Seakeeping analysis for preliminary design

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Summary

Seakeeping performance is becoming of increasing importance. With fast computers and sophisticated software readily available to designers, it is now possible for a vessel's seakeeping characteristics to be addressed much earlier in the design spiral.

Regulatory bodies and operators are becoming increasingly aware of the importance of specifying seakeeping requirements which the vessel must meet. The software tools described in this paper will help designers address these issues.

This paper gives a brief overview of what analysis techniques are available and gives a simple example of how the seakeeping performance of alternative designs may be compared.

Introduction

In recent years, greater attention has been given to vessels' seakeeping characteristics. This is due to a number of factors: proliferation of high-speed semi-displacement passenger vessels; increasing demand for passenger comfort (passengers are often able to vote with their feet by taking alternative transport, e.g. English Channel Tunnel); deployment of increasingly sophisticated systems on ever smaller naval vessels (Hunt 1999); greater pressure from regulatory bodies and the broader public for safer vessels; staggering advancements in desktop computer power; and developments in prediction and analysis tools.

The birth of modern seakeeping analysis was in the mid 20th Century as demonstrated by the landmark papers of Ursell (1949a,b), and St Denis and Pierson (1953). Continual refinements of analysis methods and mathematical techniques, combined with the availability of high performance desktop computers in the late 20th Century has made routine seakeeping analysis possible in all design offices. Analysis of a vessel's seakeeping characteristics can now take its rightful place in the overall design spiral — how often is the ocean's surface flat?

Seakeeping analysis is a much more difficult problem compared with that of calm water resistance, and until fairly recently it has taken a very poor second place in preliminary hydrodynamic design for the majority of vessels. This is particularly true in the merchant fleet, the vessel's seakeeping performance being addressed relatively late in the design spiral by means of expensive model tests. In fact, a vessel's seakeeping characteristics depend on so many interrelating factors that it is virtually impossible to say what will happen if a specific change is made to the hullform without doing reasonably detailed analysis. This is because the answer depends not only on the hullform but also on the wave conditions and the criteria against which the vessel is being assessed. Thankfully, designers now have several seakeeping tools to choose from, which are ideal for preliminary design. With these tools, a large number of design candidates may be easily and quickly compared and the best selected. Seakeeping computer programs are sophisticated enough and computers now powerful enough for a potential design to be analysed in a matter of minutes; such an assessment could not be achieved in a towing tank.

High speed craft

As the speed of vessels increases, their seakeeping becomes more important; this is especially true in the rapidly growing sector of high speed passenger vessels. Higher speeds and lighter vessels are likely to result in larger relative motions and accelerations; important issues which must be addressed (Molland and Taunton 1999).

In general there is a demand for increased performance, this tended to be speed and endurance, but now many tenders also specifically address seakeeping requirements. This has been demonstrated by the large seakeeping budget spent on the development of the Stena HSS. However, for most smaller projects, this level of investment is not feasible, especially in the early stages of the design spiral or when bidding for tenders.

Naval vessels

World navies are wanting to put more sophisticated systems onto smaller, faster vessels. Smaller vessels are more susceptible to ocean waves and hence optimisation for seakeeping performance is of greater importance. Naval vessels are increasingly optimised for seakeeping, although calm water performance is also carefully considered (Hunt 1999).

Although the seakeeping requirements for naval vessels may be quite different from those of high-speed passenger vessels, the analysis tools and techniques required are the same.

The problem

Seakeeping analysis is essentially a three part problem:

1. Estimation of the likely environmental conditions to be encountered by the vessel.
2. Prediction of the response characteristics of the vessel.
3. Specification of the criteria used to assess the vessel's seakeeping behaviour. This also defines the way in which the performance of different vessels is compared.

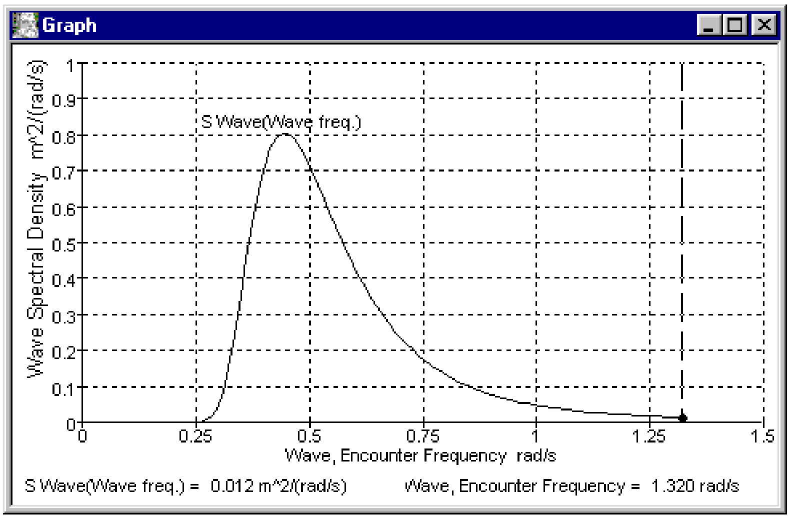
Comparison of different designs or assessment of a single design against specified criteria is dependent on accurate information for all three items listed above. Evaluation of seakeeping performance depends heavily on the environment (wave spectra) that the vessels are being subjected to and the criteria which are being used to compare the designs. This is one of the reasons why comparing seakeeping performance is much more complicated than comparing calm water resistance or power requirements to achieve a specific speed.

With appropriate analysis, it is possible to optimise a hullform for specific routes (and the sea conditions that the vessel is likely to encounter on these routes) and the characteristics which are important to the successful completion of the vessel's mission. For instance, a cargo vessel might be optimised to reduce added resistance; a passenger vessel may be optimised for passenger comfort and a naval vessel could be optimised to minimise motion on the helicopter deck. Each part of the problem, environment, vessel response and criteria, is of equal importance; however, perhaps the third is the least well understood and requires careful consideration.

Sea Conditions

Representation of ocean waves

When observing the ocean's surface, one sees a procession of seemingly random waves. The variation in surface elevation over time makes up what is referred to as a time series. For practical analysis it is usual practice to convert this time series to a frequency domain, or spectral, representation of the same data. The wave spectrum is much more useful for assessing the vessel's performance than the time series data. Naval architects have developed mathematical expressions known as idealised wave spectra. These describe the distribution of wave energy with frequency for a specified wave height and period. There are many different idealised wave spectrum formulations, two of the most commonly used are the ITTC and JONSWAP spectra. A typical idealised wave spectrum is shown in Figure 1. The wave spectrum and time series data are two ways of describing the same ocean waves. Essentially the wave spectrum implies that the "random" ocean waves can be represented by very many regular wave trains of different amplitude and period, superimposed on one another.



S Wave(Wave freq.) = 0.012 m^2/(rad/s)   Wave, Encounter Frequency = 1.320 rad/s

Figure 1: Typical idealised wave spectrum

Some of the key characteristics which describe a wave spectrum are defined below:

Zero crossing period (T_z)	The period between successive upwards or downwards zero crossings of the wave time series.
Modal period (T_0)	The most frequently occurring wave period.
Significant wave height ($H_{1/3}$)	The mean value of the highest one third of wave height measurements.
Variance of the wavy surface compared to the mean. (m_0)	The total area under the wave spectrum curve. This is equal to the variance of the time signal.
RMS	Another measure of the "average" wave elevation.

Ocean wave statistics

Over the years, statistical data regarding the likely occurrence of different sea states in the world's oceans at different times of the year have been accumulated. These data may be found in Hogben and Lumb (1967) and Hogben et al (1986). These data have been collated from observations and wave buoy measurements; with increasing satellite technology it is likely that these data will become even more detailed.

These data are normally presented in the form of a scatter diagram. This is a matrix which describes the probability of a sea state occurring of specified significant wave height and characteristic period, in a given sea area, in a specified direction, at a given time of year. See Table 1 for a typical example.

Table 1: Wave height and period statistics (after Hogben and Lumb 1967)

Area 9; December to February; North West; Percentage of observations = 11.28%

Total	0	1	10	73	210	286	236	120	50	14	0	1000
> 14												0
13 - 14								1	1			2
12 - 13							1	1	1			3
11 - 12							1	2	1	1		5
10 - 11						1	2	2	2	1		8
9 - 10						2	4	4	2	1		13
8 - 9					1	3	6	7	4	1		22
7 - 8					2	6	11	10	5	2		36
6 - 7					4	12	19	14	8	2		59
5 - 6				1	8	24	31	22	8	2		96
4 - 5				2	17	43	44	25	8	2		141
3 - 4				6	37	66	53	14	6	1		183
2 - 3			1	16	63	76	46	14	3	1		220
1 -2			4	33	66	49	17	4	1			174
0 - 1		1	5	15	12	4	1					38
	< 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	> 13	Total

Significant wave height [m]

Zero Crossing Period [s]

The idealised spectrum model and the global wave statistics data describe the sea conditions to be expected by the vessel. The next step is to predict how the vessel will respond to these conditions.

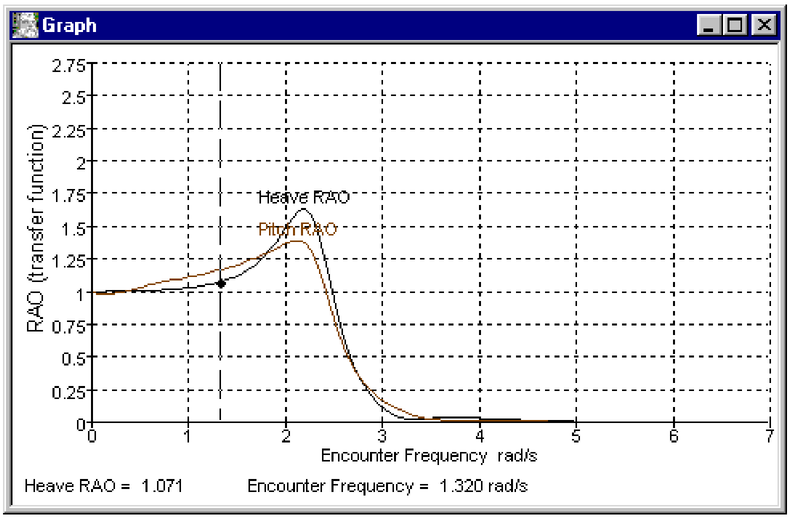
Ship response

In its simplest form, the vessel may be considered like an electronic filter. It takes an input signal (the ocean waves), filters it, and then produces an output (the vessel motions). In most cases, this simple method is quite valid, and produces useful results.

The vessel's filter function or Response Amplitude Operators (RAOs) are different for the six, rigid-body, degrees of freedom (surge, sway, heave, roll, pitch and yaw). Each motion has its own characteristics and RAO. The vessel's response in each of the degrees of freedom is simply obtained by passing the input signal (wave spectrum) through the filter (RAO) to get the output motion spectrum.

In general all the motions influence all the other motions, for example: consider the vessel moving vertically up and down in heave, if the centre of floatation is not directly above the centre of buoyancy, then the vertical heave motion will initiate a pitch motion and vice versa. This phenomenon is known as coupling. In practice, for symmetrical vessels, many of these coupling effects can be neglected (being zero or very small). It is generally considered normal practice to couple the vertical plane motions of heave and pitch and then to consider separately the coupled motions of sway, roll and yaw. Surge is normally neglected.

Typical heave and pitch RAOs, in head seas, are shown in Figure 2.



Heave RAO = 1.071   Encounter Frequency = 1.320 rad/s

Figure 2: Typical heave and pitch RAOs in head seas

The RAOs shown in Figure 2 show the typical shape: at low frequency (long wavelength), the vessel follows the wave profile, riding up and down on them like a cork, hence the RAOs tend to unity. At the high frequency end of the scale (very short wavelength), there are so many waves along the length of the hull that their net effects cancel out and the vessel is unaffected by the waves. Somewhere in between these extremes, there is normally a resonant peak. This peak occurs at the natural frequency of the vessel. At resonance, the vessel motion can be several times that of the wave; the height of the peak depends on the damping of that motion. Motions such as heave and pitch are relatively highly damped, especially when compared with roll.

There are a number of ways of estimating the vessel's RAOs: prior experience, tank tests, numerical simulation. The use of numerical models for predicting a vessel's response is very useful, since it provides a cheap means of assessing a large number of design alternatives early in the design spiral. Once the design has converged to one or two alternatives, these can then be tank tested if a higher degree of certainty is required.

Numerical methods for predicting vessel RAOs

These can be broken down into two main groups: time domain and frequency domain.

Time domain methods model the wave passing the hull. At small incremental steps in time, the instantaneous net force on the hull is computed by integrating the water pressure and frictional forces on each part of the hull. Using Newton's Second Law, the acceleration on the hull is computed, this is then integrated over the time step to compute the new vessel velocity and position. Although this procedure sounds relatively straightforward, these methods are still under development in universities and other research establishments and are not routinely used by commercial naval architects. The main problems occur in being able to accurately predict the hydrodynamic forces acting on the hull and the fast computers (even by today's standards) required to run the programs.

Frequency domain methods are simpler and less computationally intensive. Most of these methods use strip theory (Salvesen et al 1970). Basically the vessel's motions are treated as forced, damped, low amplitude sinusoidal motions. Strip theory has many simplifying assumptions, yet is fast and able to produce good results for a wide variety of seakeeping problems. The two main limitations are that vessels must be sufficiently slender (high length to beam ratio) and that the Froude number must not be too high.

Strip theory involves dividing the vessel into a number of transverse sections. Then the hydrodynamic properties of these sections are computed, assuming 2D inviscid flow, with no interference from upstream sections. From these values, the coefficients in the equations of motion may be found and this, in turn, yields the vessel's response to the waves.

The main difference between frequency and time domain methods is that for frequency domain methods, the response for a particular frequency is calculated in one step, whereas time domain methods require many thousands of time steps before a regular periodic response is achieved. Hence time domain methods require several orders of magnitude more computing resource than frequency domain methods.

Choice of seakeeping software

As has been mentioned above, there are two main analysis methods: time domain and frequency domain. The majority of commercially available software use frequency domain strip theory. The main differentiating factors between the software are: ease of use, integration with other design software and the level of post-processing available; the cost of the software tends to vary accordingly. Due to their relative cheapness (compared with tank testing) and speed, these strip theory programs are excellent for preliminary design work, or where the size of the project or vessel requirements do not warrant detailed seakeeping analysis. Numerical techniques, such as these, are excellent for comparative analysis but sometimes need correlation with previous tank or full scale data to obtain absolute measures of seakeeping performance. One of the main drawbacks with many seakeeping programs is their lack of user friendliness and onerous geometry preparation. Formation Design Systems offers the *Seakeeper* seakeeping program which integrates into its Maxsurf design and analysis suite. As with the other programs in the suite, *Seakeeper* shares the same graphical user interface as Maxsurf and reads the Maxsurf geometry file directly.

Motions criteria

These are acceptable levels of motions, accelerations or other events which can occur without affecting the vessel's mission. Such criteria may be accelerations, relative motions, relative velocities, slamming, propeller emergence, deck wetness, motion sickness incidence, motion induced interruptions etc. The statistical nature of the analysis allows the calculation of probabilities of these criteria being exceeded (or occurrences per hour). These data can then be used as a meaningful comparison of different vessels and to decide whether a vessel can operate under the specified conditions.

Motions criteria are essential if designs are to be compared. Operators need to be more informed as to what they require, so that these values can be specified in the contract. IMO are also moving towards the specification of acceptable criteria in changes being made to the HSC code.

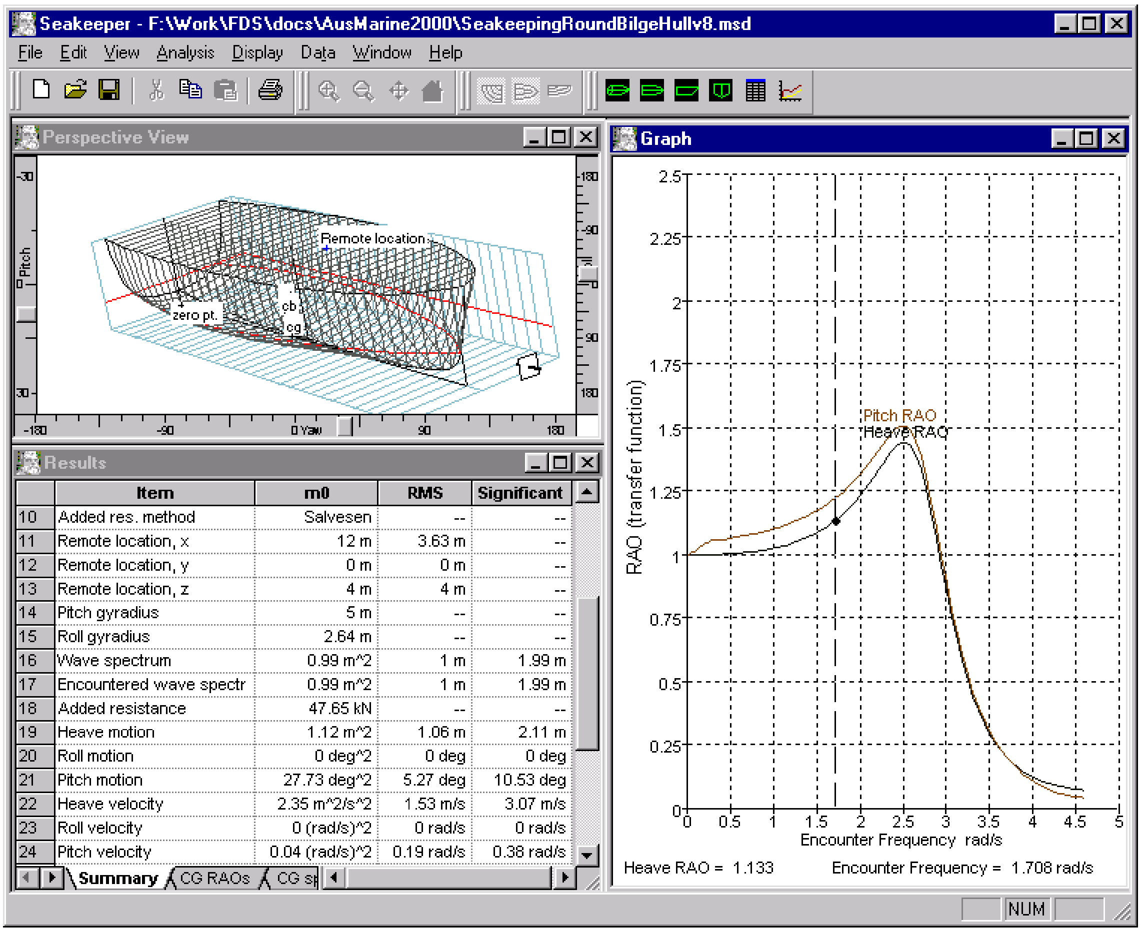
Motions criteria may also be used to determine limiting sea conditions for operability. Combined with data for the expected sea conditions on a particular route (e.g. Table 1), motions criteria may be used to predict down time, which may be used for economic evaluation of the design.

Motions criteria are discussed in various publications, e.g.: Molland and Taunton (1999); Hunt (1999); Jullumstrø et al (1999); ABCD working group on human performance at sea (1995); BS 6841 (1987) and ISO 2631/3 (1985); Lloyd (1989); Lewis (1989).

Worked example

The seakeeping properties of two designs for a 55 tonne displacement, 19m waterline length vessel are compared. The main difference in the vessels is that one is a hard chine design whilst the other is a round bilge design. Calculations were made at 12kts, in head seas, in an ITTC wave spectrum with significant wave height of 3m and zero crossing period of 7s.

This analysis was carried out using Formation Design Systems' *Seakeeper* program (pictured in Figure 3). *Seakeeper* forms part of the *Maxsurf* suite of design and analysis software.



	Item	m0	RMS	Significant
10	Added res. method	Salvesen	--	--
11	Remote location, x	12 m	3.63 m	--
12	Remote location, y	0 m	0 m	--
13	Remote location, z	4 m	4 m	--
14	Pitch gyradius	5 m	--	--
15	Roll gyradius	2.64 m	--	--
16	Wave spectrum	0.99 m^2	1 m	1.99 m
17	Encountered wave spectr	0.99 m^2	1 m	1.99 m
18	Added resistance	47.65 kN	--	--
19	Heave motion	1.12 m^2	1.06 m	2.11 m
20	Roll motion	0 deg^2	0 deg	0 deg
21	Pitch motion	27.73 deg^2	5.27 deg	10.53 deg
22	Heave velocity	2.35 m^2/s^2	1.53 m/s	3.07 m/s
23	Roll velocity	0 (rad/s)^2	0 rad/s	0 rad/s
24	Pitch velocity	0.04 (rad/s)^2	0.19 rad/s	0.38 rad/s

Heave RAO = 1.133
Encounter Frequency = 1.708 rad/s

Figure 3: Typical screen shot from Formation Design Systems' *Seakeeper* program

As has been mentioned, the starting point for most seakeeping analysis is the calculation of the vessels' RAOs. The computed RAOs for the two vessels for heave and pitch are compared in Figures 4 and 5. In these figures, it may be seen that the RAOs for the round bilge hullform are slightly higher than those of the chine hullform. However, it is necessary to calculate the actual seakeeping characteristics of interest in the expected sea conditions to decide which hull is the better option. The motion sickness incidence MSI is plotted in Figure 6; here it may be seen that both vessels would have a little less than 20% MSI after 2 hours. For a passenger vessel, on a 2 hour route this would probably be considered too high. However, this level of MSI could be acceptable on a shorter route or for other types of vessel, e.g. patrol boat. A number of seakeeping characteristics, which readily give a comparison of the two designs, are shown in Table 2. The final selection of the best hullform would depend on the acceptable operational levels of these events.

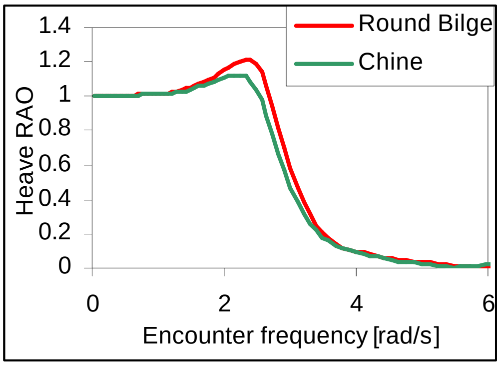


Figure 4: Comparison of heave RAOs

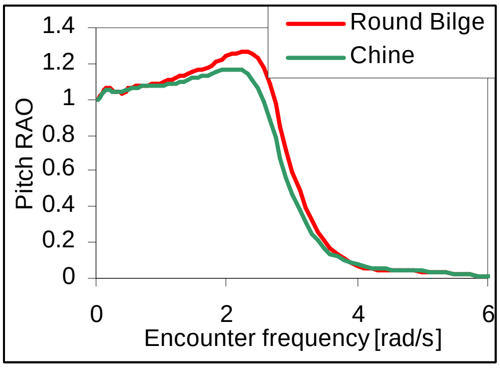


Figure 5: Comparison of pitch RAOs

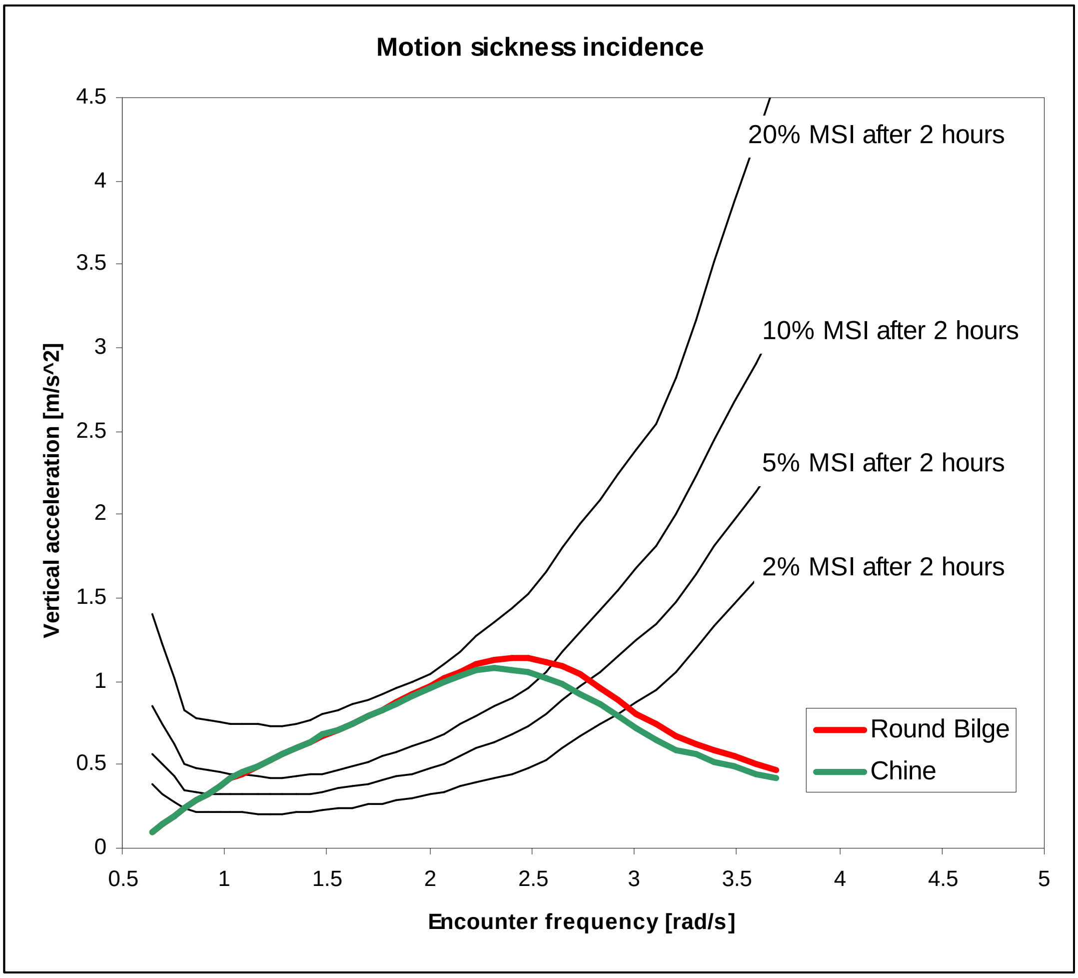


Figure 6: Comparison of MSI

Table 2: Summary of seakeeping performance

Vessel motions: 12kts; head seas; ITTC $H_{1/3}$=3m; T_z=7s	Chine	Round Bilge
MSI at bridge Propeller emergence Deck wetness Slamming Calm water resistance Added resistance	approx. 20% after 2hrs 0.0% (0.0 per hr) 0.0% (0.0 per hr) 0.4% (1.9 per hr) 30.1 kN 30.5 kN	approx. 20% after 2hrs 0.5% (2.5 per hr) 0.0% (0.0 per hr) 0.0% (0.0 per hr) 30.3 kN 27.5 kN

Conclusions

Regulations

The issue of seakeeping performance, in particular with regard to the safe operation of vessels, is being addressed by regulatory bodies, operators and the general public and this area of naval architecture will continue to receive increased attention. Already some requirements for acceptable acceleration limits are specified in the IMO HSC Code (Annex 3); one can expect to see further development of seakeeping regulations from bodies such as IMO.

This development is most likely to be in the form of performance based (numerical prediction, model test) criteria as opposed to prescriptive criteria based on statistical analysis of casualties. It is likely that other techniques such as formal safety assessments (FSA) will be also applied to the evaluation of seakeeping performance.

The effects of seakeeping on stability and analysis of dynamic stability (accounting for motions due to waves when assessing vessel stability rather than simply still water or quasi-still water hydrostatic stability) is also becoming more important; this was a heavily debated issue during the STAB 2000 conference earlier this year.

There is a requirement for the specification of standard sets of seakeeping criteria for different vessel operations and the development of methods for verifying that they have been met during acceptance trials.

Jullumstrø et al (1999) foresee more use of theoretical methods in conjunction with model tests and full scale trials in order to meet the demands of regulatory bodies and the use of systematic design standards which will address factors including seakeeping.

Numerical methods in preliminary design

Relatively simple, strip theory, motion prediction software can be used to rapidly optimise hullforms for seakeeping. Optimised hulls can have significantly better performance and seakeeping can now be addressed earlier in the design process. It is no longer acceptable to put it in the "too hard basket".

"Numerical prediction software enables seakeeping analysis to be performed with good confidence, even at high sea states across the full operational speed range. This is substantiated by the comparison of the predicted and measured Leander frigate data." – Hunt (1999), in regard to the application of strip theory methods to the design of small naval warships.

Continued development

Strip theory is an excellent tool for preliminary design or where the scale of the project or operation of the vessel does not warrant in depth seakeeping analysis. This is due to its speed and cost effectiveness. Simple seakeeping analysis using inexpensive strip theory methods should become part of the day-to-day design work of all naval architects. Where seakeeping performance is critical, large scale model tests, more sophisticated numerical modelling and correlation with full-scale trials data should be used.

Numerical prediction tools for seakeeping have not yet reached the stage where they can reliably predict absolute motions data with the accuracy of large scale model tests. However, they are very useful for comparative analysis, particularly in initial design where seakeeping performance would perhaps otherwise be virtually ignored due to constraints of time and budget.

For developments to be made to numerical and model testing techniques, correlation with the results of full scale trials is essential.

Operators need to develop a better understanding of what seakeeping criteria are critical to the successful operation of their vessels. These criteria should be specified in the design contract and measured during acceptance trials in a similar way in which other design targets such as vessel speed etc. are currently specified.

Acknowledgement

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References and Bibliography

ABCD working group on human performance at sea, (1995). Generating and using human performance simulation data to guide designers and operators of navy ships: Two large multinational programmes. In *International conference on Seakeeping and Weather*. London, England.

BS 6841 (1987). *Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.* British Standards Institute, BS 6841.

Hogben, N. and Lumb, F. (1967). *Ocean Wave Statistics.* HMSO. UK.

Hogben, N., Dacunaj, N.M.C. and Olliver, G.F. (1986) *Global Wave Statistics.* British Marine Technology Ltd. Feltham, U.K.

Hunt, S. (1999). Comparison of experimental and analytical methods for optimisation of seakeeping hullforms. In *Hydrodynamics of High Speed Craft.* RINA Conference, London, UK.

ISO 2631/3 (1985).Evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0.1-0.63 Hz. *Evaluation of human exposure to whole-body vibration - Part 3.* International Organisation for Standardisation, ISO Report 2631/3.

Jullumstrø, E., Berge, S.P., Rambech, H.J. and Fathi, D.E. (1999). *Design and operational aspects of high speed semi-planing and planing craft.* RINA Conference, London, UK.

Lewis, E.V.(Editor), (1989). Principles of Naval Architecture, Volume III. - Motions in waves and controllability. The Society of Naval Architects and Marine Engineers.

Lloyd, A.R.J.M., (1989). Seakeeping: Ship behaviour in rough weather. Ellis Horwood Series in Marine Technology. (Recently re-published by the author and available through RINA)

Molland, A.F. and Taunton, D.J. (1999) Methods for assessing the seakeeping performance of competing high speed vessel designs. In *Hydrodynamics of High Speed Craft.* RINA Conference, London, UK.

St Denis, M. and Pierson, W.J. (1953) On the motions of ships in confused seas. *Transactions of the Society of Naval Architects and Marine Engineers.*

Salvesen, N., Tuck, O.E. and Faltinsen, O., (1970). Ship motions and sea loads. Transactions, Society of Naval Architects and Marine Engineers, No. 78, pp250-287.

Ursell, F. (1949a). On the heaving motion of a circular cylinder in the surface of a fluid. *Quart. J. Mech. Appl. Math*., 2, 218-231

Ursell, F. (1949b). On the rolling motion of a circular cylinder in the surface of a fluid. *Quart. J. Mech. Appl. Math*., 2, 335-353

Biography

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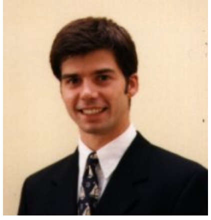

Patrick Couser graduated from the University of Southampton in 1990 with a Masters degree in Naval Architecture; in 1996 he completed his PhD in the field of high-speed catamaran resistance and seakeeping. During a varied employment history, he has worked for a number of companies in the marine and IT sectors. He now works for Formation Design Systems as a Naval Architect / Software Engineer. His current interests lie in the fields of high-speed commercial catamarans, computational methods and yacht technology.