angle increases, the angular velocity imparted to the lifeboat decreases. Also, as the CG is moved aft (the relative values of Land D change), the angular velocity decreases. This occurs because in both cases the time during which the lifeboat rotates at the end of the launch ramp decreases. The time decreases as the launch angle increases because the lifeboat is moving off the end of the ramp at a higher velocity. As the CG moves aft the time decreases because the time at which rotation begins is closer to the time at which the lifeboat is no longer in contact with the ramp. Rotation begins when the CG passes the end of the launch ramp.

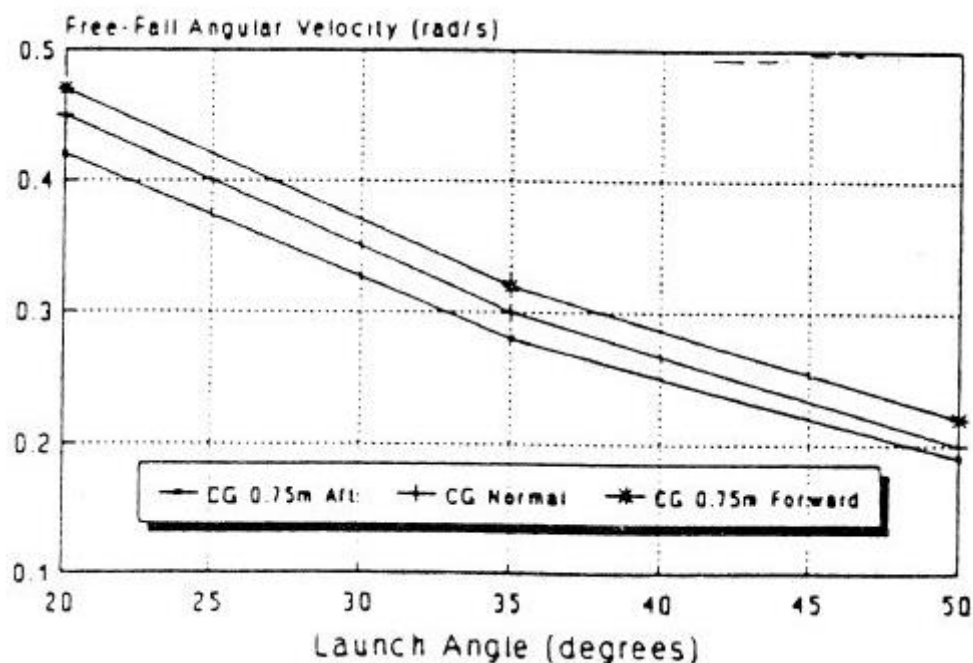


Figure 3.10 Angular Velocity During Free-Fall

3.4.2. Although the free-fall height does not affect the angular velocity, it does affect the angle at which the lifeboat enters the water. Presented in figure 3.11 is the water entry angle that results from free-fall launches from different heights. The initial launch angle in all cases presented was 35° . These data were computed with the same lifeboat represented in figure 3.10. As the free-fall height increases, the difference in the water entry angles increases. In each of these launches, the lifeboat made positive headway after water entry (Nelson, 1992).

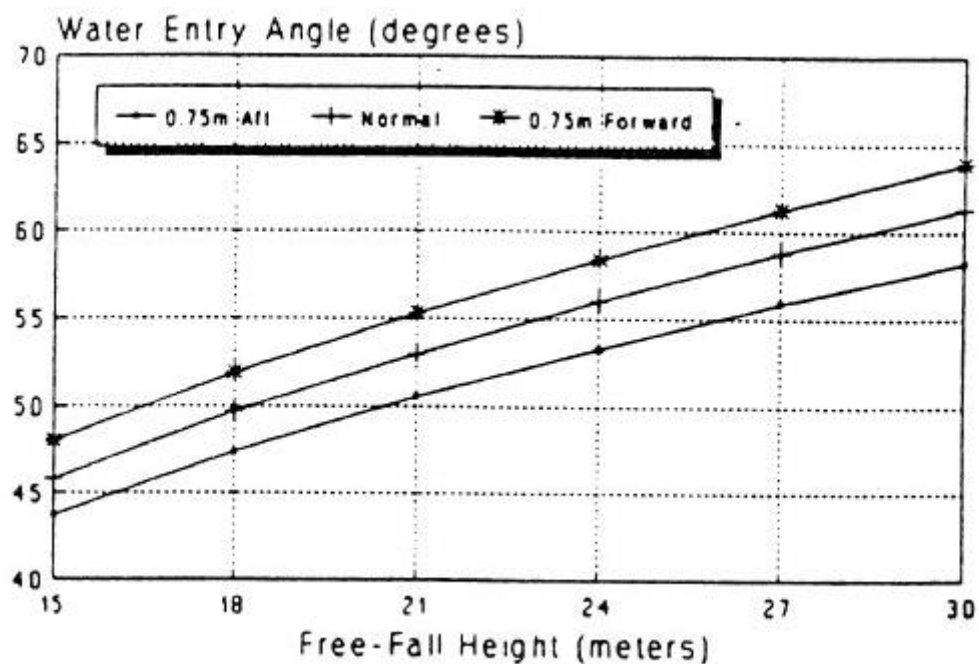


Figure 3.11 Water Entry Angle Versus Free-Fall Height for Three Conditions of Load

3.4.3. Most of the change in the angular orientation of the lifeboat occurs during the free-fall phase. Although there is a considerable change in angular momentum during the rotation phase, there is little change in angle. Presented in figure 3.12 is the orientation of the lifeboat at the end of rotation versus the angle at which it was launched. The bold line on figure 3.12 represents the angle from which the lifeboat is launched. As shown on the figure, the angular change is small, even at shallow launch angles. As the launch angle increases, the angle at the end of rotation becomes asymptotic to the launch angle. Further, the difference between the launch angle and the angle at the end of the rotation phase decreases as the launch angle increases and as the CG moves aft. The velocity of the lifeboat at the beginning of rotation accounts for these effects (Nelson, et. al., 1992).

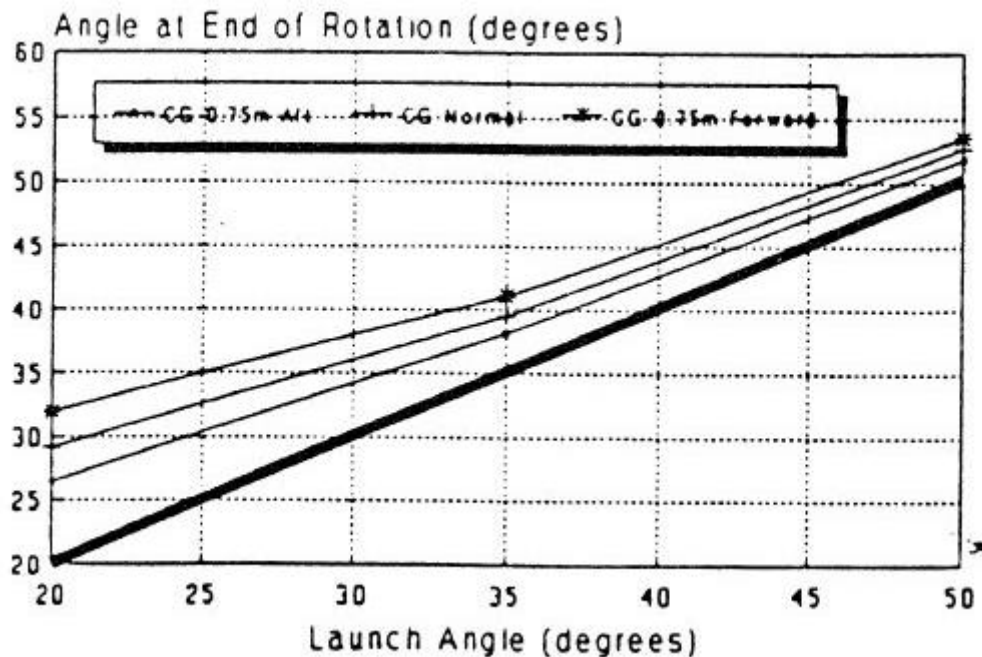


Figure 3.12 Orientation at the End of Rotation Versus Launch Angle

3.5 Water Entry Phase

3.5.1. The geometry of the lifeboat as it impacts the water and the forces acting at that time are shown in figure 3.13. The desired occurrence during water entry is that the lifeboat remain upright, return to even keel, and continues to move away from danger without using its engine. SOLAS (IMO, 1990) requires that the lifeboat make positive headway immediately after water entry.

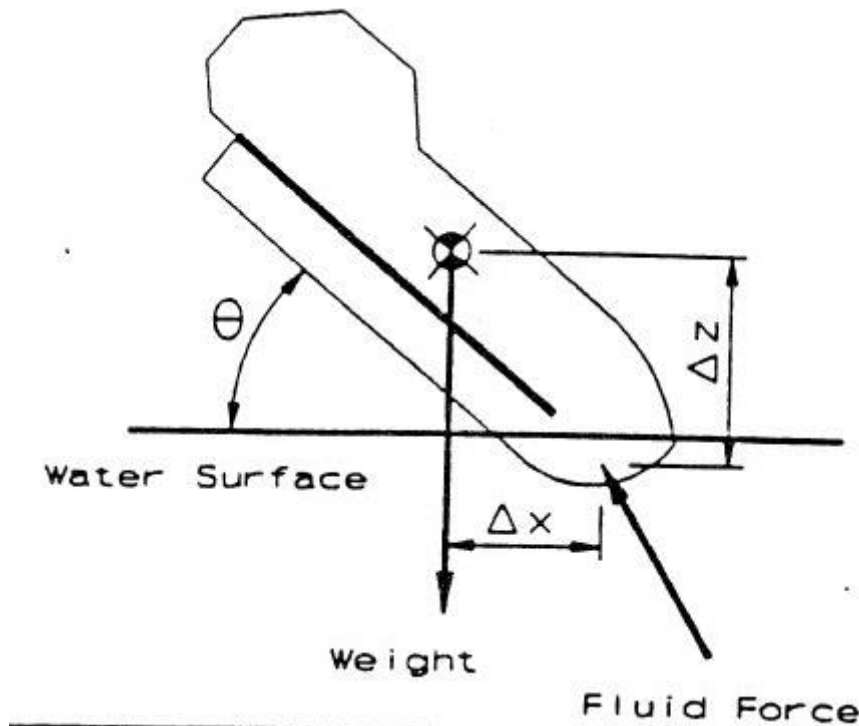


Figure 3.13 Geometry of the Lifeboat During Water Entry

3.5.2. As a result of the launch and free-fall, the lifeboat has kinetic energy at the time it contacts the water. During water entry, the fluid forces do work on the boat which causes the kinetic energy to change. The changes that occur can be represented conveniently in terms of impulse and momentum, namely (Nelson, 1992):

The left side of Equations 3.9 through 3.11 is the momentum of the lifeboat after it has been acted upon by the fluid. The first term to the right of the equal sign is the momentum when the lifeboat first contacts the water and the integral is the impulse caused by the fluid acting on the boat. During the time the lifeboat is entering the water, the vertical and rotational momentum (computed with Equations 3.10 and 3.11) become zero and the horizontal momentum (computed with Equation 3.9) should remain positive. The lifeboat stops rotating and moving vertically but continues moving in a positive horizontal direction.

$$\frac{W}{g} \dot{X}_{t+\Delta t} = \frac{W}{g} \dot{X}_t + \int_t^{t+\Delta t} (F_X \cos \theta + F_2 \sin \theta) dt \quad (3.9)$$

$$\frac{W}{g} \dot{Z}_{t+\Delta t} = \frac{W}{g} \dot{Z}_t + \int_t^{t+\Delta t} (-F_X \sin \theta + F_2 \cos \theta - W) dt \quad (3.10)$$

$$I_{\theta_{t+\Delta t}} = I_{\theta_t} + \int_t^{t+\Delta t} (F_X r_2 - F_2 r_X) dt \quad (3.11)$$

3.5.3. When the lifeboat impacts the water, a righting moment is caused by the fluid forces. This righting moment is the integrand in Equation 3.11. Its magnitude is dependent upon

several factors including the longitudinal location of the CG, the magnitude and direction of the fluid forces, and the orientation of the lifeboat at the time of water contact. As seen on figure 3.14, the magnitude of the righting moment decreases as the water entry angle increases (as the CG moves forward). This has the effect of causing the lifeboat to return to even keel slower. If the entry angle is steep enough, or if the CG is too far forward, the line of action of the fluid force can pass beneath the CG which causes the fluid force to produce an overturning moment instead of a righting moment. In an extreme situation, the lifeboat can over-rotate and become inverted when it impacts the water.

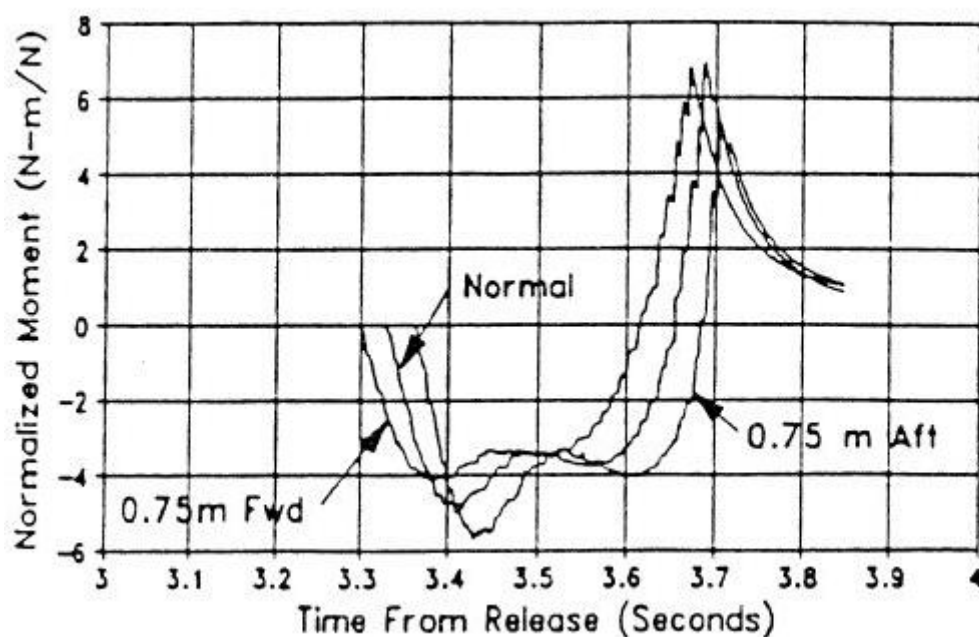


Figure 3.14 Righting Moment on Lifeboat During Water Entry

3.5.4. When conducting tests with full-scale and model lifeboats it has been observed that the headway made by the lifeboat after water impact decreases as the water entry angle increases. In some cases the lifeboat has been observed to move backward after entering the water. It has also been observed that the lifeboat dives deeper into the water as the water entry angle increases. During previous studies (Nelson, et. al., 1991) it was seen that when the water entry angle increases, the orientation of the lifeboat becomes more parallel to its direction of flight.

3.5.5. These effects can be seen in the data presented in figure 3.15 for a free-fall lifeboat launched from a height of 25 meters at an angle of 35°. The water entry angle and the trajectory angle both increase as the rate of rotation during free fall increases. Recall that decreasing ramp length causes the rate of rotation to increase. Under extreme conditions (an unusually short ramp) the water entry angle actually exceeds the trajectory angle. During these launches the lifeboat made positive headway when the trajectory angle exceeded the water entry angle by more than five degrees. The headway increased as the difference in the water entry angle and trajectory angle increased. Similar trends have been noted during analytical studies with the lifeboat being launched from different heights.

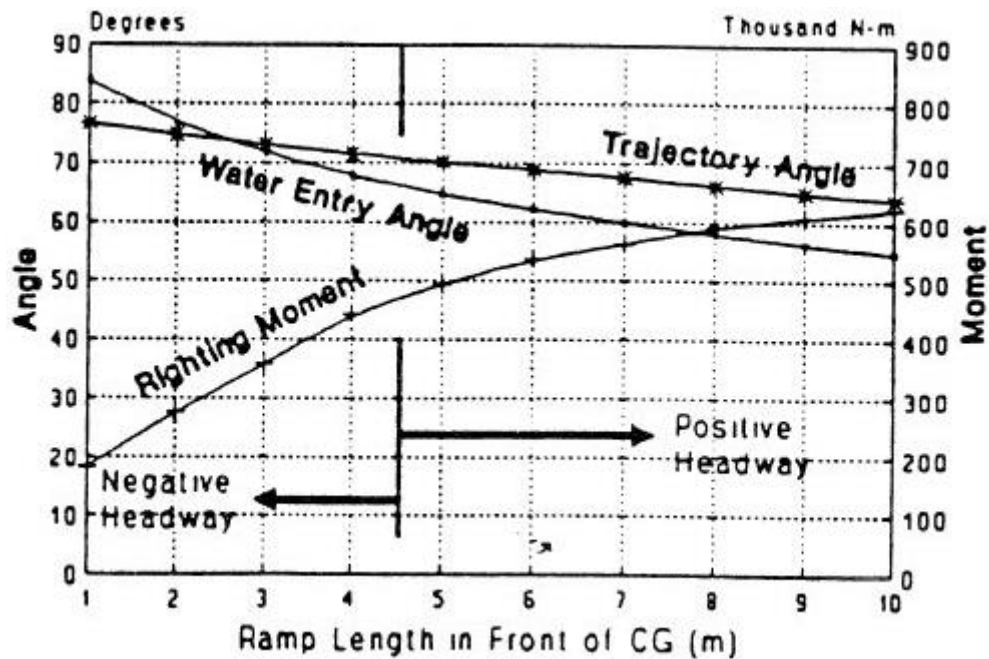


Figure 3.15 Water Entry Angle, Trajectory Angle and Righting Moment Versus Ramp Length

3.5.6. The "knee" of the righting moment curve on figure 3.15 appears to separate the regions of positive and negative headway. Similar results were found during launches from other heights. When the ramp length was equal to that at the knee of the curve, the lifeboat became dead in the water after water entry. As the length of the launch ramp was increased from that at the knee of the righting moment curve, the lifeboat made increasingly positive headway after water entry. When the ramp length was decreased from that at the knee of the curve, it made increasingly negative headway.

3.5.7. As the relative values of L and D changed, differences were noted in the acceleration forces experienced by occupants within the lifeboat. Consider the acceleration force data presented in figure 3.16 that occurred in an 11 meter lifeboat. These data are the maximum Z axis accelerations that occurred at the CG during water entry. The acceleration data are presented in the axes of the lifeboat. The Z axis is the vertical axis of the lifeboat and is perpendicular to the keel.

3.5.8. There was a significant increase in the acceleration force as the CG moved aft and an even more significant decrease as it moved forward. The overall behavior of the lifeboat was acceptable (the boat entered the water upright made positive headway after launch) in each of the launches reported in figure 3.16.

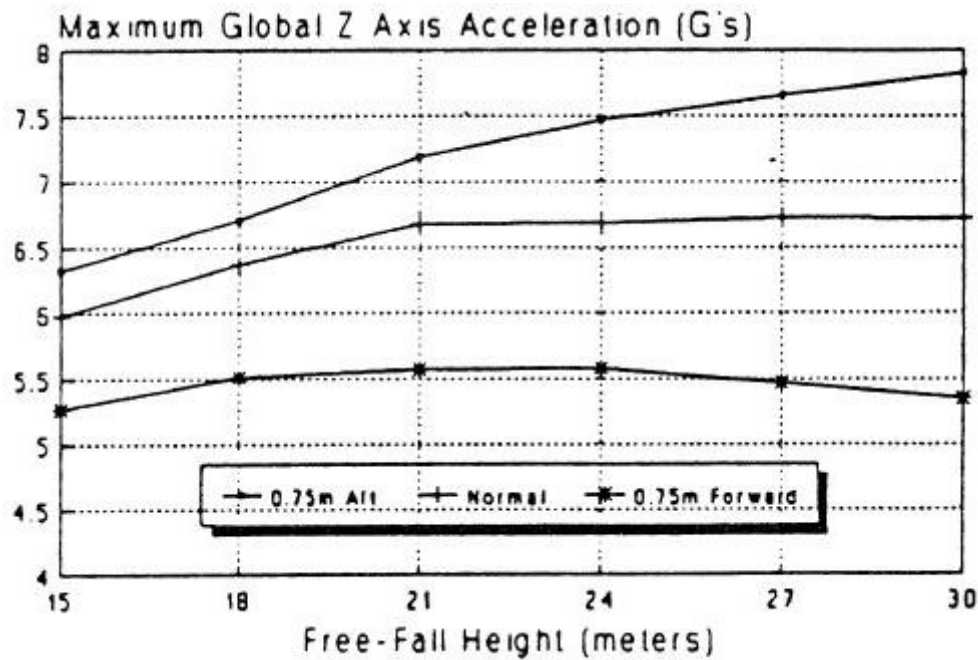


Figure 3.16 Maximum Z Axis Acceleration During Water Entry in the Axis of the Lifeboat

3.5.9. It is interesting to note that the data presented in figure 3.16 indicate the accelerations increase with free-fall height up to a certain point and then begin to decrease. For the lifeboat evaluated, this change occurs at about 28 meters when the CG is in the normal location. The change occurs at about 23 meters when the CG is forward. This phenomenon occurs because of two factors. First, as the free-fall height increases, the velocity at which the lifeboat impact the water increases and, as such, the magnitude of the fluid force increases. Secondly, with increased free-fall height there is an increase in the water entry angle. It has been shown that increasing the water entry angle causes the maximum fluid force to decrease. The interaction of these two factors affects the final performance of the lifeboat.

4.1 Preparation of Scale Models

4.1.1. Model tests are conducted to develop an understanding of the velocity, acceleration, and trajectory of a free-fall lifeboat during launch. Such studies usually are not conducted to determine the structural behavior of the lifeboat. For a scale model to accurately and reliably predict the behavior of a prototype, the various parameters of the model must be in proper proportion with those same parameters in the prototype. However, not all parameters must be in the proper proportion for the model to serve a particular task. Some parameters are not relevant to the behavior being studied or have negligible effect on the behavior of the system. These parameters, therefore, can be neglected. In this sense, there are primarily two types of models that are of interest in engineering studies: true models and adequate models. A true model is one in which all significant parameters of the prototype are reproduced to scale (Murphy, 1950).

4.1.2. An adequate model, on the other hand, accurately predicts one or more characteristics of the prototype but is not useful for predicting all characteristics of the prototype. Adequate models are often used if all parameters of the system cannot simultaneously be scaled. This is particularly true in hydrodynamic modeling (Baker, 1973). In such models, the tests must be conducted in special, and often unavailable, fluids if all of the parameters are to be correctly

scaled. Because the tests are usually conducted in water, it is impossible to satisfy both Froude's Number and Reynolds's Number unless full-scale models are used. One must decide if the phenomenon being studied is gravity-dominated in which case Froude scaling would be used or if it is drag-dominated in which case Reynolds's scaling would be used. In either instance, the model tests are limited in what they can predict but if the neglected phenomenon is insignificant, the model and test results are still adequate. Only from knowledge of the fundamental behavior of a system can insignificant parameters and the adequacy of a model for a particular task be determined.

4.2 Derivation of Model Scaling Factors

4.2.1. Before discussing methods to determine the scaling laws, it is necessary to differentiate between fundamental dimensions and derived dimensions. Fundamental dimensions are the basic quantities upon which all other dimensions are based. In free-fall lifeboat studies, fundamental dimensions commonly used are length (L), mass (M), and time (T). The dimensions of all other parameters are derived from these fundamental dimensions. For example, the units of velocity are derived from length and time as L/T (meters per second, for instance).

4.2.2. Scaling laws are commonly derived from the Buckingham Pi Theorem which states that "any complete physical relationship can be expressed in terms of a set of independent dimensionless products composed of the relevant physical parameters" (Baker, 1973). Bridgman (1931) expressed this concept mathematically in the following manner. If a system can be represented by some function:

$$\phi(\alpha, \beta, \gamma, \dots) = 0 \quad (4.1)$$

where α, β, γ , et cetera are parameters of the system, then the same system can be represented by the function:

$$\xi(\pi_1, \pi_2, \pi_3, \dots) = 0 \quad (4.2)$$

. In Equation 4.2 the term π_i are dimensionless products of the independent parameters in Equation 4.1. These dimensionless products are the scaling from which the ratio of full-scale parameters to model parameters can be determined. As will be seen later, there are fewer π -terms in Equation 4.2 than there are parameters in Equation 4.1.

4.2.3. When conducting model studies to evaluate the behavior of free-fall lifeboats, adequate models are generally used. During such studies, the rigid body kinematic behavior of the lifeboat is of primary concern. As such, only those parameters that affect the kinematic behavior of the lifeboat during the launch need to be properly scaled. These parameters, which can be determined from the differential equations of motion of the lifeboat, are presented in Table 4.1. The units presented with each parameter are its dimensions in the MLT system of fundamental dimensions. ,

Table 4.1 Parameters Affecting a Free-Fall Launch

Symbol	Parameter	Units
S	General Length Terms	L
m	Mass of the Lifeboat	M
t	Time	T
ρ	Fluid Mass Density	M/L^3
ν	Fluid Kinematic Viscosity	L^2/T
v	Velocity of the Lifeboat CG	L/T
a	Acceleration of the Lifeboat CG	L/T^2
ω	Angular Velocity of Lifeboat	$1/T$
α	Angular Acceleration of Lifeboat	$1/T^2$
g	Gravitational Acceleration	L/T^2
I	Lifeboat Second Moment of Mass	ML^2

. Because the $\dot{\gamma}_i$ terms in Equation 4.2 are products of the original parameters, and because these products are of zero dimension, an equation of dimensional homogeneity can be written as:

$$S^{a_1} m^{a_2} \rho^{a_3} \nu^{a_4} v^{a_5} a^{a_6} \omega^{a_7} \alpha^{a_8} g^{a_9} I^{a_{10}} t^{a_{11}} = M^0 L^0 T^0 \quad (4.3)$$

. The quantity on the left side of Equation 4.3 is said to be dimensionally equal to the quantity on the right side. As such, Equation 4.3 can be expressed in terms of its dimensions, namely:

$$[L]^{a_1} [M]^{a_2} \left[\frac{M}{L^3} \right]^{a_3} \left[\frac{L^2}{T} \right]^{a_4} \left[\frac{L^2}{T^2} \right]^{a_5} \left[\frac{L}{T^2} \right]^{a_6} \left[\frac{1}{T} \right]^{a_7} \left[\frac{1}{T^2} \right]^{a_8} \left[\frac{L}{T^2} \right]^{a_9} [ML^2]^{a_{10}} [T]^{a_{11}} = M^0 L^0 T^0 \quad (4.4)$$

. The exponents for mass, length, and time then can be equated which yields the three equations:

$$M: a_2 + a_3 + a_{10} = 0 \quad (4.5)$$

$$L: a_1 - 3a_3 + 2a_4 + 2a_5 + a_6 + a_9 + 2a_{10} = 0 \quad (4.6)$$

$$T: -a_4 - a_5 - 2a_6 - a_7 - 2a_8 - 2a_9 + a_{11} = 0 \quad (4.7)$$

. Equations 4.5 and 4.7 can be solved for the a_2 and a_5 , respectively. The resulting expression for a_5 can be substituted into Equation 4.6 which then can be solved for a_1 . After these expressions for a_1 , a_2 , and a_5 are substituted into Equation 4.3 and like exponents are grouped, Equation 4.3 becomes:

$$\left(\frac{\rho S^3}{m} \right)^{a_3} \left(\frac{\nu}{\nu S} \right)^{a_4} \left(\frac{a}{\nu^2 S} \right)^{a_6} \left(\frac{\omega S}{\nu} \right)^{a_7} \left(\frac{\alpha S^2}{\nu^2} \right)^{a_8} \left(\frac{g S}{\nu^2} \right)^{a_9} \left(\frac{I}{m S^2} \right)^{a_{10}} \left(\frac{tv}{S} \right)^{a_{11}} = M^0 L^0 T^0 \quad (4.8)$$

. The terms in parentheses in Equation 4.8 are the π -terms in Equation 4.2, namely:

$$\begin{aligned}\pi_1 &= \left(\frac{\rho S^3}{m}\right) \pi_2 = \left(\frac{v}{vS}\right) \pi_3 = \left(\frac{g}{v^2 S}\right) \pi_4 = \left(\frac{\omega S}{v}\right) \\ \pi_5 &= \left(\frac{\alpha S^2}{v^2}\right) \pi_6 = \left(\frac{gS}{v^2}\right) \pi_7 = \left(\frac{I}{mS^2}\right) \pi_8 = \left(\frac{tv}{S}\right)\end{aligned}\quad (4.9)$$

. It should be noted that π_6 is the inverse of Froude's Number squared and that π_2 is the inverse of Reynolds's Number for the lifeboat.

4.2.4. These π -terms form the basis of the model laws for the system. The model laws, simply stated, require that the π -terms in the prototype are equal to the corresponding π -term in the model. From the complete set of model laws for the system, and the physical constraints resulting from the environment in which the tests are conducted, the scale factors can be determined. The physical constraints encountered are:

- 1.. The tests are conducted on earth so that gravitational acceleration is the same for both the model and the prototype;
- 2.. tests will be conducted in normal atmosphere so that the properties of air are the same in both the model and the prototype; and
- 3.. The tests will be conducted in sea water so the properties of water will be the same for both the model and the prototype.

4.2.5. In free-fall lifeboat models, it is desirable to achieve a condition of geometric similarity, i.e. the model and the full-scale lifeboat have similar shape and proportions. Such bodies of geometrically similar shape are commonly called geosims (Comstock, 1967). For this condition to be satisfied, there can be only one length scale factor. In this discussion, the length scale factor, K_g , is defined to be:

$$K_g = \lambda = \frac{S_p}{S_m} \quad (4.10)$$

. Then, by equating π_1 for the model and prototype, and substituting the physical constraint that the model is tested in air and the length scale factor, it can be shown that the mass scale factor, K_m , is:

$$K_m = \frac{m_p}{m_m} = \lambda^3 \quad (4.11)$$

. The scale factor for the second moment of mass, K_I can be determined using π_7 and the length and mass scaling factors. The second moment of mass scales as:

$$K_I = \frac{I_p}{I_m} = \lambda^5 \quad (4.12)$$

. Similarly, the velocity scale factor, K_v can be found from λ to be:

$$K_v = \frac{V_p}{V_m} = \sqrt{\lambda} \quad (4.13)$$

. The length and velocity scale factors can be used with λ to show that acceleration is the same in the model and prototype. Using λ and λ for the model and prototype, the scaling factors for angular velocity and angular acceleration are found to be the same as those for velocity and acceleration, respectively. Lastly, the time scale factor, K_t , can be found using λ to be:

$$K_t = \frac{t_p}{t_m} = \sqrt{\lambda} \quad (4.14)$$

4.2.6. When using the scaling factors that have been developed thus far, the condition that Froude's Number in the model should be equal to that in the prototype has been satisfied. However, these same scale factors preclude the ability for Reynolds' Number in the model to be the same as that for the prototype. Using λ it can be seen that velocity should scale linearly with length for Reynolds' Number to be the same in the model and prototype. As such, it is not possible for Froude's Number and Reynolds' Number to be the same, respectively, in the model and prototype. It should be noted that if Reynolds' Number is to be equal in the model and prototype, the other scaling factors developed also would have to change accordingly.

4.2.7. A question arises, then, as to whether Froude scaling or Reynolds' scaling should be used. The question can be answered by examining the launch phenomenon. The launch of a free-fall lifeboat is a gravity dominated event. This is true both during the free fall and during entry into the water. During the launch, the lifeboat begins at rest and accelerates until it impacts the water. The drag forces exerted on the boat by the air during the free fall are small compared to gravitational forces. Likewise, the frictional drag forces exerted on the boat during water entry are small when compared with the inertia forces caused by impacting the water. That is to say, the viscosity of air and water have a significantly lesser effect on the behavior of the lifeboat than does gravity. Because the effect of gravity is considered in Froude's Number, and is not considered in Reynolds' Number, Froude scaling should be used in the preparation of free-fall lifeboat models.

4.3 Application of Scale Factors

4.3.1. The scaling factors necessary for Froude scaling were developed in the previous section. These scaling factors are summarized in table 4.2. The magnitude of prototype parameters are obtained by multiplying the magnitude of the model parameter by the appropriate scale factor. Or inversely, the magnitude of model parameters can be obtained by dividing the magnitude of the prototype parameter by the scale factor.

Table 4.2 Scaling Factors for Free-Fall Lifeboats

Symbol	Parameter	Units
S	General Length Terms	λ
m	Mass of the Lifeboat	λ^3
ρ	Fluid Mass Density	l
ν	Fluid Kinematic Viscosity	l
v	Velocity of the Lifeboat CG	$\lambda^{1/2}$
a	Acceleration of the Lifeboat CG	l
ω	Angular Velocity of Lifeboat	$\lambda^{1/2}$
α	Angular Acceleration of Lifeboat	l
g	Gravitational Acceleration	l
I	Lifeboat Second Moment of Mass	λ^5
t	Time	$\lambda^{1/2}$

4.3.2. To demonstrate the use of the scaling factors, consider the design of a lifeboat that is 10 meters in length and weighs 11.5 tonnes. These and other pertinent parameters of this lifeboat are summarized in the second column of Table 4.3. The parameters shown do not relate to any current lifeboat design. They are being used here only for demonstration of scaling principles. Let us also assume the naval architect wants to build a 1:5 scale model of this lifeboat to evaluate its performance.

. The scaling factors used to convert the full-scale parameters to equivalent model parameters are presented in the third column of the table. The resulting scaled characteristics of the model are presented in the fourth column of table 4.3.

Table 4.3 Scale Model Equivalent Dimensions and Launch Characteristics

Lifeboat or Launch Parameter	Full-Scale Characteristics	Scaling Factors (Full to Model)	Model Characteristics
Boat Length	10.0 m	0.2	2.00 m
Beam	3.5 m	0.2	0.70 m
Boat Height	3.4 m	0.2	0.68 m
Boat Weight	11.5 t	0.008	92.00 kg
LCG	4.8 m	0.2	0.96 m
VCG	1.7 m	0.2	0.34 m
Second Moment of Mass	42,000 kg-m ²	0.00032	13.44 kg-m ²
Launch Height	22 m	0.2	4.40 m
Launch Angle	35°	1.0	35°
Ramp Length	12.0 m	0.2	2.40 m

4.3.3. Normally the location of the CG and the second moment of mass are calculated when the lifeboat is being designed. The launch height is the design free-fall height and the launch angle is the intended angle of the launch ramp. After the model has been built, the designer should verify that the important characteristics are scaled properly and that geometric similarity of the hull has been maintained. The second moment of mass of the model can be measured using the procedure presented in the following section. If necessary, the second

moment of mass of the full-scale lifeboat can be measured using this same procedure after it has been constructed.

Table 4.4 Full-Scale Equivalent of Model Data

Lifeboat or Launch Parameter	Measured Model Data	Scaling Factors (Model to Full)	Full-Scale Equivalent
Maximum Acceleration	11.0 g's	1.0	11.0 g's
Water Entry Velocity	7.5 m/s	2.236	16.77 m/s
Horizontal Position	3.3 m	5.0	16.50 m
Water Entry Angle	55°	1.0	55°
Time of Free-Fall	0.95 s	2.236	2.12 s

4.3.4. Suppose that during the tests with this lifeboat model the data shown in the second column of table 4.4 were obtained. To find the full-scale equivalent of these data, the scaling factors shown in the third column are used. The resulting full-scale equivalent of these data are presented in the last column of table 4.4. If the model was properly scaled, and the tests were carefully conducted, these are the data that would have been obtained if the same tests had been conducted using the full-scale lifeboat. If the performance is not acceptable, adjustments and modifications can be made before the full-scale lifeboat is constructed.

4.4 Measuring the Second Moment of Mass

4.4.1. To accurately predict the launch behavior of a free-fall lifeboat using a scale model, the second moment of mass of the model and the full-scale boat must be in the proper proportion. The second moment of mass of the model (or the full-scale lifeboat) can be measured by treating the lifeboat as physical pendulum. A physical pendulum is a rigid body which is mounted so that it can swing freely in a vertical plane about some axis. The physical pendulum is a generalization of the simple pendulum which is a mass supported at the end of a weightless cord (Resnick and Halliday, 1966). Other means are available to measure the second moment of mass but these require a more difficult experimental procedure and the resulting data are therefore more difficult to interpret.

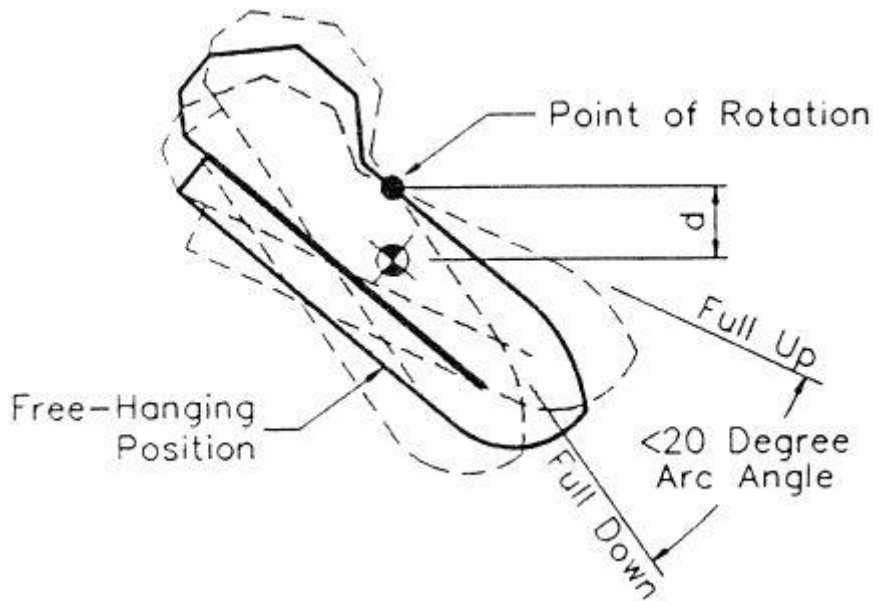


Figure 4.1 Geometry for Measuring the Second Moment of Mass

4.4.2. To measure the second moment of mass by treating the free-fall lifeboat as a physical pendulum, consider the geometry presented in figure 4.1. The lifeboat is suspended from a fixed point on the upper canopy. This point could be the recovery hook in a full-scale boat or a U-bolt in a scale model. This point becomes the point of rotation. When the lifeboat is suspended in this manner, the CG is located at a distance d directly beneath the point of rotation.

4.4.3. If the boat were to be pushed some amount and then allowed to swing freely, it would oscillate about the point of rotation as shown in figure 4.1. As the lifeboat oscillates, it is in a state of harmonic motion that can be described by the differential equation:

$$\ddot{\theta} + \left[\frac{m g d}{I + m d^2} \right] \sin(\theta) = 0 \quad (4.15)$$

. The first term on the left side of the equation is the angular acceleration and θ is the angle formed between the lifeboat in the free hanging position and the position at some other time when it is oscillating. Because the equation of motion involves the term $\sin\theta$, the lifeboat is not undergoing simple harmonic motion. However, for small angles of displacement, $\sin\theta$ is nearly equal to θ (in radians). If it is assumed that the lifeboat undergoes small rotations, the differential equation of motion can be more conveniently expressed in the form:

$$\ddot{\theta} + \left[\frac{m g d}{I + m d^2} \right] \theta = 0 \quad (4.16)$$

This equation is valid, for practical purposes, as long as the arc through which the lifeboat swings is less than about 20 degrees. From Equation 4.16, the period of the harmonic oscillation is found to be:

$$T = 2\pi \sqrt{\frac{I + m d^2}{m g d}} \quad (4.17)$$

The period-of harmonic motion is the time required for one complete oscillation to occur. Equation 4.17 can be solved for the second moment of mass which is found to be:

$$I = m g d \left[\left(\frac{T}{2\pi} \right)^2 - \frac{d}{g} \right] \quad (4.18)$$

Using Equation 4.18, the second moment of mass can be computed if the mass of the lifeboat, the period of oscillation, and distance from the point of rotation to the CG are known.

4.4.4. To physically measure the second moment of mass, then, the lifeboat should be suspended as shown in figure 4.1. It is then pushed some amount and released so that it oscillates freely in the vertical plane. As the lifeboat oscillates, the point of rotation should not move. Because small displacements are assumed in the analysis discussed previously, the arc through which the boat swings should not be greater than 20 degrees. The total time for the lifeboat to complete at least five oscillations is measured. Because of error inherently introduced into the measurement by starting and stopping the stopwatch, the accuracy of the measurement increases as the number of cycles during which the time is measured increases. The error associated with starting and stopping the stopwatch is distributed over more cycles so the error per cycle is smaller. After the time required to complete a number of oscillations has been determined, the second moment of mass of the lifeboat can be computed using the following modified form of Equation 4.18:

$$I = \frac{m g d}{4\pi^2} \left(\frac{T^2}{n} \right) - m d^2 \quad (4.19)$$

In this equation, T is the total time required for n complete cycles of oscillation. The quantity I is the second moment of mass of the model (or the full-scale lifeboat if it was used during the measurement) about the CG.

4.5 Adjusting the Second Moment of Mass

4.5.1. After a model of a lifeboat has been constructed, it is very often necessary to adjust the magnitude of the second moment of mass so that it is in proper proportion with the full-scale lifeboat. This is easily accomplished by placing two moveable weights in the model as shown in figure 4.2. The mass of the weights W_1 and W_2 are equal to m_1 and m_2 respectively. The total scaled mass of the lifeboat model, then, is equal to:

$$m = m_1 + m_2 + m_0 \quad (4.20)$$

where m_0 is the mass of the model (including equipment placed in the model) without the two weights on board. The weights are placed in the model at a distance S_1 and S_2 longitudinally from the CG and vertically at the CG. The distances S_1 and S_2 are selected so that the location of the CG does not change.

As the weights W_1 and W_2 are moved farther apart, the second moment of mass of the system increases. Conversely, as the weights are moved closer together, the second moment of mass of the system decreases. The distances at which the weights should be placed are:

$$S_1 = \sqrt{\frac{m_2(I - I_0)}{m_1 m_2 + m_1^2}} \quad S_2 = \sqrt{\frac{m_1(I - I_0)}{m_1 m_2 + m_2^2}} \quad (4.21)$$

In the above equations I is the required second moment of mass and I_0 is the second moment of mass of the model without the weights on board. If the two weights have the same mass, and that mass is equal to m_a , the equations can be reduced to:

$$S_1 = S_2 = S = \sqrt{\frac{I - I_0}{2m_a}} \quad (4.22)$$

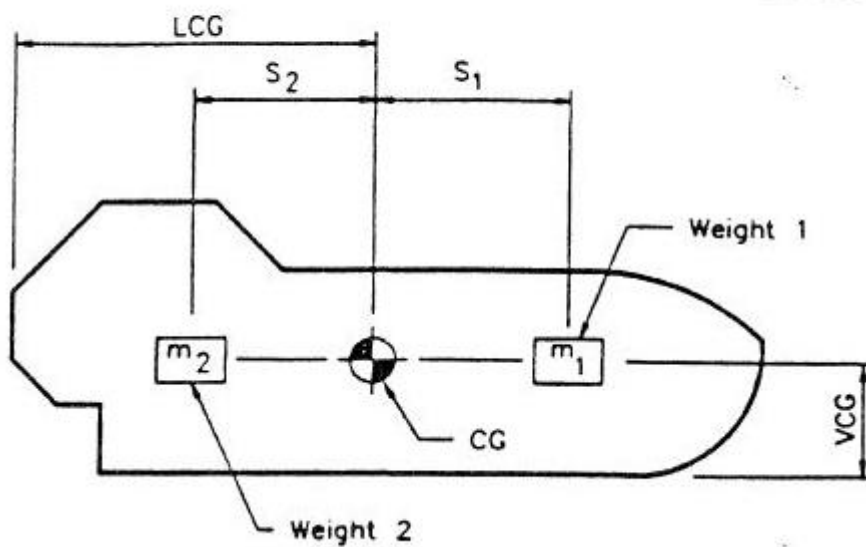


Figure 4.2 Geometry for Adjusting Second Moment of Mass

4.5.2. For this procedure to be applicable, I_0 must be smaller than that required. The second moment of mass can be increased by moving the weights around but it cannot be decreased below that which would occur if the masses were placed at the CG (S_1 and S_2 are both equal to zero). As such, the model should be built so that its mass and second moment of mass are smaller than that required. Two weights then can be properly placed in the model so that the resulting mass and second moment of mass are of the proper magnitude.

5.1 Accelerometer Selection And Placement

5.1.1. Appropriate accelerometers need to be selected, properly placed in the lifeboat, and securely mounted to obtain reliable and replicable acceleration force data over the complete

range of acceleration forces that occur during the launch of a free-fall lifeboat. Different types of accelerometers are commercially available. The type selected must have adequate response for the test being conducted. In addition, the acceleration force data must be recorded in a manner so as to accurately represent the measured acceleration field.

5.1.2. During the conduct of free-fall lifeboat prototype tests, the accelerometers used to measure the acceleration forces that occur during the launch should have a working range of 20-25 G's. Typically the maximum acceleration forces measured on the hull of the lifeboat do not exceed about 12 to 15 g's. The basis of these values is experience with the many freefall lifeboat prototype tests that have been conducted to date. However, as the mass of the lifeboat decreases, or as the height of free-fall increases, the acceleration forces tend to increase if all other factors are held constant. Therefore the actual launch conditions should be evaluated and appropriate accelerometers selected.

5.1.3. The accelerometers should be placed in the lifeboat in groups of three and oriented so as to measure all three components of acceleration at each location. The accelerometers in each group are normally oriented parallel with the principal axes of the boat. Typically three such groups are used. As shown in Figure 5.1, one group of accelerometers is placed by the side-wall of the boat at the location of the most forward seat. A second group is placed on the opposite side of the lifeboat near midships. The third group is usually located near the most aft occupant seat and on the same side of the boat as the forward group of accelerometers. Sometimes an additional group of accelerometers is placed at the helm.

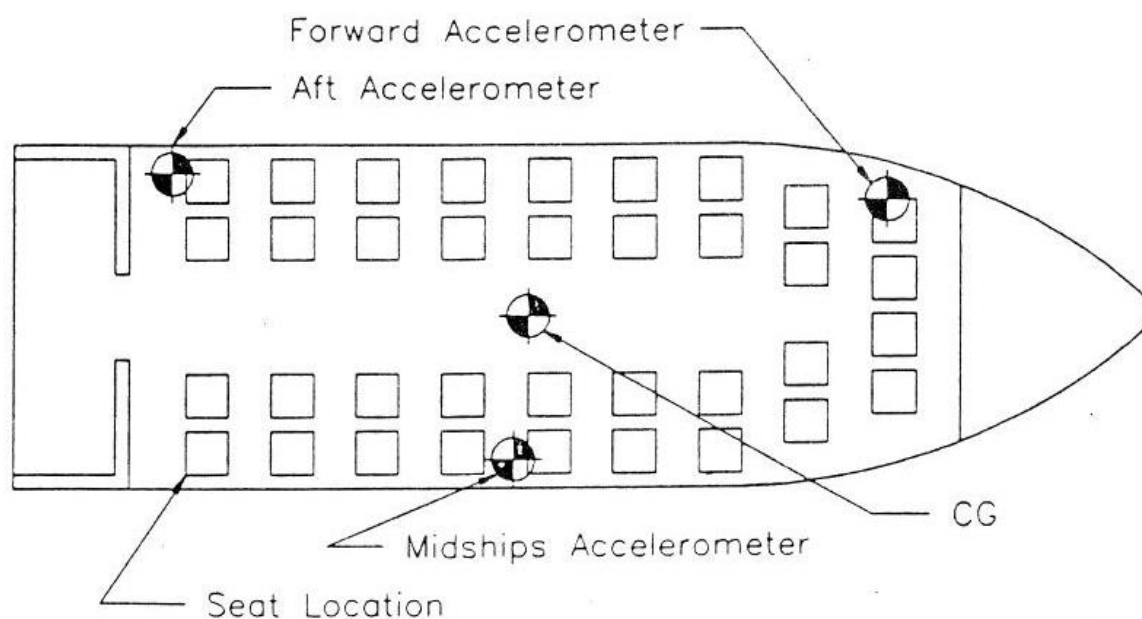


Figure 5.1 Typical Placement of Accelerometers in a Free-Fall Lifeboat

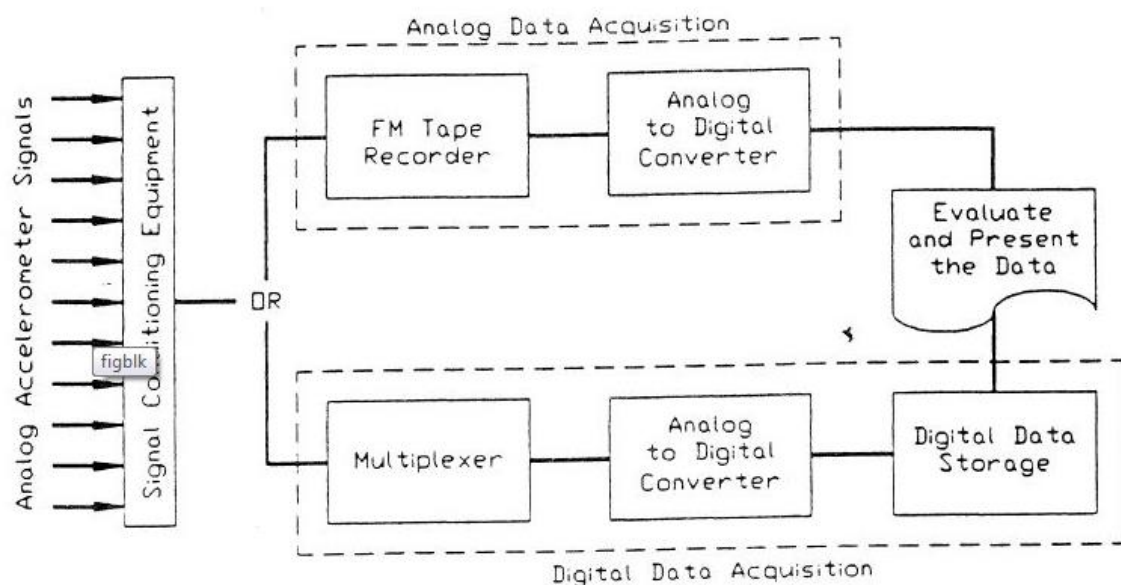
5.1.4. Because prototype tests with free-fall lifeboats are conducted with the ship on even keel and generally in good weather conditions, the lifeboat predominantly moves in a vertical plane during the launch. As such, the lateral force imparted to the lifeboat is generally negligible; the accelerometers oriented in the lateral direction will indicate negligible acceleration. However, lateral acceleration force should be measured, if possible, so that unexpected or unusual behavior can be observed and quantified. Such unexpected behavior

could result from an improperly constructed lifeboat or launch ramp or from improperly distributed mass within the lifeboat.

5.1.5. When the accelerometers are placed in the lifeboat, care should be taken to ensure that they are properly oriented with the lifeboat and that they are securely mounted on a firm support. A good place to mount the accelerometers is directly over bulkheads or deck stiffeners. By placing the accelerometers at these locations unwanted vibrations are minimized to the greatest extent possible.

5.2 Data Acquisition System

5.2.1. The measured acceleration forces can be collected and stored in either an analog or a digital format. The primary components of either type of data acquisition systems are shown in the block diagram presented in Figure 5.2. Following is a brief description of the purpose and operation of each component. A thorough discussion of data acquisition systems can be found in the Shock and Vibration Handbook (Harris, 1988).



5.2 Primary Components of a Data Acquisition System

5.2.2. The output signal from the accelerometers is an analog signal, i.e., it is a continuous signal that has a varying voltage. The magnitude of the voltage can be correlated to the acceleration force through use of a calibration factor. The signal from each accelerometer is passed through a signal conditioner. Signal conditioners primarily are used to amplify the accelerometer signal to a level that can be recognized by the data storage device. If necessary, anti-aliasing filters can be provided in the signal conditioning equipment. Signal aliasing and the need for anti-aliasing filters are discussed later.

5.2.3. If an analog data acquisition system is being used, the conditioned accelerometer signals are recorded on either an FM (frequency modulation) recorder or a direct recorder. With an FM recorder, the amplitude information of the signal recorded as a deviation from a constant carrier frequency. The actual signal is recorded when using a direct recorder. FM recorders are preferred in analog systems for two reasons. First, the recorded signals are less susceptible to change caused by poor storage conditions. Second, the lowest frequency that can be recorded with a direct recorder is about 25 hertz. With FM recorders, the signal is

faithfully recorded down to and including DC. A DC signal is effectively zero hertz. After the accelerometer signals have been stored, they can be played back through an analog-to-digital converter for processing and presentation. Analog to digital converters change the continuous signal to discrete values that have been sampled at uniform increments of time (Harris, 1988). Signal sampling will be discussed shortly.

5.2.4. When using a digital data acquisition system, the conditioned accelerometer signals are individually selected at each time-step with the multiplexer, converted to a digital value of the analog signal at that time, and stored in digital form. At every time-step, all of the signals are sampled. Digital recording of the data eliminates many of the problems associated with analog recording. These problems include wow, flutter, and limited dynamic range (Harris, 1988). A problem with digital recording is managing potentially large quantities of data.

5.2.5. Ideally, the data acquisition equipment used to collect and record the measured acceleration force data should be in the lifeboat during the launch. By placing the data acquisition in the lifeboat, there are no external cables external which can interfere with the behavior on the lifeboat. Equipment placed in the lifeboat must be capable of operating on battery power and must be able to withstand the forces exerted on it during water entry.

5.2.6. Excellent results also have been obtained using data acquisition equipment that is located on the dock and connected to the lifeboat with a waterproof umbilical cable. The mass of such a cable should be small relative to the mass of the lifeboat and it should be allowed to fall freely during the launch. By using the umbilical cable in the manner, the forces exerted on the lifeboat by the cable will be small. The headway of the lifeboat after water entry should be restricted with a painter so that the umbilical cable will not be stretched or become disconnected from the data acquisition equipment.

5.3 Sampling Rate And Alias Signals

5.3.1. Any discussion of sampling rate and signal aliasing, must include a discussion of the frequency content of the signal being measured. In the case of free-fall lifeboats, the signal being measured is the acceleration force time-history. The acceleration force time-history, which is the variation of the acceleration force with time, can be decomposed into a combination of sine and cosine curves of varying amplitudes and frequencies. This concept is represented mathematically as:

$$h(t) = \sum_{j=1}^n a_j \cos(2\pi f_j t) + \sum_{j=1}^n b_j \sin(2\pi f_j t) \quad (5.1)$$

for $t = 0$ to T

The term $h(t)$ is the amplitude of a resultant time-history at time t . The time-history is T seconds in duration. The quantities a_j and b_j are the amplitudes of the cosine and sine curves, respectively, associated with frequency f_j . n different frequencies, and associated amplitudes, are included in the analysis.

5.3.2. To obtain a more intuitive understanding of the significance of this equation, consider the curves presented in Figure 5.3. Shown on this figure are two sine curves and one cosine curve of different amplitudes and frequencies. The 2 hz and 20 hz signals are sine curves with

amplitudes of 1.5 and 0.5, respectively. The 6 hz signal is a cosine curve with an amplitude of unity. The amplitude of the combined signal at any particular time is equal to the sum of the amplitudes of the three other curves at that same time. For this particular example, then, the amplitude of the combined signal at any time is:

$$h(t) = \frac{1}{2}\sin(40\pi t) + \cos(12\pi t) + \frac{3}{2}\sin(4\pi t) \quad (5.2)$$

When considering Equation 5.2, recall that the frequency in radians is equal to 2π times the frequency in Hertz.

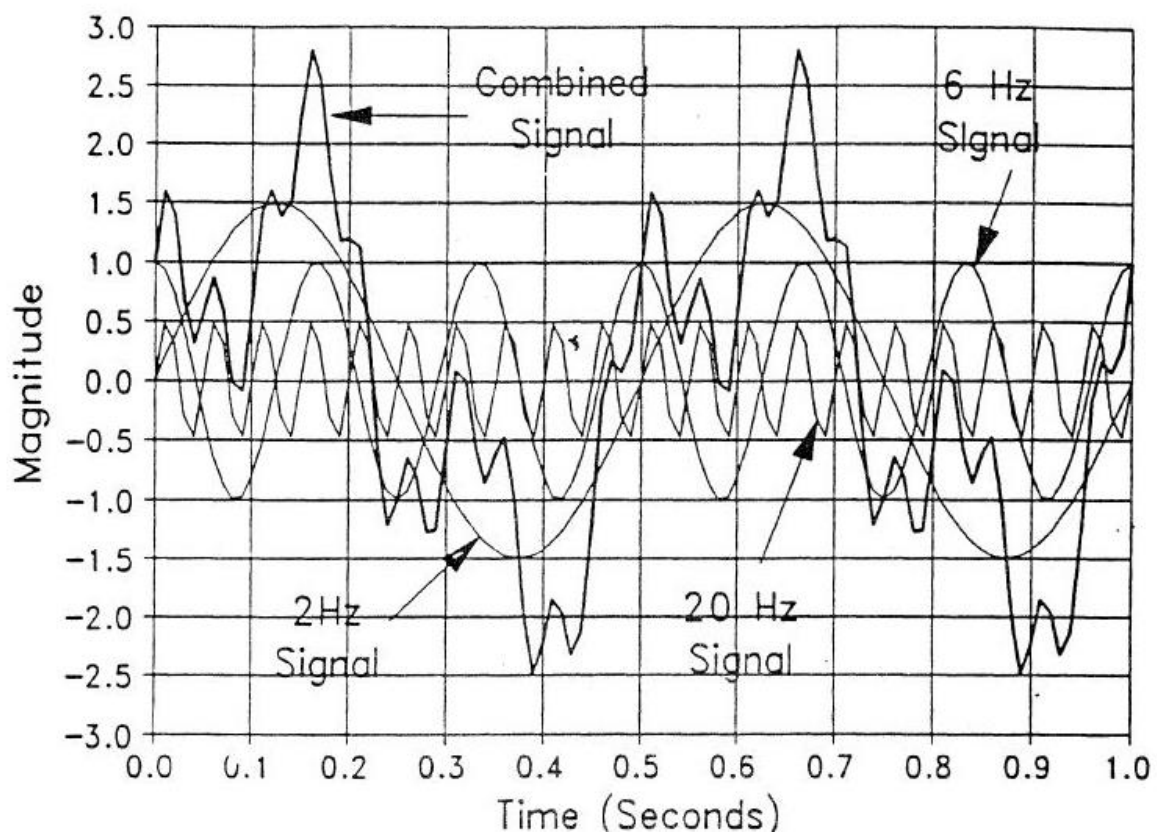


Figure 5.3 A Signal that is a Combination of Three Sinusoids

5.3.3. By using principles from calculus of complex variables, Equation 5.1 can be reduced to a form in which frequency and its associated amplitude are more readily apparent, namely:

$$h(t) = \sum_{i=1}^n A_i \cos(2\pi f_i t - \theta_i) \quad (5.3)$$

where

$$A_i = \sqrt{a_i^2 + b_i^2} \quad \theta_i = \tan^{-1} \left[\frac{b_i}{a_i} \right] \quad (5.4)$$

The term A_i is the amplitude of the resultant sinusoid and θ_i is the phase angle. With the equation presented in this form, there is a single amplitude associated with each frequency. For the example presented in Figure 5.3, a plot of the frequency content versus amplitude is shown in Figure 5.4. The frequency content of the combined curve is 2, 6, and 20 hz .

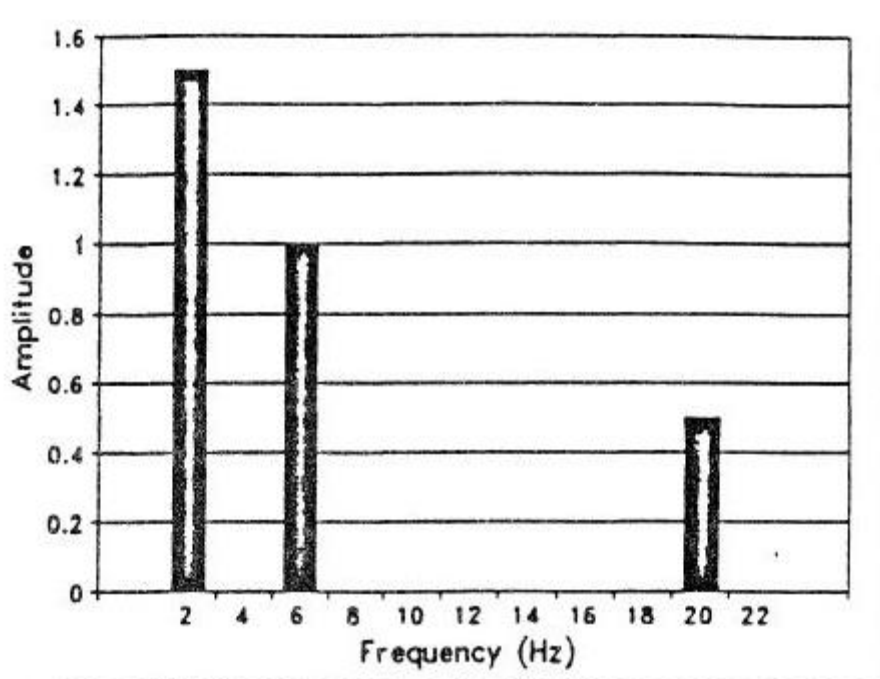


Figure 5.4 Frequency Content of Example Problem

5.3.4. Selection of a data sampling rate requires knowledge of the highest frequency that is of significance in the analysis to be performed as well as the magnitude of other frequencies with significant amplitudes present in the system being measured. Let us first deal with the highest frequency that is important in the analysis. If the sampling rate is not rapid enough an aliased signal (a false signal) such as that shown in Figure 5.5 will be returned. In Figure 5.5 the actual signal is a sine curve with an amplitude of 1.5 and a frequency of 15 hz. This sine curve was "sampled" every 60 milliseconds; these data points are indicated by the solid boxes. By sampling at this slow rate, an apparent signal with a frequency of 1 hz and an amplitude of 1.5 was obtained. The apparent signal is significantly different than the actual signal and as such is probably of very little value. In this particular case, the actual signal increases in an opposite direction from the apparent signal. Starting at time $t=0$, the actual signal initially increases positively whereas the apparent signal initially increases negatively.

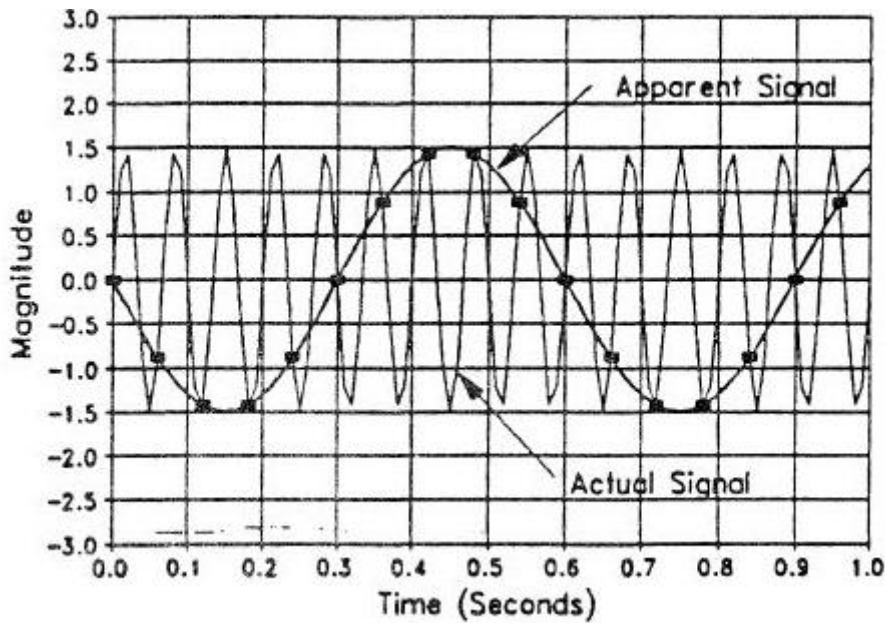


Figure 5.5 Apparent Signal from a Signal that Was Sampled at too Slow a Rate

5.3.5. Clearly, the sampling rate must be rapid enough to properly describe a signal oscillating at the highest important frequency. Although the general shape of a sinusoid can be described with as few as two data points, more data points provide a more reliable description of the shape. As shown in Figure 5.6, four data points provide a reasonable description of the shape of a sine (or cosine) curve. More data points will describe the curve better but five points generally provide an adequate description. A good "rule of thumb" often used in experimental measurement is that a signal should be sampled at a rate which will enable a sinusoid with a frequency five times greater than that of importance to be adequately described. As such, the minimum sampling rate is generally 20 times the highest important frequency. If, for example, 20 hz is the highest frequency to be considered, the data should be sampled 400 times per second (4 samples per cycle times 20 cycles per second times 5).

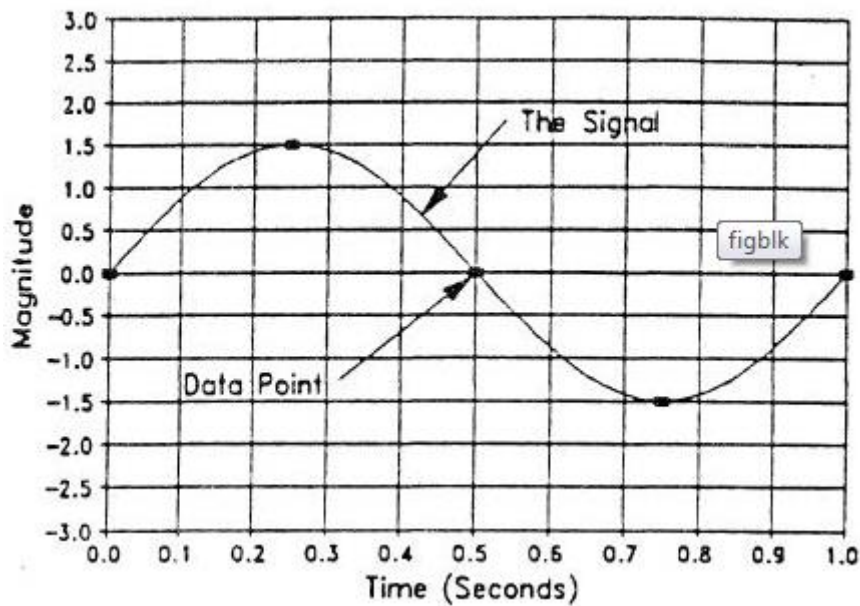


Figure 5.6 Minimum Number of Data Points Required to Describe a Sinusoid

5.3.6. One problem does however, arise in experimental measurement of mechanical or structural systems. Very often high frequency vibration is present. In free-fall lifeboat systems, such vibration occurs when the lifeboat slides along the launch ramp and again when it impacts the water. If the amplitude of the vibration is significant, the sampled signal can be an alias of the true signal (small amplitude, high frequency vibration is not a concern). An alias signal can be observed in Figure 5.7. In this example, the important frequency is 2 hz with an amplitude of 2.0. This is the "true" signal" shown on the figure. There was 15 hz noise" with an amplitude of 1.5 that was superimposed over the true signal. The resulting signal is the actual signal shown on Figure 5.1; the actual signal is that which will be measured even though it contains the unwanted high frequency data. If the actual signal is sampled enough (about 20 times the highest frequency) the unwanted frequencies can be later removed through filtering. If, however, the signal is not sampled rapidly enough to properly describe these high frequencies, the data will be aliased, the high frequency data is falsely translated into the low frequency data. The apparent curve in Figure 5.7 was obtained by sampling the data at 16 hz; such a rate is adequate for the true signal but is not adequate for the high frequency noise. As such, the apparent signal resembles the true signal but the amplitude is different; the apparent signal is erroneous and may lead to improper conclusions about the behavior of the system. A signal should therefore be sampled at a rate quick enough to describe large amplitude, high frequency vibration that may be present. After a signal has been sampled, there is little that can be done to remove the aliased power (Press, et. al., 1988). If this results in an excessively high sampling rate, anti-aliasing filters can be used to limit high frequencies in the signal before it is sampled.

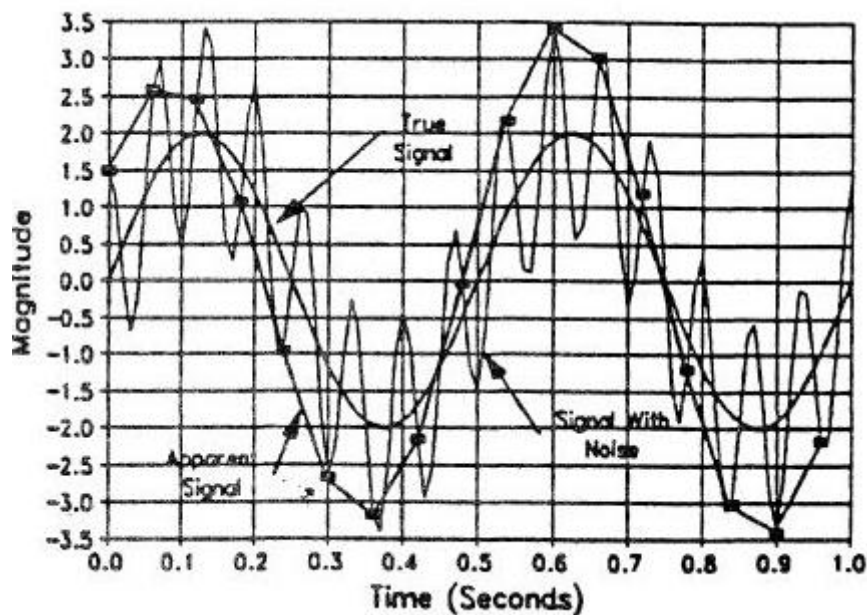


Figure 5.7 An Alias of a True Signal

5.3.7. Experience with free-fall lifeboats has indicated that sampling rates in the order of 600 to 800 hz are adequate to provide a reliable acceleration force time-histories that has negligible aliasing. Such rates have been used on both GRP and aluminum boats with free-fall heights as high as 30 meters. Care should be taken, however, to properly mount the accelerometers on rigid parts of the boat. If the accelerometers were placed in the middle of a large flat panel, for instance, this sampling is probably not rapid enough.

5.4 Filtering Measured Time-Histories

5.4.1. Because any acceleration time-history is composed of many sinusoids of different frequencies and amplitudes, it often contains sinusoids with frequencies that are of little importance or insignificant. These unwanted or unimportant frequencies can be removed from the time-history. This process is called data filtering. Filtering is performed for many reasons. Perhaps frequencies above some value are not significant for some reason. This is the case with occupant acceleration forces in free-fall lifeboats. Frequencies above 20 hz do not have a significant affect on the body and can be removed from acceleration force time-histories when evaluating occupant response. At other times electrical interference can cause frequencies of some magnitude to be introduced into the data; these should be removed before the data is evaluated.

5.4.2. In general, there are four types of filters: lowpass, highpass, bandpass, and notch. When using a lowpass filter, only those frequencies below a certain frequency are retained. The opposite is true for a highpass filter; only those frequencies above a certain frequency are retained. When using a notch filter, all frequencies except those within a specified range are retained; those frequencies within the specified range are discarded. A bandpass filter, on the other hand, is used to remove frequencies with a specified range and retain all others. After the appropriate frequencies have been discarded, the filtered time-history can be computed using Equation 5.3 and only those frequencies that were retained.

5.4.3. This concept of filtering can be represented graphically by again considering the data presented in Figure 5.3. Let us assume that we measured the data represented by the combined curve shown in that figure. Let us further assume that we want to filter this measured data with a 10 hz lowpass filter; any frequency greater than 10 hz will be removed from the data. The amplitude of the filtered time-history can be computed from:

$$A_f(t) = \cos(12\pi t) + \frac{3}{2}\sin(4\pi t) \quad (5.5)$$

Notice that Equation 5.5 is the same as Equation 5.2 after deleting the term involving the 20 hz frequency. The filtered curve represented by Equation 5.5 is shown in Figure 5.8. It is superimposed over the combined curve from Figure 5.3 so that the effects of filtering can be observed. As can be seen, the filtered curve is much smoother than the unfiltered curve.

This is characteristic of data that has been filtered with a lowpass filter.

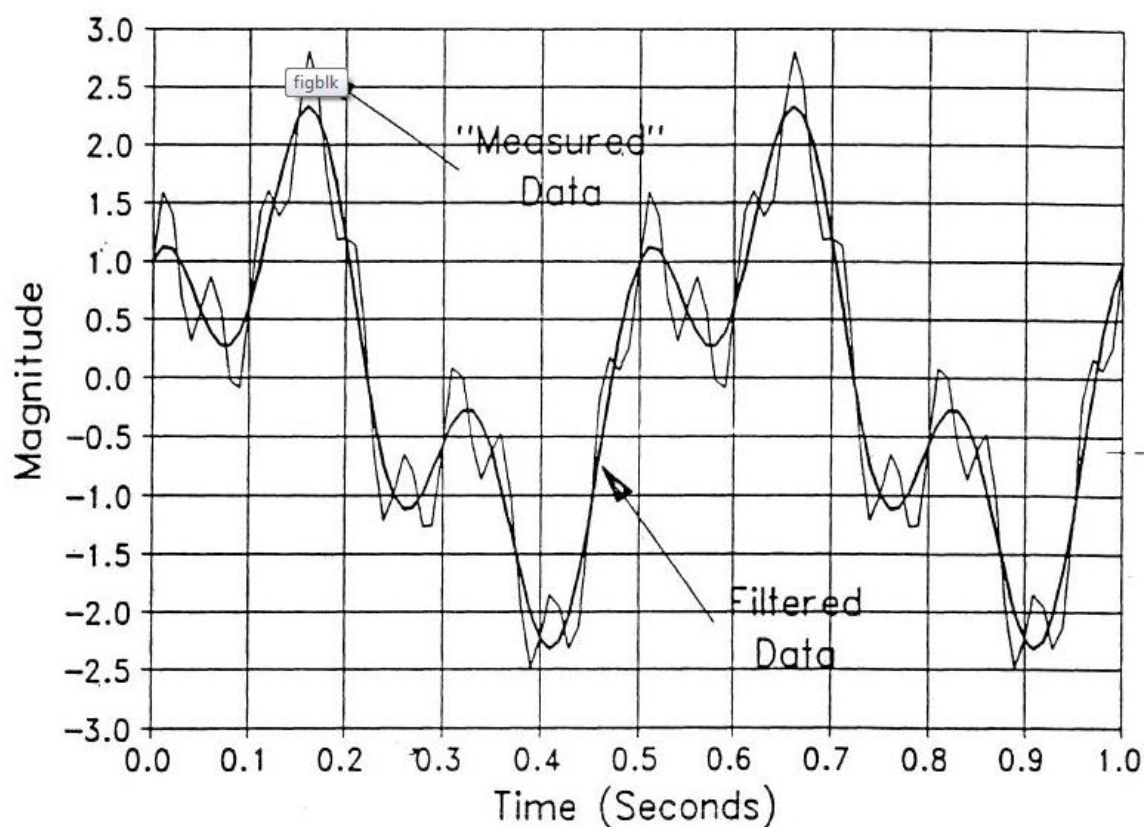


Figure 5.8 Filtered Time-History

5.4.4. Acceleration force time-histories can be filtered using either analog or digital filters. Digital filters include Fourier, Butterworth, and Chebyshev filter functions. In addition, data can be filtered in either the time domain or in the frequency domain. A complete discussion of filter functions and procedures to use them is well beyond the scope of this Circular. Interested readers are referred to Press, et. al. (1989) and Ziemer, et. al. (1983) for a more extensive discussion about filtering measured data.

6.1 Introduction

6.1.1. During the launch of a free-fall lifeboat, there is a potential for the occupants to be injured. The potential exists because of acceleration forces exerted upon the occupants when the lifeboat impacts the water. Regulations imposed by the International Maritime Organization, and by most national maritime authorities, require that the potential for injury be considered in the design of free-fall lifeboats and that it be evaluated during prototype certification tests.

6.1.2. The purpose of this section is to discuss three currently used methods to evaluate the potential for an acceleration field to cause injury. These methods are the square-root-sum-of-the-squares criteria, the dynamic response model, and the Hybrid III human surrogate. The first two methods have been adopted by the International Maritime Organization in resolution A.689(17), "Testing of Lifesaving Appliances". Of these two methods, the dynamic response model is the preferred method because it includes consideration of the magnitude as well as the duration of the acceleration force impulse. It is based upon research conducted at the United States Air Force Aerospace Medical Research Laboratory.

6.1.3. Human surrogates (dummies) are commonly used in Europe and the United States to study the effects of impact and acceleration on humans, particularly when the impact and acceleration may cause injury. During the past 40 years the complexity and lifelikeness of these dummies has been improving. The Hybrid III is the most recent dummy in this evolutionary process. It is used extensively to evaluate the potential for injury during vehicle collisions and aircraft emergencies.

6.1.4. When discussing injury, and criteria for acceptable injury, it must be remembered that injury is a spectrum extending from the trivial to the fatal. There is no clear definition of what is an acceptable injury or threshold for injury. A primary consideration, however, when evaluating injury caused by impact and acceleration is the preservation of consciousness. Escape from a stricken ship or offshore platform, or any similar emergency, depends on the maintenance of consciousness. The escape system must therefore, be designed and tested to minimize the risk of head injury. If the head is critically injured, escape may be precluded in situations from which escape would otherwise have been a relatively trivial matter.

6.1.5. The need to preserve consciousness was dramatically demonstrated in an accident involving a Nimrod aircraft. The airplane departed from an airfield in Scotland with a full crew and a number of passengers. It was flying with sufficient fuel for a normal reconnaissance flight. Shortly after departure the aircraft flew through a flock of birds. All four engines were badly affected by bird ingestion and the aircraft came down in a forest. The pilots made a well executed forced landing into trees. The inertial forces were modest and the rear crew and passengers were able to escape essentially unhurt. Unfortunately the pilots had sustained head injuries in the cockpit and were rendered unconscious. They failed to survive in the ensuing fire. Had they maintained consciousness, they would most likely have survived the accident.

6.1.6. During a maritime emergency, evacuating the ship or platform is only a part of the survival process. After moving away from imminent danger, many actions are required of the crew to enable them to be safely rescued. These tasks include care for the injured, collection and distribution of water and rations, preservation of a reasonable environment, and sending position notification reports to search and rescue parties. These tasks can be conducted only if the occupants do not sustain injury as a result of the free-fall launch.

6.1.7. The bases of methods currently used to evaluate the potential of an acceleration field to cause injury to the occupants in a free-fall lifeboat are discussed in the following parts of this section. The discussion is not intended to be a thorough discourse on human injury resulting from acceleration forces. Rather the discussion is intended to provide the reader with insight into the bases of the methods used as well as their strengths and weaknesses as an indicator of injury potential. Prior to beginning the discussion of injury potential criteria, the co-ordinate systems used when evaluating human tolerance are presented.

6.2 Co-Ordinate Systems

6.2.1. Two co-ordinate systems commonly are used when discussing acceleration forces in free-fall lifeboats. The first co-ordinate system is associated with the lifeboat. The X axis of the lifeboat is the longitudinal axis. It is parallel to the keel and is positive toward the bow. The Y axis is the lateral axis of the lifeboat. It is positive to the port side. The vertical axis the Z axis which is positive upward. These axes are shown in Figure 6.1. Acceleration forces on the hull of the lifeboat are measured in this co-ordinate system.

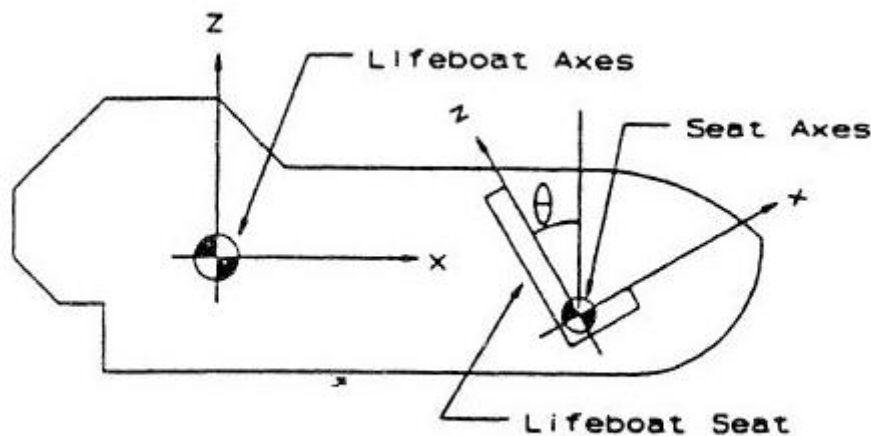


Figure 6.1 Lifeboat and Seat Coordinate Axes

6.2.2. The second co-ordinate system is associated with the seats in the lifeboat. The x axis of the seat is perpendicular to the chest and is positive to the front. The y axis is the lateral axis. It is parallel to the shoulders and is positive to the left. The seat z axis is parallel to the spine and is positive upward. These axes, and common notation for referring to them, are presented in Figure 6 2. The co-ordinate system associated with the seats in the lifeboat is the co-ordinate system commonly used to discuss acceleration forces in the Hybrid III dummy.

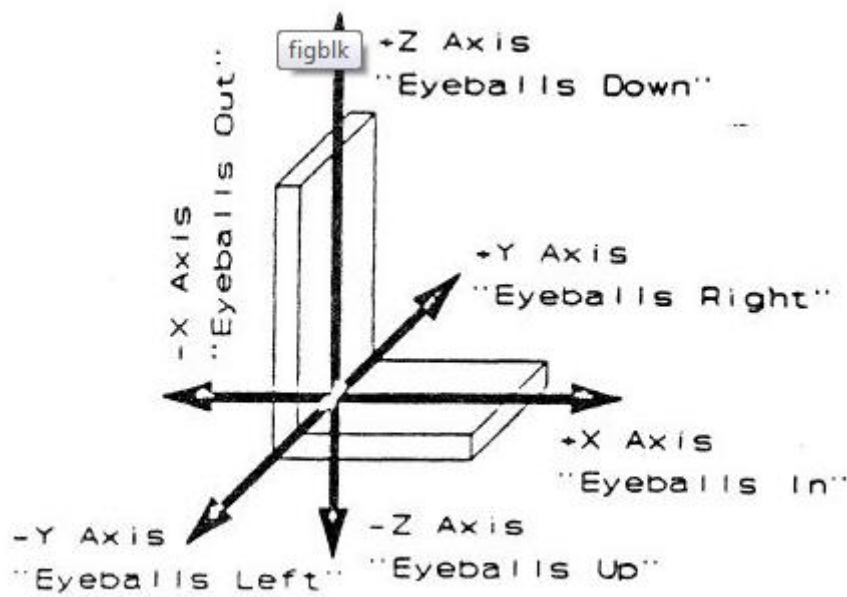


Figure 6.2 Coordinate Axes and Notation for Accelerations Acting on the Body

6.2.3. An injury potential analysis considers acceleration forces acting in the axes of the lifeboat seat because it is in these axes the passengers experience the forces. The seats in a free-fall lifeboat usually are reclined relative to the axes of the lifeboat and are often rearward facing. Acceleration forces in the axes of the lifeboat at a seat location can be transformed into the axes of the seat at that location using the following transformation:

$$\begin{Bmatrix} A_x \\ A_y \\ A_z \end{Bmatrix}_i = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} A_x \\ A_y \\ A_z \end{Bmatrix}_i \quad (6.1)$$

The quantities A_x , A_y and A_z are the acceleration forces in the axes of the lifeboat. The quantities A_x , A_y and A_z are the acceleration forces in the axes of the seat. The angle θ is the angle through which the seat has been reclined as shown on Figure 6.1. The constant k in Equation 6.1 is equal to unity if the seat is forward facing and is equal to -1 if the seat is rearward facing. The subscript i indicates the step in the time-history at which the transformation is being performed; the transformation is performed at all steps in the acceleration force time-history.

6.3 SRSS Acceleration Criteria

6.3.1. The square-root-sum-of-the-squares (SRSS) acceleration criteria is based upon the assumption that the domain of safe acceleration forces can be defined by an ellipsoidal envelope bounded in each co-ordinate direction by some value. Such an envelope for acceleration forces in the x-z plane is shown in Figure 6.3. Injury should not occur as long as the acceleration forces are within the shaded region of the envelope. The limiting values incorporated into the revise recommendation for testing lifeboats by IMO for each axis of the envelope are $15 \, g_0$ in the $\pm x$ axis and $7 \, g_0$ in the other co-ordinate axes. These are the

values indicated on figure 6.3. The SRSS criteria was cast as an interaction equation of the form:

$$CAR_i = \sqrt{\left(\frac{A_{ax_i}}{15}\right)^2 + \left(\frac{A_{ay_i}}{7}\right)^2 + \left(\frac{A_{az_i}}{7}\right)^2} \quad (6.2)$$

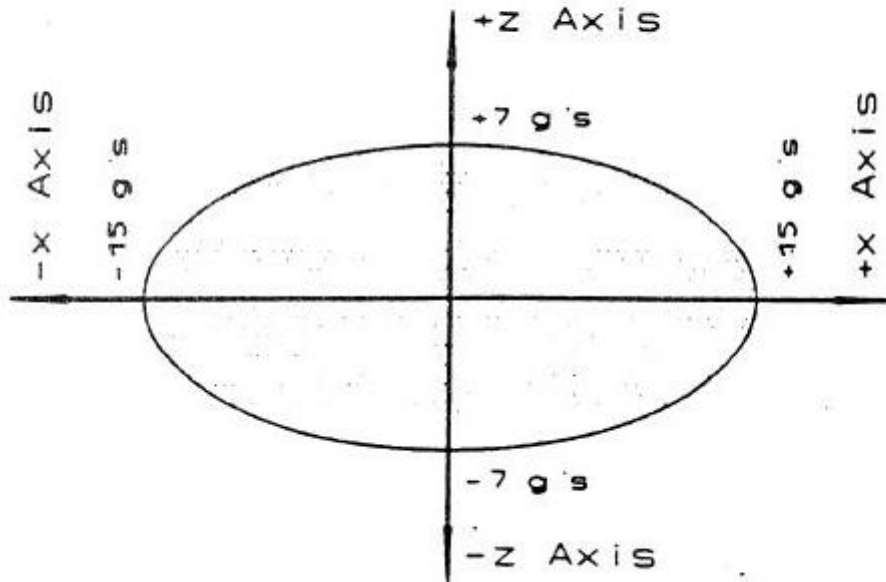


Figure 6.3 Ellipsoidal Safety Envelope for Acceleration Forces in the x-z plane

6.3.2. The combined acceleration response (CAR) is a measure of the potential for the acceleration field to cause human injury. It varies with time and is computed from acceleration force time-histories measured in the axes of the seat at the seat support. Before computing the CAR time-history, the acceleration force time-histories are filtered with a 20 hertz lowpass filter because higher frequency acceleration forces generally are not injurious. The peak value of the CAR time-history is called the CAR Index occur if the CAR Index is less than unity. Injury should not occur if the CAR Index is less than utility.

6.3.3. Although application of the SRSS criteria is very straight forward, this method for evaluating acceleration forces has a weakness in that it considers only the magnitude of the acceleration force. The duration of the force is not considered. As will be seen, the potential for an acceleration force to cause injury is dependent upon its magnitude as well as its duration. The limiting values in the SRSS procedure were selected so that injury should not occur regardless of the duration. As such, the SRSS criteria tends to overestimate the injury potential of an acceleration field. The dynamic response criteria and the Hybrid III manikin are more rational methods to evaluate injury potential because both methods provide a measure of body response to the magnitude and duration of the acceleration force.

6.4 Dynamic Response Criteria

6.4.1. Much research on human tolerance to acceleration has been conducted at the United States Air Force Aeromedical Research Laboratory (AFAMRL) in Ohio. The most extensive

work dealt with accelerations causing compression along the spine. This is positive $+G_z$ or "Eyeballs Down" acceleration. Less work has been conducted on accelerations perpendicular to chest and parallel to the shoulders. This research has formed the basis of the dynamic response criteria accepted by IMO.

6.4.2. To determine the injury potential of an acceleration field, Brinkley and Shaffer (1971) introduced the concept of the Dynamic Response (DR). The basis of this concept is the supposition that each body axis can be idealized as an independent single degree-of-freedom spring-mass system that is subjected to known seat accelerations (Brinkley and Shaffer, 1984). This model is shown in figure 6.4. It was originally developed to evaluate the effects of acceleration along the spine, but has been expanded to evaluate the effects of acceleration perpendicular to the chest and parallel to the shoulders.

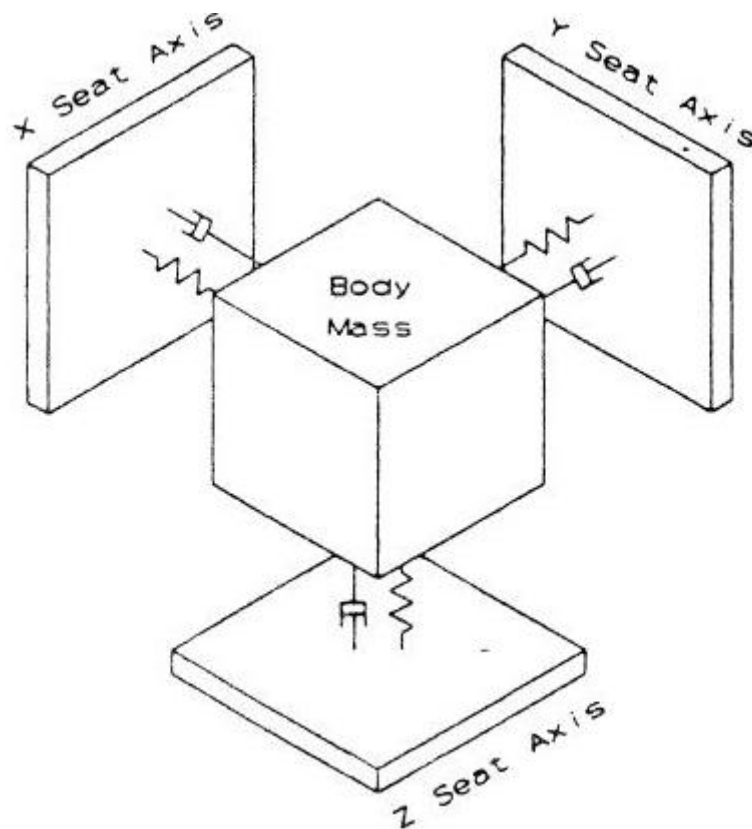


Figure 6.4 Independent Single Degree-of-Freedom Representation of the Human

6.4.3. The dynamic response is computed by:

$$DR(t) = \frac{\omega^2 \delta(t)}{g} \quad (6.3)$$

. where ω is the undamped natural frequency for the axis studied, $\delta(t)$ is the displacement time-history of the body mass relative to the seat support, and g is gravitational acceleration. Values for the natural frequencies in each co-ordinate axis have been found through research conducted at AFAMRL. These values for a 50th percentile 28 year old male in a fully restrained seat and harness are presented in Table 6.1

6.4.4. The DR computed with Equation 6.3 represents an equivalent static acceleration of the body mass in an undamped system. The peak value of the DR curve is called the Dynamic Response Index (DRI). It can be used as an indicator of the potential for acceleration forces to cause human injury.

Table 6.1 Parameters of the Dynamic Response Model

Coordinate Axis	Natural Frequency (rad/s)	Damping Ratio
X	62.8	0.100
Y	58.0	0.090
Z	52.9	0.224

6.4.5. Brinkley and Shaffer (1984) defined three risk levels for acceleration forces directed along the spine. These risk levels are characterized as high, moderate, and low. They relate to a 50%, 5% and 0.5% probability of injury, respectively. The 50% probability of spinal injury is the highest rate observed for USAF ejection seats. It should be noted that there was no spinal chord damage associated with these injuries. The moderate risk level, which is currently used in USAF ejection seat design, is midway between the high risk and low risk levels. The low risk level corresponds to acceleration conditions used routinely without incident during test conducted with volunteers at the AFAMRL. The three injury curves presented by Brinkley (1985) for the +z axis are shown in Figure 6.5. Each curve, which represents a constant DRI at the appropriate risk level, was computed from half-sine acceleration impulses acting at the seat support. The DRI limits presented by Brinkley (1985) for each risk level are shown in Table 6.2 .

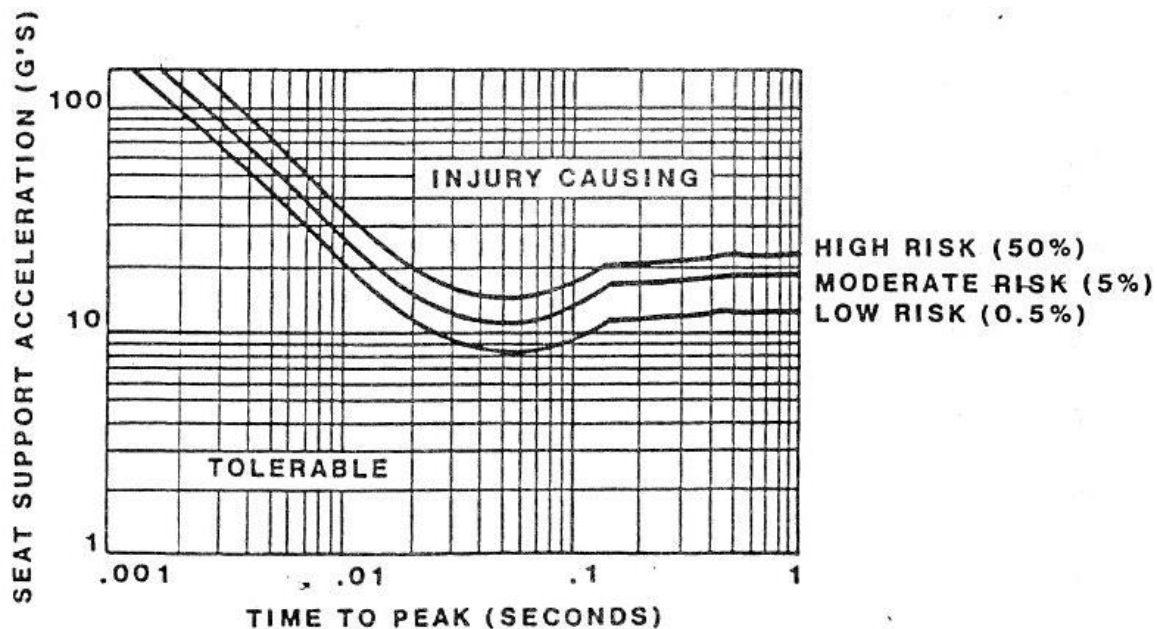


Fig 6.5 Three Risk Levels For Acceleration Acting In the +Z Axis (Brinkley, 1985)

6.4.6. The risk levels for the $\pm x$, $+y$, and $\pm z$ axes were determined without the benefit of a statistically based method such as that used for the $+Z$ axis (Brinkley and Shaffer, 1984). The high risk levels were determined by calculating the peak response of the mathematical model to acceleration conditions known to cause major injuries or potentially serious sequelae. The low risk levels were determined on the basis of calculated model responses to acceleration conditions that have been used numerous times for noninjurious tests with human subjects in research laboratories. The moderate injury level was assigned as the midpoint between the high and low levels. The DRI limits for these axes are presented in Table 6.2.

Table 6.2 DRI Limits for three Risk Levels

Coordinate Axis	DRI Limits (G's)		
	High	Moderate	Low
+X	46.0	35.0	28.0
-X	46.0	35.0	28.0
+Y	22.0	17.0	14.0
-Y	22.0	17.0	14.0
+Z	22.8	18.0	15.2
-Z	15.0	12.0	9.0

6.4.7. The response limits presented in Table 6.2 are for single axis accelerations. Normally, components of acceleration are acting in each co-ordinate direction simultaneously. The effects of multi-axial acceleration can be evaluated with an ellipsoidal envelope. The boundaries of the envelope in each direction are the DRI limits presented in Table 6.2. The seat accelerations to which the occupant is subjected, then, are limited by:

$$\sqrt{\left(\frac{DR_x(t)}{DRI_x}\right)^2 + \left(\frac{DR_y(t)}{DRI_y}\right)^2 + \left(\frac{DR_z(t)}{DRI_z}\right)^2} \leq 1.0 \quad (6.4)$$

. DRI_x , DRI_y , and DRI_z in Equation 6.4 are the limiting DRIs in the x,y, and z co-ordinate directions, respectively, for a particular risk level. DR_x , DR_y and, DR_z are the calculated dynamic responses of the body mass in the same directions

6.4.8. The number of computations required to evaluate an acceleration field can be reduced if the apparent relative displacement of the body mass with respect to the seat support is used directly to determine acceptability instead of computing the DR. This approach is valid because, as shown in Equation 6.3, the DR is a linear function of the relative displacement.

6.4.9. The displacements permitted by the IMO criteria are presented in Table 6.3. These allowable displacements were computed from the DRI limits presented in Table 6.2 and the natural frequencies presented in Table 6.1. The "Training Condition" corresponds to a 0.5% probability of injury. This was deemed to be the maximum acceptable for training exercises because these acceleration forces will be experienced several times. The "Emergency Condition" corresponds of a 5% probability of injury. This level was deemed acceptable in potentially life threatening situations.

Table 6.3 Suggested Displacement Limits for Lifeboats

Acceleration Direction	Displacement (in)	
	Training	Emergency
+X-- Eyeballs In	2.74	3.43
-X-- Eyeballs Out	2.74	3.43
+ Y-- Eyeballs Right	1.61	1.95
-Y-- Eyeballs Left	1.61	1.95
+ Z-- Eyeballs Down	2.10	2.49
+Z--Eyeballs Up	1.24	1.66

6.4.10. When relative displacements are used as the basis for determining the acceptability of an acceleration field, the effects of multi-axis accelerations can be evaluated with the Combined Dynamic Response Ratio (CDRR). The CDRR represents a displacement envelope that is analogous to the acceleration envelope implied in Equation 6.4. It is computed by:

$$CDRR_i = \sqrt{\left(\frac{\delta_{x_i}}{S_x}\right)^2 + \left(\frac{\delta_{y_i}}{S_y}\right)^2 + \left(\frac{\delta_{z_i}}{S_z}\right)^2} \quad (6.5)$$

. S_x , S_y , and S_z in Equation 6.5 are the allowable displacements in the x, y, and z co-ordinate directions, respectively, for a particular risk level. δ_{x_i} , δ_{y_i} and δ_{z_i} are the apparent computed relative displacements of the body mass with respect to the seat support. The peak value of the CDRR time-history is called the CDRR Index. A CDRR Index that is less than or equal to unity indicates the particular risk level has not been exceeded. When this analysis is performed, the acceleration data are not filtered. If an acceleration force does not have a significant influence on the human, it should not have a significant influence on the response of the model.

6.4.11. Although Brinkley has shown a good correlation between spinal injury and DRI, experience with Royal Air Force ejections indicates that the incidence of spinal injury is not as well correlated with the DRI. Anton (1991) has presented a series of 223 "within envelope" ejections in which the discrepancy between predicted injury rate and observed injury rate is very wide. The DRI indicated that the injury rate should be about 4% but the actual injury rate was 30-50% depending on the type of seat used.

6.4.12. A possible explanation for this discrepancy is the type of harness used in military aircraft in the United Kingdom. The preferred harness type is the simplified combined harness (SCH) which provides restraint in normal circumstances but becomes the parachute harness after ejection. The harness is part of the seat equipment. The torso harness, on the other hand, is favoured by the US forces. It is fitted to the crew member and worn out to the aircraft where it is attached to the seat.

6.4.13. The torso harness is recognized to provide slightly better coupling between the man and the seat. This coupling is important in reducing "dynamic overshoot," the effect in which the occupant experiences greater dynamic forces than those applied to the seat. There is, in essence a second mass spring damper system operating at the interface between the seat and

occupant. This second spring damper can, however, be incorporated into the dynamic response model but knowledge of seat coupling and cushion stiffness is necessary.

6.4.14. The effects of seat/occupant coupling, and the apparent effect of this coupling on observed injury rates, indicates a strong need for free-fall lifeboats to be equipped with a properly designed harness system. The issue of harnesses is discussed later in this paper.

6.5 Hybrid III Anthropomorphic Model

6.5.1. Anthropomorphic models are mechanical surrogates of the human body that can be used to assess the potential for human injury of prescribed impact and/or acceleration environments. Such human surrogates are designed to mimic pertinent human physical characteristics so that their mechanical responses simulate human responses. The time-histories of these mechanical responses are analyzed to estimate the potential for various types and severity of injuries to humans. The results of these analyses are based upon the assumption that the anthropomorphic model and the human are exposed to the same impact or acceleration environment (Mertz, 1985).

6.5.2. The Hybrid III is a 50th percentile adult male frontal impact dummy developed by General Motors in 1976. It is based on the ATD 502 dummy which is an advanced test dummy developed by General Motors in 1973 under a contract with the National Highway Traffic Safety Administration. The ATD 502 featured a head which had human like response characteristics for hard surface forehead impacts, a curved lumbar spine to achieve human like automotive seating posture, and a shoulder structure designed to improve the belt-to-shoulder interface which was a problem with the Hybrid II (Mertz, 1985). The Hybrid III maintained the head, lumbar spine and shoulder of the ATD 502. Design changes were made in the Hybrid III to improve the impact response biofidelity of the neck, chest, and knees. The biofidelity characteristics of the Hybrid III dummy are presented in Table 6.4.

Table 6.4 Biofidelity Characteristics of the Hybrid III Anthropomorphic Model (Mertz, 1985)

Body Part	Biofidelity Attributes	Biofidelity Deficiencies
Head	Exterior size and shape of 50th percentile adult male. Human like head-to-neck attachment location. Human like mass and sagittal plane mass moment of inertia. Human like response for deforming surface impacts. Human like response for hard surface forehead impacts.	Mass moment of inertia may not be human like for other than the sagittal plane. Hard surface impact response may not be human like for side top and rear of head.
Neck	Human like fore/aft bending response.	Lateral bending response may not be human like. May be too stiff in axial compression.
Thorax	Exterior size and shape of 50th percentile adult male. Human like mass. Human like impact response for fore/aft compression due to distributed sternal impacts.	Rib cage geometry not human like. Mass distribution not human like. Lateral impact response not human like. Concentrated load impact response not human like.
Lumbar	Provides human like sitting posture.	Bending response not human like.
Pelvis	Human like pelvis shape.	Mass and mass distribution not human like.
Legs	Human like ranges of motion. Human like knee response.	Mass distribution not human like. Joint resistances not human like.
Arm	Human like range of motion.	Mass distribution not human like. Joint resistance not human like.
Shoulder	None	Mass distribution not human like. Load-deflection responses not human like.

6.5.3. Accelerometers were incorporated into the Hybrid III to measure the orthogonal linear components of acceleration in the head and chest. Force transducers were incorporated to measure the forces and bending moments between the head and the neck at the occipital condyles (Mertz, 1985). Transducers were also incorporated to measure displacement of the sternum relative to the thoracic spine and axial femoral loads. Presented in Table 6.5 are the injury-predictive capabilities possible with the Hybrid III.

Table 6.5 Injury-Predictive Capability of the Hybrid III Anthropomorphic Model Head, Thorax, Neck, and Lumbar (Mertz, 1985)

Body Part	Injury-Predictive Capability
Head	Brain injury and/or skull fracture predictions based on linear acceleration measurements possible for deforming surface impacts to front, top, back, and side of head and for hard surface impacts to forehead Brain injury prediction due to sagittal plane rotational effects possible
Neck	Measured neck loads provide a basis for predicting neck injuries
Thorax	Thoracic injuries related to gross thoracic acceleration, sternal acceleration, and gross fore/aft thoracic compression
Lumbar	None

6.6 Hybrid III Injury Potential Criteria

6.6.1. By using an instrumented manikin, assumptions regarding the behavior of the seat/occupant coupling can be avoided. There still remains a potential problem when it comes to interpreting the data collected from the dummy, however. There are no clearly defined criteria for injury risk as a function of parameters measured in the dummy. This is due to a number of factors. Firstly, there is no agreed level of injury that should serve as a threshold for tolerance. Injury is a spectrum extending from the trivial to the fatal. Secondly, there are wide differences in the tolerance of individuals to the same insult. The description of a person as having "weak bones" is not altogether a case of uninformed lay labelling. Ignoring the well recognized but rather rare cases of bone disease causing brittleness, there is a wide variation in the structural strength of normal adult healthy bone. This variation is in the region of three to one. Following is a discussion of generally accepted criteria for evaluating data collected from a Hybrid III human surrogate.

6.6.2. **Head Injury Criteria.** The bony skeleton of the head may be fractured by blunt or sharp trauma. Generally speaking, however, it is not so much the existence of a fracture which is important, rather the impairment of consciousness which accompanies the fracture in the immediate aftermath of the injury. This impairment of consciousness can hinder, or prevent, the next and may be vital actions necessary to survive.

6.6.3. Impairment of consciousness can be caused with or without a fracture to the skull. The mechanisms involved are not well understood but there is a relationship between the amount of energy imparted to the brain during an impact, the rate of transfer of the energy and the result in terms of impairment of consciousness. This concept was incorporated by Gadd (SAE,1986) into a weighted impulse criterion for establishing a severity index (SI) which is:

$$SI = \int_0^T a(t)^{2.5} dt \quad (6.6)$$

. In Equation 6.6, $a(t)$ is the resultant acceleration time-history (in $G\hat{o}s$) at the center of gravity of the head and T is the duration of the acceleration impulse (in seconds). Gadd proposed a tolerance value of 1000 as the threshold of concussion from frontal impact.

6.6.4. The National Highway Transport Safety Administration (NHTSA) defined a new criterion based on the SI. This criterion is called the Head Injury Criterion and is defined by NHTSA to be:

$$HIC = \left[(t_2 - t_1) \left\{ \left(\frac{1}{t_2 - t_1} \right) \int_{t_1}^{t_2} a(t) dt \right\}^{2.5} \right]_{MAX} \quad (6.7)$$

Where t_1 and t_2 are the initial and final times (in seconds) of the interval during which the HIC attains a maximum value. HIC replaced 81 in later versions of the Federal Motor Vehicle Safety Standard (FVMSS 208) with a value of 1000 specified as the concussion tolerance level (SAE 1986).

6.6.5. The HIC index can be easily calculated from a dummy head impact using the data from a triaxial accelerometer located at the center of gravity of the head. HIC values of 1000 are associated with a concussion hazard and therefore represent a threshold value which should be avoided. It is interesting to note, however, that in a study by Hogson and Thomas (SAE 1986) it was concluded that the HIC interval ($t_2 - t_1$) must be less than 15 ms in duration in order to pose a concussion hazard even if the HIC exceeds 1000.

6.6. 6. **The Ambulatory System.** The importance of the ambulatory system cannot be underestimated in any survival situation. Here, the forces in the lower limbs of the Hybrid III dummy can be measured during an impact. The critical bending moment for the adult femur is 248 N-m. Studies on ejection seats, where the magnitude of the acceleration vector in the Z direction was 10 G have produced bending moments of 170 N-m. This is fairly safe margin for healthy adults in a free-fall lifeboat, however, one must consider the injured survivor. These forces in a already fractures lower limb could have fatal consequences as it is well recognised that severe shock can ensue from an inadequately treated femoral fracture.

6.6. 7. **The Neck.** The neck is a complex structure and has a wide range of injury mechanisms. The range of movement in the neck is considerable. It ranges from simple flexion (forward bending) and extension (rearward bending) to complex combinations of flexion, lateral flexion and rotation. The strength of the human neck is not the same in all directions but the atlanto occipital junction (between the top of the neck and the base of the skull) can tolerate 88 N-m in flexion without causing injury (Mertz, 1971).

6.6.8. During a recent trial involving a free-fall lifeboat launched from 30 meters, bending moments of 11 N-m were recorded in the neck of a Hybrid III dummy. These records were made on an inadequately restrained dummy in order to assess the risk of neck injury in the event of a precipitate departure. Because of the free-fall height and the lack of restraint, this case represents most of the worst conditions that can be envisaged. It is noteworthy that the bending-moments recorded in the dummy neck during normal launches with this same lifeboat were approximately 3.5 N-m. This experimental evidence illustrates the importance of having a suitable harness. It also allows the operator/regulator to evaluate the risks involved in not having the harness properly adjusted.

6.7 Considerations In Design Of Harnesses

6.7.1. The purpose for having a seat harness in a free-fall lifeboat is to restrain the occupants in the seats during the free fall and subsequent water entry. Serious injury could result if an occupant was to float free of the seat during free fall or was ejected from a seat during water

entry. Also, as has been discussed, coupling between the occupant and the seat has an affect upon the potential for injury and the ability to infer that potential.

6.7.2. Restraint of the occupant must begin with the pelvis. The pelvis can be effectively restrained with a lap belt that has its anchor point situated so that the plane of the loop formed by the buckle is below the iliac crest and the "H" point (the H point is located 8.65 cm above the seat pan and 13.72 cm in front of the seatback). This ideal configuration results in the buckle being located as low on the abdomen as possible. If the belt is located too high on the abdomen, it is possible for the occupant to slide under the belt during an impact (submarining). As such, it is important that the position of the lap belt is not dependent on how the shoulder harness is adjusted. Tightening the shoulder harness should not cause the lap belt to be drawn upward.

6.7.3. Restraint of the torso is achieved through use of a shoulder harness. The shoulder harness must be configured so that, when properly worn, the occupant does not slide out from behind it. An ideal arrangement is to have straps that pass over the shoulders. The upper anchor of the straps should be above the shoulders and located as close to the center of the seat as possible. The lower anchor should be low on the seat and below the lap. If the shoulder belts are connected to the lap belt, the point of attachment should be to the side of the pelvis so the final position of the lap belt is not dependent upon the adjustment of the shoulder harness.

6.7.4. A final consideration in the design of a seat restraint system must be ease of use. The seat harness must be easy to don with minimum training, it must be easy to intentionally release, and its configuration must be compatible with the type of lifejacket intended to be used in the lifeboat. Because time is of the essence during an emergency, and because the lifeboat should not be launched until all occupants are seated and restrained, the harness should be designed so that: 1) the proper way to wear the seat harness is fairly obvious, 2) there are not an excessive number of components that must be found, and 3) the buckles and adjustments are easily reached (including those times when all seats are filled). The buckles and anchors must be designed so that they do not release under the inertial loads caused by water impact. At the same time, buckles should be designed so that they can be quickly released if it were necessary to evacuate the lifeboat.

6.8 Use Of Injury Potential Criteria

6.8.1. When a human surrogate such as the Hybrid III is used to evaluate the potential for injury, the effects of occupant-seat coupling as well as the effects of the water entry forces can be determined. Because the data obtained from a dummy are predictive, it is possible to identify the type of injury that would likely occur, if an injury were to occur. However, because of the high acquisition cost of a dummy (a dummy can cost in excess of \$100,000 USD), such evaluations tend to be quite expensive.

6.8.2. Because of the complex nature of human injury, and continually evolving knowledge about injury thresholds, data obtained from a dummy are best interpreted by medical practitioners with experience in human impact. These data can be used as the basis for quantitative and qualitative predictions about the type and severity of injury that may result. Medical judgement also must be used to apply the results obtained from a dummy to the broad range of individuals that are likely to use particular free-fall lifeboat. The response of a dummy is representative of the response of a particular class of people (e.g., 50th percentile

males). The opinions rendered by all medical practitioners in these matters should be similar but may not be necessarily identical.

6.8.3. The SRSS criteria and the dynamic response criteria are two economical and quantitative methods which can be used to infer the potential of an acceleration field in a free-fall lifeboat to cause injury to the occupants. The results obtained from these methods are easily interpreted; acceptability is based upon not exceeding a prescribed value. Of these two methods, the dynamic response criteria is preferred because the duration of the acceleration impulse is explicitly considered in the evaluation.

6.8.4. For the dynamic response and the SRSS criteria to provide a reasonable indication of occupant safety, good coupling must exist between the occupant and the seat. Neither method can explicitly evaluate the effects of occupant-seat coupling. Such an evaluation can only be performed with a human surrogate. Good occupant-seat coupling can be obtained, however, through proper use of a seat harness such as that which has been described.

6.8.5. When using the dynamic response or the SRSS criteria, it also must be remembered that neither method can predict if an injury will occur nor what that injury will be. Rather, the criteria merely provide an indication of the potential for an injury to occur. If the criteria suggest that an unacceptable condition exists, it may be prudent for the manufacturer to evaluate the acceleration field using a human surrogate before making extensive design changes. Also, use of a dummy would be prudent if harness arrangements significantly different from those discussed are used and may be justified if the lifeboat is to be certificated for free-fall launches much in excess of 40 meters.

Appendix A i Suggested Free-Fall Lifeboat Prototype Test Program

Suggested Free-Fall Lifeboat Prototype Test Program

		Resolution A.689(17)
Day One	Weigh Prototype Lifeboat	
	Lifeboat Seating Space Test	6.8
	Engine Out of Water Test	6.11.5
	Lifeboat Freeboard Test	6.9.4-5
	Ability to Tow Liferaft	6.11.1
	Ability to be Towed at 5 knots	6.12.1
	Air Supply Test	6.16
	Hook Release Test	6.10.5-6
Day Two	Self-Righting Test	
	Lifeboat in light condition.	6.15.1.2
	Fully loaded lifeboat	6.15.1.1
	Flooded Stability Test	6.9.1-3
	Flooded Capsizing Test	6.15.3
Day Three	Lifeboat Overload and Seating Strength Test	
	Free-Fall from 1.3 times Certification Height	6.4.7-9
	100 kg mass in critical seat(s)	6.7.2
	Free-Fall Lifeboat Free-Fall Test	6.6
	Full rated load from Certification Height	6.6.3.1
	50% forward load from Certification Height	6.6.3.2
	50% aft load from Certification Height	6.6.3.3
	Operating Crew Only from Certification Height	6.6.3.4
Day Four	Operation of Engine and Fuel Consumption	6.11.1
	Four Hour Endurance Test	
	Verify speed of 6 knots	
	Measure fuel consumption	
	Verify Operation of Compass	6.11.7
	Conduct during endurance test	
	Water Spray and Fire Tests (if required)	6.17

Notes on Suggested Prototype Test Program

1.. The suggested test program was ordered so that, to the greatest extent possible, related tests and tests which overlap are conducted at the same time. Additional time may be required if other full-scale launches are to be conducted or if model testing is to be conducted at the same time as the prototype tests.

2.. It has been suggested that the overload and seating strength test be conducted before the free-fall tests because performance of the lifeboat is a moot point if the lifeboat does not have adequate strength. Modifications that may be necessary to provide adequate strength may have an effect on the performance of the lifeboat. Also equipment that must be placed in the

lifeboat for the free-fall tests can become damaged if a structural failure were to occur during these tests.

3.. The order of the free-fall tests has been suggested so that the handling of ballast is minimized.

4.. The operational tests were placed after the strength and free-fall tests because the operation of the lifeboat after it has been launched must be demonstrated.

5.. It has been suggested that the fire test, if required, be conducted last because the lifeboat can become damaged during this test (and still pass the test) in a manner that may preclude conduct of other tests.

Appendix B i Suggested Surveyor Summary Evaluation Form

Free-Fall Lifeboat Prototype Tests				
Resolution A.689(17)	Lifeboat Test	Acceptability Criteria	Results and Observations	Pass
	Weigh the Fully Equipped Lifeboat Without Persons on Board	Expected Weight: _____	Measured Weight: _____	
6.4.7 to 6.4.9	Free-Fall Lifeboat Overload Test	The fully loaded and equipped lifeboat should have sufficient strength to withstand a free-fall launch from a height of 1.3 times the free-fall certification height. There should be no significant damage to the lifeboat as a result of this test and it should pass the engine operation test in 6.11.1.	Free-Fall Height = _____ Weight = _____ Condition After Launch Engine Operation (6.11.1)	
6.6	Free-Fall Lifeboat Free- Fall Test	The fully equipped lifeboat should make positive headway and the acceleration forces measured at the location of worst occupant exposure should satisfy the requirements of 6.18 during launches from the free-fall certification height with the following occupant loads: 1. Fully Loaded Lifeboat . 2. Occupants Forward of CG only 3. Occupants Aft of CG only 4. Launching Crew Only	Free-Fall Height Drop 1 = _____ Drop 2 = _____ Drop 3 = _____ Drop 4 = _____ Results of Acceleration Force	

			Measurements:	
6.7.2	Lifeboat Seating Strength Test (Conducted With Overload Test)	The seats experiencing the highest acceleration forces should be able to support a 100 kg mass when the lifeboat is launched from a height of 1.3 times the free-fall certification height.		
6.8	Lifeboat Seating Space Test	The number of persons, all wearing lifejackets, for which the lifeboat is to be certified should be able to board the fully equipped lifeboat, be seated, and be ready for launch in not more than three minutes. The lifeboat should then be manoeuvred to demonstrate that there is not interference with the occupants. Also, walkways within the lifeboat should have a non-slip surface.	Seat Pitch: _____ Seat Height: _____ Seat Width: _____ Boarding Time: _____	
6.9.1 to 6.9.3	Lifeboat Flooded Stability Test	The fully equipped and loaded lifeboat should have positive stability when filled with water to represent the flooding that can occur when the lifeboat is holed i at the worst location below the water surface.		
6.9.4 to 6.9.5	Lifeboat Freeboard Test	The fully equipped lifeboat, loaded with 50% of the persons for which the lifeboat is to be certified seated on one side, should have a freeboard of not less than 100 mm nor less than 1.5% of the lifeboat's length.	0.015 x Length = _____ Required Freeboard = _____ Measured Freeboard = _____	
6.10.5	Operational Overload Release Mechanism of	The free-fall release mechanism should operate effectively when loaded with a force of at least 200% of the normal load caused by the fully equipped and loaded lifeboat.	Required Working Load = _____ [Sin(Launch Angle) x Weight] Required Test Force: _____ [2 x Working Load] Measured Force: _____	

6.10.6	Ultimate Strength Release Mechanism.	of The free-fall release mechanism should be able to withstand a force of at least 6 times the working load of the hook without failure.	Working Load: _____ 6 x Working Load: _____ Measured Force: _____	
6.11.1	Engine Operation and Fuel Consumption	The fully loaded and equipped lifeboat should be operated for 4 hours, be capable of a speed of 6 knots, and be able to tow a 25 person liferaft at a speed of 2 knots.	Test Duration: _____ Speed: _____ Fuel Consumption: _____ Calculated Endurance: _____ Towing Force: _____	
6.11.5	Engine Out of Water Test	The engine should not be damaged when operated for 5 minutes in conditions simulating normal storage.	Test Duration: _____ Engine Condition:	
6.11.7	Compass Operation	The compass should operate satisfactorily and not be affected by fittings and equipment in the lifeboat.		
6.12.1	Lifeboat Towing Test	The lifeboat should not be damaged when towed at a speed of not less than 5 knots in calm water on even keel.		
6.15.1 to 6.15.2	Self-Righting Test	The lifeboat should be incrementally rotated through angles of heel up to 180 degrees. Upon release, the lifeboat should always return to a normal upright position without assistance. The test should be conducted with the lifeboat in the fully loaded condition and in the light condition.	Fully Loaded: Light Condition:	
6.15.3 to 6.15.5	Flooded Capsizing Test	When rotated to a heel angle of 180 degrees and released, with all entrances and openings secured in the open position, the lifeboat should attain a position in the water that permits an above-water escape for the occupants.		

6.16	Air Supply Test	With all of the entrances and openings in the lifeboat closed, the air supply should be able to maintain a small positive pressure inside the lifeboat for a period of 10 minutes. The inside pressure should not exceed the outside pressure by more than 20 mbars.	Test Time Start: _____ Finish: _____ Tank Pressure Start: _____ Finish: _____ Internal Pressure: _____	
6.17.1 to 6.17.7	Fire Test	The lifeboat should be enveloped in fire for a period of 8 minutes. At the conclusion of the test the lifeboat should be in such condition that it can continue to be used in the fully loaded condition.		
6.17.8 to 6.17.10	Water Spray Test	The delivery rate should be to the satisfaction of the Administration. The water film should cover the boat when the boat is listed and trimmed 15 degrees.	Engine RPM: _____ Pump RPM: _____ Suction Pressure: _____ Delivery Pressure: _____	