PARAMETRIC ESTIMATION OF THE DIRECTIONAL WAVE SPECTRUM FROM SHIP MOTIONS

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SUMMARY

A parametric estimation of the directional wave spectrum based on ship motions is presented. The estimation of the sea-state parameters is essential to have an updated data base of the main characteristics of the sea-state, which are useful for several applications on open-sea such as offshore platforms installations and safe ship navigation. The sea-state parameters at a fixed position can be obtained using a traditional waverider buoy. The analogy between the ship and the buoy is clear thus, it is possible to obtain an estimate of the wave spectrum at the location of an advancing ship by processing its wave-induced responses similarly to the traditional waverider buoy. In the parametric procedure the estimated wave spectrum is a-priori assumed to be composed of one parameterized spectrum or by the summation of several parameterized spectra, e.g. the generalized JONSWAP spectrum. Genetic algorithms are applied to found the best estimation of wave parameters. The wave estimation method is validated against numerical simulations and full scale tests in a patrol ship.

NOMENCLATURE

$\|\cdot\|$	L_2 norm
$\Gamma(x)$	Gamma function
ω	Wave frequency (rad s^{-1})
ω_e	Wave encounter frequency (rad s^{-1})
β	Ship heading (deg)
γ	Peak intensification factor
s	Wave spreading factor
g	Acceleration of gravity (m s^{-2})
V	Ship speed of advance (m/s)
H_s	Significant wave height *(m)*
T_p	Wave period (s)
$\bar{\beta}$	Mean wave direction (deg)
$\Phi_i\ (\omega_e, \beta)$	Complex-valued ship transfer functions
$E\ (\omega_e, \theta)$	Directional wave spectrum
$S_{ij}(\omega_e)$	Cross spectrum of ship response

1. INTRODUCTION

The knowledge of environmental conditions is one of the most important aspects for the safety of critical operations at sea. The wave buoy has been a reliable source of wave measurement data, and from analogy the vessel can also be used as a directional wave buoy with an adequate degree of confidence.

In the literature there are reports about the estimation of sea state parameters using measured ship responses (e.g. motion data) where the ship, to make an analogy, acts as a wave rider buoy for which reason the methodology is called the “wave buoy analogy”.

Iseki & Ohtsu (2000) proposed a stochastic method to estimate the directional wave spectra using a Bayesian modelling procedure. In such method, the spectra can be estimated as coefficients of multivariate linear regression model. This procedure presents a formulation to deal with the triple-valued function problem, also towing tank experiments and onboard experiments were carried out. Their conclusion was that the directional wave spectrum can be estimated from the vector-valued time series recorded on a running ship, even in following seas.

Tannuri et al. (2003) presented parametric estimations for stationary vessels. The WAMIT program was used to determine the transfer functions. Tests with a scale model ship were conducted and changes in encounter frequency and a study of the influence of ship load has been correctly addressed.

In Nielsen (2005, 2006) the theory of a parametric and a nonparametric modelling procedure was proposed. It is also outlined in detail how to take into account a vessel being underway, independently if the estimation is performed by parametric or non-parametric modelling. The main part of the paper was devoted to the analysis of numerical and full-scale data including comparisons with data from a wave radar system.

Pascoal et al. (2007) estimated the wave spectra from wave frequency motions of a vessel at zero or low advance speed. Minimization of a cost functional that indicates how well the estimated spectrum results in the measured motion spectra was based on sequential quadratic programming and a genetic algorithm. Pascoal and Guedes Soares (2008) extended that approach so as to make non-parametric estimations, in which case they were also able to deal with two-peaked spectra. For an application in which the spectral estimation was included in a on-board decision support system (Perera et al. 2012) the approach adopted was a different one based on filtering and in this way it was possible to fuse information from other sensors and in this way improve the estimates (Pascoal, and Guedes Soares 2008).

From the literature review, one can conclude that there are two main options to approach the estimated ocean wave spectra: using parametric and nonparametric formulations. The parametric formulation consists in giving a spectral shape with known analytical description but unknown parameters, such as the JONSWAP, while the non-parametric is a minimization where only a non-negativity constraint on the spectral amplitude is mandatory but the form is otherwise not specified this is sometimes called hyper-parametric representation.

Nonlinear gradient based minimization procedures have been used in parametric representations by Tannuri et al. (2003). It was found that the minimization domain is not globally convex, which means that global search schemes must be used to some initial point, and Pascoal et al. (2007) proposed genetic algorithm (GA) based minimization to conduct parametric estimations.

Genetic Algorithms has been applying in engineering problems along to the past decades, meanly because GA are a powerful tool broadly applicable to search and optimization techniques that can solve many complex problems subject to complex constraints, Gen & Cheng (2000). Complex constrains such as for example the parametric formulation of the wave spectrum during the in the estimation process.

In the present paper, the parametric procedure for estimating wave spectrum, based in ship motions, is addressed, so that it is the underlying wave parameters that are being sought. Genetic algorithms for minimization plants were applied.

In order to verify the wave estimation method numerical simulations and full scale tests are carried out. Hence, in simulations from generated ship responses based on a theoretically know wave spectrum, the estimated procedure is tested. Following the numerical simulations, estimations were performed using full scale data from trials carried out onboard of Portuguese Navy patrol vessel.

This paper is organized as follows. In Section 2, the mathematical formulation for the parametric method is addressed. In Section 3 presents the numerical simulations. Section 4 presents the estimations based on full-scale data and Section 5 is the conclusion.

2. MATHEMATICAL FORMULATION

2.1 DESCRIPTION OF THE PROBLEM

In the scope of this work some assumptions were adopted in order to simplify the estimation procedure: 1) The ship responses are assumed to be linear with the incident waves, 2) The formulation of waves consider deep water, 3) The complex-valued transfer functions $\Phi_i\ (\omega_e, \beta)$ and $\Phi_j\ (\omega_e, \beta)$ for the ith and jth responses yield the theoretical relationship between the ith and the jth components of the cross spectra and the directional wave spectrum $E\ (\omega_e, \theta)$ through the following integral equation (for details see Bhattacharyya 1978),

$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e, \beta)\overline{\Phi_j(\omega_e, \beta)}E(\omega_e, \theta)d\theta \tag{1}$$

with $\overline{\cdot}$ denoting the complex conjugate.

In order to simplify the formulation the fixed position can be taken coincident to the ship axis, it is wave direction can be given relative to the ship course, that is, $\beta = \theta$. Hence, (1) is rewritten

$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e, \beta)\overline{\Phi_j(\omega_e, \beta)}E(\omega_e, \beta)d\beta \tag{2}$$

As a general remark on (2) it should be noted that the directional wave spectrum $E\ (\omega_e, \beta)$ is convolved with some known response function $\Phi_i\ (\omega_e, \beta)$, to compute a signal $S_{ij}\ (\omega_e)$, the cross spectra. Thus, if the opposite is done in the estimation of the directional wave spectrum, $E\ (\omega_e, \beta)$ is basically deconvolved from (2), which is called deconvolution.

As proposed by Iseki (2000), the directional wave spectrum is advantageously estimated in the wave frequency domain, ω_0, however, when the right-hand side of (2) is transformed into a true wave frequency, the so-called triple-valued function problem arise. This problem is ruled by the deep-water relationship between the encounter and the wave frequency,

$$\omega_e = \omega_0 - \omega_0^2 A \qquad , \quad A = \frac{V}{g} cos\beta \tag{3}$$

It should be noted that in following waves, $\beta \in [-\pi/2\,; \pi/2\,]$, for certain speeds, three wave frequencies yield the solution to the triple-valued function problem. Therefore, in following sea and with $\omega_e < 1/4A$, when (2) is transformed into the wave frequency domain, the following three wave frequencies all have to be considered, as it cannot beforehand be determined which of the frequencies is the real true one,

$$\begin{aligned} \omega_{01} &= \frac{1-\sqrt{1-4A\omega_e}}{2A} & \left|\frac{d\omega_{01}}{d\omega_e}\right| &= \frac{1}{\sqrt{1-4A\omega_e}} \\ \omega_{02} &= \frac{1+\sqrt{1-4A\omega_e}}{2A} & \left|\frac{d\omega_{02}}{d\omega_e}\right| &= \frac{1}{\sqrt{1-4A\omega_e}} \\ \omega_{03} &= \frac{1+\sqrt{1+4A\omega_e}}{2A} & \left|\frac{d\omega_{03}}{d\omega_e}\right| &= \frac{1}{\sqrt{1+4A\omega_e}} \end{aligned} \tag{4}$$

hence, the transformation into the wave frequency domain is

$$\begin{aligned} S_{ij}(\omega_e) = &\int_{-\frac{\pi}{2}}^{\pi} \Phi_i(\omega_{01}, \beta)\overline{\Phi_j(\omega_{01}, \beta)}E(\omega_{01}, \beta)\left|\frac{d\omega_{01}}{d\omega_e}\right| d\beta \\ &+ \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \Phi_i(\omega_{01}, \beta)\overline{\Phi_j(\omega_{01}, \beta)}E(\omega_{01}, \beta)\left|\frac{d\omega_{01}}{d\omega_e}\right| d\beta \\ &+ \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \Phi_i(\omega_{02}, \beta)\overline{\Phi_j(\omega_{02}, \beta)}E(\omega_{02}, \beta)\left|\frac{d\omega_{02}}{d\omega_e}\right| d\beta \end{aligned}$$

$$+\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \Phi_i(\omega_{03},\beta)\overline{\Phi_j(\omega_{03},\beta)}E(\omega_{03},\beta)\left|\frac{d\omega_{03}}{d\omega_e}\right| d\beta$$
$$+\int_{-\pi}^{-\frac{\pi}{2}} \Phi_i(\omega_{01},\beta)\overline{\Phi_j(\omega_{01},\beta)}E(\omega_{01},\beta)\left|\frac{d\omega_{01}}{d\omega_e}\right| d\beta \quad (5)$$

where it is important to notice that the second and the third line, which correspond to following seas, is only considered for $\omega_e < \frac{1}{4A}$.

Thus, this multivariate model expression can be represented in matrix form as presented by Nielsen (2005).

$$b = Af(x) + w \quad (6)$$

Here b is the cross spectrum vector, which is composed of real and imaginary parts of the cross spectrum responses. matrix A denotes coefficient or system matrix composed of the products of the complex transfer functions and w is Gaussian white noise sequence vector which has zero mean and variance σ^2.

2.2 PARAMETRIC FORMULATION

The parametric formulation is based on the procedure proposed by Pascoal et al. (2007), however the present formulation includes the influence of the speed of advance of the ship, that means a completely different arrangement and dimensions of matrix involved in the estimation procedure.

Basically, the relationship between the measured response spectra and the directional wave spectrum is given by expression (6), including information on the equivalence of energy. Without the introduction of white noise, no assumption is made on the error between the measured and the calculated response spectra which means that the directional wave spectrum $f = E(\omega,\beta)$ can be sought in the least squares sense by solving,

$$min\,\chi^2 \equiv min\|Af - b\|^2 \quad (7)$$

Multiple peaked spectra can be dealt with by considering two independent JONSWAP models as proposed by Guedes Soares (1984), although spectra with strong frequency overlap are complicated cases. The formulation hereafter deals only with single peaked spectra.

$$S_W(\omega|H_s,T_p,\gamma) = cH_s^2 \exp\left(-\frac{1.25}{\omega_q^4}\right)\gamma^{\alpha} \quad (8)$$

with

$$c = \frac{5}{2\pi\{16T_p^{-1}[1.15 + 0.168\gamma - 0.925/(1.909+\gamma)]\}} \quad (9)$$

and $a = \exp\left[-\left(\frac{\omega_q - 1}{2\beta}\right)\right], \beta = \begin{cases} 0.07, & \sigma_q < 1 \\ 0.09, & elsewhere \end{cases}$

where $\omega_q = \frac{\omega}{\omega_p}$, $\omega_p = \frac{2\pi}{T_p}$

is the peak angular frequency and γ is the peak intensification factor. The directional spreading function is:

$$D(\beta|s,\bar{\beta}) = 2^{2s-1}\frac{\Gamma(s+1)\Gamma(s)}{\pi\Gamma(2s)} cos^{2s}(\beta - \bar{\beta}) \quad (10)$$

with $|\beta - \bar{\beta}| < \pi/2$ and $\boldsymbol{s}$ the spreading factor, $\bar{\beta}$ the mean direction of wave propagation and $\boldsymbol{\Gamma(x)}$ the gamma function.

The optimal wave spectrum estimated by the parametric method is found from the optimization of the parameters

$$\{H_s \quad T_p \quad \gamma \quad \bar{\beta} \quad s\} \quad (11)$$

The cost function in these procedures may be written in a quite general form as in Pascoal et al. (2007),

$$f = \sum_{i=1}^{N^2} e_i\, e_i^* \quad (12)$$

The errors are initially determined on a frequency by frequency basis and will have the following form for each cross spectrum,

$$e_r = W_r \frac{\{\sum_{j=1}^{L} A_{j,km}\Delta\omega \,.\, f(x_{km}) - \sum_{r=1}^{L} b_r.\Delta\omega_e\}}{\sum_{r=1}^{L} b_r.\Delta\omega_e} \quad (13)$$

where, $A_{j,km}$ is the matrix related the ship complex transfer functions $W_r = \lambda\sum_{i=1}^{M}|A_{rM}|^{-1}$ average performed on r (14), with

$$\lambda = \begin{cases} 5 & if\ r \equiv heave \\ 2.5 & otherwise \end{cases} \quad (14)$$

The value λ is considered bigger for the heave motion because it is well know that to be motion with the more accurate numerical estimates.

The ship motions considered for the estimation procedure are generally a set three motions Tannuri et al. (2003), i.e. {heave, roll and pitch} or {sway, heave, pitch}.

3. VALIDATION WITH NUMERICAL SIMULATIONS

3.1 ESTIMATIONS FOR BULK CARRIER SHIP

In order to test the parametric estimation procedure, numerical simulation based on ship motions, time series and a known one directional wave spectrum are computed in this section. Thus, it is possible to check the formulation and the program for many kinds of errors, and to some extent, the applicability and correctness of the parametric estimation.

It should be mentioned that the generated time series correspond to a specific mean heading direction between the ship and the waves. However, the estimations carried out for the generated time series does not contain information about wave direction.

The model for the first simulations is a bulk carrier of 160m length between perpendiculars, 27m of breadth and 11m of draught. Complete information is shown in the Table 1.

Table 1: Bulk carrier characteristics

Length,Lpp	161.7 m
Breadth,B	27.00 m
Draught,T	11 m
Δ	36 586 ton

The speed of advance is fixed in 15 knots for this ship. For estimation three responses were considered, i.e. heave, pitch, and roll, as was suggested by Nielsen (2005) and Tannuri et al. (2003).

The complex transfer functions are calculated using a in house software based on strip theory where details can be found in Fonseca and Guedes Soares (1998).

Genetic algorithms (GA) are a possible choice to provide an adequate basin for the convex minimization and can be applied to our problem. The GA used here was designed by Lothrop (2003) and suffered only minor changes in order to be applied to this problem. The floating point representation was chosen for all variables. Those parameters that were problem specific are provided in the Table 2, as presented by Pascoal et al. (2007).

Table 2: Considered genetic algorithm parameters.

Population	1000
Generations	30
Xover	70 % for 30 pairs
Mutate	5%

Figure 1 presents the generated and estimated wave spectra in polar form, for head waves for the bulk ship. The generated waves have a parameter Hs =2 m and Tp=12s and mean theta direction of the waves is 120 deg. The estimated significant wave height has a Hs= 2.2 m, Tp=12s and mean theta of 107 deg. The estimated wave spectra have a good agreement for significant wave height and peak wave period, however the mean theta direction present a difference of 13 deg. This happens because the discretization of headings considers 30 deg. between two consecutive headings, which can be overcome using a finer discretization for wave headings.

At least the estimated spectra have good agreement with the generated one, and the errors are acceptable.

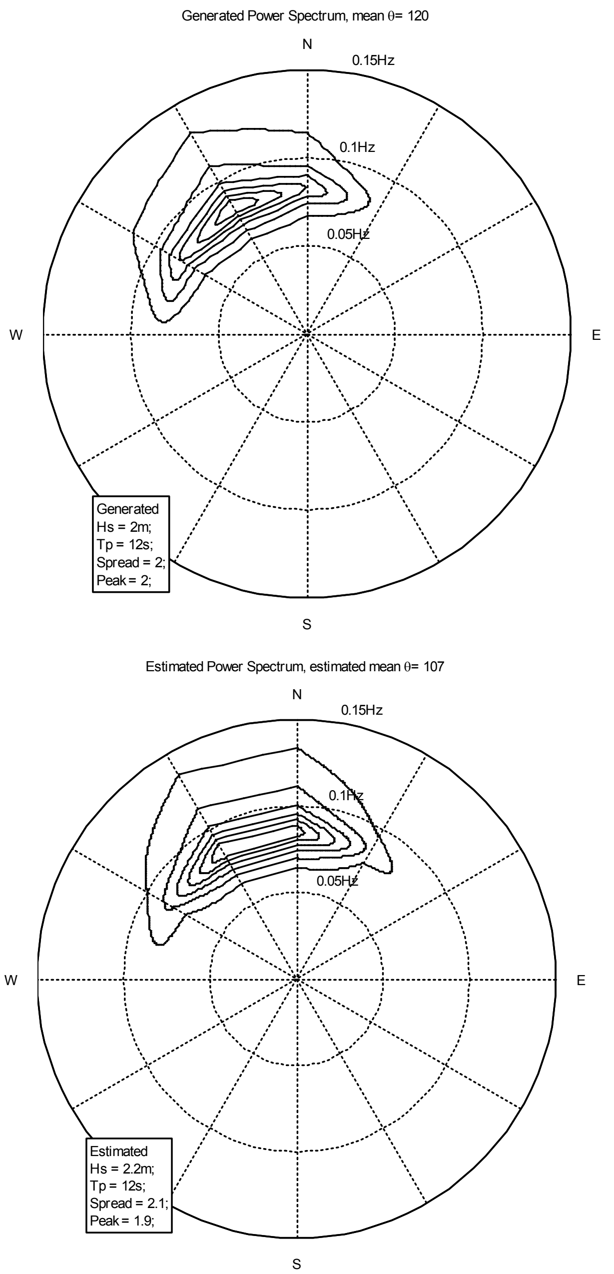


Figure 1: Directional estimations for the bulk carrier in head waves.

The Figure 2 presents the generated and estimated wave spectra for following seas on the bulk carrier, respectively. The generated wave spectrum was constructed using a JONSWAP formulation with significant wave height of 2m and peak wave period of 12s and mean theta of 60 deg. The estimated wave spectra has Hs=1.6 m and Tp=12s and mean theta =60.5 deg. The estimated wave spectra has a good agreement for the waves peak period and the mean wave direction, they are almost the same. But in the estimation of significant wave height some error arises, which is due to the fact that the minimization function depends of the energy content below the power curve. The directional spectra not only considers the three parameters discussed before but also depends on the spreading function, that as in this case compensate the error in significant wave height, because the peak enhancement factor γ of the generated spectrum was 2 and this parameters for the estimated increased to 2.2.

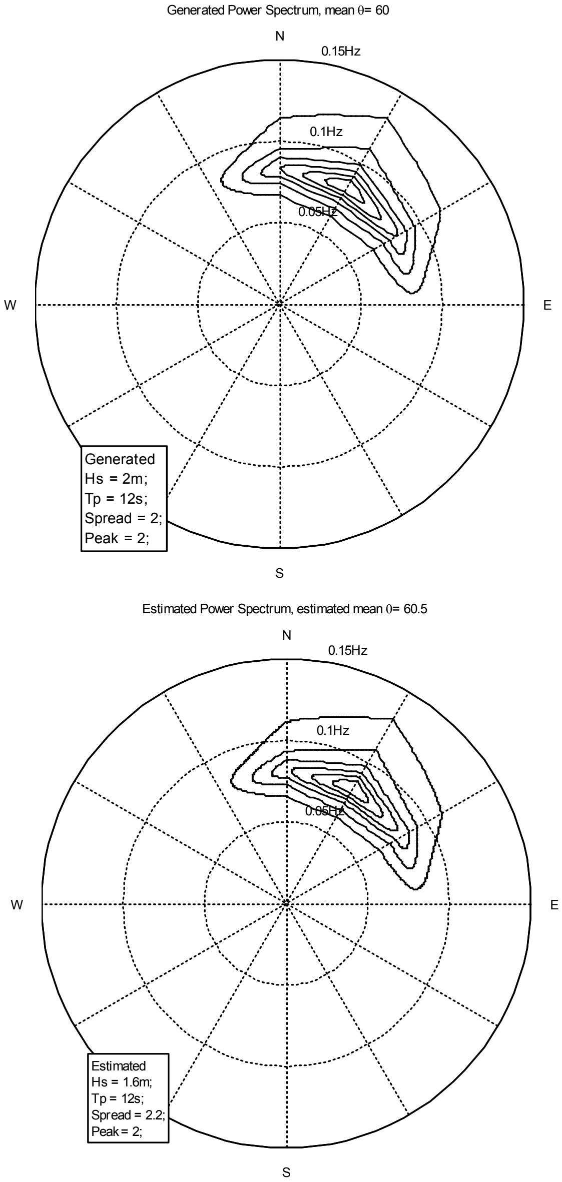


Figure 2: Directional estimations for ship 1 in following waves.

Table 3 shows the results of several estimations using the genetic algorithm for the bulk carrier. The significant wave height considered were from 0.5 to 4m and the wave period from 6 to 18 sec. From the table it is seen that the parametric modeling estimate the energy content of the wave spectrum close to the generated wave fields. Thus, the mean values of the estimated significant wave height Hs are more or less identical in the individual cases, with the exception of the cases A and D. It is seen that the error on the significant wave height is, in most of cases, less than 25% of the generated value (with the exceptions of the cases A and D). In the case of the wave peak period Tp good agreement was found in all the cases with errors less than 15%.

Table 3: Set of generated and estimated wave parameters for ship 1

Case		Hs (m)	Tp (s)	γ	β (deg)	s
	Generated	0.5	6	2	150	2
A	Estimated	0.2	6.9	2.3	130	2.2
	Error (%)	60	15	15	13.3	10
	Generated	0.75	9	2	150	2
B	Estimated	0.76	8.8	2.1	150	2.3
	Error (%)	1.3	2.2	5	0	15
	Generated	1	8	2	150	2
C	Estimated	0.75	8.1	1.9	111	2.2
	Error (%)	25	1.25	5	26	10
	Generated	1.5	10	2	150	2
D	Estimated	2.1	8.7	2.4	161	2
	Error (%)	40	13	20	7.3	0
	Generated	2	13	2	150	2
E	Estimated	1.7	12	1.8	150	2.3
	Error (%)	15	7.7	10	0	15
	Generated	2.5	12	2	120	2
F	Estimated	2.6	13	2.4	110	2.4
	Error (%)	4	8.3	20	8.3	20
	Generated	3	10	2	120	2
G	Estimated	2.4	10	1.6	123	2.5
	Error (%)	20	0	20	2.5	25
	Generated	4	18	2	150	2
H	Estimated	3.4	18	1.8	149	2.2
	Error (%)	15	0	10	0.7	10

Additionally, in order to study the reliability of the method, estimations and representations for double-peaked wave spectra are carried out. The estimations were computed for the bulk carrier described in Table 1 also the speed of advance was considered.

The model describing double peaked spectra was proposed by Guedes Soares (1984) and consequently both the swell and wind sea components were fitted by JONSWAP representations. Since the numerical conditioning of these minimization problems is very poor, it is important to start with adequate parameter estimates.

Figure 3 shows the generated and estimated of double-peaked waves in polar form for the bulk carrier. The generated wave has a parameters for swell Hs =2.5 m, Tp=10s and mean theta direction of the wave 150 deg. and for wind sea Hs= 2 m, Tp=12 s and mean theta direction of the wave 30 deg .The estimated wave system has a parameters for swell Hs =2.4 m, Tp=9.6 s and mean theta direction of the wave 150 deg. and for wind sea Hs= 2 m, Tp=10 s and mean theta direction of the wave

28.2 deg. In the case of generated wave the peak intensification and the spreading factor were fixed in 2 and the estimated values were 2.1 and 2.5 respectively.

At least the estimated spectra have good agreement with the generated one, and the errors are acceptable, however is important to mention that to obtain good estimates, adequate initial parameters should be considered.

3.2 ESTIMATIONS FOR SMALL VESSEL

The second ship is a small one of 84 m of length between perpendiculars, and 15 m of breadth. Details of the vessel are presented in table 4. In order to conduct a study of the influence of ship length, one additional ship was considered and results of the Parametric estimation for directional wave spectrum in head and following seas are presented in Figures 3 and Figure 4.

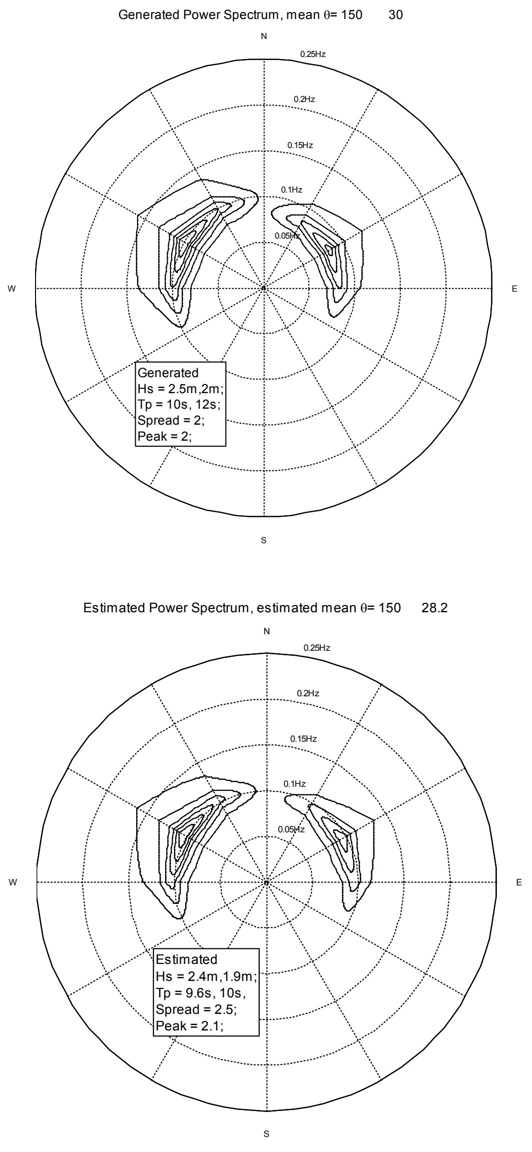


Figure 3 Double-peaked wave estimations for ship 1bulk carrier.

Figure 4 presents the generated wave spectrum and the estimated wave spectrum, for head seas on the ship 2. The generated wave spectrum has parameters, Hs=2m, Tp=12s and the mean theta direction, 120 deg. The estimated wave spectrum has parameters, Hs=1.9m, Tp=13s and mean theta direction, 115 deg. The estimation in this case was pretty good for the significant wave height and the mean theta, however the wave period present and error compared with the estimation for the bulk ship 1. This error is due to the direct relation between the estimation frequencies and the ship length. For small ship the transfer function has a resonance frequency at high frequencies and it is the reason why more significant errors appear in the wave period.

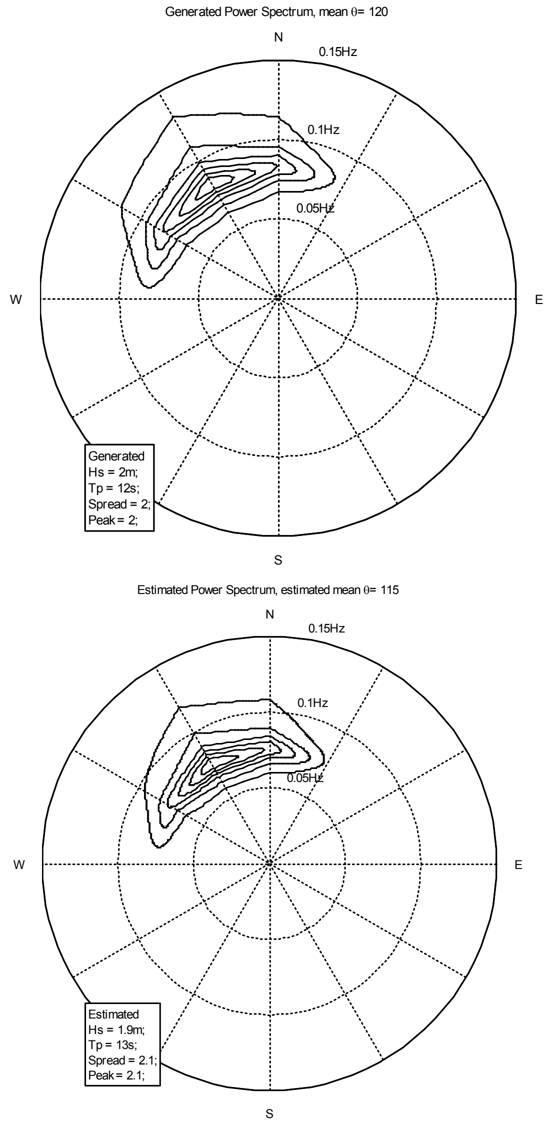


Figure 4: Directional estimations for ship 2 in head waves.

Table 4: Main characteristics of ship 2

Length,Lpp	84.1 m
Breadth,B	15.3 m
Draught,T	4.75 m
Δ	3316 ton

In order to evaluate the capabilities of the parametric method in following waves, additional estimation was carried out. Figure 5 presents the generated and estimated wave spectrum for ship 2. The generated wave spectrum has parameters, Hs=2m, Tp=12s and mean theta direction of 60 deg. The estimated spectra has Hs=2.2m, Tp=12s and men theta direction, 70 deg. In this case the estimated spectrum present small errors for all the parameters. These errors were expected because the triple-valued-problem in encounter frequency.

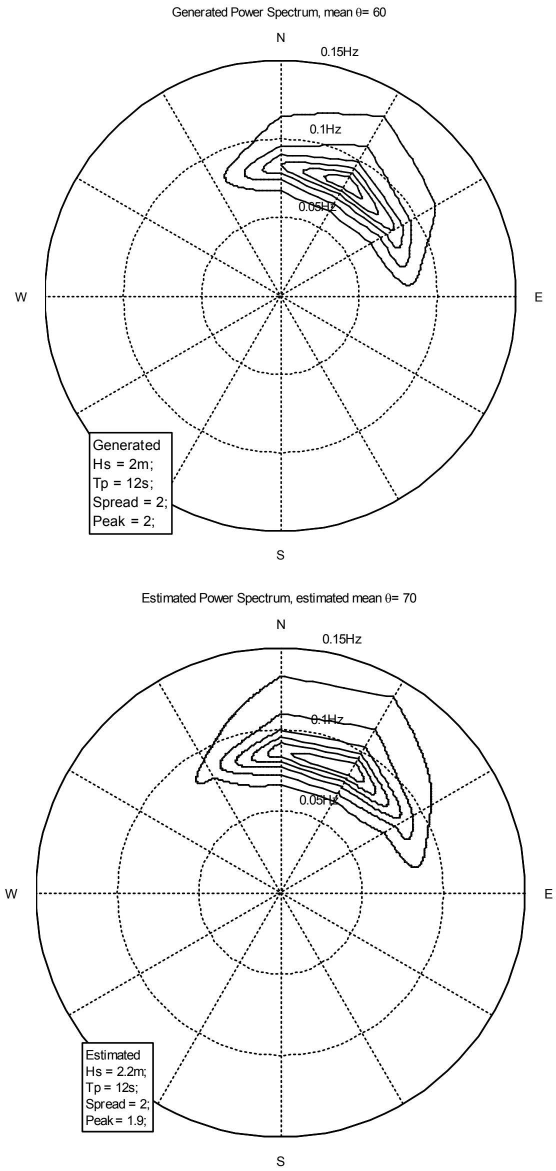


Figure 5: Directional estimation for ship 2 in following waves.

Table 5 presents the estimated sea state parameters for the same sea states as have been presented in table 4 for the parametric estimator of ship 2. As was expected the errors obtained for the second small vessel are less than the first ship. From the table it is seen that the parametric modeling estimate the energy content of the wave spectrum close to the generated wave fields. Thus, the mean values of the estimated significant wave height Hs are more or less identical in the individual cases. It is seen that the error on the significant wave height is, in most of cases, less than 20% of the generated value. In the case of the wave period Tp good agreement was found in all the cases, with the exception of the case A , It is seen that the error on the wave period is, in most of cases, less than 18% (with the exceptions of the cases A) of the generated value with errors less than 15%.

Table 5: Set of generated and estimated wave parameters for ship 2

Case		Hs (m)	Tp (s)	γ	β (deg)	s
	Generated	0.5	6	2	150	2
A	Estimated	0.53	7.9	2.4	147	1.6
	Error (%)	6	31.7	20	2	20
	Generated	0.75	9	2	150	2
B	Estimated	0.62	8.9	1.8	153	2.2
	Error (%)	17.3	1.1	10	2	10
	Generated	1	8	2	150	2
C	Estimated	0.79	8	1.7	138	2.1
	Error (%)	21	0	15	8	5
	Generated	1.5	10	2	120	2
D	Estimated	1.3	9.9	1.5	119	1.7
	Error (%)	13.3	1	25	0.8	15
	Generated	2	13	2	150	2
E	Estimated	1.6	14	2.1	146	2.4
	Error (%)	20	7.7	5	2.7	20
	Generated	2.5	12	2	120	2
F	Estimated	2.6	11	1.5	104	1.9
	Error (%)	4	8.3	25	13.3	5
	Generated	3	10	2	120	2
G	Estimated	2.7	11	2.2	115	2
	Error (%)	10	10	10	4.17	0
	Generated	4	18	2	150	2
H	Estimated	3.3	19	2.1	132	1.9
	Error (%)	17.5	5.6	5	12	5

4. VALIDATION WITH FULL-SCALE TRIALS

4.1 DEVELOPMENT OF THE DATA ACQUISITION SYSTEM

A data acquisition system for monitoring ship motions is presented in this section. The system has taken as a reference work presented in Perera et al. (2012). The system is composed by a set of sensors and equipment for navigation such as accelerometers, inclinometers, gyros, GPS, wave radar and anemometers. The system also has capabilities to monitor and record additional signals from the vessel system, i.e. from the odometer, shaft rpm, rudder order, etc. The core of the system is composed by a unit Navigation System which has a set of 3 accelerometers and 3 angular rates. In order to increase the system reliability an additional sensor was added for the monitoring of the vessel motions, i.e. OCTANS that has another 3 accelerometers and 3 angular rates. This way two sets of measurements for each ship motion was recorded, i.e. surge, sway, heave, roll, pitch and yaw. The duplication of the ship motion measurements was to reduce the uncertainty of acquired data. Namely both set of measurements were compared each other, and the data from the equipment that presents less noisy and more accurate signals was used to compute the estimations.

To synchronize all signals coming from the sensors a reconfigurable embedded control and acquisition system, Compact-Rio, from National Instruments was used. The Compact-Rio is a rugged hardware system that includes I/O modules, a reconfigurable Field-Programmable Gate Array (FPGA) chassis, and an embedded Real Time controller.

The system presented was installed onboard and tested with success in a patrol vessel of the Portuguese Navy. The tests were carried out in 'Rio Tejo', Lisbon, Portugal. The data collected is analyzed at the end of this section.

Figure 6 shows the user interface of the main LabVIEW program. In this interface are displayed all signals monitored. The picture of the small vessel in dark corresponds to the schematic representation of the ship behavior in real time. Furthermore, the wind speed and the wind direction are displayed. Other important chart presents the wave elevation. The ship speed and course over ground are also displayed in the user interface.

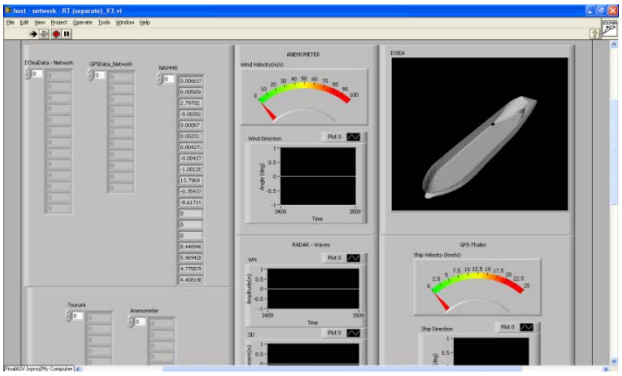


Figure 6: User interface of the data acquisition system.

4.2 DESCRIPTION OF THE FULL-SCALE SHIP TRIALS

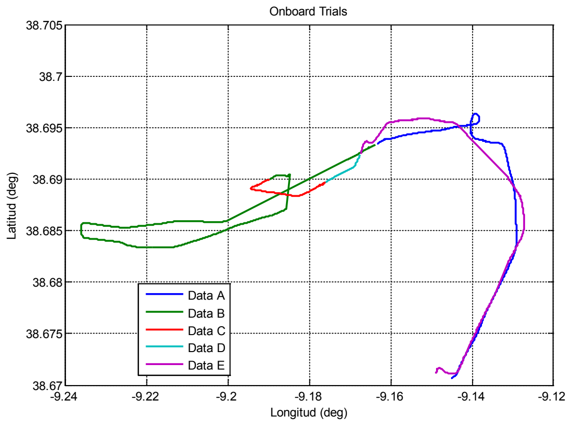
The on-board trials conducted on the Portuguese Navy vessel from the "Sagitario" class, were carried out in "Rio Tejo", with ship speeds between 7-15 knots and low wind conditions. It was not possible to plan a comprehensive program to collect full-scale data to verify the parametric estimation method. However it was possible to take advantage of a short test trip of the ship in the Tagus estuary and although the existing wave conditions were not intense enough, some measurements were made and used here.

The data from GPS and anemometer were compared with the meteorological data available from the Portuguese coast, which was found to be in reasonable agreement. The results from the two accelerometers coincide with each other. The wave records from the onboard wave radar allowed a clear distinction between the lower frequency waves and the exciting waves (supposedly around a frequency of 1.2 rad/sec). Table 6 shows the main characteristics of the Navy vessel.

Table 6: Main characteristics of the Portuguese Navy vessel "Sagitario"

Length Overall, LOA	28.4 m
Breadth, B	5.95 m
Depth,D	3.5 m
Draft,T	1.39 m
Displacement	75 ton

Figure 7 shows the set of collected data and the location of the tests.



a)

b)

Figure 7: a) Sets of data collected during the trials; b) Place of the tests, Lisbon.

Figure 8 presents the time –series of the wave elevation for the data A, obtained from the wave radar, this data has a significant wave height 0.16 m and wave period of 4.2s.

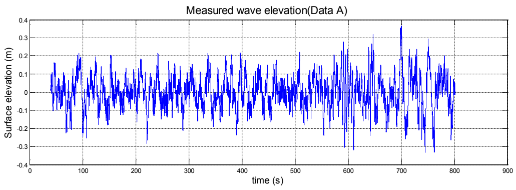


Figure 8: Time-series of the wave elevation for data A.

4.2. (a) Analysis of the results of the full scale ship trials

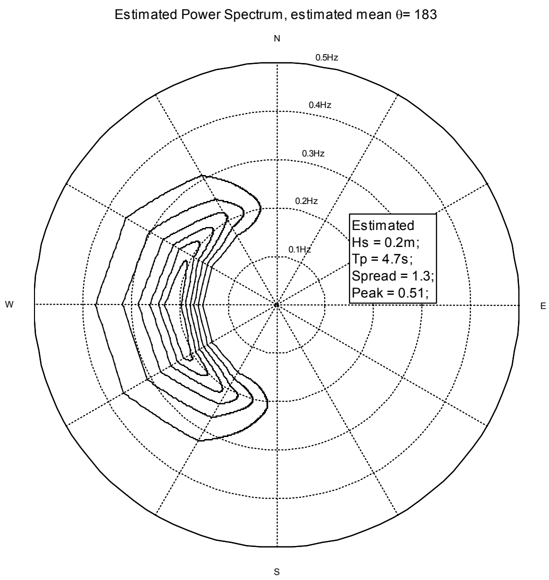
The parametric estimations for the collected data during the tests are presented in this sub section of the chapter. There are two plots for each data set: 1) The estimated spectra using the measured motions; 2) The comparison between the estimated spectra and the measured wave spectra recorded by the radar wave sensor.

The data A represents the recordings from the departure from the Navy dock until the cross under the bridge "25 de Abril". Figure 9.a shows the estimated wave spectra for data A, the significant wave height, 0.2 m and the wave period, ≈5 sec. and the mean wave direction, 183 deg. These parameters are compatible with the results of Santos et al. (1999), from which the average wave periods in "Rio Tejo" were from 5 to 7 sec. The estimations are also coherent with the presented by Rusu et al. (2009) from which the significant wave height at Tagus estuary were from 0.2 to 0.6m depending in wind direction and intensity.

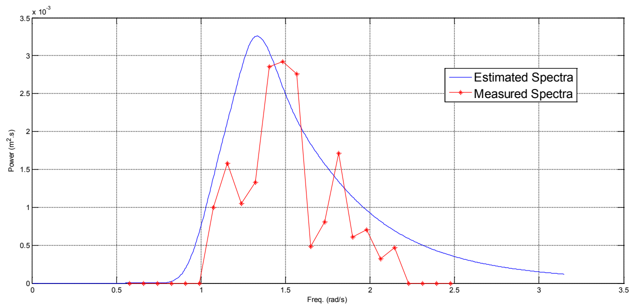
The comparison between the measured and estimated wave spectra for data A is given in Figure 9.b. The measured spectrum is plotted only in the range of the estimated frequencies. It can be seen in Figure 9.b that the measured spectrum has more than one peak. The measured and estimated spectra have similarities and also differences. The main energy of the waves is spread in a frequency range that is the same for both, although the predicted spectrum is not showing the division in two spectra. In low significant wave heights any energy in a different wave component will have an immediate effect in appearing as another peak in the spectrum. The presence of wind was not considered and the accuracy of the equipment were close to the maximum admissible value.

Table 7 presents the set of wave parameters estimated from the data recorded during the trials, the Data B are the corresponding records from the cross under the bridge and straight navigation along the river, the significant wave height, 0.4 m and the wave period, 5.3 sec. and the mean theta direction, 183 deg. The Data C are the corresponding records of "Rescue" manoeuvres (Emergency naval rescue operation of a civilian), not part of the planned test, yet was considered for analyses, the estimated wave spectrum for the data C, the significant wave height, 0.3 m, the wave period, 5.2 sec. and the mean theta direction, 215 deg. The Data D was not analyzed because it is too short, i.e. ≈8 minutes and as is known the sea-state can be considered constant every 20 minutes. The Data E represents the corresponding records of "coming back" to the Navy dock, using the same sailing path of test A, the significant wave height, 0.46 m, the wave period, 7.1 sec. and the mean theta direction, 178 deg.

These estimated parameters are also coherent with the presented by Santos et al. (1999). and by Rusu et al. (2009).



a)



b)

Figure 9: a) Estimated wave spectrum, b) Comparison between estimated and measured wave spectra for Data A.

Table 7: Estimations from the 5 runs

Data	Hs (m)	Tp (s)	γ	β (deg)	s
A	0.2	4.7	0.51	183	1.3
B	0.4	5.3	1.2	183	2
C	0.3	5.2	0.85	215	1.3
D	-	-	-	-	-
E	0.46	7.1	2	178	1.7

5. CONCLUSIONS

The feasibility of estimation of directional wave spectrum based on ship responses measurements was analysed. Good results were obtained for numerical simulations and full-scale data.

The numerical estimations were computed based on simulated time-series ship responses. These time-series were calculated using the ship complex transfer functions and known wave spectrum.

The influence of the ship length was addressed in this study and better results were achieved for small vessels than what was presented by Pascoal et al. (2007).

The influence of following waves affects negatively the estimations, due to arise of the triple-valued of the wave encounter frequency.

A system for monitoring of ship responses was developed and tested with success on a Navy vessel. The LabVIEW environment was used for programming the system, representing an advantage since the time spent on programming was reduced. The hardware used has low power consumption, thus it can be installed in several ships without "disturbing" the vessel normal power consumption.

The use of redundant accelerometers and inclinometers improved the reliability of the vessel motions recordings.

The estimation of the wave characteristics in "Rio Tejo" was presented and good results were achieved. Five different recorded data was analysed and the average significant wave height was and wave period were 0.4m and 6s, respectively.

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