Roll Motion of Yachts at Anchor

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What is the problem?

Your clients invest considerable resource in acquiring a yacht which is luxurious and safe. Part of their dream is to be able to anchor in a secluded bay surrounded by nature with 5 star luxury on board. The reality can turn into a stomach churning nightmare if the vessel starts to roll - exit your next commission.
Roll motion is a nuisance on both motor yachts and sailing yachts for the following reasons:

- it causes sea sickness
- crew and passengers may fall and hurt themselves
- embarking and disembarking become difficult and possibly dangerous
- noise is generated through water slap on the hull and motion of inadequately secured objects
- some on board equipment will not perform adequately

All yachts roll to a greater or lesser extent when subject to waves. When the vessel is on passage and travelling at reasonable speed the roll motion can be controlled by the use of fin stabilisers. Roll motion reduction in excess of 40% is readily achievable using this well proven technology (Haywood et al. 1995). However, when the vessel is moving slowly or is at anchor, fin stabilisers do not work because they require water to flow over the foil at high speed in order to generate the roll-reducing forces. A different solution is required when the vessel is not moving through the water.

What influences rolling?

A rolling yacht has a natural frequency of roll, just like a pendulum. If you heel it over in calm water then let it go, it will oscillate at a set frequency. This frequency is called the natural frequency. If instead of just letting the yacht oscillate, you expose it to sequences of regular waves of various frequencies, the motion will be greatest in waves which have a frequency the same as the natural frequency of the yacht. The roll frequency may be calculated from :

$$f = \frac{1}{2\pi}\sqrt{\frac{gGM}{k^2(1+\sigma)}}$$

where:
f = natural roll frequency
k = roll gyradius (a measure of the mass inertia)
σ = added inertia coefficient
g = acceleration due to gravity
GM = transverse metacentric height

So the natural frequency of the yacht depends on the following:

- the transverse stability. A vessel with a large transverse metacentric height will have a higher natural frequency than an equivalent vessel with a low metacentric height. This is why most catamarans have a more rapid motion than monohulls.
- the roll mass moment of inertia of the yacht, AND the inertia of the water particles surrounding the yacht that are accelerated as a consequence of the yacht motion. This latter component is called the added inertia. A yacht with a large mass moment of inertia in roll will have a slower natural frequency than a yacht with a small inertia. So if there are large masses on board which are placed either at the maximum beam, or very high up or very low down, the roll inertia will be large and the frequency slow. The added inertia of the surrounding water is determined by the underwater shape of the vessel. A yacht with semicircular cross sections which rolls about the waterplane will have no added inertia - there is no way for the roll motion of a circular shape to accelerate the flow, because the shape in the water does not change with roll angle. A square section yacht will have a high added inertia, as water must be accelerated as the shape rolls through the water. A keel will also have a high added inertia as the water must accelerate round it as it rolls (Newman 1977), (Lloyd 1989).

How can roll be reduced?

Roll reduction goals

Whilst the most obvious way of reducing roll motion is to avoid anchoring in waves, most of the most attractive bays are, by nature of their geography, places where waves can work their way into, so there is no avoiding them. Many possible solutions are available and a few of them will be discussed here briefly. However, before investigating design solutions, we need to identify the two possible targets that such solutions must aim at - avoiding resonance and increasing damping. Avoiding resonance is achieved by making the natural roll frequency of the yacht as different as possible from the range of wave frequencies likely to be experienced. Damping is the opposition to roll motion. It does not affect the natural frequency, rather it determines the motion amplitude at that frequency.

Changes to mass inertia and GM

If a new design is to operate in known locations then it might be possible, in theory at least, to design it such that the natural frequency differs from the dominant wave frequencies in those locations. Revisiting equation 1 above to estimate the natural roll frequency, typical input values for a sailing yacht are:

k = 0.5 beam
$\sigma = 0.1$
GM = 1m

So a vessel with 8m beam would have a natural roll frequency of about 0.25Hz; unfortunately this is typical of the wave frequencies encountered in semi-sheltered bays. There is not a lot you can do to alter this, as the GM is usually strongly controlled by other criteria and the mass inertia is also controlled by the mass distribution and general arrangement. At first glance it might seem that the frequency could be increased by increasing the beam. However, GM increases as the square of the beam (approximately) so a wide yacht will in fact have a higher natural frequency. The added inertia can be changed by changing the hull shape, but the resulting change

in frequency is very small. e.g. doubling the added inertia coefficient typically only makes a 5% change in the natural roll frequency.
Note that the weight of the yacht does not enter into the equation; a heavier yacht will have the same roll frequency as a lighter yacht of equivalent shape and mass distribution. However, heavier yachts often do not require such a high GM and the extra mass tends to be in the extremes of the yacht (top, bottom and well outboard) leading to a higher gyradius. So a heavy yacht tends to have a longer roll frequency than a light one because of the gyradius and GM change, not simply because of the mass difference.

Flopper-stopper

A flopper stopper is similar in configuration to the smaller paravanes used by fishing boats. It consists of a hinged flat plate positioned horizontally below the surface well outboard of the yacht. The rig is held by, for example, a spinnaker pole braced athwartships. As the yacht rolls the flat plate absorbs energy by being pulled through the water. This creates a roll-opposing moment. As the yacht rolls back, the hinge allows the flat plate to fold and offer minimal resistance. This latter characteristic is employed to eliminate the complication of compressive loads in the bracing structure. It is common to rig a flopper stopper on each side of the yacht.
These devices should work, but preliminary full scale tests conducted by the author have not shown any measurable effect on roll motion (Klaka 2000). It would be foolish to write them off - more thorough tests are planned. One difficulty with flopper stoppers is the logistics of deploying them in the presence of a current; they tend to become unstable.

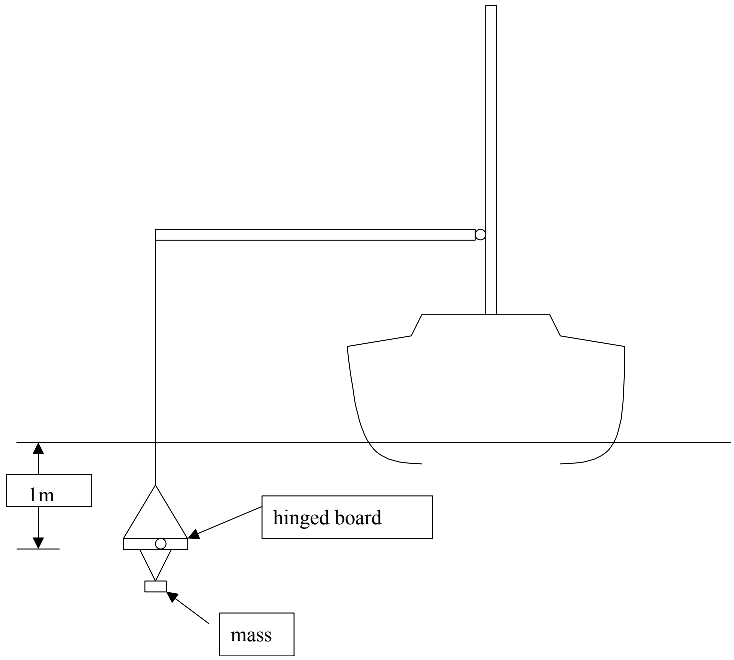

Figure 1 Flopper stopper setup

Anti-roll tank

This is a tank, usually filled with water, with shape tuned to yield a natural sloshing frequency close to the natural frequency of the yacht. The tank is configured so that the sloshing water is out of phase with the roll motion, thus generating an opposing roll moment. This can be very effective at wave frequencies matching the natural frequency of the tank, but is heavy, voluminous and can lead to stability problems. It can also be noisy.

Changes to hull underwater sections

The section shape will determine the section damping and added inertia coefficients. We are mainly concerned with damping here, as it has already been noted that the hull added inertia has comparatively little effect on motions.
Damping is generated by a number of mechanisms:

- the biggest contribution comes from generating vortices (large eddies) as the yacht rolls. Vortices are most easily generated at sharp edges e.g. chines, keels and rudders.
- the next most significant contribution comes from generating waves as the yacht rolls. A square or triangular section hull will generate some waves as it rolls; those waves require energy to exist, and the energy comes from the roll motion. So the bigger the generated waves, the more energy is being taken from the yacht, so the less energy is available to generate the roll motion. Circular section hulls do not generate waves as they roll provided the roll centre is in the waterplane (why should they? the shape in the water doesn't change with roll angle), so do not have any wave damping.
- there is also a damping contribution from the friction between the water and the rolling yacht, but this is usually so small it can be neglected.

Computer modelling carried out by the authors has demonstrated that, for a sailing yacht at least, the hull sections contribute little to the total damping, so there is little scope for improvement through this variable. However, if radical hull forms are permitted in the vessel specifications, there is scope for some innovative thinking here. For example, the use of chines, steps, winglets etc. could yield worthwhile improvements.
On motor yachts, the hull shape generates a higher proportion of the total damping, because the appendages are relatively small in area. However, the corollary of this is that motor yachts roll more because they don't have as much damping, so need a "bigger fix".

Additions or changes to keel or rudder

This is perhaps the design area of greatest flexibility with potentially greatest impact. More on this in a moment.

Steadying sails

These have similar potential to underwater appendages in terms of roll motion reduction. The challenge lies in maintaining effectiveness for all wind strengths without creating operational difficulties.

The tools required to arrive at a solution

There are numerous possible design solutions to reduction of roll motion, of varying degrees of complexity and effectiveness. In order to assess their effectiveness, scientific techniques must be used to generate the required data.

Full scale measurements in calm water.

It is difficult to calculate the natural frequency of a new design because the mass estimate does not usually include enough information for an accurate prediction of the roll mass moment of inertia - it makes for a very large spreadsheet which has to be customised for every design. The process can be much simplified if an existing similar design has had its roll motion characteristics measured afloat. This involves a simple quick experiment in calm water, similar to an inclining experiment (it is logistically simplest to conduct it at the same time as the inclining experiment). Just heel the yacht over a few degrees then let it go and time its natural frequency of oscillation. If a suitable roll motion sensor is available then valuable information on the roll damping can also be obtained (Klaka 2000). Using the existing design as a datum, the roll inertia for a new design can be calculated with reasonable accuracy. You now know what wave frequency you wish to avoid.

Computer modelling

In order to provide solutions to the rolly yacht problem a computer program was developed by the authors using equations that model the physics of the problem. The model is a non-linear time domain solution of the roll equation, with appendages modelled in horizontal strips (Klaka, Krokstad & Renilson 2001). It was originally developed as a tool for preliminary investigation of a much more in-depth investigation of roll motion. It uses a relatively simple approach and has been validated against both full scale measurements and scale model tests in an ocean wave basin .

Graphical description

It is appropriate at this stage to summarise the roll motion characteristics graphically:

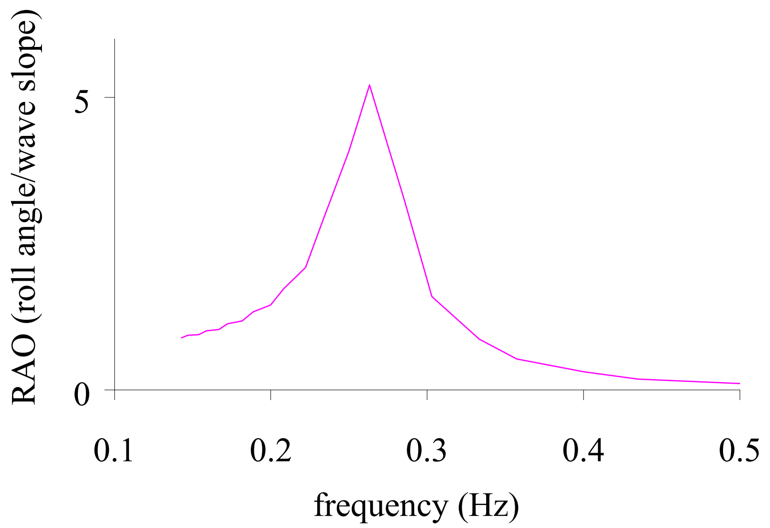

Figure 2 A typical RAO curve

The vertical axis is the roll angle (non-dimensionalised by dividing by wave slope) and the horizontal axis is wave frequency. The resonant peak is evident, its position determined by vessel inertia and transverse stability, whilst its height is determined by the amount of damping. This graph is much the same as for any object which experiences forced oscillation e.g the characteristics of flexible engine mounts or the flexure of a hull panel in waves. The graph is usually referred to as an RAO (Response Amplitude Operator) or transfer function.

Some general findings

Some interesting results have emerged from the work to date . Firstly, the computer program was validated against full scale trials on a sailing yacht (Klaka 2000). The yacht was anchored in a number of semi-sheltered bays at a range of angles to the dominant wave direction. The roll motion and the waves experienced were measured, with and without a steadying sail. The results agreed very well with those predicted by the simple computer model, as shown in Figure 3 and Figure 4

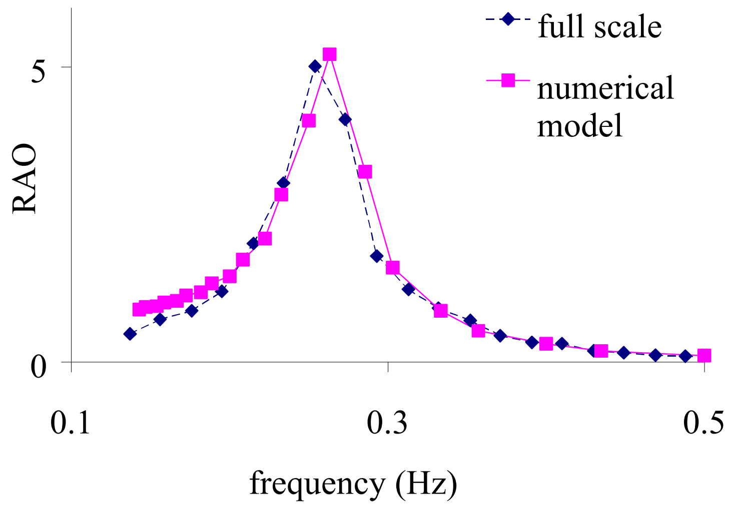

Figure 3 beam seas, no sail

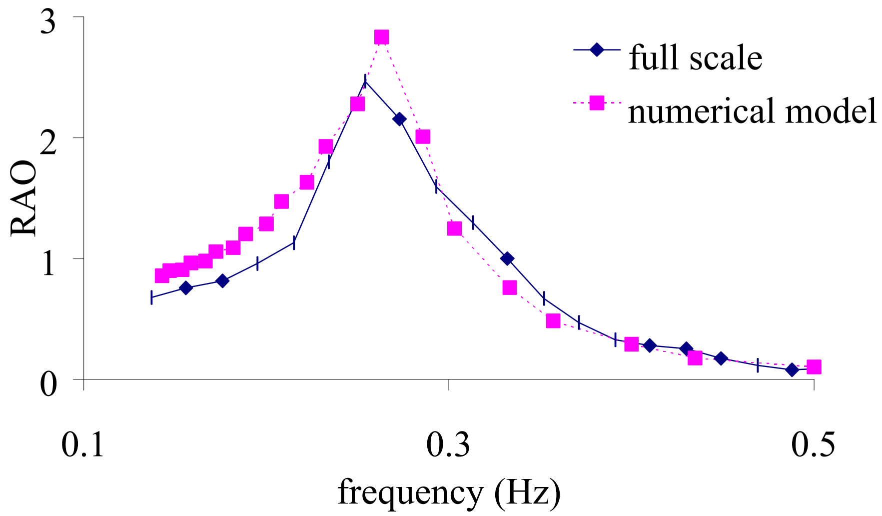

Figure 4 beam seas, sail hoisted

Secondly, the computer model having been validated it was run for a number of different appendage configurations - see Figure 5. The results show that the damping generated by the hull sections is negligible; the hydrodynamic damping is dominated by the keel and rudder. This is because the yacht sections are closer to a circle than a rectangle, so do not generate strong vortices. The keel and rudder, however, generate very large vortices and also contribute substantially to added inertia.
The hoisting of a sail increases the damping further, for the same reason that the keel and rudder increase the damping.

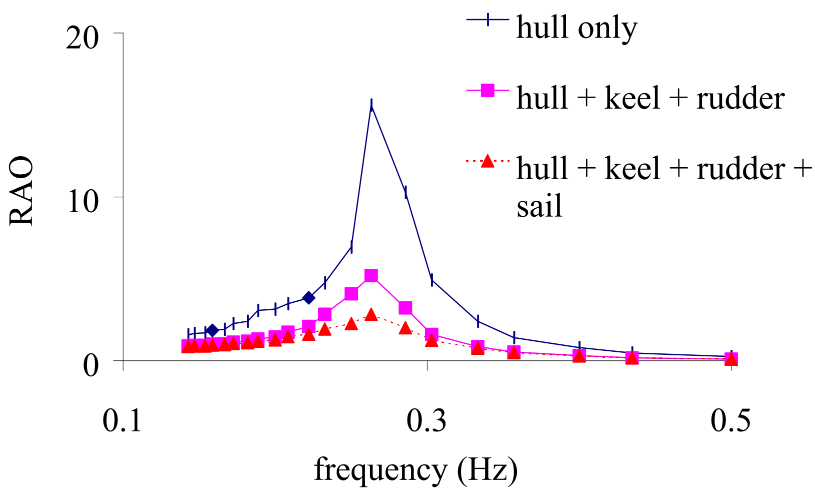

Figure 5 effect of keel, rudder and sail on roll - computer predictions

Having established that the appendages are a major influence, it was decided to conduct scale model experiments in the controlled environment of a wave basin, in order to gain a better understanding of the physics of the problem (Klaka 2001a). The scale model was not a realistic hull shape but one with minimal roll damping. The model was a 1.5m long cylindrical section hull form with changeable keel. Two different keels were tested over a range of wave frequencies, amplitudes and directions:

- a full depth flat plate keel of aspect ratio 1
- a half depth flat plate keel of aspect ratio 0.5

The tests were conducted such that the GM, displacement and mass moment of inertia in roll were kept the same for each keel configuration. Clearly, this is not what would happen with a real design, but it means that any changes in performance between the keels can be attributed solely to hydrodynamic effects.

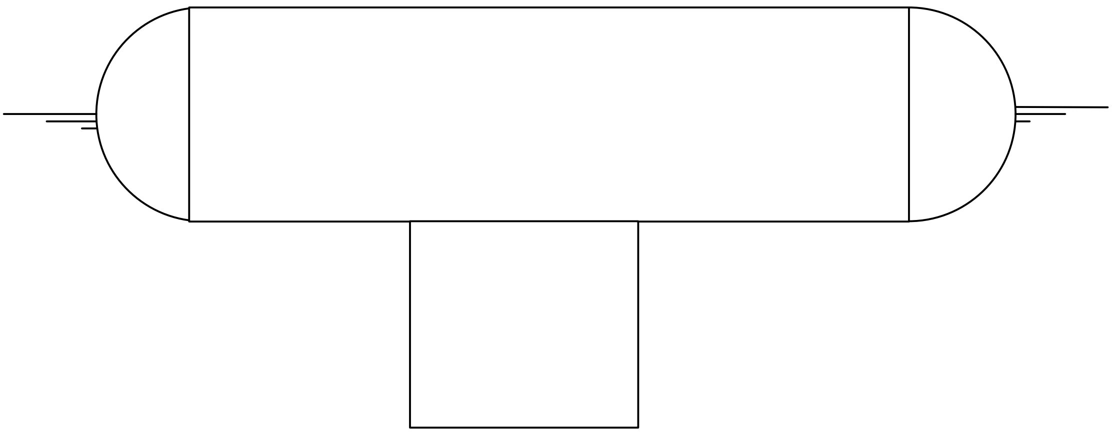

Figure 6 full depth keel

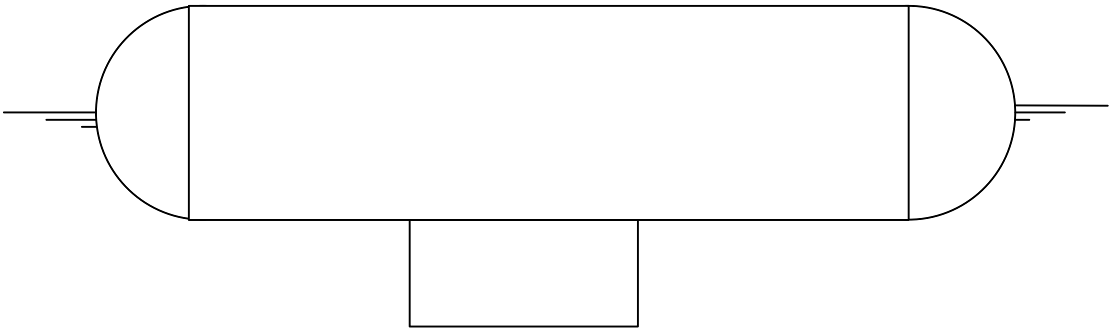

Figure 7 half depth keel

Note that the half depth keel was half the area of the full depth keel i.e. chord length was not changed. The results are shown below.

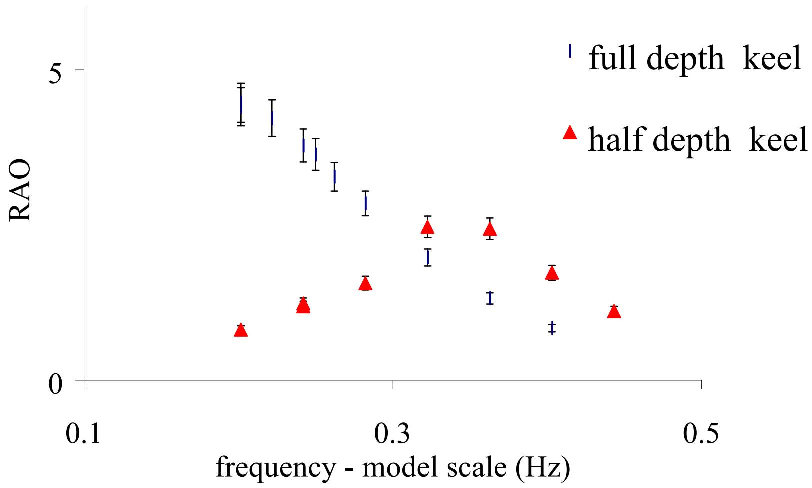

Figure 8 Effect of keel draft

It was observed that the half depth keel had less damping than the full depth keel, but there was also a change in the natural frequency. The natural frequency for the half depth keel was much higher than that for the full depth keel, because it had much less added inertia. This shift in natural frequency makes comparison of damping effect difficult - the RAO for the full depth keel is higher at low frequency partly because wave slope is lower for a given wave amplitude. Also, the wave force is of different magnitude at different frequencies.

So the appendages dominated the roll motion characteristics. The computer model was then run to replicate the experimental conditions. The absolute values of the motion were not as accurately predicted as for the full scale trials, but the output captured the comparative performance of the two keels very well.

What is the problem really?

Just when you thought we have finished, we need to go back to square one and make sure the proposed solution is solving the correct problem. All the discussion so far has assumed that the goal is to reduce the amplitude of the roll angles exhibited by the yacht. If the problems of roll motion listed in the first paragraph are revisited, it becomes evident that roll angle is not necessarily the correct metric. For example,

people tend to fall when on deck as a consequence of large lateral accelerations, rather than simply large roll angles. Motion sickness on the other hand is dominated by vertical accelerations, with the tolerance limit varying with the frequency of the motion (Lloyd 1989) and accelerations in sinusoidal motion are proportional to roll frequency squared. So in order to assess the design options fully, the roll motion must be calculated not simply in terms of roll angle, but in accelerations in various directions, and the spread of frequencies over which they occur. Fortunately most of this information is available once the vessel motions are known, it just requires a bit more processing of the predictions in order to get to the final results.
We must also consider the nature of the wave field. It is important to note that the RAO just defines the response of the vessel to each wave of a particular frequency over the range of frequencies in the horizontal axis. In order to calculate the roll of that vessel in a particular wave pattern we need an additional piece of information - a description of the waves experienced by the vessel. This is usually provided in the form of an energy spectrum

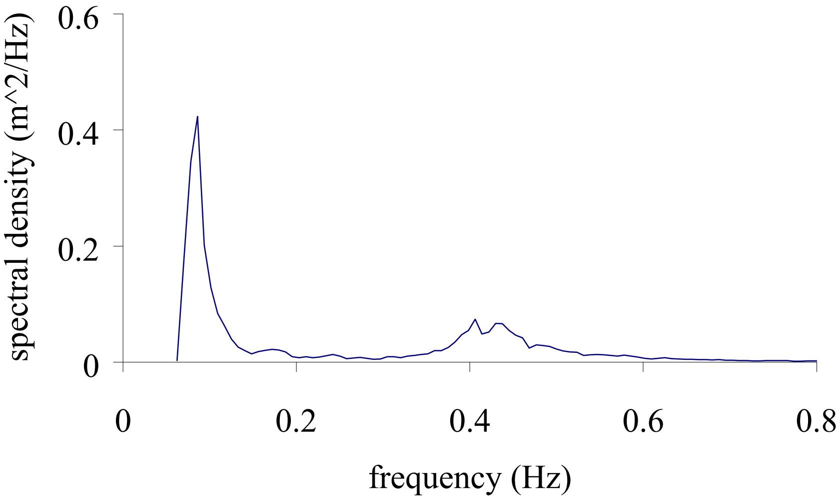

Figure 9 typical wave spectrum

Whilst a full explanation of this spectrum is complex (Tucker 1991), its significance can be summarised as follows:

- the horizontal axis is wave frequency, the same as in the RAO graph.
- the vertical ordinate is related to the wave amplitude at that wave frequency (strictly it is the wave energy spectral density).
- the area under the graph is proportional to the significant wave height of the total wave field (strictly it is the variance of the wave surface elevation). The significant wave height (the average of the one-third highest waves) is approximately 4 times the square root of the area under the wave spectrum.

In order to calculate the roll motion of the yacht in that wave field the vertical ordinates of the wave spectrum are multiplied by the ordinates of the RAO squared at the corresponding wave frequency, to yield a third and final graph, the roll motion spectrum. The area under this curve yields the significant roll motion amplitude, which is what we are really after - how much this yacht rolls in that particular wave field.
If, instead of the roll angle RAO, a vertical acceleration RAO is used in this process, then the area under the final spectrum represents the vertical acceleration rather than the roll angle. So a comprehensive analysis would result in a number of response

spectra for the yacht, covering motion amplitudes, velocities and accelerations in all directions over a range of wave conditions.

Conclusions

The Centre for Marine Science and Technology at Curtin University has developed a simple but effective computer model of roll motion for academic research investigations and applied it to practical design problems. It can provide useful predictions for designers. The effect of appendage design (fin keels, bilge keels, rudders, sails flopper stoppers etc.) on roll motion can be assessed for a range of circumstances. This capability can be used to optimise the design and/or operation of a yacht with a view to improving safety and comfort at anchor. Of course it is never quite such a simple process as that. It would be an impossibly difficult task to model all the physics accurately; simplifications and assumptions must be made in order to keep the task to a manageable size. That is why full scale validation is so important - to provide a reality check on the assumptions made in the program. Each application of the code requires slightly different assumptions and simplifications to be made, which must be tested by comparing with experimental results. As the code is developed, so confidence in its answers increases.

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