MONITORING WAVE ENVIRONMENT AND SHIP RESPONSE

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SUMMARY

This papers covers the summer 2001 state of the art on the possibilities of environment monitoring and coupling of the measured data with ship response models. The operational relevance and use of monitoring systems is discussed. For this purpose the paper reviews the methods to model waves, focuses on wave sensors and describes methods to calculate ship response to waves.

NOMENCLATURE

ω	Circular frequency
ρ	Density of water
β	Wave direction relative to ships heading
ζ	Wave surface elevation

1. INTRODUCTION

All vessels and structures operating in the marine environment are subject to actions of waves, wind and current. Merchant shipping, yachting, dredging, fishery, and offshore, heavy transport and cable laying industries have a quit different approach to handle and deal with wave loads. Depending on the affected operational parameters, the attention is focused on various issues. Some of these are:

- Extreme motion and acceleration levels, crew discomfort, cargo damage, workability, operability.
- Relative wave motions, slamming, whipping and springing, side shell fatigue, wave bending moments.
- Green water structural- and cargo- damage.
- Ultimate stability issues, capsizing, parametric roll.
- Manoeuvrability.
- Mooring and structural dynamics.

Standing in the wheelhouse of a particular ship there is nothing much that can be done to the wave environment itself. It is however useful to be able to recognise particular effects in the sea state, before they are experienced in the response of the structure as mentioned above. Crews might be able to change the operational parameters of the vessel e.g. heading and speed in order to avoid damage before it occurs.

In this paper the outline of advisory systems will be discussed. For this the mathematical representation of a sea state will be described briefly. Also the behaviour of ships in waves will be discussed. Several types of sensors available for measuring the sea state parameters will be discussed and finally the state of the art in nowadays wave measurements and advisory systems will be summarized.

2. GENERAL OPERATIONAL SEEKEEPING GUIDANCE AND ASSISTANCE SYSTEM

The effects as mentioned in the introduction can be thought of as caused directly by waves or motions or by a combination of these. The first target of operational seakeeping advisory tools should be to provide information on the actual sea state in the direct vicinity of the vessel combined with the motion response and relative wave heights around the vessel. The latter with the ship sailing with arbitrary speed and relative wave headings.
With this information the likelihood of exceedance of specific operational limiting parameters can be derived using dedicated (software) models as shown in Figure 1.

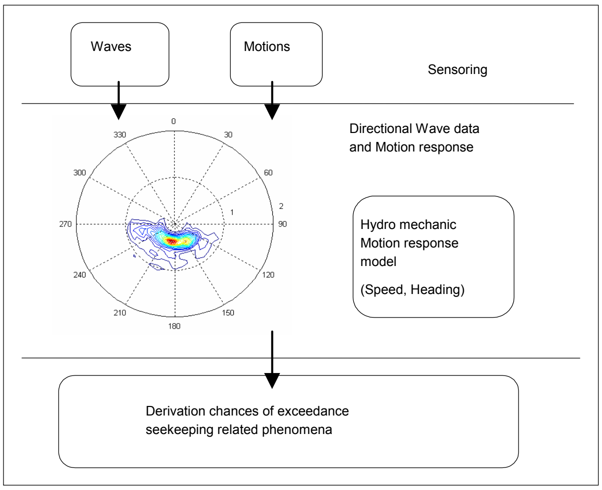

Figure 1. System outline

The scope of this paper is limited to the measurement of the wave data and the derivation of ship motions. The models required for the evaluation of the chances for exceeding specific operational envelopes are not discussed in detail.

3 THE WAVE ENVIRONMENT

How is a wave environment described? Looking at a sea surface one may be wondering at the apparent incomprehensible ever-changing behaviour of the waves.

In general most waves are wind driven. Depending on the wind condition and history the waves may be building, fully developed or decaying. Older waves systems coming in from other locations may have different characteristics from the locally building sea. Developing seas are usually short crested. Older swell components may have long regular crests. Obviously it is difficult to describe a sea state in detail. Following is a brief resume of the used models.

3.1 2D SEA SURFACE IN TIME

The sea comprises of travelling gravity waves coming from various directions. Wavelength and height, travelling speed and direction describe the characteristics for separate wave components. The water surface in a particular area and time window is defined by a number of wave components that passes by in that period. The combined effect of these passing waves will produce the actual sea surface.

In linear wave theory the behaviour of separate waves can be described in reasonable detail. The behaviour of a sea comprised of many waves can be described using a summation of many separate waves coming from various directions. For deep water and non-breaking waves the following describes a multi-directional sea state typically producing short crested waves.

$$\zeta(x,y,t) = \sum_{k=1}^{M}\sum_{j=1}^{N} A_{jk}\sin\left(\omega_j.t - k_j\left(x.\cos(\beta_{jk}) + y.\sin(\beta_{jk})\right) + \varepsilon_{jk}\right)$$

$$\begin{aligned}&\textit{where } j \textit{ indicates the number of wave components } (1-N)\\ &k_j \textit{ is the wavelength of the } j^{th} \textit{ wave component,}\\ &\textit{and the index } k \textit{ indicates the various wave directions } (1-M)\end{aligned}$$

Each separate wave component has a circular frequency ω_j, wavelength k_j, direction β_{jk} and height A_{jk}.

3.2 WAVE SPECTRA

The coefficients A_{jk} may be written in the form of a so-called frequency spectrum as follows:

$$\tfrac{1}{2}A_{jk}^{\ 2} = S(\omega_j,\beta_k)\Delta\omega\Delta\beta$$

Where S(ω) is the wave spectrum or wave variance spectrum. It can be derived that the variance of the sea surface at a particular location behaves as:

$$\sigma^2 = \sum_{j=1}^{N}\sum_{k=1}^{M} A_{jk}^2/2 = \int_{\omega=0}^{\infty}\int_{\beta=0}^{2\pi} S(\omega,\beta)\,d\omega\, d\beta$$

If for a particular sea state the directional wave spectrum is known then a statistically representative sea surface can be calculated. If the phase angles of the separate wave components are known as well then also the actual sea surface can be calculated.

The so-called full directional wave spectrum is therefore a very powerful tool to represent a particular sea state. It is however not easily measured. What can be easily measured is the non-directional or Point Spectrum. This is the Variance spectrum of the wave elevation at one single X, Y position.

This spectrum is usually represented as S (ω) and follows

$$\zeta(t) = \sum_{j=1}^{N} A_j\sin\left(\omega_j.t + \varepsilon_j\right)$$

$$\tfrac{1}{2}A_j^{\ 2} = S(\omega_j)\,\Delta\omega$$

This spectrum can be easily estimated from measurements by interpretation of a measured time series of vertical wave displacements.

Short crested waves cannot be described using the one-dimensional spectrum. In order to account for this the wave spreading principle was introduced. It is assumed that the combined wave energy from a point spectrum is distributed around a principal direction. Spreading has a bandwidth that is described by the spreading function. An example is as indicated in:

$$\begin{aligned}&S(\omega_j,\beta_k) = S(\omega_j).f(\theta)\\ &\quad \textit{where:}\\ &\quad f(\theta) = \tfrac{2}{\pi}\cos^2(\theta), \quad -\pi/2 < \theta < \pi/2, \quad \theta = \beta_k - \beta_{mean}\\ &\quad f(\theta) = 0, \quad \textit{elsewhere}\end{aligned}$$

A synthesised full directional spectrum can be derived from a single point spectrum using a mean direction and (standard) spreading function. This easily derived directional spectrum has been widely adopted in wave measurements recently.

3.3 STATISTICS AND SPECTRAL MOMENTS

Apart from the spatial and the spectral representation, the behaviour of the wave surface can also be described in a statistical manner. The sea surface has a mean level with a particular variance, dominant wave direction and period as mentioned earlier. Ship crews observing wave environments describe the sea state in terms of significant wave height, wave period and direction. If older wave systems are also present a subdivision in a wind sea and a swell component is made. For each of these a significant wave height, a period and a wave direction is usually logged. It is found that particular relations exist between the visually observed data, statistical information and wave spectra. First the concept of spectral moments is introduced.

$$m_k = \int_0^{\infty}\omega^k\ S(\omega)d\omega$$

For k=0 this indicates the variance m_o. Then m_1 and m_2 are referred to as the first and the second spectral moment.

It is found that the estimates of the significant wave height correspond to the average of the highest 1/3 of the measured waves. Usually the significant wave height is written as $H_{1/3}$. The period corresponds to the mean zero upward crossing period T_{mzup}. Following expressions link these observed values to spectral parameters.

$$H13 = 4\,\sigma = 4\sqrt{m_0}$$

$$T_{mzup} = 2\pi\sqrt{m_0 / m_2}$$

Using these expressions the estimates for the spectral parameters m_o, m_1, and m_2 can thus be retrieved from visual observations. A frequency point spectrum can be now be derived using the spectral moments and application of a standard sea state spectrum description, for instance PM, Jonswap or ITTC formulations.

3.4 EFFECT OF FORWARD SPEED

A ship sailing in a wave field at particular speed V encounters the waves at different frequencies depending on speed and relative direction to the waves. The shape of the wave and its geometric effect on the vessel do not change at varying speeds. It is only the frequency that changes. In the frequency domain using wave spectra this transformation can be done relatively straightforward.

The transformation of the wave frequencies to encounter frequencies is governed by the wavelength, propagation speed, the relative wave direction and the ship speed. Water depth affects greatly the wave propagation speed. For this discussion we limit the scope to deep water (in general greater than 300 meter). For deep water the relation between encounter and global wave frequency is:

$$\omega_e = \omega\left(1 - \frac{\omega V \cos(\alpha)}{g}\right)$$

With this transformation the spectral densities S (ω) can be mapped to corresponding S (ω_e). As the variance for the encounter sea state and the global sea state should be the same it follows that besides the scaling of the frequency axis also the spectral density itself must change. This is illustrated as follows:

$$S(\omega_e)\,d\omega_e = S(\omega)\,d\omega$$

$$S(\omega_e) = S(\omega)\frac{d\omega}{d\omega_e}$$

$$\frac{d\omega}{d\omega_e} = 1 \Big/ \frac{d\omega_e}{d\omega}$$

$$\frac{d\omega_e}{d\omega} = 1 - \frac{2\omega V \cos(\alpha)}{g}$$

The derivative dw/dw_e is not analytically continuous because of the zero point in dw_e/dw. When using discretized wave spectra the contributions for discrete frequency bands can however consequently be mapped from frequency band to frequency band without problems.

The transformation also applies for each frequency band in the directional wave spectrum. The full 2D spectrum may be transformed to an encounter spectrum. The wave encounter spectrum may be used to generate a wave surface as it is "felt" by the vessel.
Higher wave frequencies (short wavelengths) will result in negative encounter frequencies indicating that the ship is overtaking the waves. Their apparent frequency is $|\omega_e|$.
When the direction and length of the wave components is unknown the transformation from encounter to earth fixed frequency is not unique as indicated in Figure 2 for following or stern quartering waves. The figure illustrates that three different wave components have the same encounter frequency of 0.1 rad/s.

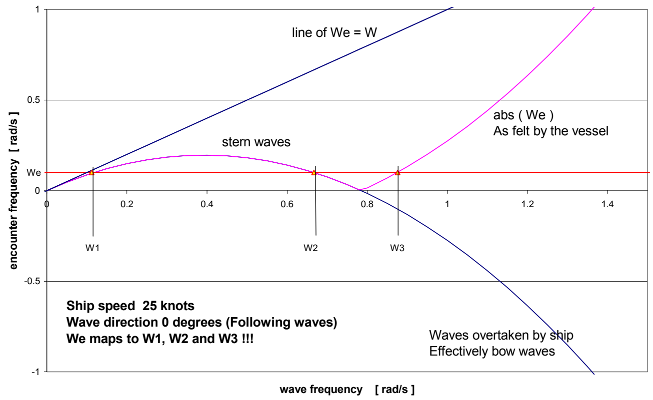

Figure 2 . Wave freq - Encounter wave freq

This ambiguity in the wave encounter frequency makes it difficult to do numerical wave calculations in the ω_e domain. In fact it is not possible to scale a point spectrum in ω_e back to the ω domain without information on the direction of the corresponding wave component. An assumption for the wave direction and wave length is required to make this transformation possible.

3.5 SUMMARIZING WAVE PARAMETERS.

The description of the wave surface has been briefly discussed from detailed back to few parameters. Summarizing, a sea state may be described as:

- A sum of an old wave system called swell and a wind driven newer system called wind sea.
- Each of these components has a significant wave height, mean zero upward crossing period and direction and spreading.
- A wave point variance spectrum can be derived from the $H_{1/3}$ and T_z or be calculated from a measured time series of wave elevations.
- Using the mean direction and spreading the point spectrum can be converted into a full 2D directional

wave spectrum. This spectrum may also be derived from measurements if the direction of separate wave components can be determined.

- A vessel with forward speed perceives the actual sea state through changing encounter frequencies. The variance in the sea state does not.
- The transformation from the global or earth fixed sea state description to the ship encounter frequency is possible. The transformation from ship encounter back to the global system of coordinates is difficult.
- The full 2D wave spectrum can be transformed into a representative 2 dimensional wave surface. If the phase angles of the wave components are also known then the actual sea state surface may be reproduced as indicated by:

$$\zeta(x,y,t) = \sum_{k=1}^{M}\sum_{j=1}^{N}\sqrt{2S(\omega_j,\beta_k)\Delta\omega\Delta\beta} \quad * \quad \cdots$$
$$\cdots \quad \sin\left(\omega_j.t - k_j\left(x.\cos(\beta_k) + y.\sin(\beta_k)\right) + \varepsilon_{jk}\right)$$

This completely describes the wave surface both in time and space. In theory the actual surface could be predicted even into the future. The problems and inaccuracies that make that difficult are the deep water condition and the linear theory. In shallow water the bottom geometry usually makes the water depth a significant function of the x,y position. The different propagation speed and wave profiles disturb the linear summation criteria. The linearity assumptions fail in higher wave conditions. The energy dissipation due to breaking waves is not covered. Extreme waves can thus not accurately be represented.

4 WAVE SENSORS

A wave sensor for operational purposes implies that the results are directly available for interpretation on board. In the above the various means to describe a sea state have been covered. What equipment does exist to measure either earth or encounter frequent information for the parameters describing the sea surface? That is:

- 2D wave surface outline ζ (t, x,y)
- 1D wave elevation history ζ (t)
- Variance spectra (S (ω,β) and S (ω))
- Peak and valley distributions (H13 & Tz)

Shipborne possibilities for obtaining wave information can be categorized as follows:

- visual estimates
- of the bow down looking level gauges
- submerged pressure gauges in bow & side plating
- reverse engineering using ship motions
- radar back scatter directional systems
- coherent radar directional radar systems
- now- and forecasts based on :
  - fixed platform level gauge(s)
  - (directional) wave rider buoys
  - seabed ADCP
  - sea roughness (SAR)
  - Doppler shift systems.

4.1 VISUAL

Visual observations from crews provide information on swell and wind sea contributions. For these the significant wave height, zero upward crossing period and dominant direction are given. It is found that the results from various crews depend on the experience and ship size. Crews on larger ships appear to provide lower wave estimates than on smaller vessels. Ship motions may play a major part in this. During night-time no visual observations are possible. This illustrates the value of instrumented wave measurements for night-time operation.

4.2 RELATIVE WAVE HEIGHT

A number of sensors work based on the measurement of relative wave height around the ship. Examples of these sensors are: vertical radar level gauge, acoustic level gauge and pressure gauges measuring pressure or local water column height.

In the value of a relative wave height the following parameters are included:

- Undisturbed wave profile
- Sensor displacement (1^{st} order ship motions)
- Diffraction wave profile by ship motions
- Refracted wave effects (“upwind effect”)
- Wave shielding effects (“downwind”)

It is clear that a relative wave height sensor requires corrections. The effect of vertical sensor displacement is easily corrected by measuring local displacement. The wave disturbance due to the vessel is however highly sensitive for direction. The sensor does not measure information on the wave direction. The effect can thus not be accounted for automatically. Commercial relative wave height sensors usually assume undisturbed waves.

The sensors are usually placed at the bow in the centreline. Pressure gauges are highly influenced by local dynamic pressure effects. Diffraction pressures, wave refraction, intermittent submerging of the sensor and slams make it difficult to get sensible data from pressure gauges.
The often applied over the bow down-looking surface radar is highly influenced by the local wave pattern induced by the vessel. Following waves are shielded, Bow waves are refracted, ship motions cause diffraction waves etc. Acoustic systems are in addition to this much influenced by presence of spray in the measurement area.
In general measurements taken from the sea surface in the close vicinity of the ship are too affected by the

presence of the ship to allow reliable wave observations under all conditions (e.g. relative headings). For slender ships the accuracy is best particularly in bow waves. More blunt bow shapes introduce large errors in the results due to wave refraction and dynamic swell up.

4.3 RADAR BACK SCATTER SYSTEMS

Radar backscatter systems are based on the radar reflections coming from wind ripples on wave crests. Depending on wave height and wind strength, wave crests show up in received X-band radar data. In the radar plots the wave crests show up allowing the distinction of wavelengths and “crest intensity”. Using 2D and 3D Fourier algorithms the wave surface can be derived when assuming a relation between the intensity of the reflection and the wave height. The result is a full 2D directional sea state description in terms of wave -lengths, -speeds and -heights per direction. By using the dispersion relation the wavelengths can be transformed to the frequency domain and be put into wave variance spectra as earlier described. This approach promises complete wave data providing all information required to model the sea state. In fact it should be possible to obtain all required data to predict the behaviour of the sea in the direction of the wave propagation in the close future.

The problem with the backscatter technology lies in the reliability of the scaling function from reflection intensity to wave height. In lack of wind speed there are no reflections so no wave crests are shown. In high seas the effects of shadowing of waves and the fact that the sea is already at maximum roughness may be problematic. Validations are still in progress. The produced results are increasingly accurate from various providers. Two comparisons between off the bow radar and a X-band radar based system are shown in Figure 3.

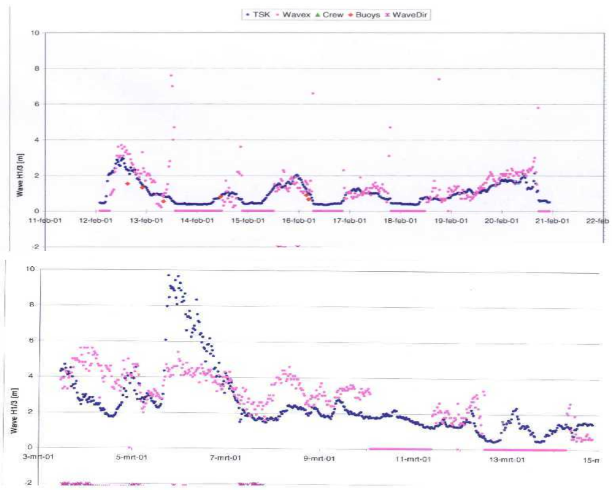

Figure 3. Long term comparisons of vertical relative wave height. Radar and directional wave radar results. Above good registration, below poor correlation.

The lighter dots referring to measurements by a Marine Radar based system, the darker taken from of the bow vertical wave radar. The systems were installed on a 24 knots container vessel.

4.4 COHERENT DIRECTIONAL WAVE RADAR

Coherent directional wave radars (CORA) are based on the fact that is it possible to derive the speed of the wave surface from the received radar reflection. The wave surface speed is related directly to the orbital motions. The orbital motions are related to the wave height and length. As such it is possible to derive the actual wave height distribution from coherent radar measurements. Operational systems have not been widely adopted yet on sailing ships as to the author’s awareness.

4.5 REVERSED ENGINEERING

Reversed engineering comprises the derivation of undisturbed wave information from a combination of the measured ship motions with calculated motion and relative wave height RAOs.

The simplest approach is to directly derive the undisturbed encounter spectrum from the measured ship motions using numerically calculated RAOs. This is relatively straightforward but depends on the ship size and its sensitivity to the actual waves. I.e. it is not possible to derive wave estimates from the motions of a non-moving vessel. For smaller vessels this approach has proved to be working. In general the wavelengths should be in excess of 2/3 the ship length to induce significant motions.

A related approach is to derive the wave environment by interpreting the wave distributions around the vessel on all sides. (MARIN DPJIP 2001). By using the measured ship motions and the effect of the diffraction waves the measured wave data can be compared with calculations. By performing a best fitting selection of the calculated wave with measurements, the wave energy and direction can be estimated.

The latest and perhaps most feasible approach is to use wave directional information from e.g. directional wave radar systems and calculate normalized motions responses using RAOs. By comparison of the calculated motions with the measured motions the wave energy can be estimated. The combination of wave energy and wave directional spectrum provides a full complete wave description.

4.6 REMOTE WAVE MEASUREMENTS

There are various sources of information that can be used to obtain remote wave data on board. These vary from networks of moored wave rider buoys to now-, fore- and hind-cast data and satellite observations. Fixed buoys information is usually accurate. The buoy grid is however restricted to just few areas in the coastal

regions. The same goes for under water ADCP set-ups and fixed platform wave radar.
Satellite observations based on Doppler shift and SAR technology have a much wider coverage across the world. They are increasing their accuracy for wave height and direction estimations. The update rate at any particular position is however rather low. Satellites pass each grid position of 1.5x1.5 degrees about once every day.
Regular ships weather forecast and now cast information is usually based on models that are fed with observations from vessels sailing offshore. Due to the accuracy in the input data the provided results are usually indicative at best. No short term or local effects are included.

5 SHIP MOTION RESPONSE IN WAVES

Ship responses to the wave environment vary from:

- Added resistance, speed reduction, fuel consumption
- Structural loads caused by waves. E.g. slamming, green water, general wave bending and torsion, side shell fatigue.
- High motion and acceleration levels due to direct (linear) wave response.
- Induced motions caused by non linear wave response

If the wave environment is known or described then what other basic information is needed to allow an operational approach to the mentioned topics?

The induced ship motions in the encountered wave field play a major role in all mentioned issues. Added resistance is partly caused by the energy that is lost into the generated waves. The chances of occurrence for high peak loads can be numerically estimated when a reliable model is available calculating ship motions and local relative wave heights and relative wave speeds. Induced linear and non linear motions can be directly used to calculate the motion and acceleration levels at any point on the (rigid body) ship.

For a sound operational application of measured wave data it is therefor required to have an online model to predict and evaluate effected ship motion response. The comparison of the actual ship motion state with the limiting criteria will be done using the measured wave data, the measured ship motions and the predicted ship motions and relative wave heights.
Specialized software modules can use the wave data and the ship motions to derive information and chances of exceedance for particular events related to cargo loss, slamming etc.
Effects of other headings and speed settings on the criteria can be calculated using linear and non linear RAOs. The results may be used to show the crew operational safe envelopes in terms of speed and heading in the actual wave conditions.

5.1 WAVE INDUCED LINEAR SHIP MOTIONS

In linear theory it is assumed that a wave with a circular frequency w and coming from a particular direction, will cause a motion effect that acts in that same direction. Bow waves will cause pitch, beam seas roll etc. A twice as big a wave will cause a two times bigger motion response.

The relations between the incoming waves and effected ship motions but also between local relative wave height and motions can be expressed in so-called RAOs or Response Amplitude Operators. $H(\omega,\beta)$.

$$S_{xx}\left(\omega_{ej}\right)=\sum_{k=1}^{M}H^{2}\left(\omega_{ej},\beta_{k}\right)S_{\zeta\zeta}\left(\omega_{ej},\beta_{k}\right)$$

where H is a complex function in order to obtain the phase relations in the summation

The RAOs can be derived using diffraction or strip theory software. The results of these calculations can be transformed to the encounter frequency domain for direct operational application on board in the encountered waves for each ω_j. By summation of the contributions of waves with various frequencys coming from various directions the total motions response may be calculated.

5.2 NON LINEAR EFFECTS

Non linear motions and effects refer to the phenomena that are more difficult to describe than was mentioned earlier. In general for instance when a twice as big an excitation results in a three times higher response or even when without obvious loads high outputs are found. Examples are:

- Sagging/Hogging effect
- Bow flare immersion
- Bow emergence (slamming / whipping)
- Green water
- Parametric rolling

The earlier described linear theory can not predict the effects directly. For implicit calculations nonlinear approach and often time domain calculations will be required. For operational guidance and assistance systems this is still out of scope. What can be done however is to recognize the conditions under which particular non linear phenomena come into significant effect. This either by interpreting the measured wave environment, the calculated- or measured- motions or by a combination of these.

As an example the nonlinear Parametric roll response is mentioned here. Parametric roll is a phenomenon that occurs in conditions where under head or stern waves a vessel starts to roll without sideways excitation. Roll angles over 20 degrees plus minus have been reported. The roll motion may build up under particular conditions quite rapidly and may seriously hazard stability, structural integrity of ship and cargo and crew safety.

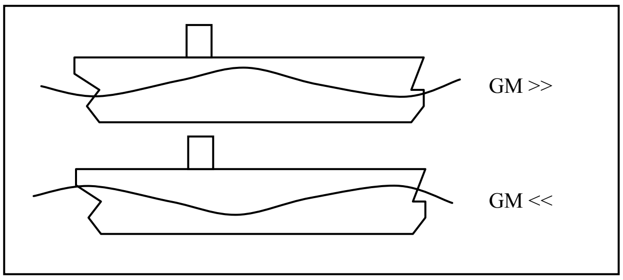

Figure 4. Effect of waves on moment of stability

Parametric roll is rooted in the fact that little excitation is required to excite a ship in its natural period roll motion. The excitation in the parametric roll case comes not from direct wave excitation but from amplification of initial roll motions by changes of the restoring moment of stability in the Roll natural period. A wave with wavelength close to equal the ships length coming from astern or forward will pass the ship with encounter frequency ω_e depending on the ship speed. Because of the outline of the waterplane area, when the midship section is on a wave crest, the moment of stability is higher then when the midship section is on a wave through. Figure 4. If the motion phase and the wave encounter phase angles vary 90 degrees than the variations in righting moment may be interpreted as a negative damping term. Figure 5. This will cause resonance when the transferred energy is higher than the dissipation by the regular roll damping. Roll motions will increase until the roll damping equals the negative excitation damping.

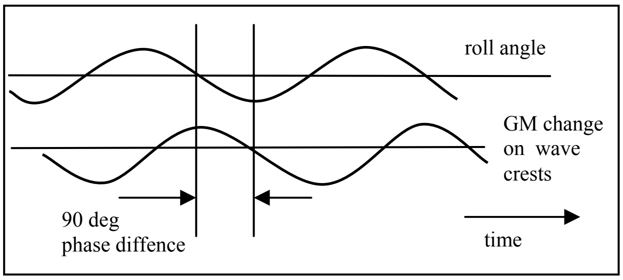

Figure 5. negative damping by varying GM

The criteria for occurrence of this effect lie therefor in the combination of:

- a wave length around the ships length with
- encounter frequency close or equal to the roll resonance period.
- significant induced variations of the GM due to the changes of the waterplane area when passing the wave profile.

The likelihood of occurrence for this condition can be evaluated by a dedicated software module from a full directional wave spectrum plus the ship speed and heading and a calculated GM response to waves.

6 STATE OF THE ART.

Having discussed the various wave representation techniques, sensor types and approaches to model ship response in the waves, we come to the current state of the are and the direction that developments will take in the coming time.

The most accepted technology for on board wave measurements is at this time still in off the bow relative wave height measurements. These provide the most cost – effective off the shelf instrumentation. The instrumentation can be done very rapidly and straightforward. No extensive calibrations are required. Problems are encountered in following waves and when blunt bow shapes are used. No directional information can yet be achieved from the systems.
The state of the art and in the very near future the equipment of choice will be based on radar back scatter systems. Combination of wavelengths and directions from the radar image with wave energy estimates from vertical wave height and ship response will provide accurate and complete wave information allowing statistical description of the wave climate in the close vicinity.

The acquisition and evaluation of the wave information from the radar images takes typically 2 minutes. The process is aimed at the statistic representation of the sea state so no separate wave component phase information is retained. The availability of fast computing systems, dsp's and algorithms will eventually allow the online calculation of the wave data. This will allow the real time decomposition of the sea surface in its separate wave components and allow prediction of the wave surface in the future in the path of the sailing ship.

It is likely that in few years it will be possible to predict the incoming wave train that a vessel will encounter in the coming minute(s). This will make it possible to allow guidance and assistance in avoiding extreme waves, assistance in extreme motion related manoeuvres, helicopter operations, station keeping, optimal dynamic positioning / tracking etc. These real time wave surface systems require faster acquisition and computation models than currently available. The use for ship crews is yet unclear because little time will remain between the recognition of a threatening condition and its moment of occurrence.
Perhaps in that area lies yet the biggest challenge: With the technology is about to be there, how to present the available information to the crew in an comprehensible way such that it is used and adopted.

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