Motion and Seasickness of Fast Warships

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ABSTRACT

In this paper the coupling between the sea, the ship and humans is studied. In previous researches mathematical models of fast ship's motions have been determined. In the literature there are models of human sickness and models of the sea. This knowledge about seasickness, waves and ship motion has been gathered. Using this information it is possible to extract some criteria for the captain (manoeuvring), for ship designers and for actuators engineering. Taking advantage of the models obtained, a study of seasickness prediction has been done, and some interesting results are presented.

1 INTRODUCTION

Anacharsis, brother of Caduides the king of the Scythians, was a philosopher who traveled around the East Mediterranean and the Black Sea in the 6th century BC. His mother was Grecian woman and the contemporaneous Greeks said him that he exhorted moderation and good criteria in everything he did, for example saying "the vine bears three clusters of grapes: the first wine, pleasure; the second, drunkenness, the third, disgust" [1]. As a seaman, he had to travel in different kinds of sea conditions and he had one of the best references, with the same philosophy, listened about seasickness "people may be divided into three classes; the living, the dead and the seasick".

Seamen know that nothing is better than a sunny day sensation in a quiet sea and a sweet little breeze on the face. Nothing worse under a heavy storm, and between them are the most of the sailing days at sea. Seasickness is a form of motion sickness that is due to erratic stimulation to the brain from sensory receptors and is prompted by constantly changing movements ending with symptoms such as lethargy, nausea, cold sweat, stomach cramps and vomiting.

The sense of spatial orientation sends the brain the information about the space situation and this sense is regulated by the interaction of the body systems to detect motions; the inner ears, eyes, skin pressure receptors, muscles and joint sensory neural receptors. Motion sickness appears when the brain receives conflicting messages from these systems. A simple brain conflict example is when reading a book in a ship, the eyes send similar information to "we observe no motion" but the inner ears send "we feel the ship motion due to the waves".

Warship crew and weapons reduce the effectiveness under bad weather, so a better acknowledgement of the ship motions, vertical accelerations, seasickness and stabilizing actuators are really needed.

In previous researches mathematical models of the ship's motions have been determined [2]. Besides this, knowledge about seasickness and waves has been gathered. It is possible to extract some criteria for the captain (manoeuvring), for ship designers (on design time) and for actuators engineering (modifying the ship's performance). Taking advantage of the models obtained, a study of seasickness prediction has been

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done, and some interesting results have been obtained. Using these results, it is possible to broad the captain's instrument panel, the CFD ship design tools, and the information to design actuators and control systems to improve the ship's behaviour.

The problem of seasickness induced by ship motions is analyzed by using a chain of three filters, figure 1. Each filter is a model: one about excitation due to waves, other about ship motion response, and the third about seasickness effects. The following figure represents this approach:

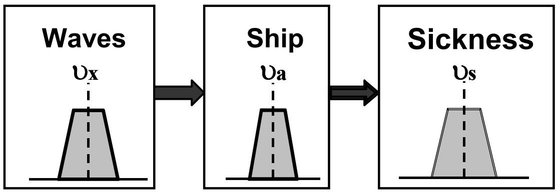

Figure 1: The analogy: A chain of filters.

This analogy will be explored and quantified, obtaining a frequency-domain procedure.

As established by O'Hanlon and McCauley (1974) [3], seasickness (MSI) is a cumulative effect. Each wave induced motion contributes to the MSI increase. More wave amplitude causes more ship motions amplitude and this implies the MSI increases. It is possible calculates the MSI contribution of a wave with a certain amplitude and frequency of encounter. For a given ship's speed and heading, a curve can be plotted relating wave amplitude and frequency of encounter. A wave density of distribution vs. frequency can be found too, this distribution can be obtained from the wave power spectrum. With this distribution, the total MSI can be obtained adding the contribution of each wave to the total MSI.

The paper details the filters and how they change when the sea conditions, ship's speed and heading vary. Several sea states spectra, ship's speeds and heading have been considered. Next section considers the modelling of the three filters, in particular to obtain knowledge of the problem. The third section shows three possible applications of this knowledge to alleviate seasickness on ship.

2 MATHEMATICAL MODELS AND KNOWLEDGE OF THE PROBLEM

2.1 Sea Modelling

Wind generated wave start with small ripples which will travel across the surface in more or less the same direction as the wind. If the wind continues to blow for long ripples will advance and grow in length and height. At the same time the wind generate new ripples on the surface of the growing waves and these ripples will grow into waves themselves. There is a mixture of wave lengths and heights superimposed on each other. Lloyd (1998) [4] devotes two chapters of his book to the sea modelling.

The relative importance of each frequency on the waves may be quantified in terms of a wave amplitude energy density spectrum, usually abbreviated as Wave Energy Spectrum. This Wave Energy Spectrum is defined so that the area bounded by a frequency range is proportional to the total energy (per square meter of sea surface) of all components within that range of frequencies. So the spectral ordinate is

$$S_\zeta(\omega_n) = \frac{\zeta_{n0}^2}{2\cdot\delta\omega} \qquad \left(\frac{m^2}{rad/s}\right) \tag{1}$$

where ζ_{n0} and ω_n are the amplitude and frequency coefficients of the Fourier series fitting.

Generally it is impossible to obtain the same Wave Energy Spectrum twice. But it is a current practice to use idealized wave spectra formulas for open and coastal conditions. Expressions for power spectra of waves can be obtained from literature [4] and [5].

2.1.1 Open Ocean Spectrum.

The International Towing Tank Conference (ITTC) has adopted the Bretschneider Spectrum (2) as the standard wave energy spectrum to represent the conditions in open ocean, long-crested seas.

$$S_B(\omega) = \frac{4\cdot\pi^3\cdot H_{1/3}^2}{\omega^5\cdot T^4}\cdot\exp\left(\frac{-16\cdot\pi^3}{\omega^4\cdot T^4}\right) \qquad \left(\frac{m^2}{rad/s}\right) \tag{2}$$

where $H_{1/3}$ is the Significant Wave Height[1]; T is the Dominant Wave Period, related with the peak period by $T = T_p / 1.408$.

2.1.2 Costal Sea Spectrum

In coastal waters with limit fetch it is used a variation of the above spectrum. In this case the energy is more concentrated around the peak frequency. The Join North Sea Wave Project spectrum, JONSWAP, represents this situation (3).

$$S_J(\omega) = 0.658\cdot 3.3^J\cdot S_B(\omega) \tag{3}$$

where

$$J = e^{-\frac{\left(\frac{\omega\cdot T_0}{2\cdot\pi}-1\right)^2}{2\cdot\gamma^2}} \qquad \text{and} \qquad \gamma = \begin{cases} 0.07 \; for\; \omega < \dfrac{2\cdot\pi}{T_p} \\ 0.09 \; for\; \omega > \dfrac{2\cdot\pi}{T_p} \end{cases}$$

The World Meteorological Organization (WMO) has scaled the severity of the sea state using a number for several sea conditions, the Sea State Number (SSN). This SSN represents a sea state conditions defined by several parameters, for example the significant height and the peak period. The parameters define completely the Sea Spectra. Figure 2a compare Bretschneider and JONSWAP spectra for SSN5.

2.1.3 The Spectrum Observed by a Moving Ship

As it is well-known, sea spectra suffer changes when it is seen by a moving ship [4]. For instance, the peak of a spectrum will be seen by a moving ship with another frequency, and the frequencies of spectrum will now shifted according (6).

$$\omega_e = \omega - \frac{\omega^2\cdot U}{g}\cdot\cos(\mu) \tag{6}$$

[1] The mean value of the highest third of many measurements of mean wave heights.

It is a matter of frequency of encounter with waves, which depends on U, the speed of the ship, and μ, the heading angle (let us take 180º for heading seas). To preserve the energy represented by the spectrum the value of the ordinate is modified according to the expression (7).

$$S(\omega_e) = \frac{S(\omega)}{1 - \frac{2 \cdot \omega \cdot U \cdot \cos(\mu)}{g}} \tag{7}$$

For instance, for heading waves (μ=180º), SSN 5 and several speeds the shifting and modification of the Bretschneider spectrum is shown in figure 2b.

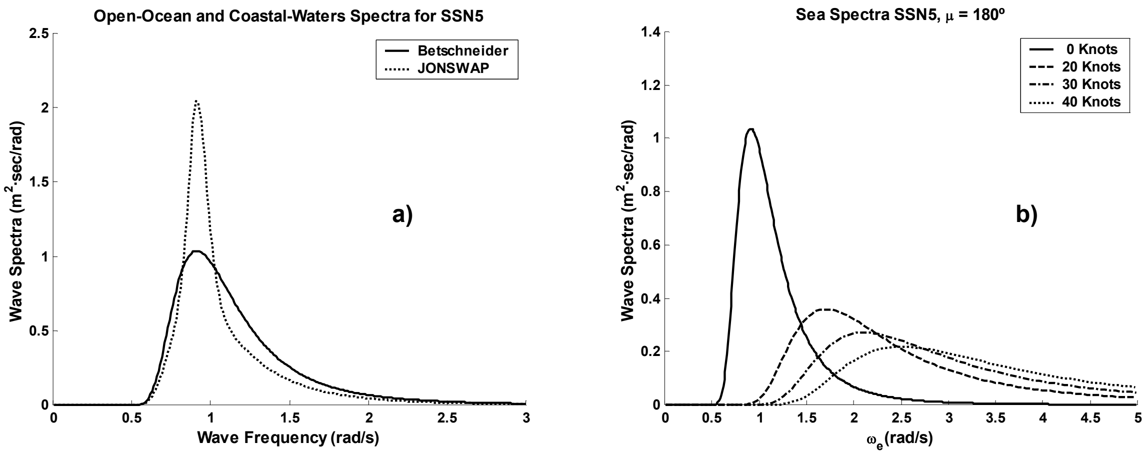

Figure 2: Bretschneider and JONSWAP Spectrum (a). Shifting of Bretschneider Spectrum (b).

2.1.4 Wave Envelope and Probability Density of Waves

The wave steepness is defined as H/λ, with H being the wave height (twice the wave amplitude) and λ the wave length. During this research in a seakeeping basin *Canal de Experiencias Hidrodinamicas de El Pardo* (CEHIPAR), Madrid, regular waves with 1/30, 1/40 and 1/50 steepness were used.

Supposing a wave steepness of 1/m, the wave amplitude is related with wave frequency (8).

$$\zeta(\omega) = \frac{H(\omega)}{2} = \frac{\lambda / m}{2} = \frac{\pi \cdot g}{m \cdot \omega^2} \tag{8}$$

The wave amplitude curve is subjected to the shifting of the equation (6) too.

A sort of probability density of waves frequencies is obtained, *f(ω)*, dividing the power spectrum by the energy associated to each frequency (9).

$$f(\omega) = \frac{S(\omega)}{\zeta^2(\omega)/2} = \frac{2 \cdot S(\omega) \cdot m^2 \cdot \omega^4}{\pi^2 \cdot g^2} \tag{9}$$

Using this probability density, the mean amplitude of waves can be easily calculated (10),

$$\bar{\zeta} = \int_0^\infty f(\omega) \cdot \zeta(\omega) \cdot d\omega = \frac{2 \cdot m}{\pi \cdot g} \int_0^\infty S(\omega) \cdot \omega^2 \cdot d\omega \tag{10}$$

Figure 3 shows power spectra, wave amplitude and probability density for SSN5 and ship's speed of 20 and 40 knots. The wave steepness 1/40 is selected.

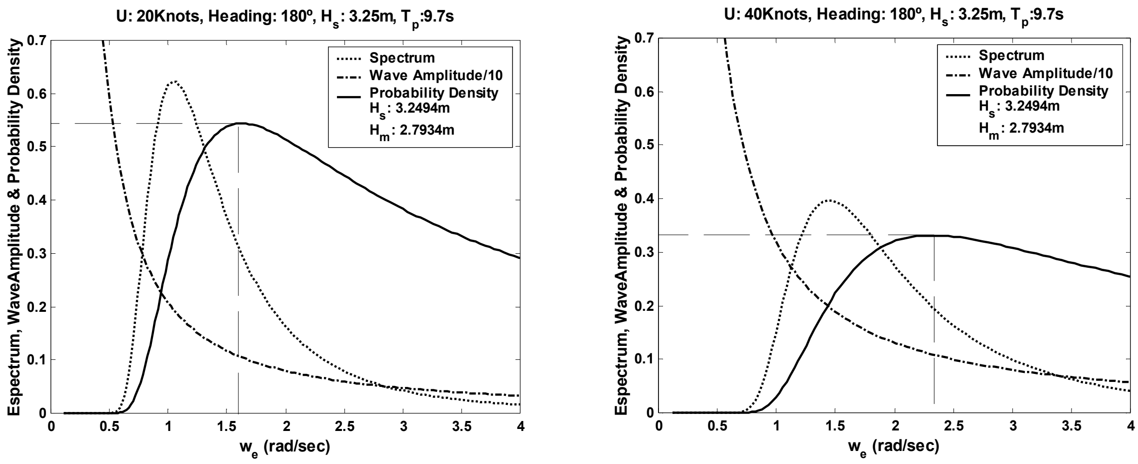

Figure 3: Power spectra, wave amplitude and probability density for SSN5

2.2 Ship Modelling

Usually ship motion is characterized using RAOs (Ratio Amplitude Operators [4]). It is possible to obtain the RAOs of a ship from real measurements, from model scale tests or from CFD (Computer Fluid Dinamic) programs. The degrees of freedom of a ship that contribute to vertical motion are heave, pitch and roll, these motions are the main factors which led to the seasickness. Since seasickness depends on the amplitude and frequency of the vertical accelerations, it is necessary to obtain the RAO of the place where seasickness will be evaluated. This RAO is obtained operating with heave, pitch and roll in the complex domain, to bear in main the phases. A different RAO is obtained for each particular place of the ship, for example in a lateral near the bow, where passengers can experiment the largest vertical motions (WVM, the worst vertical motions). Vertical accelerations are also measured at the same point where WVM is measured; let us denote this acceleration as WVA. The WVA RAO is the WVM RAO multiplied by the square frequency, result of equation (11). This WVM may be selected for tank sites, weapon, work stations or equipments, etc.

$$\begin{gathered} WVM(t) = A \cdot \sin(\omega_e \cdot t); \\ WVA(t) = \frac{d^2 WVM}{dt^2} = -\omega_e^{\,2} \cdot A \cdot \sin(\omega_e \cdot t); \\ |WVA| = \omega_e^{\,2} \cdot |WVM| \end{gathered} \tag{11}$$

Figure 4 shows the WVM and the WVA for SSN5 and 20, 30 and 40 knots ship speeds with head seas. The ship can be seen as a band-pass filter. Longer hulls will mean a shift of the frequency band to lower frequencies. In any case, it is important to pay attention to the 1 rad/sec frequency. A ship with a frequency band around 1 rad/sec is prone to causing seasickness.

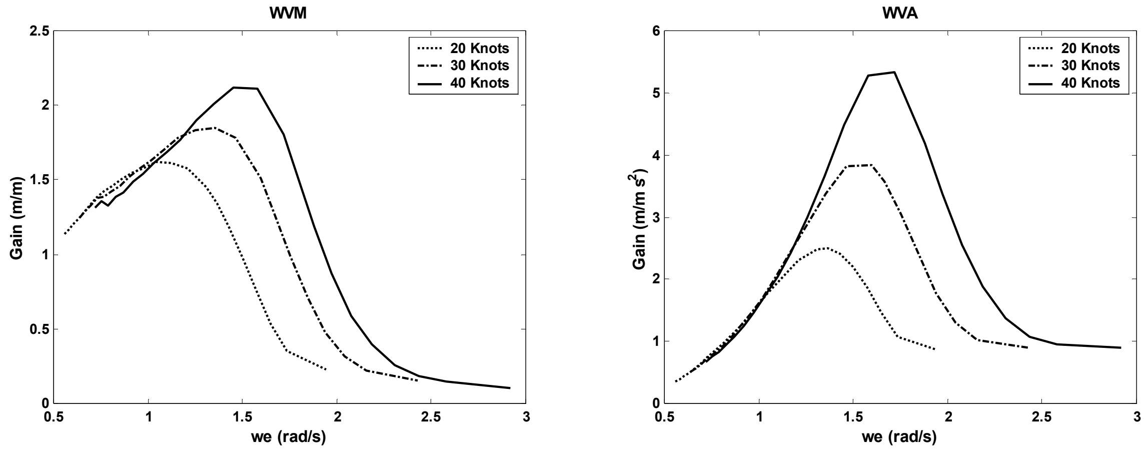

Figure 4: WVM and WVA frequency response for head seas, and 20, 30 , and 40 knots.

2.3 Sickness Modelling

There are several sources of scientific and technical information concerning seasickness. For instance the already cited study of O'Hanlon and McCauley (1974) [3], the base of MIL-STD-1472C defining "vomiting incidence", the standard ISO 2681:1985 and 2631:1990 [6] or the British Standard 6841:1987[7] on whole-body vibrations. These indices are good for short trips. Over longer periods, a few hours to few days, adaptation of the motions occurs, then the sensibility of humans to sickness decay too. There are other indices that do not refer to sickness, for example the Motion Induced Interruptions (MII) [4], which quantify the number of times that the crew must to interrupt a certain task to keep equilibrium.

In this paper the Motion Sickness Incidence index (MSI) proposed by O'Hanlon and McCauley (1974) is used. In a classic experiment O'Hanlon and McCauley measured the motion sickness response of over 300 American male college student paid volunteers. None of the students had any recent acclimatization to motions. They were tested in pairs in a ship motion simulator which was capable of driving the small enclosed test cabin through a vertical sinusoidal motion with amplitudes up to about ±3.5 m. The cabin had no windows so that the subjects could not receive any visual motion cues and their only task was to monitor their state of nausea by pressing buttons on a control panel. The experiments lasted for up to two hours, or until the subjects vomited. They conclude that sickness is a cumulative effect related to vertical accelerations of certain frequencies. There is a frequency band around 1 rad/s, where the MSI presents a maximum value. In [3] a mathematical model of MSI was found, as expressed in equation (12),

$$MSI = 100 \cdot \left[0.5 \pm erf\left(\frac{\pm \log_{10}(|a_z|/g) \mp \mu_{MSI}}{0.4} \right) \right] \tag{12}$$

where *erf* is the error function, a_z is the vertical acceleration in a chosen place averaged over a half motion cycle. Supposing sinusoidal motions, a_z can be obtained from the WVA amplitude A_{WVA}, according to (13),

$$|a_z| = \frac{\int_0^{T/2} A_{WVA}(\omega) \cdot \sin(\omega \cdot t)\, dt}{T/2} = \frac{A_{WVA}(\omega)}{\pi/2} \tag{13}$$

and μ_{MSI} is (14)

$$\mu_{MSI} = -0.819 + 2.32(\log_{10}\omega_e)^2 \qquad (14)$$

where ω_e is the dominant frequency (rad/sec) of encounter with waves. Figure 6a shows that MSI has a main resonance frequency, 1 rad/sec.

These formulas show that MSI is a non linear function of the frequency and mean acceleration, but they do not contemplate that a ship crew become habituated with exposure duration. On example of this habituation is shown in figure 6b, that represents a case of the percentage of the crew who vomit versus hours at sea. It is necessary a certain time on initial exposure of about half hour and the MSI rises to maximum which is allocated in a margin of 3 to 5 hours and gradually decreases. In this case in two days all the crew become habituated.

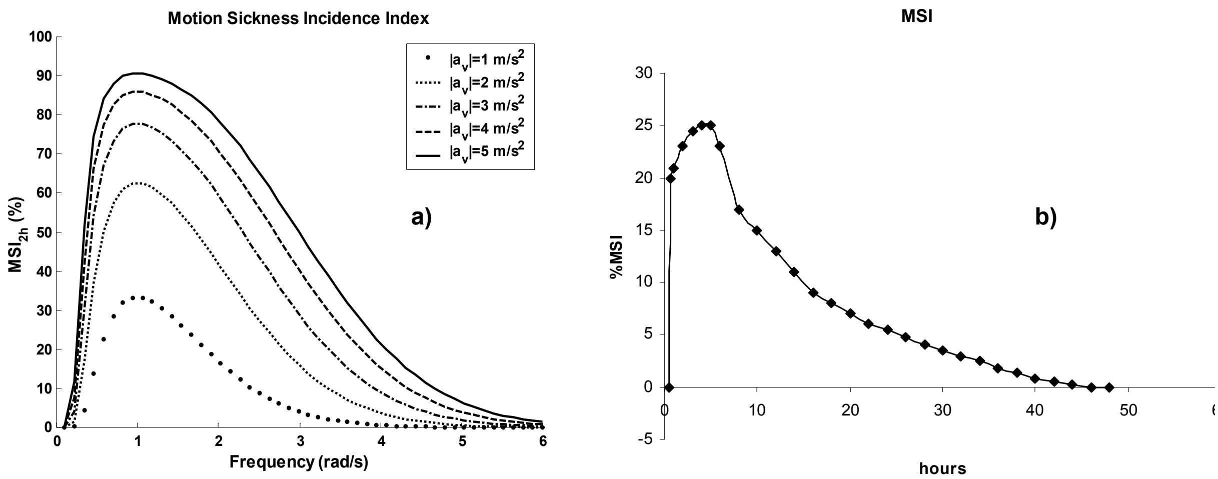

Figure 6: Motion Sickness Incidence index

2.4 Union of Filters

Figure 7 shows the procedure to obtain the MSI on a ship sailing with a particular SSN, speed and heading.

Figure 7: Procedure to evaluate the Sickness.

Starting from the left there is a chain of three blocks which calculates the MSI contribution of a wave with a certain amplitude and frequency of encounter for a given ship's speed and heading. Using the Wave Amplitude Envelope (8) as input of the Ship filter (WVA) (11) the WVA amplitude, A_{WVA}, is obtained for each frequency. So it is possible to obtain the contribution of a wave frequency to the MSI using the sickness filter, (12), (13) and (14). Figure 8 shows this contribution in function of the wave frequency, for a fast ship at 20 and 40 knots with heading sea using O'Hanlon index.

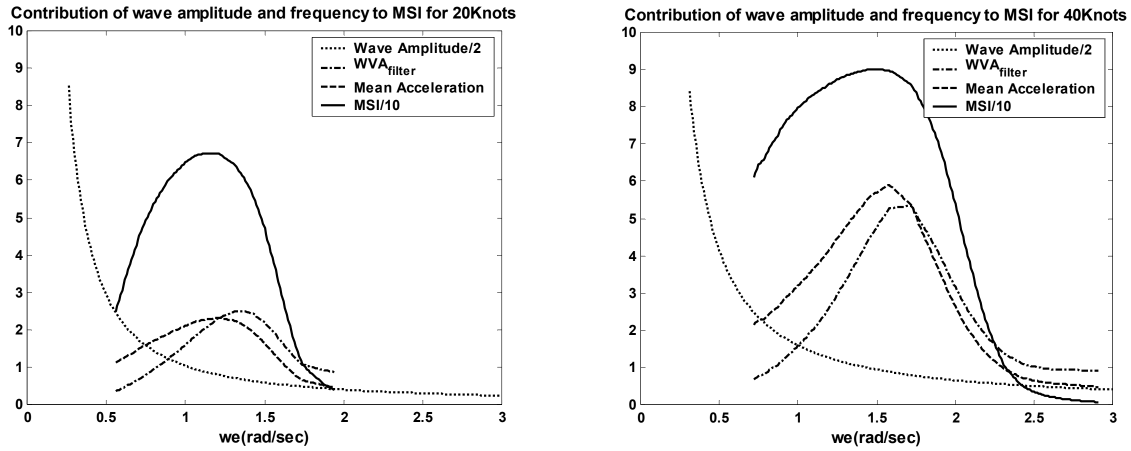

Figure 8 Contribution of waves to MSI in function of wave frequency for 20 and 40 Knots

Finally, carrying out the operations described by the block diagram of figure 7, the total MSI index is obtained integrating the above MSI envelope weighted by the density function associated to particular conditions (SSN, spectrum, speed and heading). Figure 9 shows these results for Bretschneider spectrum, heading seas and two different speeds. This is a frequency-domain representation which shows that total MSI can be obtained from the area in dark.

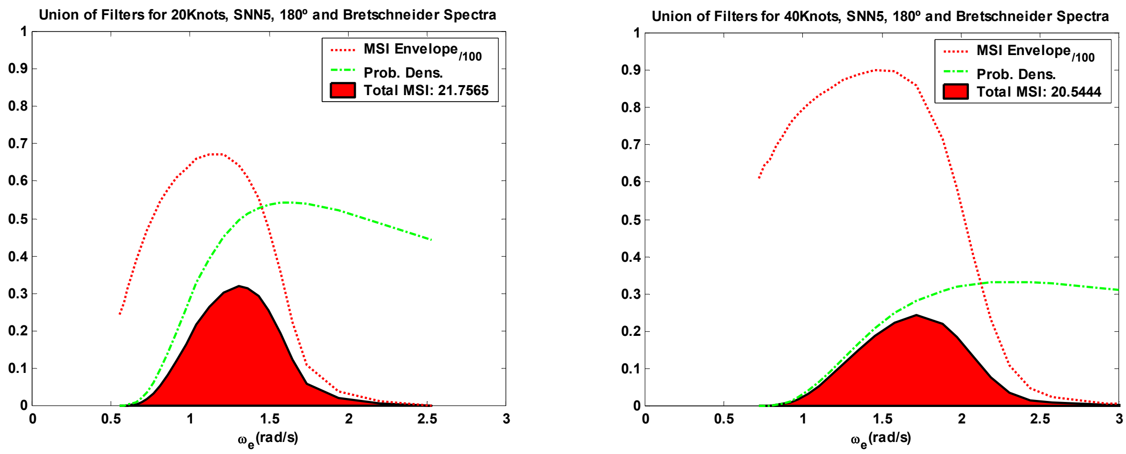

Figure 9: Computation of the total MSI for two different speeds.

3 APPLICATION OF KNOWLEDGE

3.1 Designing the Ship

On ship design time it is possible to obtain the RAO's of the ship using a CFD program. Using the algorithm presented in this paper it is possible to compute the total Sickness index in each place of the ship, for costal or open waters, for a several speeds and headings. Usually ships are designed to be used in some particular trips and the more frequent conditions of sea, speed and heading of this trip are known, but warships tends to be more versatile. It is possible optimize the ship design to work well on this conditions. Figure 10 shows the steps of this process.

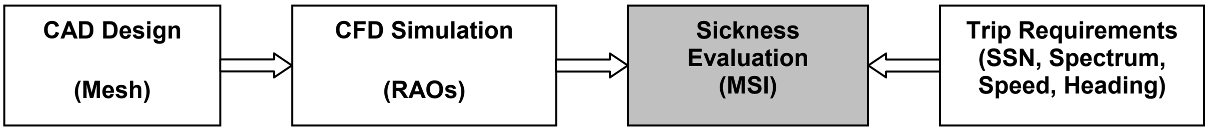

Figure 10: Steps to design a ship bearing in mind the sickness.

Figure 11 shows the sickness evaluation of a fast ship for head seas, and a SSN5 JONSWAP spectra.

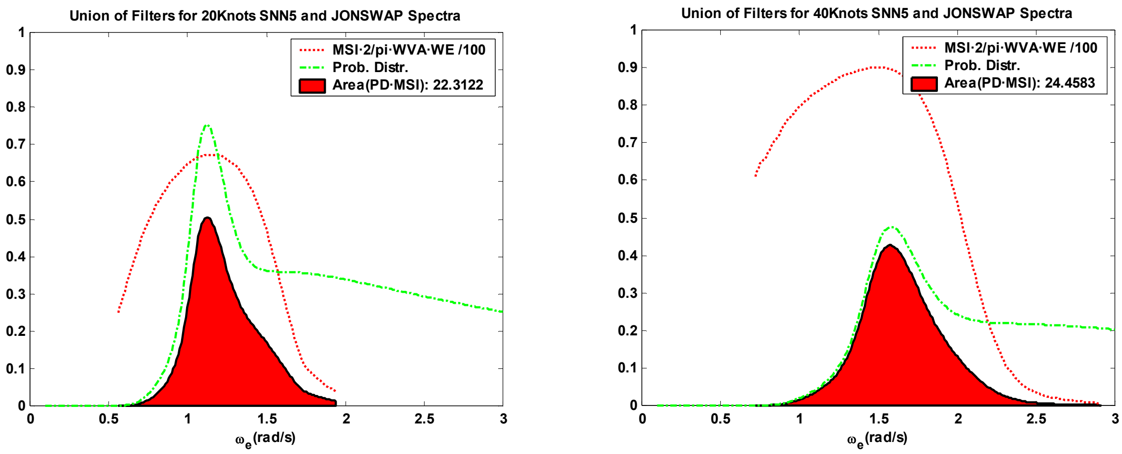

Figure 11: Filters coupling with JONSWAP statistics.

The performance of the ship from the sickness point of view is better if the two filters do not agree in resonance frequency. For example, Bretschneider spectrum, figure 9, generates less MSI than JONSWAP spectrum, figure 11, because the peak of JONSWAP agrees with the peak of the MSI envelope. This ship behaves better for Bretschneider than for JONSWAP spectra. The design of the ship must be optimized with respect to the operational conditions: coastal or open seas, SSN, speed, predominant heading, etc.

3.2 Improving a Built Ship

Sometimes the ship has been built or designed, and its operational range wants to be increased. It may be obtained by applying active control. To do this, it is necessary to use actuators like t-foils, flaps, fins, interceptors, stability tanks, etc. It is very important to optimize the characteristics and locations of the actuators in order to obtain the maximum motion reduction. Figures 9 and 11 show the band width and the main frequency that the actuators must affront. The band width of the problem is important for the control system engineer, because it determines the speed of the actuator and the controller design. Using the mathematical models of the ship [2] and the automatic control algebra, it is possible to close the control loop problem in the frequency domain, to obtain the ship controlled acceleration response. Using this new acceleration response, the total MSI may be computed to quantify the improvement.

3.3 Sailing the Ship

This knowledge of the sea-sickness can be transferred on sailing time to the master on screen. So, the information may be provided to the captain as figure 12 that shows local sickness indices on each place of the ship for two different headings, a) head seas and b) beam seas.

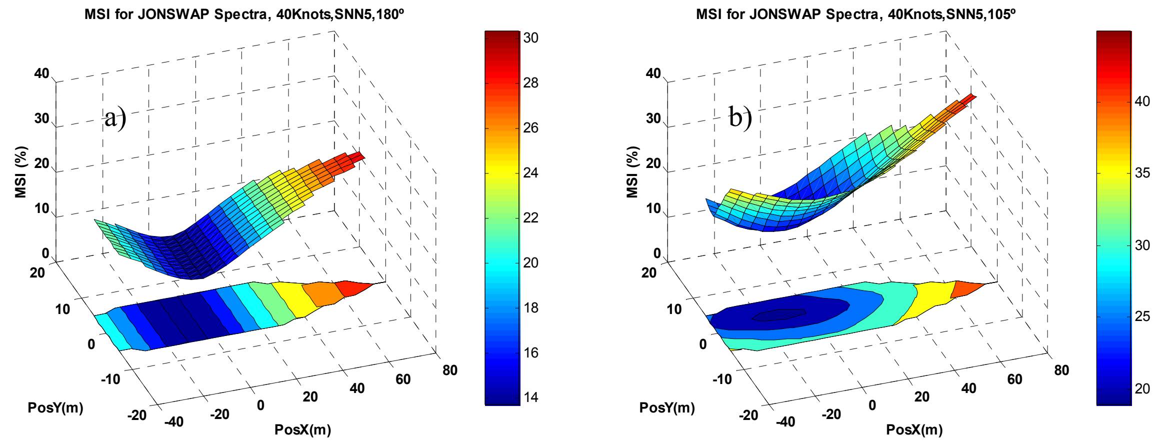

Figure 12: MSI on a desk of the ship, a) heading seas, b) oblique seas.

These figures show that in general the ship behaviour is worst in situation b). Figure 13 shows the master how to reduce the sickness index, in a particular place, slightly modifying the speed or heading of the ship. White lines show how the MSI changes when the speed or heading is modified. Of course the results agree with the practice because the heading is very influent on sickness. The figure shows the evolution of sickness for two different places, a) on the side near the bow, and b) on the side near the c.o.g. In case a) it is possible to reduce the sickness increasing the speed, this is not possible in case b).

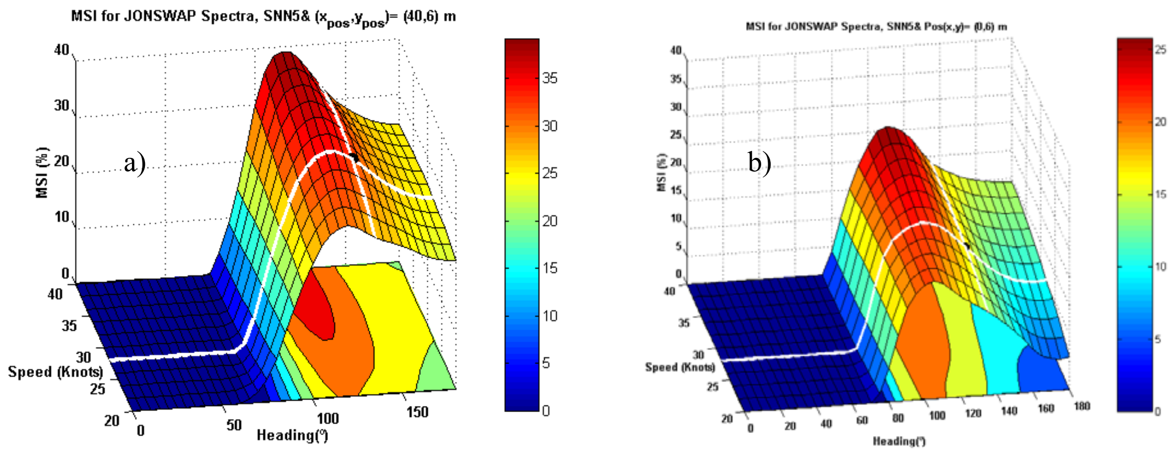

Figure 13: MSI on two lateral places, a) near the bow, b) near the c.o.g.

Mainly, it is important to alert if there is a heave resonance situation for a particular SSN, the peak of the MSI envelope and Wave Probability Density match up.

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