Some Effects of Dynamics on Damage Stability

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ABSTRACT

The concept of dynamic stability is introduced in relation to damaged vessel survivability. After comparing dynamic and static stability, some forms of dynamic instability, generally related to vessels with forward speed, are discussed. There then follows a discussion of two relevant series of experiments for damaged ro-ro vessels. The paper concludes with the view that the concept of stability in relation to the survivability of a damaged vessel should not be restricted to transverse stability alone.

INTRODUCTION

One of the most significant advances in recent years in the study of damage stability has been the introduction of dynamics into the analysis. This has been done using physical models to explore and illuminate the problem with the result that computer simulations, (which incorporate our understanding of the physics gained from physical models) are now becoming available.

This recognition of the important role dynamics can play in damage stability heralds a major advance in the study of ship stability. However, like all advances into new fields of endeavour, it brings with it a number of unanswered questions which indicate fruitful areas of further research.

The purpose of this paper is to mention some of these areas, illustrated by the result of recent work carried out at BMT. First, however, the general notion of dynamic, as distinct from static, stability must be mentioned

DYNAMIC AND STATIC STABILITY

The terms dynamic and static stability are used throughout this paper.

By **static stability** is meant the tendency of a body to return to its original condition after being perturbed.

By **dynamic stability** is meant the tendency of the body to return to its original motion after a perturbation.

A vessel which is statically stable could be, for example, an intact vessel which, when heeled to an angle returns to the upright because of the hydrostatic restoring moment due to buoyancy. Static stability is a well-known concept and forms the basis of most calculations of ship stability at the design stage. Note that no motion is considered in static stability; once the motion of the vessel, as it rolls back to the upright, is introduced, dynamic stability comes into play.

Many restoring forces and moments exist in the world of dynamic stability, but that which limits roll motion (as distinct from the main driving force of buoyancy) is primarily that of damping. This may be of viscous origin and, when present, allows the roll motion to die away gradually until the equilibrium, upright, position is regained.

The theme of this paper therefore, is to look at the effects of motion – dynamics – in connection with damage stability and to see how such effects can modify conclusions drawn from a slavish adherence to information obtained solely from statics.

This is therefore broadening the concept of stability from the narrow idea of static transverse stability, related to capsize, to stability of the vessel in general, with particular reference to the damaged case.

DYNAMIC INSTABILITIES

The advent of high speed passenger-carrying vessels in the waters of the world brings with it the spectre of dynamic instability. If such a vessel is damaged at speed, any ingress of water so caused could result in a catastrophic dynamic instability leading to capsize, sudden stops or "pitch poling". In other words, the speed and motions of the vessel make any sudden change in statics – mass, inertia and attitude – potentially lethal.

The capsize of the "Herald of Free Enterprise" is a frightening testament to this. The amount of water initially taken on board through the bow doors would almost certainly not have capsized the intact vessel at rest; with the added ingredients of speed and turn a catastrophic capsize resulted.

Various forms of dynamic instability have been identified, many for high speed craft. The ITTC High Speed Marine Vehicle Committee identified some of these and listed them in its report to the 21st ITTC in 1996. The following list gives these, with some additions:

1. **Loss of GM due to Wave System**

If a displacement vessel moves fast enough, its wave system can be characterised by crests at bow and stern combined with a trough amidships. If the hull form is fine enough, the loss of buoyancy and waterplane area caused by the wave trough can cause an apparent loss of transverse GM. The vessel may then loll over to one side or the other.

In some cases this heel may couple into yaw and the vessel begin to turn. The turn may induce further heel, which induces further yaw and so on. Taken to extremes the vessel may suffer a catastrophic heel and turn, leading to capsize.

2. **Course Keeping**

Poor dynamic stability about the vertical axis gives rise at best to poor course-keeping and at worse to loss of control. Although problematic in themselves, these tendencies become more serious from a safety perspective as speed increases. In extreme cases a "calm water broach" can occur if the yaw instability couples into heel.

3. **Bow Diving and Plough-In**

Bow diving and plough-in at wave speed occur when a vessel, moving into or with a wave system, comes off one wave and ploughs into the next. For a high speed passenger ferry carrying vehicles, the need for adequate buoyancy forward (possibly a problem for catamarans with fine forebodies) together with adequate bow door arrangements is essential if the vessel is not to be engulfed.

4. **Porpoising**

Porpoising is a well-known pitch instability which affects high speed planing craft. It is now amenable to elimination by design, but was the cause of catastrophic accidents to some early high speed vessels.

5. **Chine Tripping**

Chine tripping is experienced on planing hard chine monohulls when turning. The chine may dig in and cause a powerful and sudden heeling moment. In extreme cases the vessel could roll over at high speed.

6. **Take Off**

High speed catamarans may experienced large aerodynamic lift forces and pitch moments at speed or in waves. This is caused by air flow over and under the bridge deck which, in extreme cases, could cause the vessel to lift from the water and rotate in pitch. At present such behaviour is confined to high speed, light weight, vessels.

7. **Spray Rail Engulfing**

A high speed vessel receives a not inconsiderable amount of lift forward from the spray rails, which, on some designs, may double as fenders. Tank tests have shown that, once a certain speed is exceeded, these may cease to deflect the bow wave or spray and become engulfed. When this happens the bow may drop, to the accompaniment of large sheets of green water thrown into the air at the bow. Speed may reduce at the same time. In extreme cases bow dive may occur.

8. **Effect of Critical Speed**

Recent tank tests and full scale trials on a high speed passenger catamaran in shallow water have identified loss of directional stability when moving at or near the critical speed. This speed is defined as

$$\sqrt{gh}$$

Equation 1

where h is the water depth and is about the speed at which solitary waves or solitons may be shed and hydraulic jumps created. Whether or not solitons are shed, it is common for the vessel's own wave system to be characterised at such speeds by a high, steep, and often breaking, following wave similar in form to a hydraulic jump. This is situated just astern of the vessel and its upstream influence gives a tendency to broach. This is perhaps analogous to the loss of directional stability experienced by aircraft flying through the transonic speed range and has been felt not only by the present-day vessels in shallow water, but also by high speed torpedo boats passing through a narrow, shallow, harbour entrance at speed in World War 2.

Outstanding Issues with Dynamic Instabilities

Some of the dynamic instabilities identified above have resonances with "conventional" as well as high speed ferries. Instabilities 1 to 3 fall into this category; the added problems caused by damage leading to water ingress at speed are so obvious that they do not need emphasising here.

The remaining instabilities may be dismissed as only pertaining to high speed specialist vessels. Such a dismissal would ignore the trend in modern high speed passenger vessels to push speeds ever higher in both deep and, increasingly, shallow waters.

It would seem therefore that the following issues are outstanding, all of which would benefit from focussed research:

- continue to identify, by means of tank tests and experience, further forms of dynamic instability.

- explore, by means of physical model testing and, later, numerical models, the effect of water ingress through damage openings on such instabilities.
- identify design methods and test techniques which identify and eliminate potential dynamic instabilities at the design stage.
- include linear and angular velocities in numerical capsize prediction models.
- investigate in more detail the physics of the instabilities listed above with a view to eliminating them by design and/or rules of operation.

EFFECT OF FORWARD SPEED ON CAPSIZE

As a gesture towards the thesis of this paper that dynamic effects on damage instability can be of importance, a short series of model experiments was carried out as part of BMT's internally-funded research. The aim was to investigate whether the introduction of a steady forward speed to a damaged model, in stable equilibrium at rest in calm water, could induce instability.

The model used for this was that of the "Pride of Bruges" with a tapered damage opening amidships. The model was run at a range of steady forward speeds in calm water and head waves with two damaged freeboards (each with its corresponding GM) and a note was made of the heel angle.

CALM WATER EXPERIMENTS

Figure 1 shows the results obtained at the small residual freeboard equivalent to 0.25 metres with a corresponding GM of 2.7 metres. Although there was some measurable effect on heel as speed increased, heel angles were extremely small, no water came aboard and transverse stability was not compromised. Observation of the flow showed that the damage opening caused virtually no disturbance to the free stream and there was no evidence of flow transfer between the free stream and the flooded compartment below the subdivision deck.

This experiment indicated that hydrodynamic effects from a "clean" damage opening, fundamental to the usual drifting type of damage stability model tests, were negligible. Clearly in such a situation, where the damage is located amidships, dynamic instabilities will not arise.

But is the clean cut damage opening typical of what actually happens? In a real situation the damage will generally occur when one or both ships are moving, causing the plating of both to tear and buckle. If the ships subsequently break away from each other, especially if both are still moving, further tearing of the hull structure is likely. It is therefore more likely that damage openings in real accidents will be anything but clean and could have flaps of metal hanging in or out of the opening. Furthermore, the vessel will almost certainly not be stopped in the water after break-away and will in all probability be moving, turning and heeling.

This scenario paints a quite different picture to that of the vessel moving at zero drift angle, with a clean damage opening. In order to explore this, a further series of experiments was carried out. In these, the damage opening was modified to incorporate a flap to represent the possible after-effects of torn metal as the ships break apart (Figure 2). The experiment was then repeated, and Figure 3 shows the result.

Over a threshold speed the flow impinging on the flap rose up to enter the subdivision deck, even though the model had a residual freeboard equivalent to 1.0 metre and a GM equivalent to 1.01 metre. Once water had entered the subdivision deck, it gathered on the damage side due to an initial heel angle of 0.1° in that direction. Increasing speed caused more water to come aboard, the heel to increase and the residual freeboard to reduce. Ultimately as speed increased further the subdivision deck became engulfed and the model capsized.

When the experiment was re-run with a 2° drift angle which opened the damage to the on-coming flow, events were even more dramatic and capsize occurred rather more rapidly (Figure 4). The implications of this result were:

- if the damage had been forward at a point where the curve of the hull was equivalent to a 2° (or more) tangent angle, then water would have been taken aboard at zero drift angle.
- if the vessel had been turning after break-away with a drift angle of 2° or more, water would have been induced to flow on to the subdivision deck over a give speed.

EXPERIMENTS IN WAVES

When head seas, equivalent to a height of about 2.1 metres, were introduced into the experiment, water was taken aboard at a speed some 3 knots less than that for calm water and a capsize resulted (Figure 5). Reducing the residual freeboard to 0.25 metres resulted in water coming aboard at all speeds – due to the waves themselves at low speeds and due to the flap and waves at the higher speeds.

CONCLUSIONS

What conclusions, if any, can be drawn from such a brief study? Some do suggest themselves and these are:

1. A clean damage amidships induces no loss of stability due to forward speed in calm water at speeds up to 20 knots.
2. A flap representing torn shell plating which extended beyond the side shell had a major effect in calm water

by causing water to enter the subdivision deck at forward speeds above 10 knots.

3. Head seas increase the chance of water entry and capsize.
4. Drift angles which open the damage to the oncoming flow increase the chance of water entering the subdivision deck with a "flapped" type of damage.

It may be argued that some of these conclusions apply only to forward speeds well in excess of those likely to be experienced by a conventional ro-ro ferry, such as the Pride of Bruges, after breakaway following collision. While this may be true, it may be remarked that high speed ferries, whether monohull or multihull, may well have such high residual speeds after collision.

OUTSTANDING ISSUES

This work has been of a preliminary, exploratory nature and could be followed up with more detailed studies. These could include:

1. Increase the degrees of freedom to incorporate sway, yaw and heel.
2. Vary the position of the damage opening.
3. Explore the effect of a "scoop" type of damage opening.
4. Determine limiting intact GM values with forward speed.

DYNAMICS OF WATER INGRESS

Dynamic effects are relevant not only to whole body motions, but also to details of the fluid flow at or near the damage location. Details of water ingress or egress have been studied by others elsewhere, but coupling it with the effects of ingress and egress on body motions has received little attention.

Because of this, the UK Marine Safety Agency (now the Marine and Coastguard Agency) funded a research study into the topic to be carried out by BMT under the auspices of the Ship Stability Research Centre at the University of Strathclyde. This provided a valuable opportunity to focus on the details of water ingress and egress at a damage opening confined to the case of a damaged, drifting, vessel.

It was decided at the outset that this study would be driven by a series of specially-designed model experiments, the results of which would both identify, and provide data for, a model of motion damping due to water ingress and egress.

METHODOLOGY

In order to measure damping, the use of captive models was necessary. Conventional techniques had to be modified to allow for the fact that the mass, and hence draught, of the model could change throughout a run as floodwater accumulated on the subdivision deck.

This implied that model state would change with time and hence vary throughout a run. This called for an analysis technique which would, if necessary, cater for such variation. One was developed, based on parameter identification and using an assumed regression model, for both intact and damaged cases.

Both heave and roll motion was required because observation of freely-drifting model tests had suggested that heave played as important a part as roll in the physics of water ingress and egress on a damaged model. A system was therefore devised, using computer-controlled hydraulic actuators, which could apply both heave and roll in any desired combination. An advantage of this system was its ability to provide any type of motion rather than be restricted to the purely sinusoidal.

In addition to studying the forces and responses of the captive model, it was felt to be of value to compare water ingress and egress with the same model, but with it free to move when excited by beam waves. Disconnecting the hydraulic actuators achieved this goal.

Damping was measured using the force and moment response of the captive model to a known input motion, while water on deck was measured in the usual way by a series of strategically-placed wave probes. All experiments were recorded by two video-cameras showing water movement on the deck and through the damage opening.

Simple models representing the mid-body only were used, one having a conventional midship section while that of the other was semi-circular. The latter was chosen so that its form damping in roll would be as small as possible.

RESULTS OBTAINED

Results were obtained for a number of cases involving pure roll, pure heave and coupled heel/roll with the captive model. A range of regular waves was used with the model when free to move.

Damping was found to be best represented by a "linear plus quadratic" model. Figure 6 shows the deduced coefficients for linear form damping of the intact model with a ship-shaped body section, while Figure 7 shows the deduced coefficients for the quadratic component. Figures 8 and 9 show the equivalent coefficients for the damaged case, also indicating the effects of halving the size of the damage opening.

Figure 10 shows a comparison of the deduced quantities of water on deck for similar forced and free motions; it may be noted that the pure roll motion resulted in the least quantity of water build-up.

CONCLUSIONS

The main conclusions of the study were as follows:

1. Side and deck damage do in fact have an effect on the stiffness and damping terms in the equations of motion.
2. Length of side damage has a negligible effect on stiffness, although the shortest length tested appeared to have an effect on quadratic damping terms.
3. Of the motions of roll and heave, the latter appears to be dominant in getting water on the subdivision deck, while the former is helpful in drain-off or trapping on the side remote from the damage if there are no deck obstructions.
4. The motion of the floodwater on deck seemed to have little effect on body motions, other than inducing a mean heel and bodily settlement in the water as the mass of water on deck increased.
5. Wave or motion frequency (as well as amplitude) is important in determining the amount of water which gains access to the subdivision deck.
6. Phasing between heave and roll is important in determining the amount of water on deck.
7. Floodwater egress through the damage opening is similar to weir flow; floodwater ingress is not.

OUTSTANDING ISSUES

The study was revealing, but some issues remained outstanding. Among these were:

1. A full hull damaged model on the motion rig should be used to explore the effect of hull shape.
2. The effect of freeboard, damage position and GM on the stiffness and damping terms, should be explored.
3. Integrate the additional stiffness and damping model into numerical flooding/capsize models.

CONCLUDING REMARKS

This paper has promoted the thesis that dynamic stability, in its many forms, should be the foundation upon which questions of damage and survivability should be built. This implies that considerations of the survivability of ro-ro vessels (for example) should not be confined solely to consideration of transverse stability. The advent of lightly-built high speed passenger-carrying vessels to the waters of the world demands that our horizons for their safety be broadened. No longer will traditional design methods, rooted in statics, be satisfactory for such vessels, especially if they are damaged. The behaviour of the vessel in the immediate post-collision phase may be crucial to their survivability.

The time is right for a new approach.

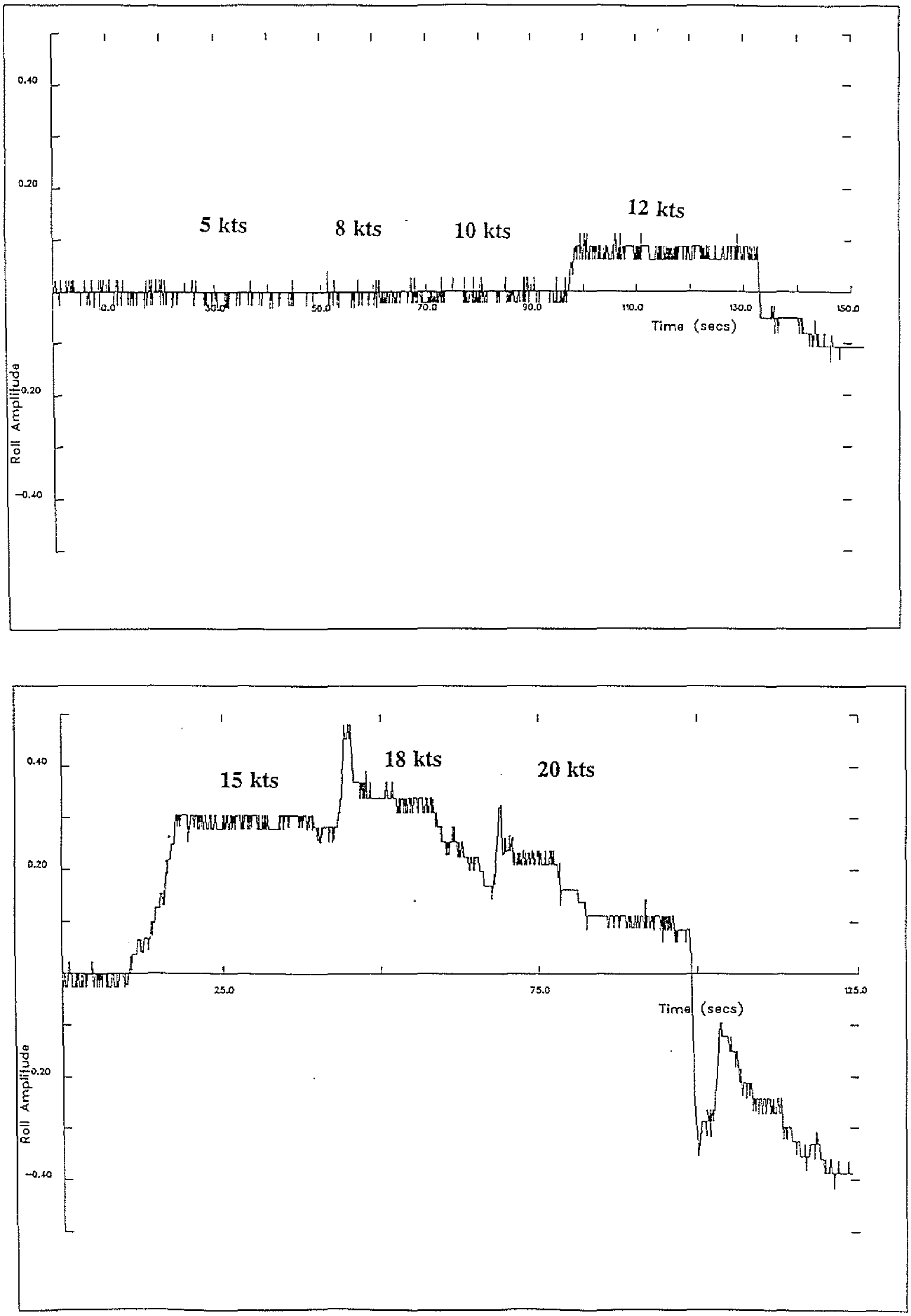


Figure 1. Measured Heel Induced by Forward Speed - Clean Damage Opening

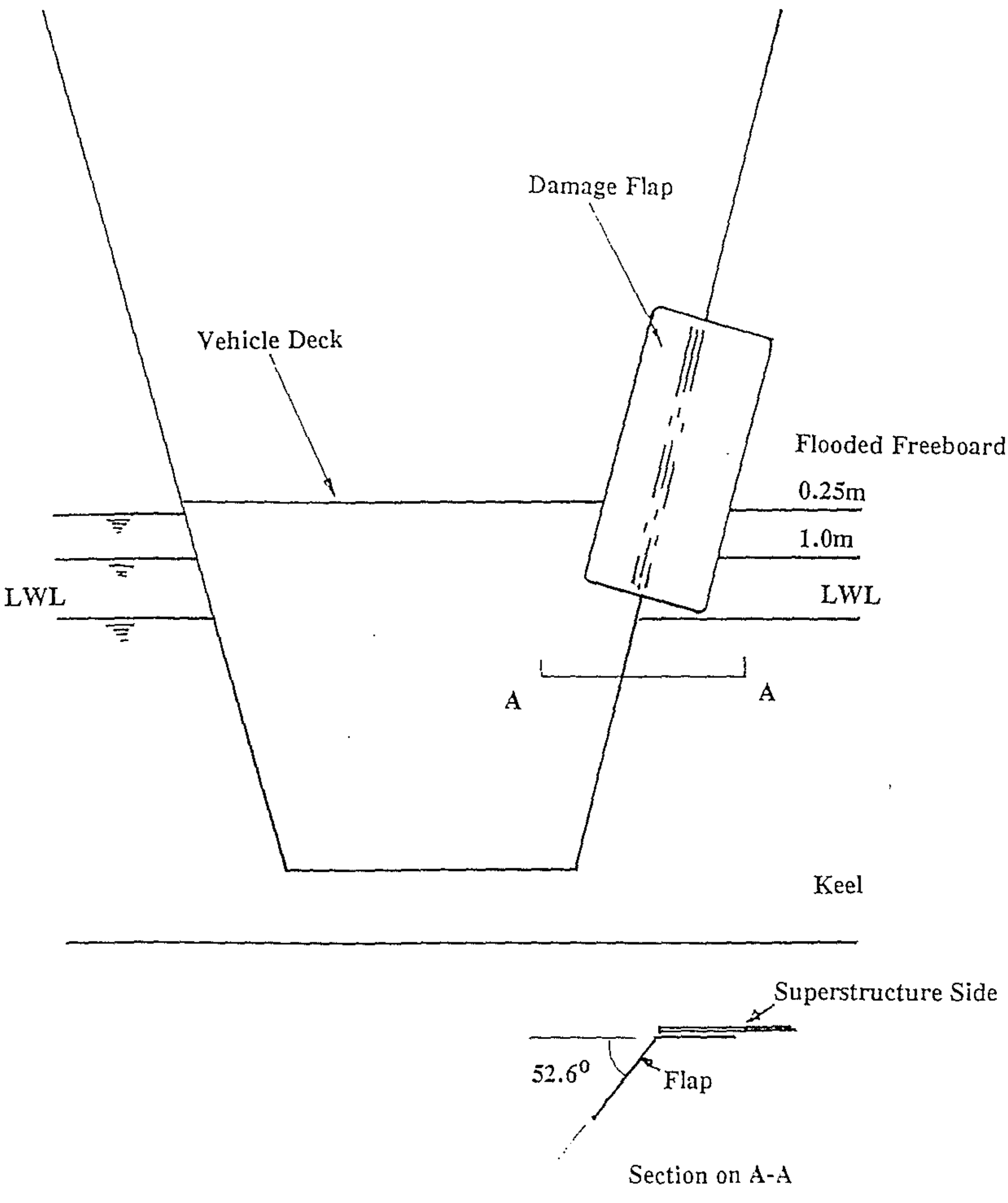


Figure 2. Damage Flap Configuration

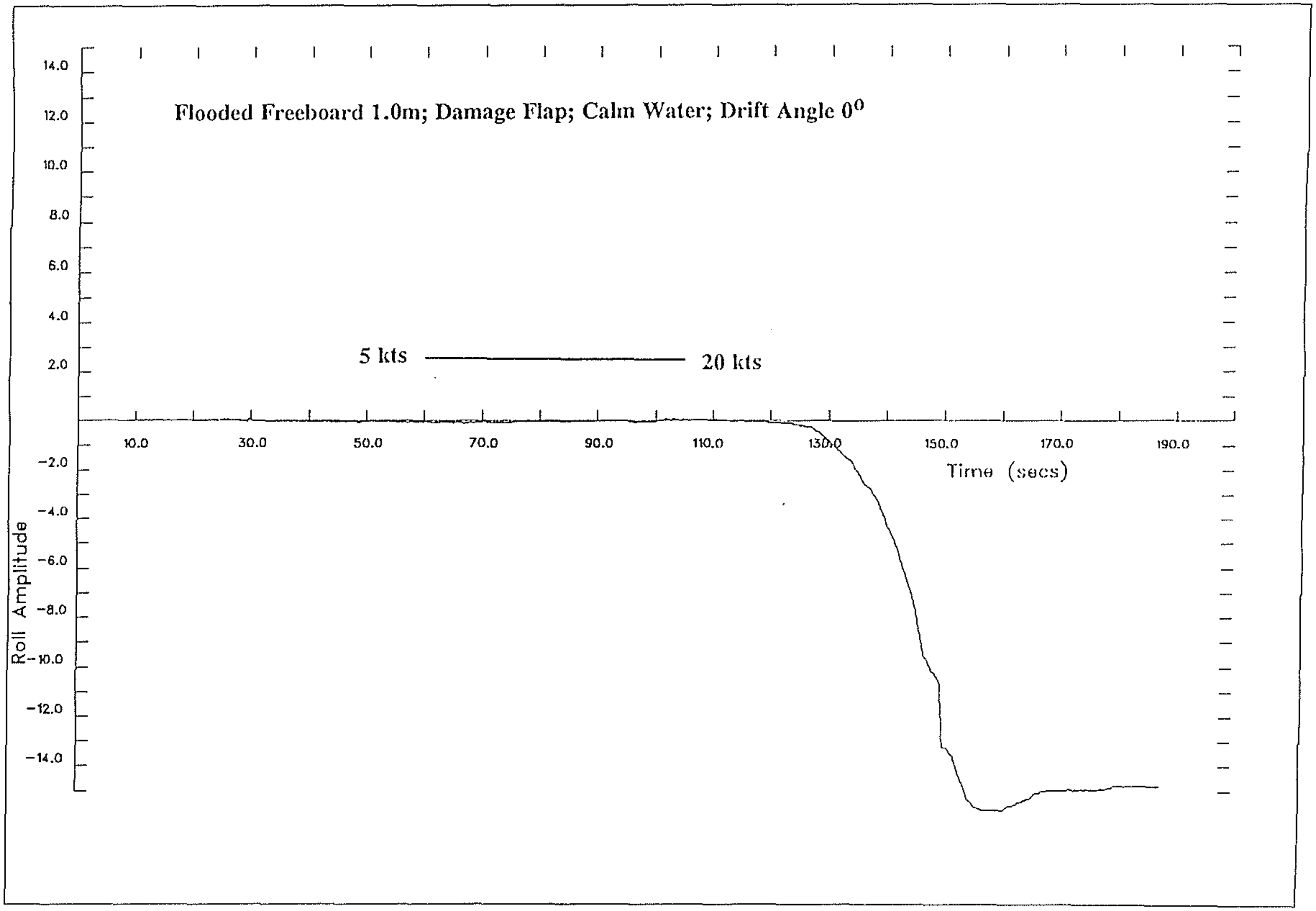


Figure 3. Measured Heel Induced by Forward Speed - Effect of Flap

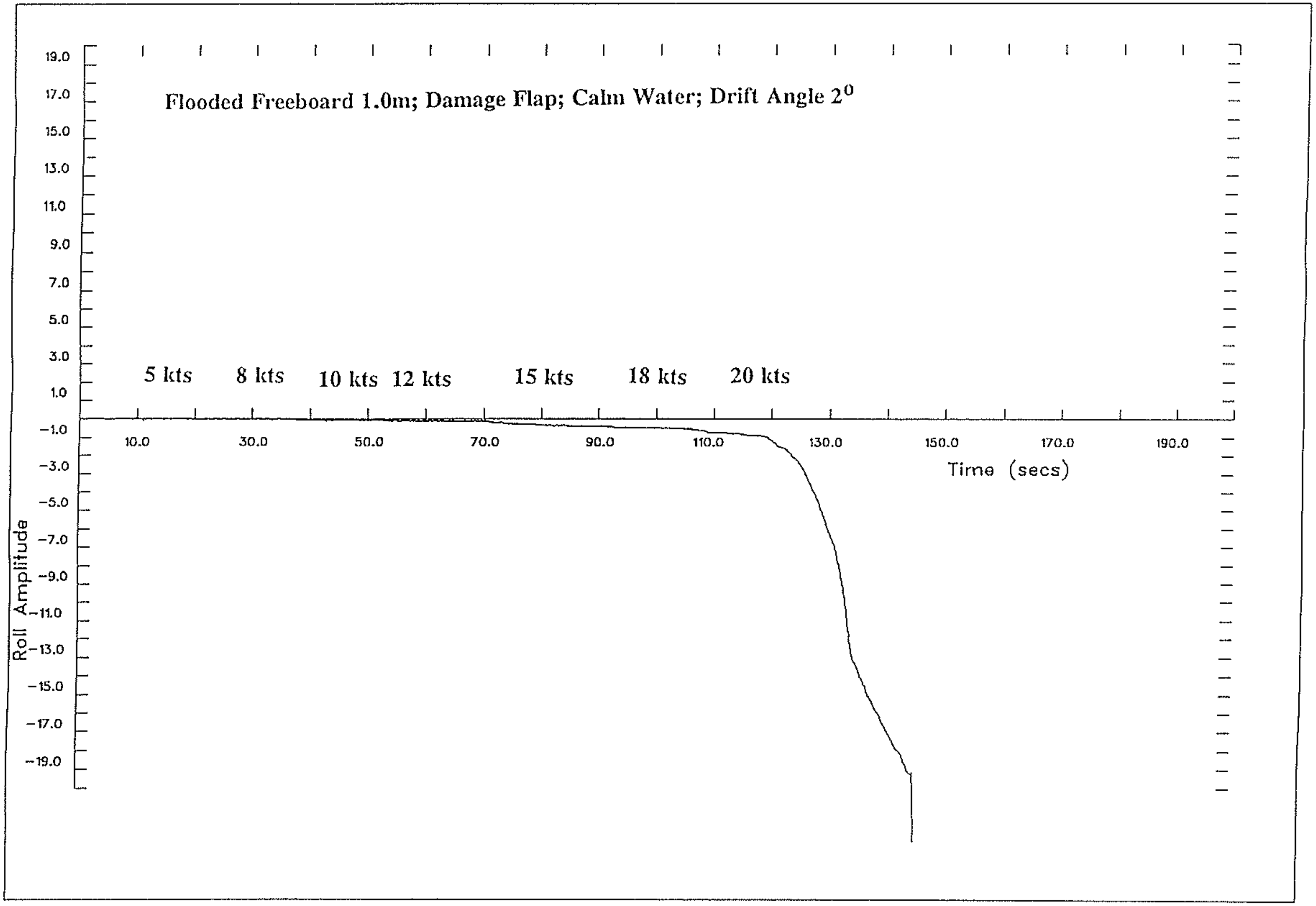


Figure 4. Measured Heel Induced by Forward Speed

- Effect of Flap and Drift Angle

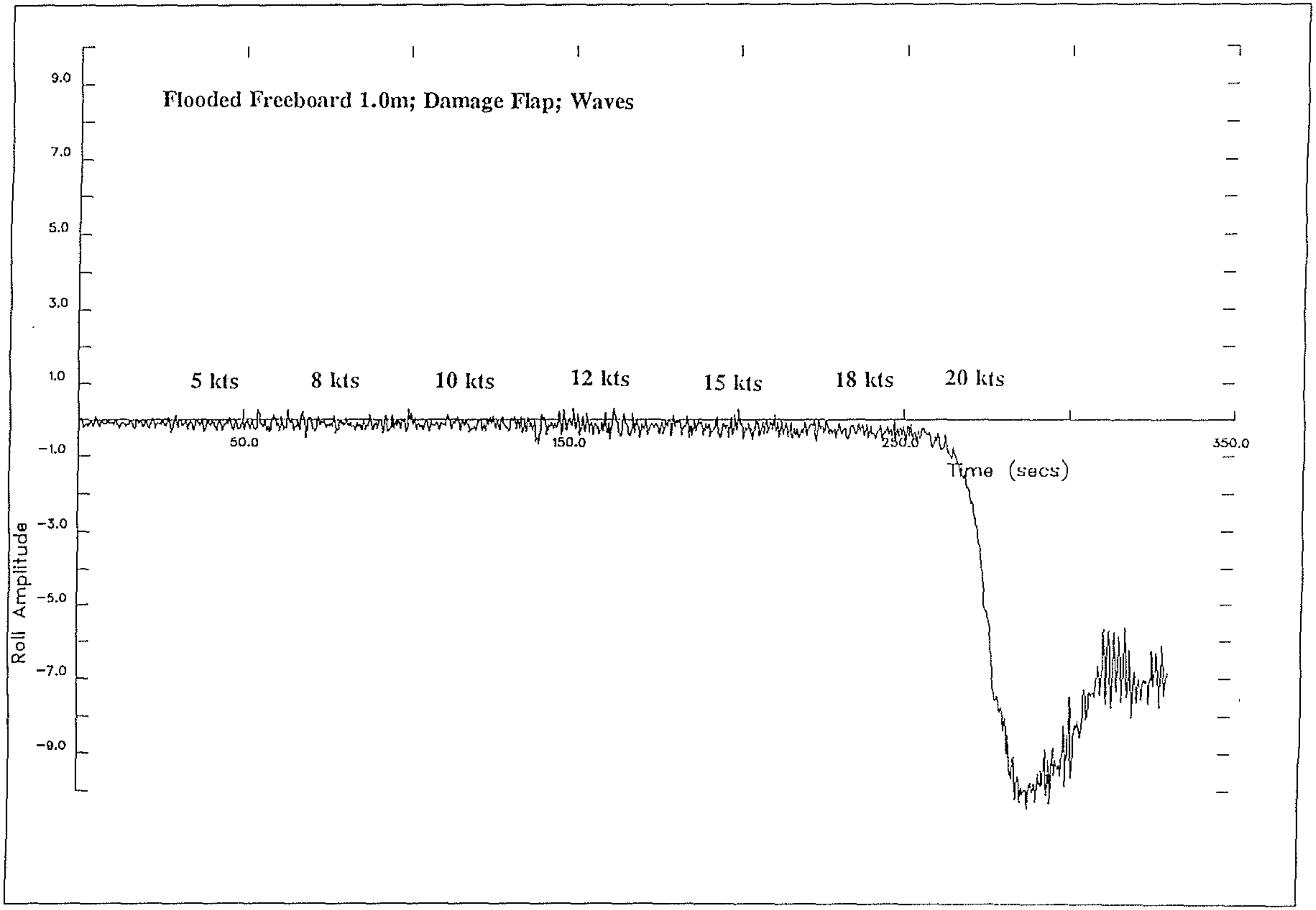


Figure 5. Measured Heel Induced by Forward Speed - Effect of Head Waves

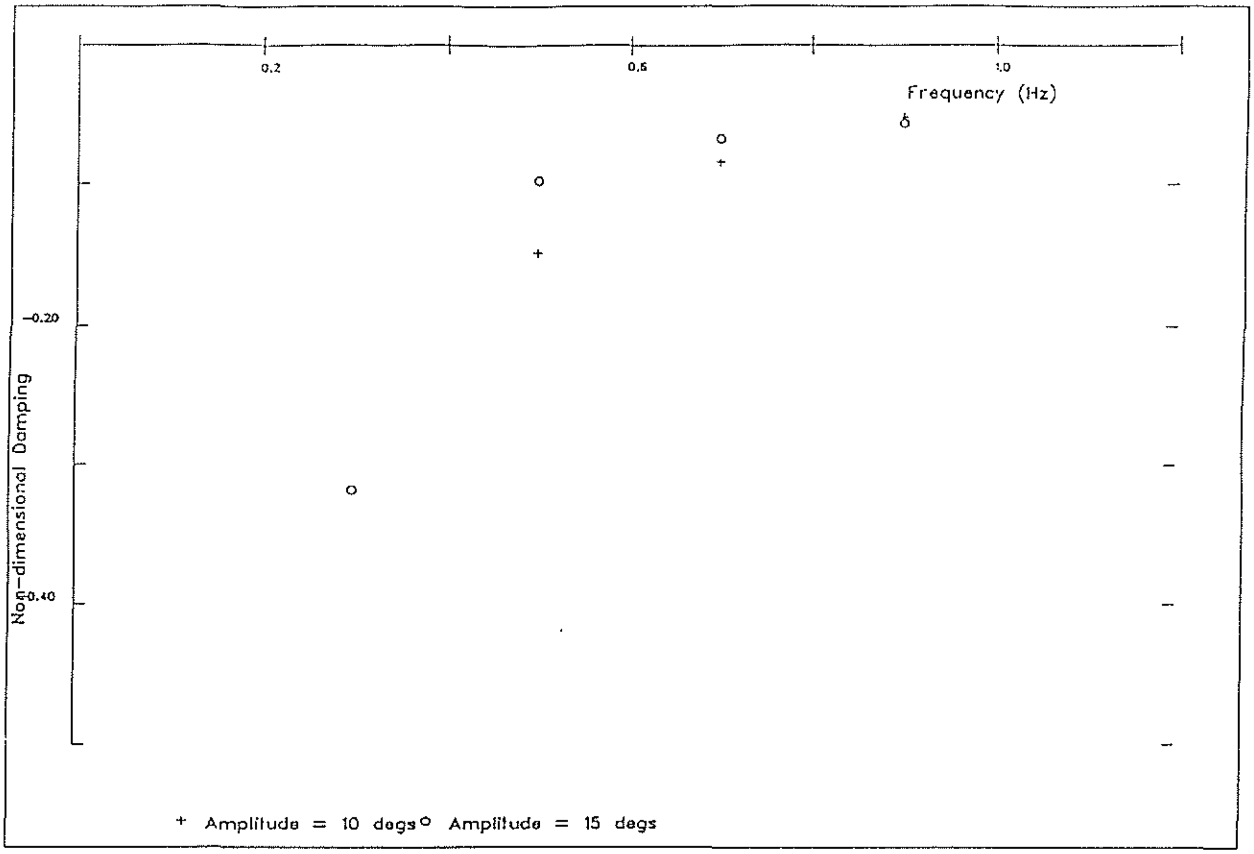


Figure 6. Deduced Linear Damping Coefficient in Forced Roll - Intact, Ship Section

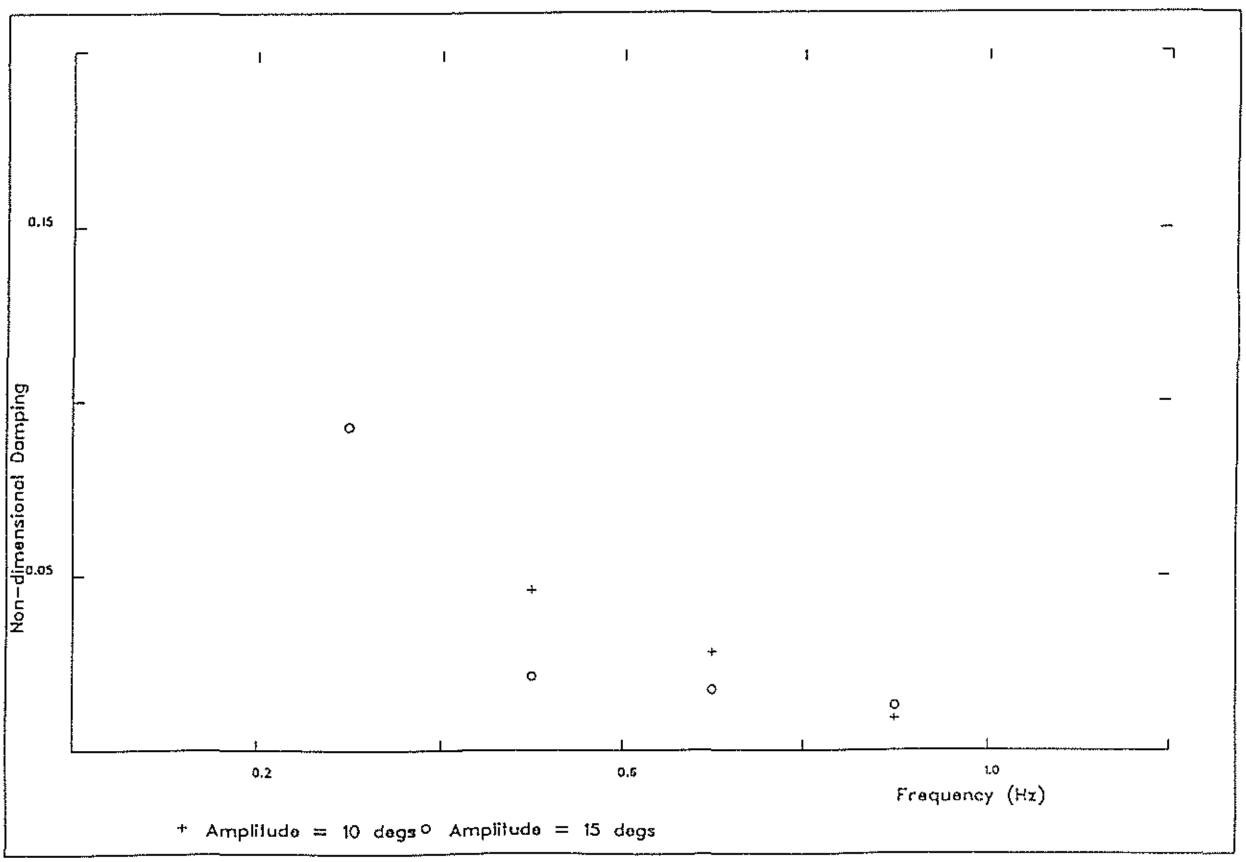
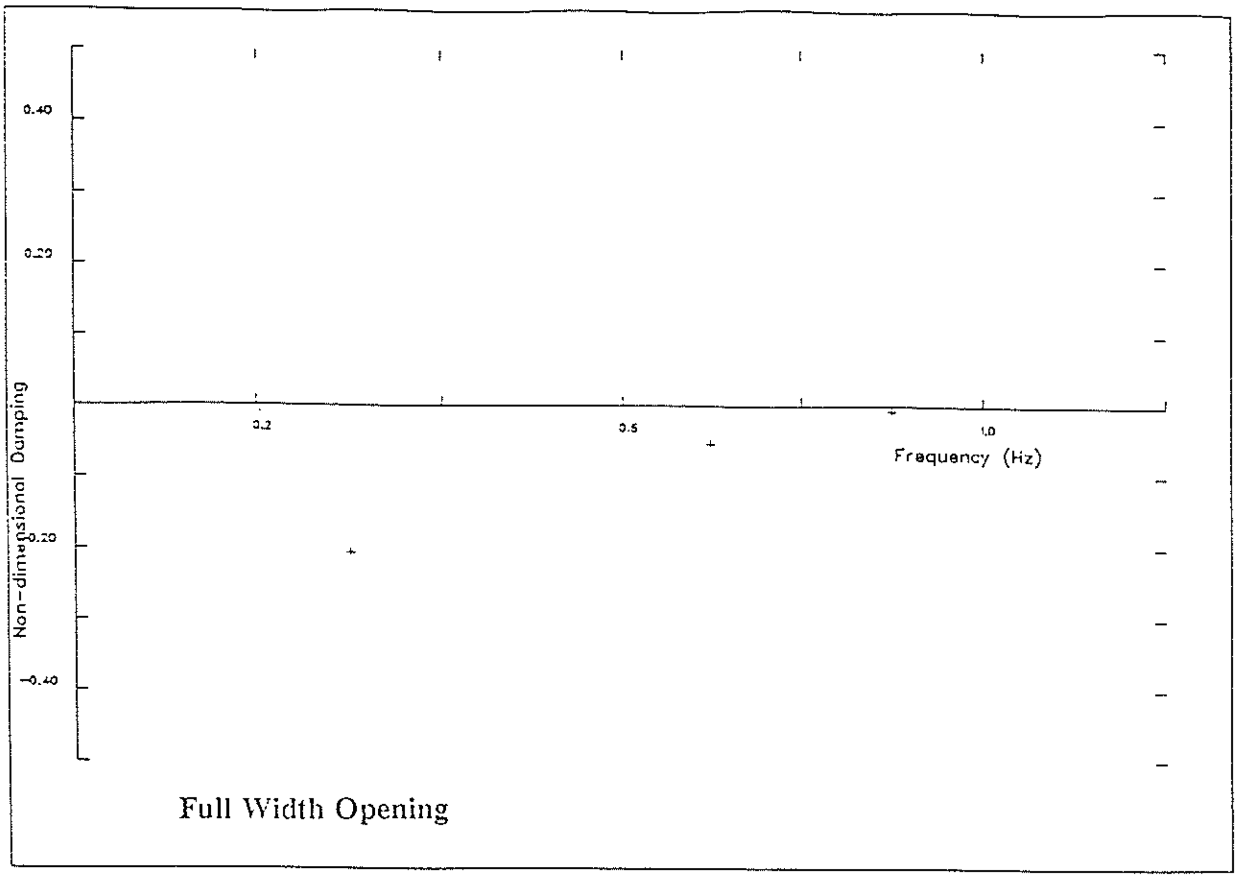


Figure 7. Deduced Quadratic Damping Coefficient in Forced Roll - Intact, Ship Section



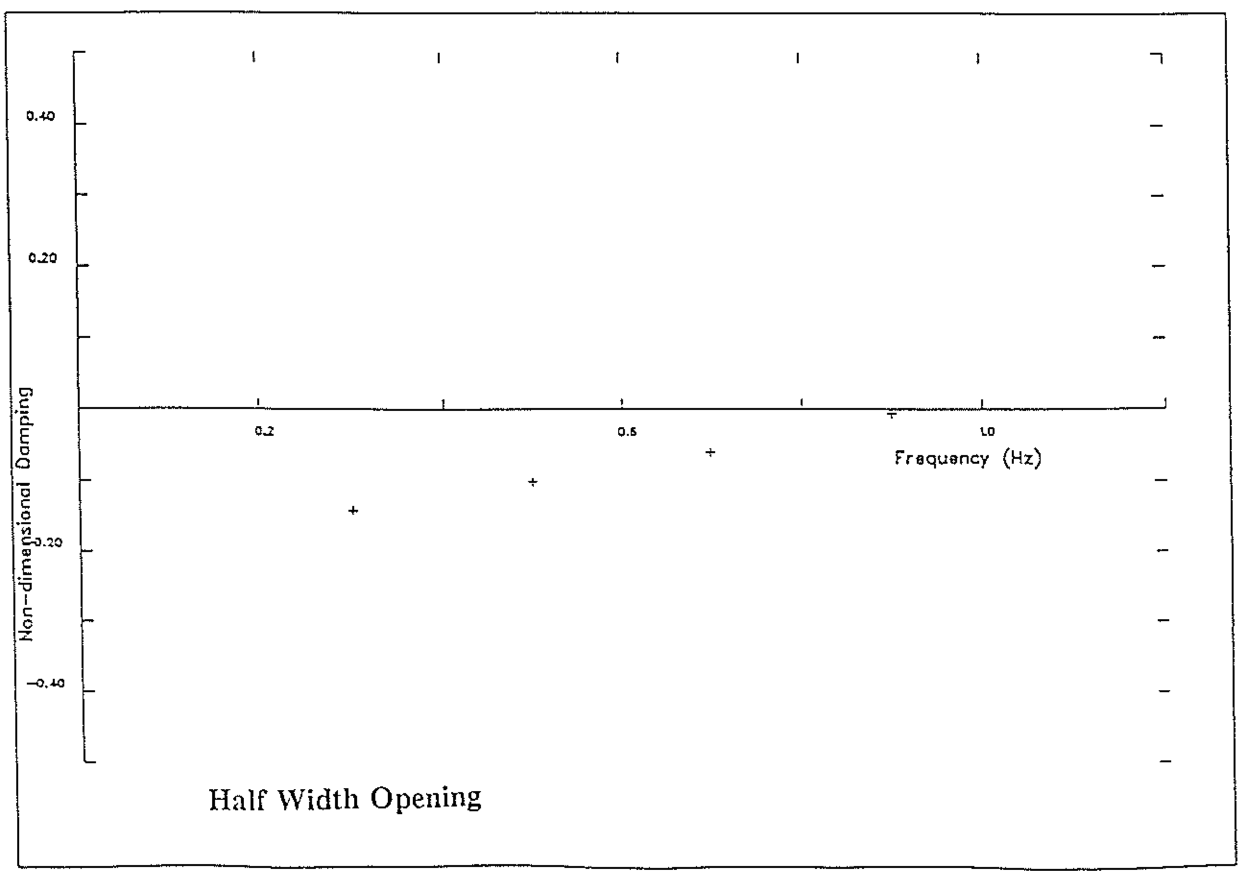
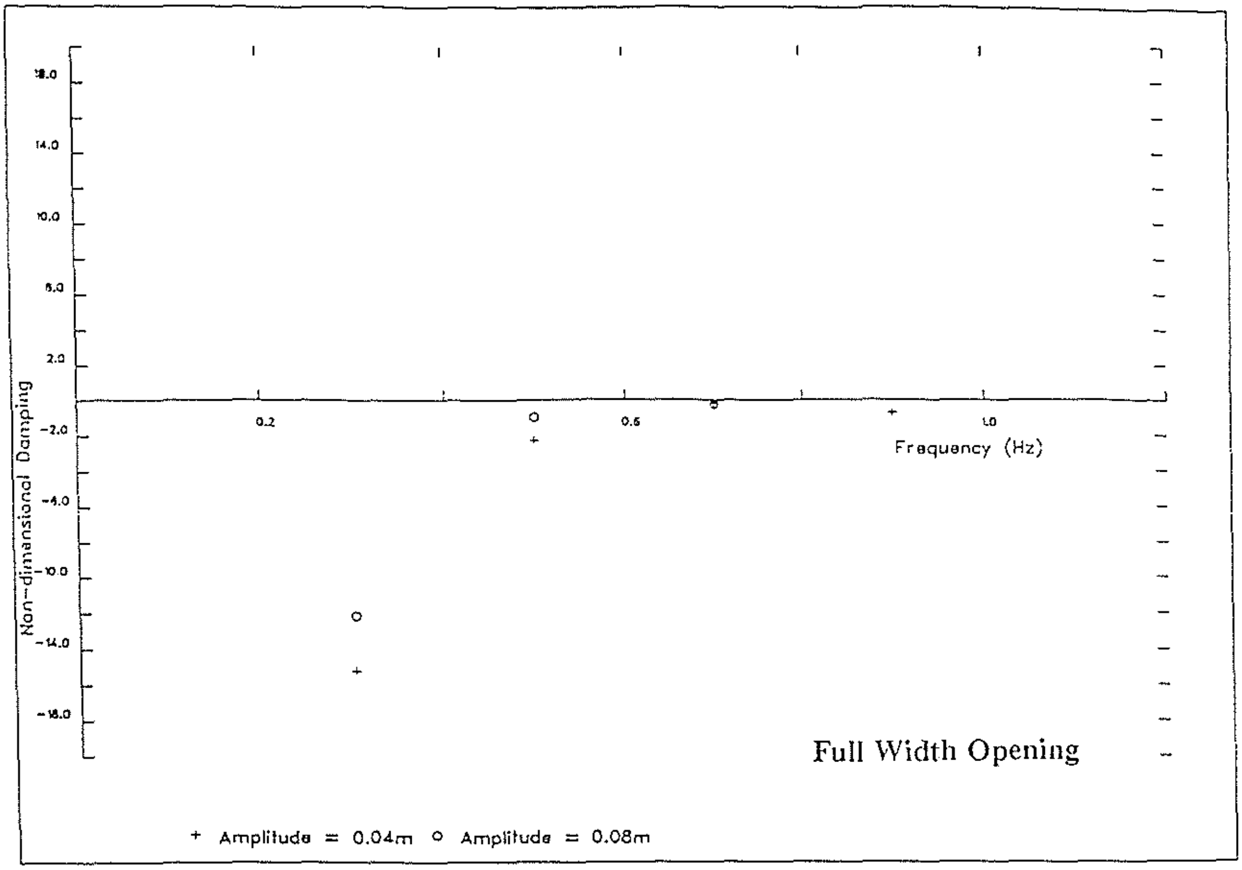


Figure 8. Deduced Linear Damping Coefficients in Forced Roll - Effect of Damage Opening Size



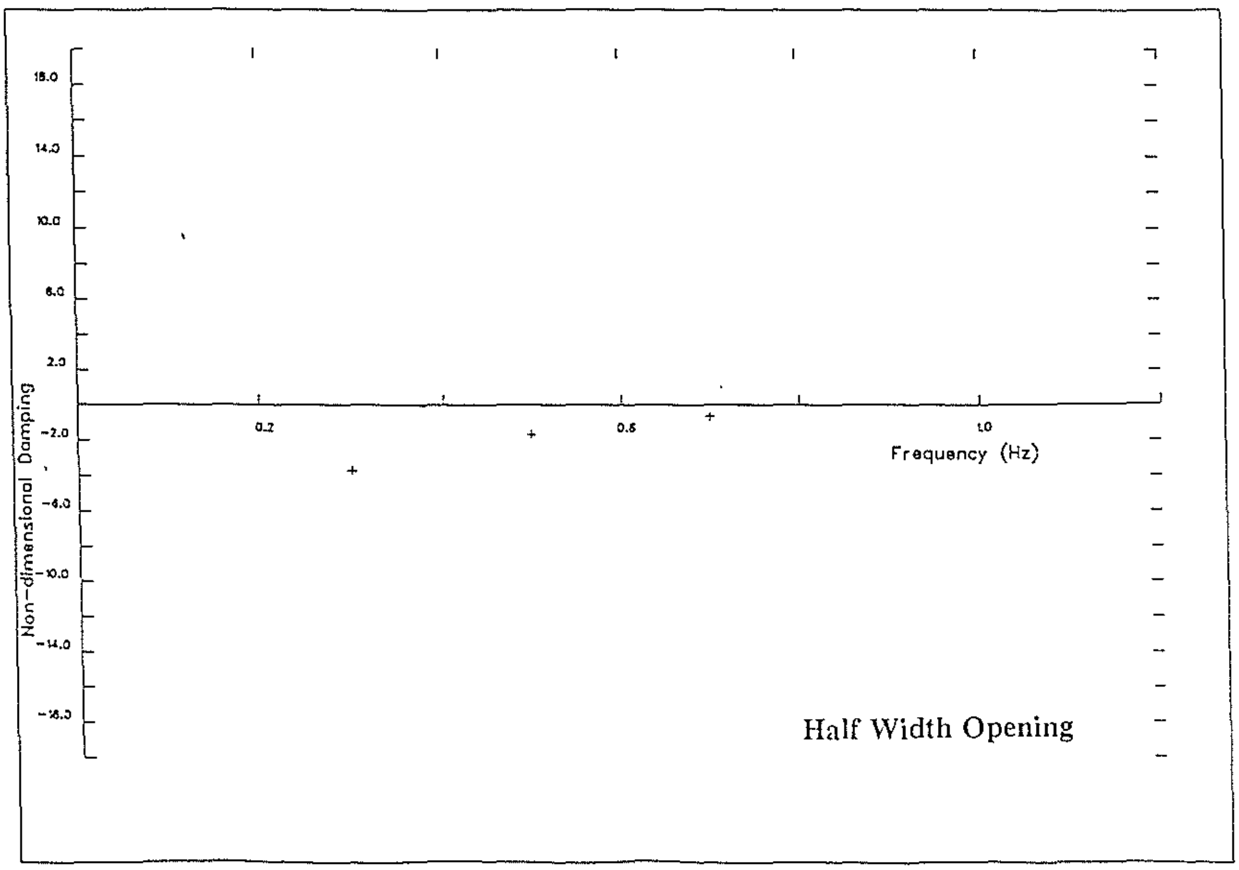


Figure 9. Deduced Linear Damping Coefficients in forced Heave - Effect of Damage Opening Size

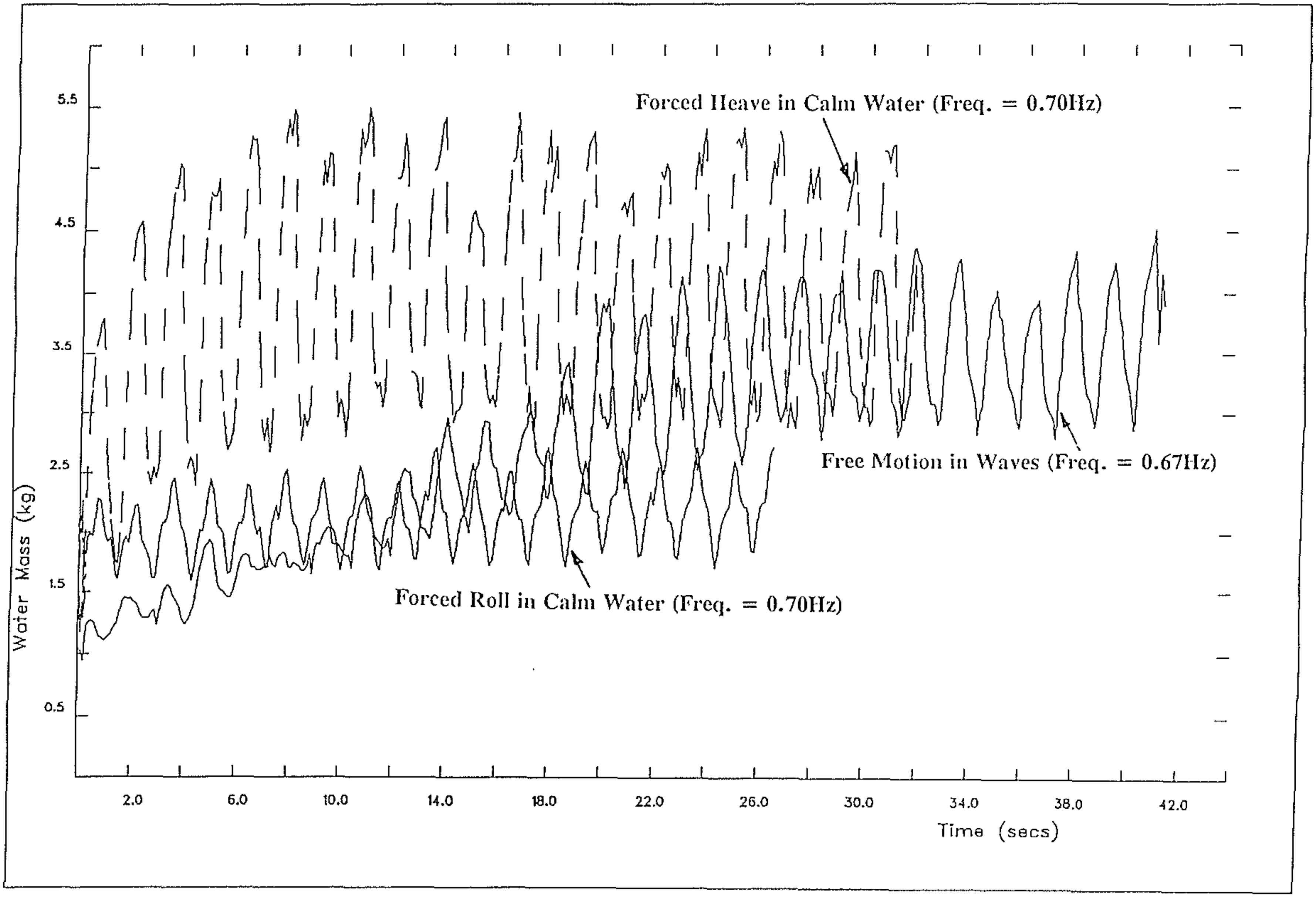


Figure 10. Comparison of Water on Deck