Seventh International Conference
The Jack-up Platform: Design, Construction and Operation
City University, London, September 1999.

JACK-UP MODELTESTS FOR DYNAMIC EFFECTS ON INTACT AND DAMAGED STABILITY

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Abstract

Model tests in severe sea conditions have been conducted aimed at investigation of the robustness, reliability and margin of stability for a large triangular jack-up, meeting HSE 4th edition guidelines. Both intact and damaged conditions have been tested. Apart from wind, co-linear waves were present as well.
The size of the compartments was enlarged above normal dimensions such that the criteria laid down in HSE guidelines were met for a single VCG value, irrespective of the rig being intact, damaged or having a flooded center compartment.
The results of these tests are discussed in terms of hydrostatics and hydrodynamics. It was found that there is a large influence of waves on the occurrence of a capsize event. For near capsize conditions the motional behavior did deviate considerably from a linear model. High skew was observed in the angular motions. In addition, the extreme angles were much higher than expected extremes based on a linear model of the motions.

1. INTRODUCTION

Mid 1999, model tests in waves were done with a model of a large jack-up. These tests were the results of earlier investigations of BMT for HSE on hydrostatic stability of jack-ups when being afloat. Financial support by the European Union was received for these tests. The background to the tests and actual tests are described in a separate paper [ref 1], the present paper discusses some of the background and presents results of the tests, both in terms of hydrostatics and hydrodynamics.

This paper is to be read in conjunction with [ref 1].

2. HYDROSTATIC CALCULATIONS

The aim of the model tests was to investigate the robustness, reliability and margin of stability for a jack-up meeting HSE 4th edition guidelines. In order to do so, a typical large jack-up formed the basis of an otherwise non existing unit. The jack-up chosen was the MSC CJ-62. The compartment arrangement of this unit was modified such that the highest allowable position of the center of gravity was the same for the intact and damage cases. This was achieved by enlarging the damaged compartments to a size exceeding their actual size up to a factor of 5. Figure 2.1 shows the damaged cases tested. Initially case D1 was included, however due to the deckhouse, capsize was hard to initiate. In cases D2 and D3 the deckhouse was rotated to starboard.
The calculations were done using MSC's program DAMAST [ref 3].

In the initial calculations (done before the tests), the deckhouse and cantilever were not included. After the tests, the model used in the calculations was modified such that it reflected the actual model as close as possible. This included wall thickness, ballast weights, the deckhouse and part of the cantilever. The substructure (around the derrick) was not included. The various positions of deckhouse and cantilever were taken into account in the final calculations. The initial calculations resulted in the **initial VCG**. The final calculations resulted in a somewhat different allowable vertical center of gravity (AVCG) value compared to the initial calculations:

	final model *(with deckhouse)*	*Highest value without capsize, for tested conditions*
Intact	Initial VCG + 0.3 m	Initial VCG + 13.9 m
Damage case A1	Initial VCG - 0.3 m	Initial VCG - 4.3 m
Damage case B1	Initial VCG + 0.1 m	Initial VCG - 3.1 m
Damage case C1	Initial VCG + 2.4 m	Initial VCG + 2.5 m
Damage case D2	Initial VCG + 1.0 m	Initial VCG – 3.1 m
Damage case D3	Initial VCG - 6.0 m	Initial VCG – 6.2 m

Table 1.1. Review of AVCG values based on the HSE guidelines

The relevant criteria used are:

- Intact	second intercept at 30 degree
- damaged	area ratio 1.0
- center filled	area ratio 1.0

The other criteria are not governing for the schematized unit. Note that downflooding was not considered as one usually either closes the openings or during the design process they are put in a location such that down flooding does not occur before the second intercept.

For case D3 (center filled completely), the AVCG is much less than that of the remainder cases. However, this case was just an extension of case D2 (partly filled) and not designed to meet the criteria at the initial VCG.

For the center compartment filled cases (D2 and D3), the displacement increases by the amount of water in the center compartment. Thus for the same wind moment, the wind arm is reduced.

The types of damages considered are:

- case A1	side damage under cantilever
- case B1	corner damage around leg well
- case C1	side + corner damage
- case D2	center filled 66%
- case D3	center filled 100%

Figure 2.2 shows the righting arm curves for the various conditions. Noteworthy is that in the damaged and center compartment filled cases, the range of positive stability is quite small (in view of the roll and pitch motions due to waves).

In the calculations, the direction of the heeling axis is such that the lowest AVCG is obtained. Later, in the calculations for the various conditions tested, the direction of the heeling axis is according to the capsize process.

3. IMPLEMENTATION OF WIND IN THE MODELTESTS

[Ref 1] contains an extensive description of the model tests. In these tests, the wind moment has been introduced by a weight shifted horizontally. Though one can view this as an overturning wind moment, it can also be seen as if a new floating structure is created. The righting arm of this structure is obtained by introducing a shift in righting arm equal to the wind arm at the considered heel angle. Doing so for the intact calculation does hardly change the hydrostatic characteristics of the rig. However, for the damaged condition, looking at the transformed righting arm curve in this way shows a unit with much less range of positive stability (figure 3.1). In addition, the position of the damaged compartment relative to the wind moment becomes relevant. When the damage is at leeward, the wind overturning moment *reduces* the range of positive stability. When the damage is at windward, the wind moment *increases* the range of positive stability. In such a case, a lower wind speed results in a *reduced* range of positive stability.

As shown by the model test, capsize against the wind is a possibility to be considered, especially for the filled center compartment cases.

Figures 3.2 to 3.4 show some typical positions for the various damaged cases -with the initial VCG- at the first intercept point with the wind arm.

4. RESULTS OF THE MODELTEST

This chapter is meant to highlight some of the findings and results of the tests. Results of hydrostatics and hydrodynamics will be discussed. Seen the results, it is not possible to reach precise values of the VCG above which capsize will take place. This is neither possible nor desirable. Instead, one must view the results in terms of capsize likely to occur in the given environment and the prescribed vessel condition.

The tests also revealed a motional behavior that deviated considerably from the usual linear model used in motion calculations.

Looking at the test results, it became clear that the intact, damage to the side and center compartment filled cases are distinctly different. Thus, each is discussed separately.

4.1. INTACT

The intact condition (tested in 12 m significant waves at the initial VCG) did not show any tendency to capsize. This confirmed earlier observations with modeltest with the actual CJ-62. However, the raise in VCG required to initiate capsizing was unexpectedly high. The center of gravity could be raised by about 14 m above the initial VCG before capsize occurred. At this position, the range of positive stability is even less than 20 degrees.

When raising the VCG, it was noted that the roll and pitch motions became less violent. This is not surprising as the reduction in stability shifts the natural roll and pitch frequencies to lower values. Also, the stability reduces greatly (and becomes even negative) when increasing the heel angle above the equilibrium position. As shown in figure 4.1 the extreme heel angle (from even keel) for an intermediate VCG is even less than for the initial VCG. However, increasing the VCG by about 13 m above the initial value, results in an increase of the extreme heel angle.

Of interest is the ratio between extreme heel angle and the range of positive stability (i.e. second intercept). These ratios have been determined in the usual way for capsize to leeward. When the capsize direction is to windward, the actual second intercept for rotation to windward is used. As shown in figure 4.2, for the stable cases the ratio is higher than 1.0, but approaches 1.0 for VCG values near the upper (stable) limit.

From the visual observations, differences were noted in motional behavior for stable and unstable conditions. For the initial VCG, the distribution of the instantaneous heel angles is highly symmetrical and follows a Gaussian distribution. However, for the marginally stable condition the distribution is distinctly skewed with larger values for heel in the direction of capsize (see figure 4.3). For higher VCG values, the low frequency content of the heel motion increases dramatically. For the VCG at which capsize occurs (inital VCG +14.5 m) the low frequency motion is dominating whilst the first order wave induced motion has vanished almost completely (see figure 4.4 and 4.5)

For the intact condition with wind, the rig capsized to leeward. However for one test *without* wind the rig capsized towards windward. Note that in the tests wind and waves were co-linear.

4.2. SIDE DAMAGE

For the side damage cases, the compartments were redesigned such that for the same VCG as for the intact condition, the area criterion of 1.0 was just met. This generally resulted in relatively large steady heel angles and small ranges up to the second intercept, see also figure 2.2. As shown in figure 4.6 the following is found for damage case A1.

	Final model i.e. for initial VCG-0.3 m (AR = 1.0)	*Highest value without capsize, for tested conditions = initial VCG-4.3 m*
steady heel no wind	8.2	6.6
steady heel with wind	10.3	7.6
second intercept	15.2	23.0
area ratio	1.0	2.7
from 1st to 2nd intercept	4.9	15.4

Table 4.1. Review of heel angles and area ratios, case A1

As can be seen, a large increase in the range of positive stability must be created in order to prevent capsize in 9 m waves.

Looking at the ratio between extreme heel angle from the even keel and the second intercept, also for the side damage cases capsize is likely to occur when this value reaches 1.0, see figure 4.7. Note that for the cases involving a capsize event, the extreme dynamic heel of a similar test of the closest non capsize case was used.

As was observed for the intact condition, also for the side damaged condition, the low frequency pitch and roll motions did increase when increasing the VCG. However, whilst for capsize to leeward, the relative importance of the low frequency content was modest, when capsizing to windward (damage also to windward), the low frequency content was dominating (see figure 4.8 and the next table)

	LF energy	*high frequency*
capsize to leeward	20%	80%
capsize to windward	80%	20%

Table 4.2. Percentage low frequency pitch motion (case A).

This is also highlighted in figure 4.5. From these figures, it is seen that when the risk of capsize increases, the amount of low frequency angular motion increases as well. However, as shown in figure 4.5 it is seen that there is no consistency in the percentage of low frequency energy measured for the capsize cases. Both low and high values are found. Though a relationship exist between low frequency pitch or roll energy and capsizing, the type of damage and capsize mechanism must also be considered.

Also for the side damage cases, asymmetry in the distribution of the angular motion was observed with larger angles for rotation towards the capsize direction then for rotation away from the capsize direction.

When separating the total angular motion in a low frequency part (0-0.3 rad/sec) and a wave frequency part (above 0.3 rad/sec) it is seen that the distribution of the instantaneous motions with *wave* frequencies do still follow the Gaussian distribution (see figure 4.9). Thus, the skew is mainly caused by the low frequency motion. This conclusion is irrespective of having the damage at lee- or windward.

The wave making facility of DHI allows for a high repeatability of the tests. This allows for a good comparison between the angular motion for a near capsize condition with those of actual capsize event. Such a comparison for case A1 is shown in figure 4.10. Due to the slight difference in position in the wave field, a minor shift in time is seen. Nevertheless, up to the moment where overturning occurs, the two signals are highly identical. The two signals start to deviate from each other just before the occurrence of the capsize event. The pitch motion for the capsized condition is gradually increasing whilst for the stable condition it remains the same. Once a large pitch motion has occurred, due to the lack of restoring moment, the rig is not able to revert to the initial mean position to the same extend as the stable rig is. This eventually leads to a capsize event. From this figure, it is also seen that in this case, capsizing involves several extreme pitch motions after each other.

Though the above given findings are quantified for case A1, the results for cases B1 and C1 are very similar. Of the three cases, case A1 turned out to have the lowest VCG for which it did not capsize. The critical VCG for case B1 was about 1.20 higher than for A1. For case C1, the critical VCG was about 1.80 m higher than for A1.

For all side damage cases, the capsize direction was always into the direction of initial heel as caused by the damage

4.3. CENTER COMPARTMENT FILLED

In several accidents with jack-ups under tow, flooding of internal compartments did occur. This can be due to damage of the vent pipes or houses due to deck loads swashing around. Also improperly secured hatches may cause flooding. In the guidelines, such accidents are covered by requiring *any* compartment to be damaged or freely flooded. Thus, in a hydrostatic calculation, the level inside the compartment is equal to the static outside level.

For the tests, it was decided not to damage but to fill the large center compartment of the jack-up. This compartment was without obstructions and thus did allow the water to move freely from one side to the other. The height of the double bottom was adjusted such that at 66% filling, the level inside equaled the outside seawater level. In this case, the AVCG was slightly higher than for the intact condition (case D2 initial VCG+1.0 m). The importance of the free surface effect is shown in figure 4.11.

In addition to the partly filled situation, also the fully filled situation was tested. As shown in chapter 2, for the fully filled condition, the AVCG is considerably lower than for the partly filled situation. In the stability calculations, the effect of the water inside the center compartment is taken into account by a weight increase. The increase itself is just the weight of the water whilst the center of gravity of the increase is based on the actual position of the water inside the compartment. As the righting arm is now related to the original weight plus the water inside the compartment, the wind heeling arm is to be reduced compared to the other damage cases.

For the center compartment filled, the same types of analyses were done as for the intact and side damaged cases. In contrast to the intact and side damage tests, for the center compartment filled, the most critical VCG was related to capsize to *windward.* It is felt that the main reason for this behavior is the high degree of submergence of the windward side of the rig and almost symmetric location of this compartment. In this respect, one should also remember that when the capsize direction is to windward, the wind overturning moment helps to stabilize the unit. So without wind, capsize can be expected at lower VCG values than as found with wind.

The ratio between extreme heel angle and second intercept is shown in figure 4.12. For the cases where capsize is to windward, the actual second intercept for rotation to windward is used. Amazingly, for the cases where capsize is to leeward, the ratio drops even below 1.0. When capsizing to windward (i.e. the most critical case), the ratio at which capsize occurs is just slightly below 1.0. Be reminded that for capsize to windward, the second intercept is larger than for capsize to leeward (see also figure 3.1)

When comparing this case with the intact or side damage cases, it was observed that the amount of green solid water on deck was much larger in this case. This is partly due to the reduced freeboard and partly due to the static heel angle being quite small. Having a smaller mean heel angle means that water does not flow off the deck as easily. The resulting increased presence of green water seemingly prevents capsize when one expects it to happen. As an example of this effect, see the pitch motion for identical rig orientations as given in figure 4.13. For the side-damage case (case A1), the mean pitch angle has a tendency to increase during the passage of a couple of high waves (at around 2450 sec). However, for the center compartment filled case (D3), the mean pitch reduces in these same waves. The actual capsize for case D3 occurs at a later instant, at about 2630 seconds. The direction into which the rig rotates in these high waves is just opposite (i.e. to windward) when compared to the side damage case.

The filled center compartment case differs from the side damage cases in its deep draft and its small mean heel angle. The latter leads to the observation that the static heel angle has a distinct influence on the dynamic stability of the unit. When looking at the video recordings of the side damaged case, during the passage of a group of high waves the rig attained a position where either the windward or the leeward side was deeply submerged. The large amount of added mass, having an offset relative to the center of the rig causes a large coupling between heave and pitch (or roll). This effect, which is far less pronounced when the center compartment is filled, may be the reason for the difference in behavior for the two cases.

5. MOTIONAL BEHAVIOR

As shown in the previous chapter, a marginally stable unit differs from a highly stable unit in the following way:

- low frequency content of the angular motions increase, especially when capsize occurs to windward
- the distribution of the instantaneous angles becomes skewed. Further study reveals that this is mainly due to a high skew in the *low frequency* part of the signal
- the motional behavior deviates from the usual linear model. Apart from the skew mentioned above, it is also seen in the ratio between extreme and RMS roll or pitch motion as shown in figure 5.1. For the intact cases with a high stability, this ratio is about 3-4, which is typical for a Raleigh distribution. When reaching critical VCG values, this ratio reaches values up to six with one instance of 11.5. The same, is found for the damaged and center compartment filled cases

6. FURTHER CONSIDERATIONS

6.1. ENVIRONMENT

The various regulations (HSE, IMO etc) prescribe the windspeed for which the wind overturning moment is to be determined:

-	intact	51.5 m/s (100 knots)
-	damaged	25.8 m/s (50 knots)

During the tests, the windspeed for the intact condition was set to 70 knots, being more related to a restricted ocean tow (instead of unrestricted). However, instead of looking at the wind as an isolated factor, also the corresponding wave climate was added (respectively 12 and 9 m significant height). The presence of the waves proved to be decisive for the occurrence of a capsize event. Note that wind was introduced in a static manner thus excluding any gustiness. Introducing gustiness may have worsened the situation. Underlying to the area ratio method is that wind suddenly picks up from zero to full speed. This amount of gustiness is not a realistic model of reality.

As became obvious from the tests, the wave conditions have an important influence on the possibility of occurrence of a capsize. This has also been observed with model tests of RoRo ferries.

6.2. TYPE OF DAMAGE

As shown in the tests, there is a clear distinction between flooding of a center compartment and (waterline) damage to a side tank. Damage to a side tank can be caused by a vessel or can be due to cracks in the hull structure. However, as reported by [ref 2], these are not the main causes of loss of a jack-up during tow. Most accidents, in so far stability is concerned, are related to flooding of internal spaces due to damaged deck closures, hatches, air vents etc. Such flooding does not stop when the internal level equals the outside seawater level but will continue till the compartment is full.

For the unit as tested, looking at the side tanks as flooded compartments instead of as damaged compartments does not lead to different conclusions. This is because these tanks are that large that, when damaged, they are almost completely filled. For the center compartment, the situation is different. For the damaged cases (i.e. *free flooding*), the internal level is about 66% of the total height. This is approximately equal to the tested cased D2. Compared the fully filled case (D3) with the partially filled case (D2) the AVCG for which the model as tested did not capsize was about 2 m lower. This is much less than the difference (between D2 and D3) of 7 m as given in table 1.1

The important issues with respect to damage (or flooding) are the types of damage and the safety margins to be applied. Is there a justification for giving the same importance to side damage as to free flooding of an internal compartment? When considering free flooding, is it sufficient to limit the internal level to the mean outside level or should a compartment be filled completely, or 50 % for that matter? A particular problem is the formulation of the safety margin. In the present guide line, the safety margin (or accepted risk) is in the type of damage, the windspeed, second intercept (intact only), and area ratio. When aiming at an approach where wave action is included, safety can be found in various key factors like:

- margin to critical wave height
- margin to critical VCG
- margin to second intercept
- degree of flooding

When looking at compartment flooding, also the ratio of ingress in relation to time needed for counter measures or evacuation should be considered.

7. CONCLUSIONS

Model tests have been conducted with a large triangular jack-up in severe sea conditions. Both intact and damaged conditions have been tested. The size of the compartments were enlarged above normal dimensions such that the criteria laid down in HSE guidelines were met for a single VCG value, irrespective of the rig being intact, damaged or having a flooded center compartment.

The overturning effect from the wind was simulated by a weight located on the deck. For the heel angles of interest, this results in an almost constant overturning moment. The rig was exposed to waves of 12 m (intact) and 9 m (damaged) significant height. Some tests were done with reduced wave heights or without wind.

In view of the above, the findings are strictly for the situation as tested. One must be cautious in extending the conclusions to jack-ups different from the abstract unit tested in being smaller, rectangular or having a different layout.

From the test, the following is concluded.

1. For intact conditions:
   At the initial VCG, which resulted in the second intercept at 30 degree, the rig was very stable in waves. The VCG had to be raised by 14.5 m in order to initiate a capsize. With wind, capsize occurred to leeward whilst for one test without wind, capsize to windward was observed.

2. For side damage conditions:
   At the initial VCG, resulting in an area ratio of 1.0, capsize in waves was observed. The VCG had to be lowered by about 4 m in order to obtain a marginally stable unit. Capsizing was always to the initial heeled direction as caused by the damage. When the damage was at windward (thus capsizing to windward), the critical VCG was slightly higher than when the damage was at leeward.

3. For the center compartment (partially) filled cases:
   Also for these cases, the VCG has to be lowered below the values set by the area criterion of 1.0. When partially filled the VCG had to be lowered about 4 m. When filled completely the VCG had to be lowered by only 0.2 m. For these cases, the initial heel is small. Nevertheless, similar to the side damage cases, capsize was towards the direction of initial heel. Surprisingly, the most critical VCG was related to capsize to *windward*.

4. The ratio between second intercept and extreme list angle is a reasonable indicator for a possible capsize. For the intact and side damage cases, a ratio of 1.0 or less generally resulted in a capsize. This also applied to the center (partly) filled cases when capsizing to windward. For a capsize direction to leeward, the ratio could be as low as 0.45-0.65.

5. Compared to non critical VCG situations, motions for critical VCG values were characterized by:
   - high degree of low frequency motions (< 0.3 rad/s)
   - small first order motions when capsizing to windward
   - highly skewed probability distribution of the low frequency part of the motion
   - increased ratio between extreme and RMS angular motions

6. When considering a revision of today’s stability requirements, the following aspects should be taken into account:
   - large margin to capsize as observed for intact condition
   - low probability of damage to side compartments
   - the probability of flooding due to damage of watertight integrity on the main deck
   - rate of flooding
   - size, shape and arrangement of the jackup
   - large influence of wave conditions
   - the probability of combined occurrence of wind, waves, and damage
   - definition of acceptable risk level
   - the special nature of the towage operation

7. REFERENCES

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[ref 2] Standing R G
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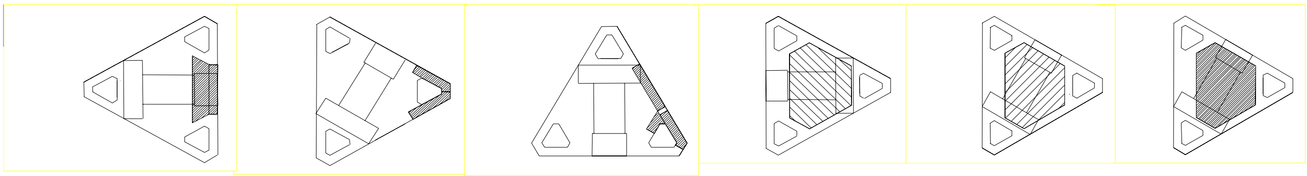
[ref 3] Santen, JA van
Stability Calculations for Jack-Ups and Semi Submersibles, CADMO 1986, Washington



Case A1 Case B1 Case C1 Case D1 Case D2 Case D3

Figure 2.1 Review of various damaged cases

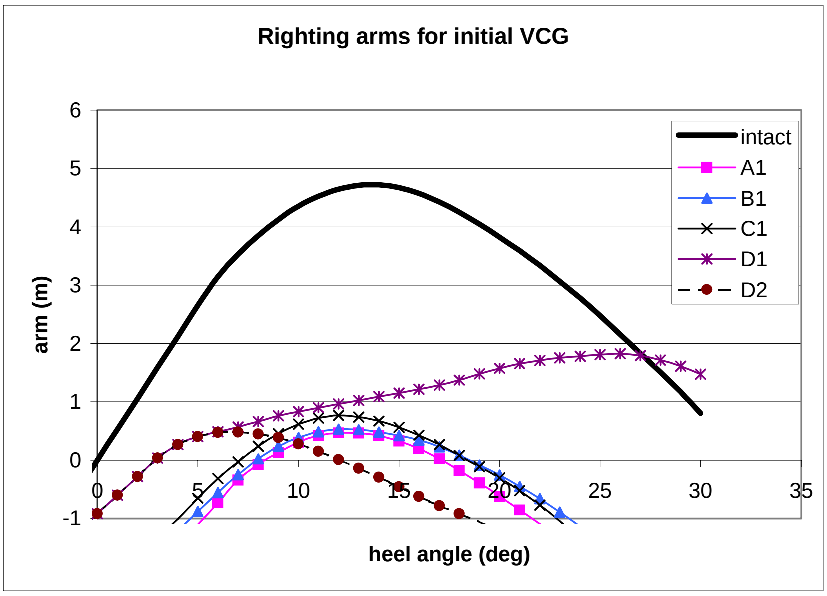


Figure 2.2 Righting arms for various cases

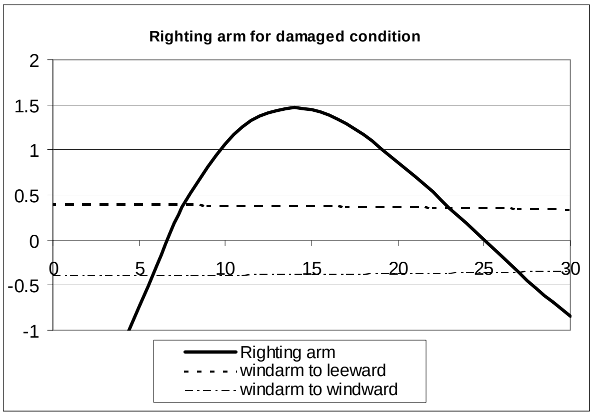


Figure 3.1-a Righting arms case A1

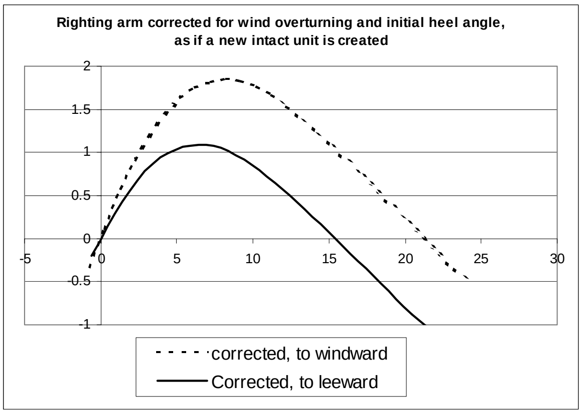


Figure 3.1-b Righting arms, windarm removed

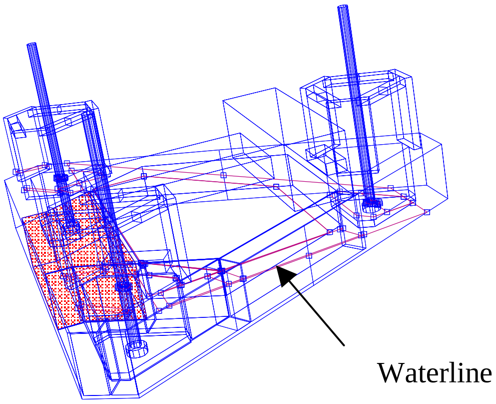


Figure 3.2 Case A1, Initial VCG

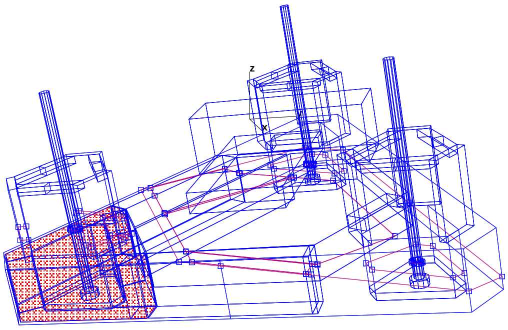


Figure 3.3 case B1, initial VCG

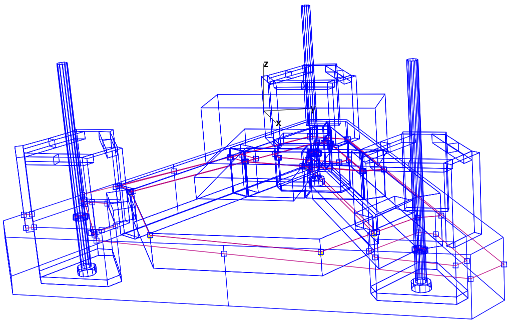


Figure 3.4 Case D2, initial VCG

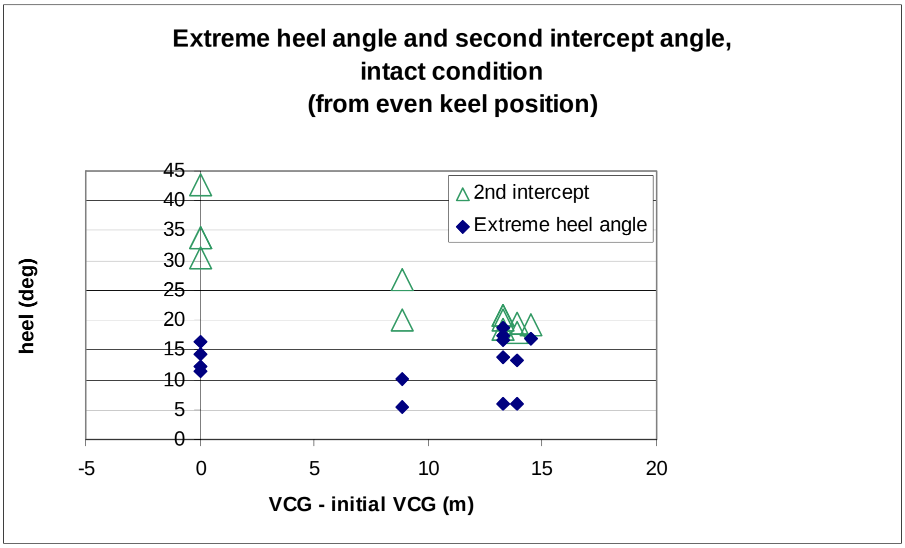


Figure 4.1 Extreme heel angles and second intercepts, intact condition

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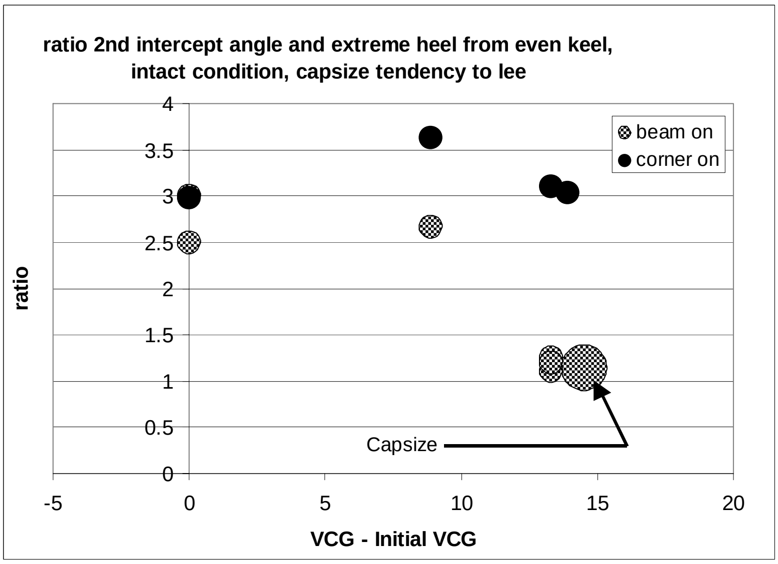


Figure 4.2-a Ratio 2nd intercept and extreme heel for rotation to leeward

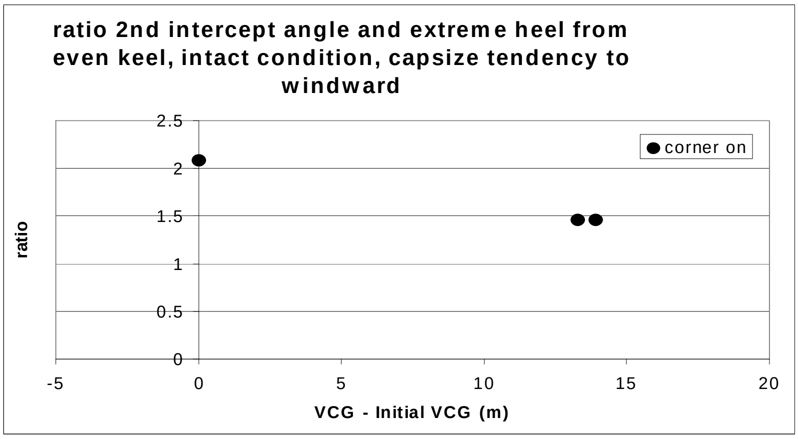


Figure 4.2-b Ratio 2nd intercept and extreme heel for rotation to windward

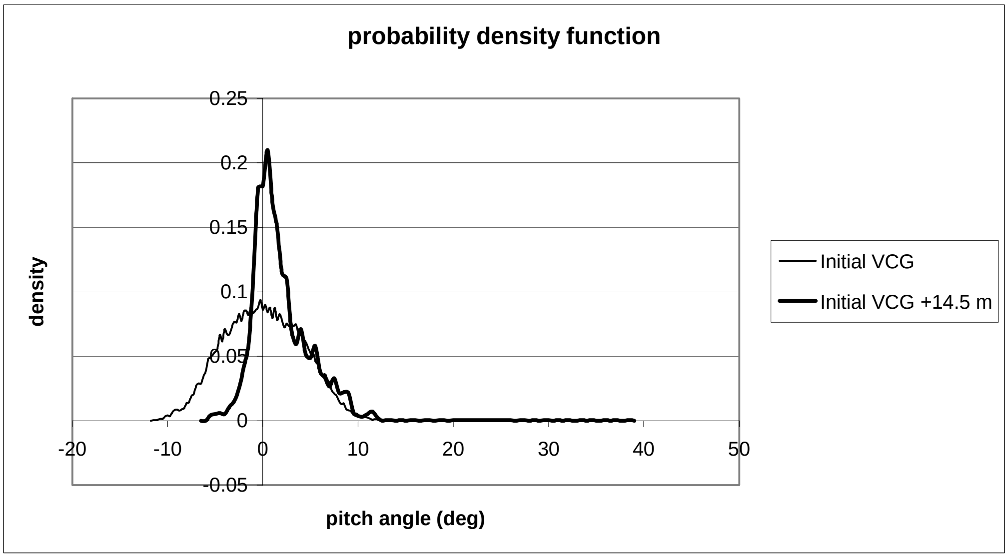


Figure 4.3 Probability density distribution of the pitch motion for a stable and unstable condition

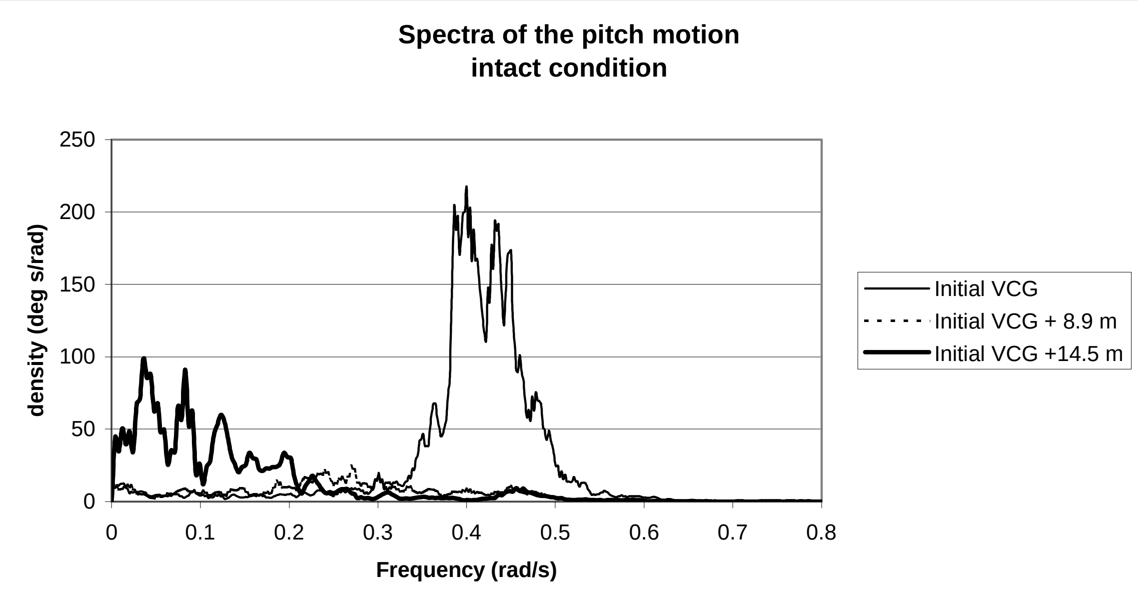


Figure 4.4 Pitch motion spectra for various VCG values

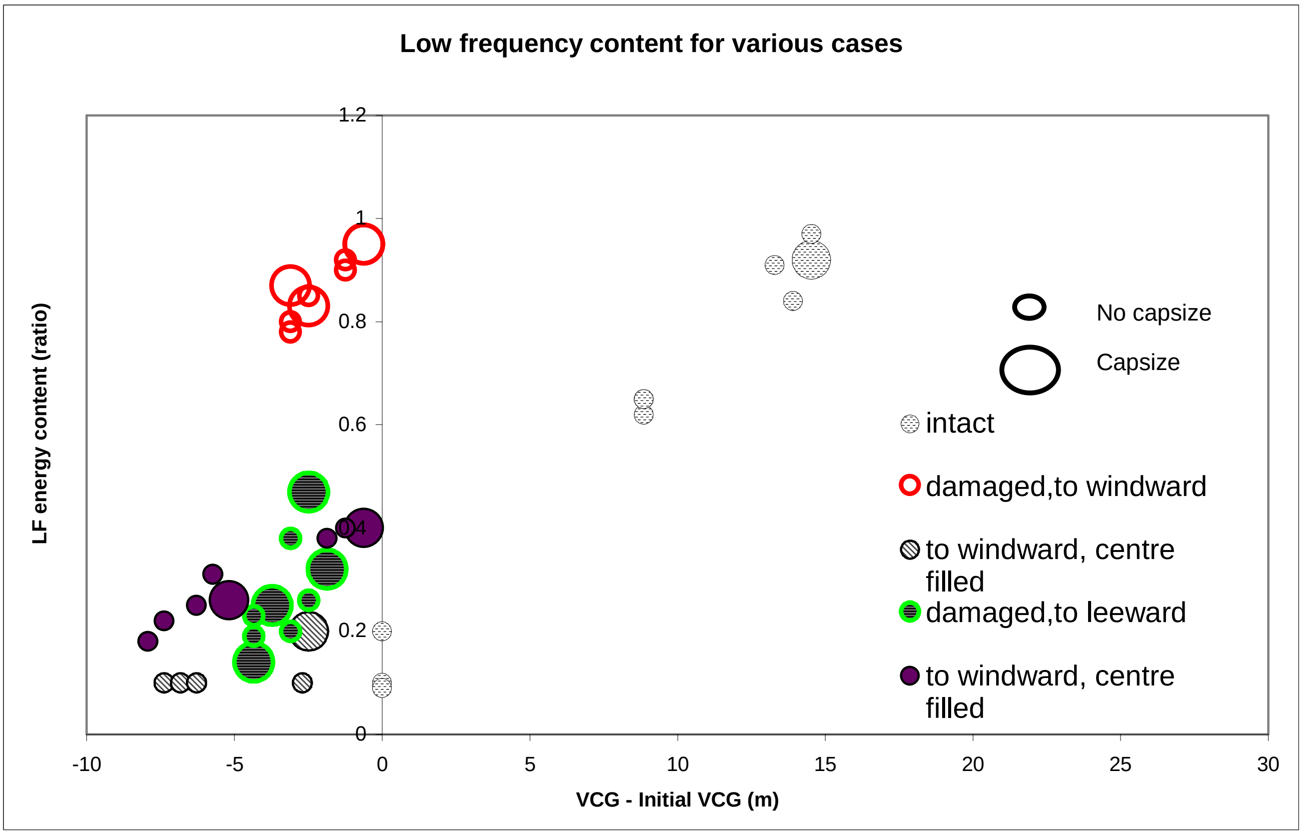


Figure 4.5 Low frequency content of the angular motion for various cases

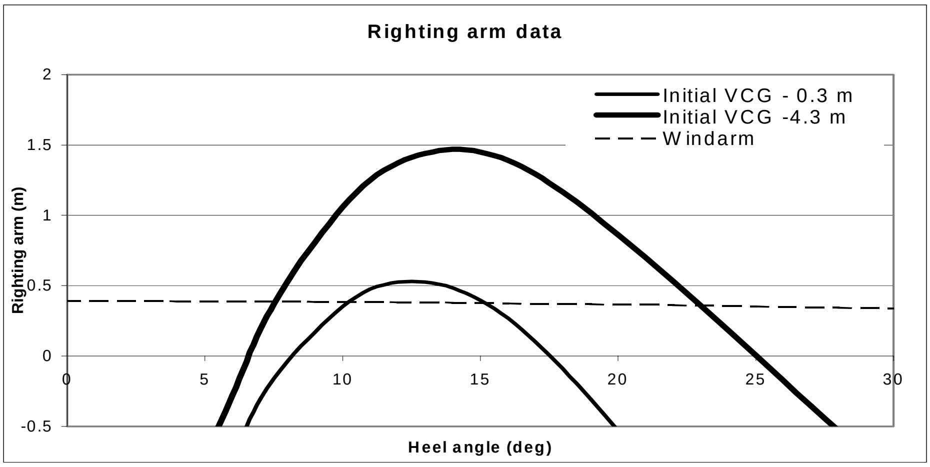


Figure 4.6 Righting arms for Case A1

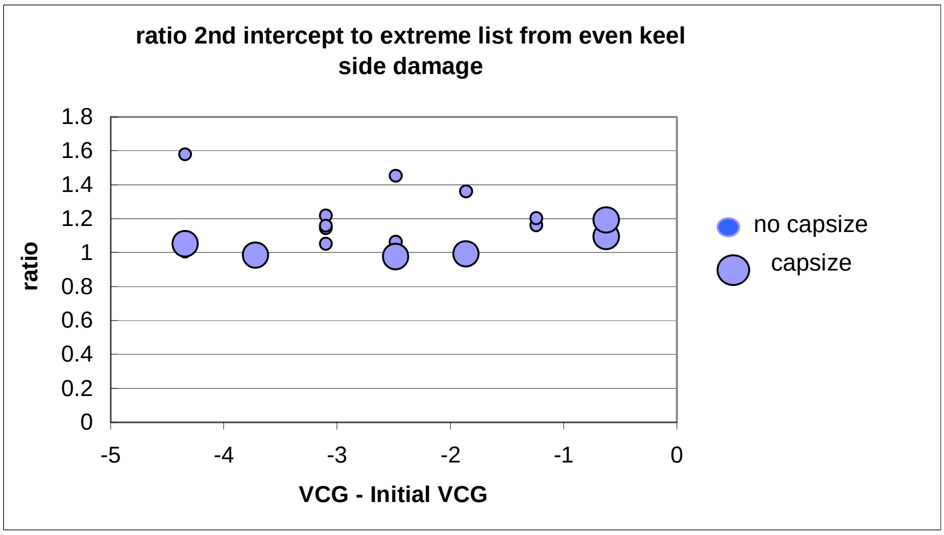


Figure 4.7 Ratio second intercept to extreme heel angle for side damage cases

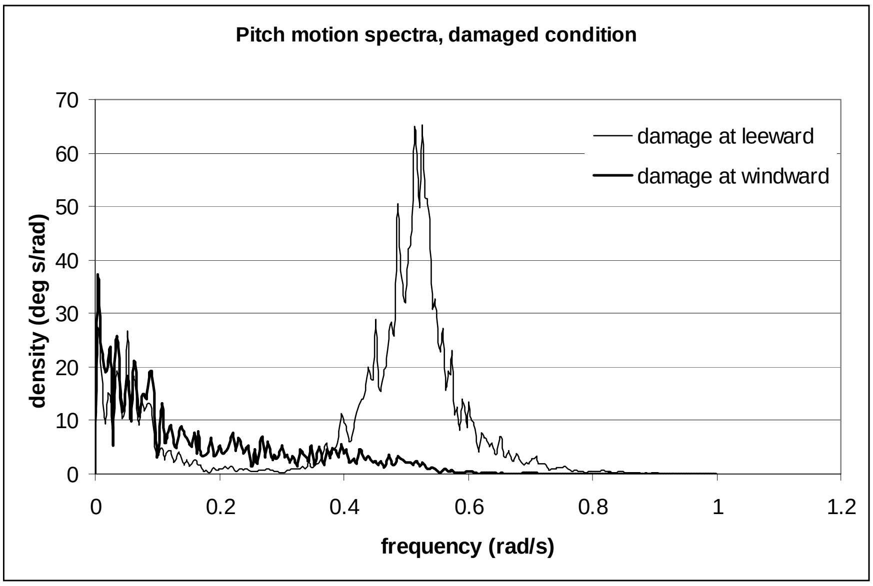
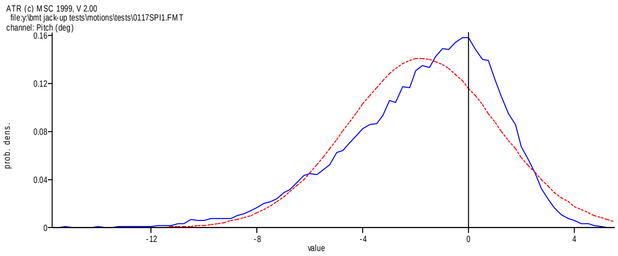


Figure 4.8 Pitch motion spectra for damage at leeward and at windward



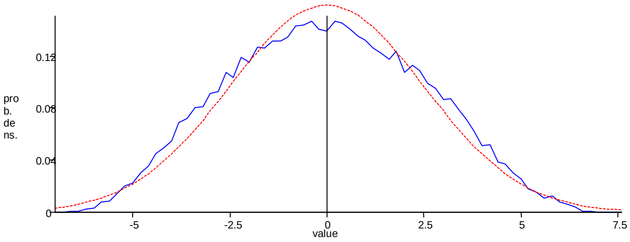


Figure 4.9-a Distribution total signal

Figure 4.9-b Distribution wave frequency part

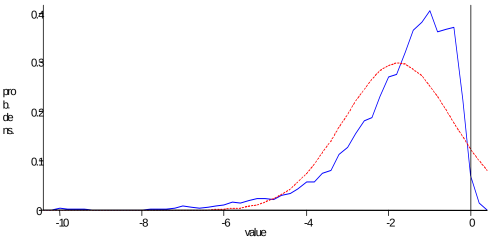


Figure 4.9-c Distribution low frequency part

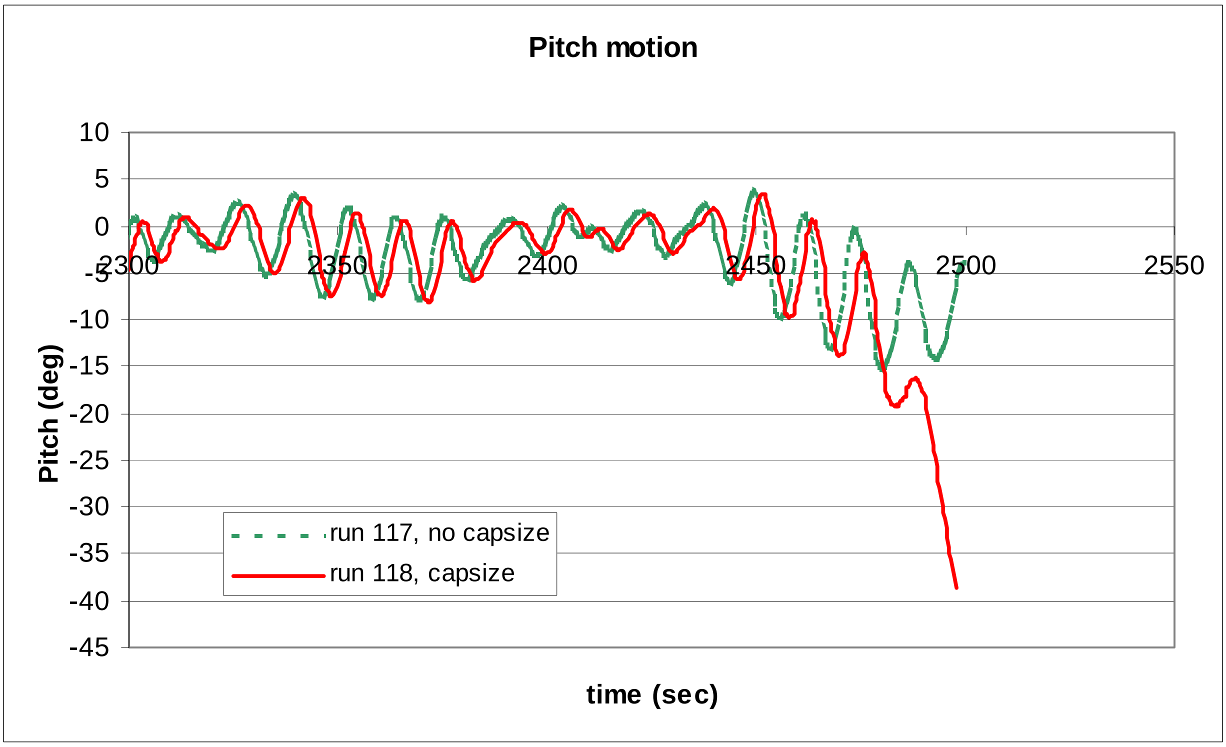


Figure 4.10 Pitch motion just before a capsize event

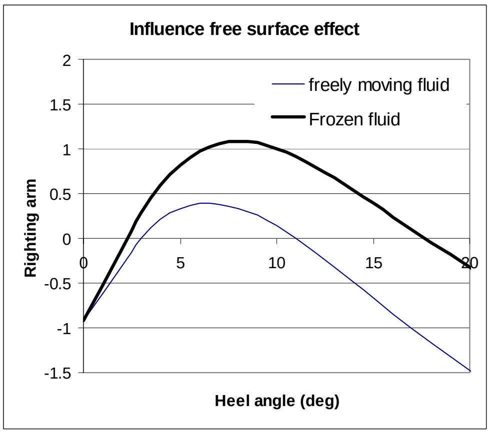


Figure 4.11 Case D2, influence of free surface effect on righting arm

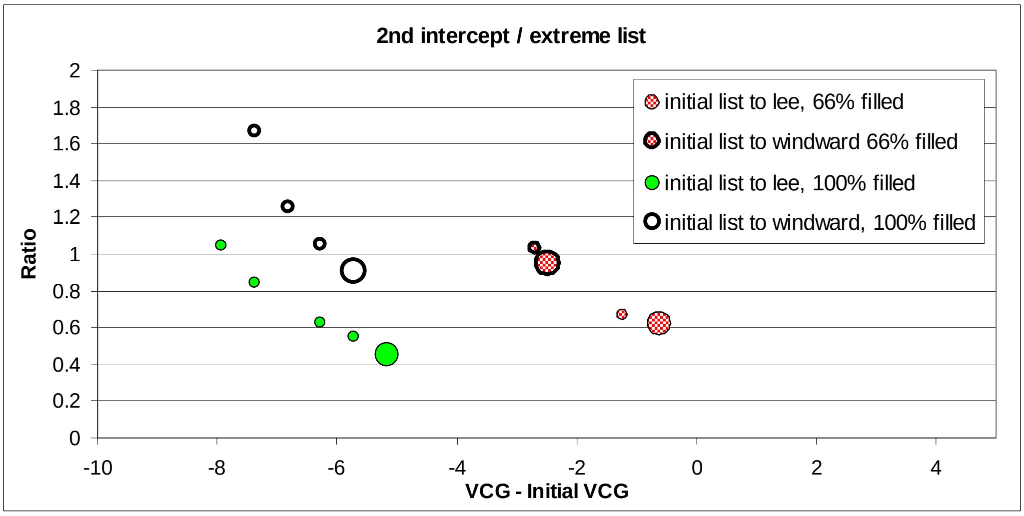


Figure 4.12 ratio second intercept to extreme heel angle, center filled cases

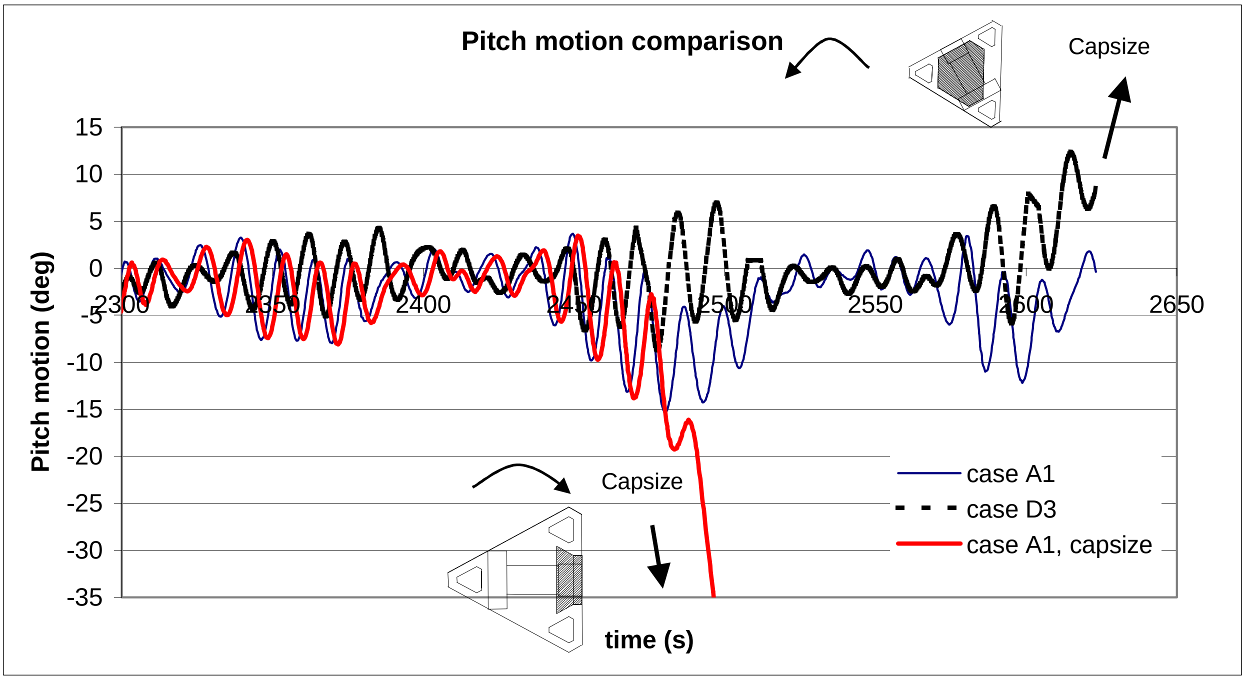


Figure 4.13 Comparison pitch motion just before a capsize event, case A1 en D3

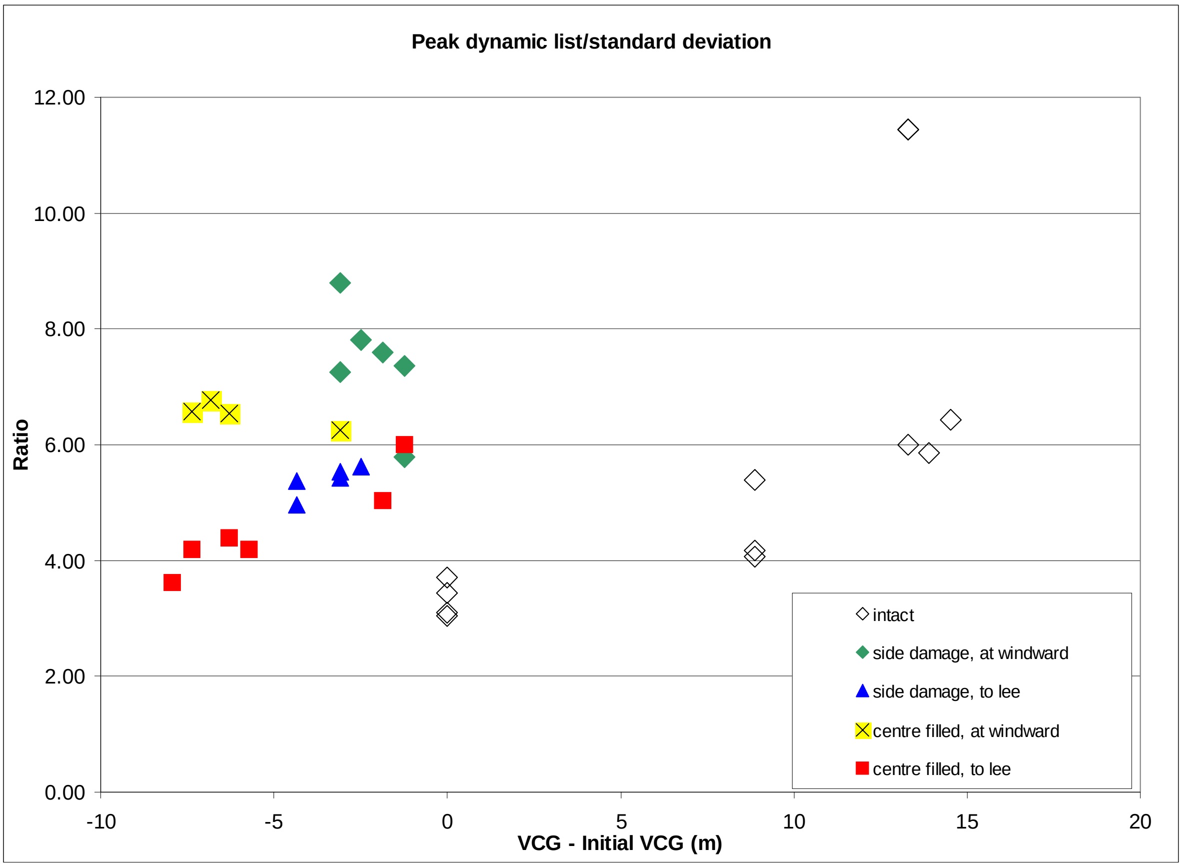


Figure 5.1 Ratio between extrme dynamic list angle and standard deviation