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The Naples Systematic Series – Second part: Irregular waves, seakeeping in head sea

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ABSTRACT

The main aim of this study is to characterize the dynamic behavior of the *Naples Systematic Series* (*NSS*) in irregular head sea. A further aim of the study is to provide data to detect the influence of hull form on the seakeeping performances in the planing and semi-planing speed range.

The *NSS* derives from a parent hull that has shown to behave well in rough seas, characterized by high deadrise angles of the bottom at the bow, to reduce acceleration. All the models of NSS were tested in three different sea states and in Fr range from 0.515 to 1.197. The relatively high Froude numbers associated with the forms of the series make inappropriate the statistical analysis usually carried out to describe the behavior of the displacement ships.

To overcome these unsuitableness, Cartwright Lounguet Higgins, extreme value and normal distribution fittings have been furnished for heave and pitch maxima and minima; gamma and extreme value have been furnished to represent acceleration in the centre of gravity and bow.

Finally, a case study is presented to show a useful procedure for designer evaluation.

1. Introduction

To build an experimental campaign on a systematic series gives the opportunity to correlate single feature of the hull form to performance: the systematic variation of the hull shape allows to keep a strong affinity between the models, reducing the influences of other hidden form variations. (see Figs. 9–15)

The Naples Systematic Series (*NSS)* published in De Luca and Pensa (2017), furnish characterization of hull forms highlighting the influences of the slenderness ratios L_{WL}/B_{WL} and Ⓜ in terms of performance in calm water. In this study the experiences are extended to the ship motions and accelerations in irregular head sea.

The high-speed hard chine hulls undergo hydrodynamic pressures that grow up with speed, to reach the full planing. This dynamic implies, mainly in rough water, significant variation of trim, sinkage and wetted surface due to the strong and quite impulsive variations of hydrodynamic pressure. These circumstances make a strongly non-linear seakeeping behavior of the planing and semiplaning hulls and, consequently, the classical performance representation made by the response amplitude operators based on the first order cannot be used, as described in Fridsma (1971).

To overcome these difficulties in Fridsma (1971) and in Zarnick and Turner (1981) the extended campaigns of tests carried out on prismatic hulls in head sea have been analysed applying Cartwright Lounguet Higgins, CLH, and exponential probability density function, PDF, to describe respectively heave-pitch motion and vertical acceleration. All these results show very high peak acceleration, suitable represented by an exponential distribution. Differently, due to the hull forms studied by this work, the data measured shown not negligible negative maxima in the vertical acceleration trends. To take into account these negative maxima values and to fit them effectively, it was decided to adopt extreme value distributions; also Gamma distribution was fitted, according to Taunton et al. (2011) nevertheless extreme value PDF returns the best fitting. Begovic et al. (2016), referring to the typical seakeeping behavior of planing craft, describe heave and pitch maxima and minima and three different PDF. These data have been fitted with the statistical functions Normal, CLH, and extreme value. Differently, for the acceleration maxima, the functions Exponential, Gamma and Weibull have been applied.

Studies on the behavior in rough water (regular or irregular) of Hull Systematic Series, where presented by Soletic (2010), Taunton et al. (2011) and Grigoropoulos and Damala (2011). Soletic (2010) presented the seakeeping performances of the US Coast Guard Systematic series -

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Nomenclature & abbreviations

$A_{1/n}$	Mean of 1/n highest amplitude of a generic magnitude
A_X	Area of maximum transverse section (m^2)
A_T	Area of transom (m^2)
B	Beam or breadth, moulded, of ship hull (m)
bh	Bare hull
B_{WL}	Maximum moulded breadth at water line (m)
f_p	Peak frequency
Fr	Froude number
Fr_B	Froude number based on breadth
Fr_∇	Froude displacement number
g	Acceleration of gravity
CG	Centre of gravity
$H_{1/n}$	Mean of 1/n highest height of a generic magnitude
Hs	Significant wave height (m)
KM	Transverse metacentre above keel (m)
K44	Roll radius of gyration (m)
K55	Pitch radius of gyration (m)
L_{CG}	Longitudinal centre of gravity (m)
L_{WL}	Length of waterline (m)
Ⓜ	Length-displacement ratio ($L/\nabla^{1/3}$)
RT_{Mw}	Total resistance of model in waves (kg)
RT_M	Total resistance of model (kg)
T	Draught, moulded, of ship hull (m)
Tp	Peak period (s)
V_{CG}	Vertical centre of gravity (m)
β_T	Deadrise at the transom (deg)
$\beta_{0.5}$	Deadrise at 0.5 L_{WL} (deg)
$\beta_{0.75}$	Deadrise at 0.75 L_{WL} (deg)
Δ	Displacement (buoyant) force (kg)
γ	Overshoot parameter
τ_S	Trim at rest (deg)
CDF	Cumulative Distribution Function
CLH	Cartwright Longuet Higgins
DII	Dipartimento di Ingegneria Industriale
NSS	Naples Systematic Series
PSD	Power Spectral Density

published in Kowalyshyn, D.H., Metcalf, B., (2006) in the speed range $Fr_B = 0.28–2.63$. Grigoropoulos and Loukakis, 2002 describe the behavior of the NTUA Double-Chine hull series in pre-planing speed range. Taunton et al. (2011) presented the seakeeping performances of stepped hulls, whose performances in calm water where presented in Taunton et al. (2010). Data is presented in terms of probability distribution and, applying ISO 2631, vibration dose factor, pointing the attention on human factor performances. The models have constant dead-rise and have been tested in the speed range $Fr_B = 1.75–6.77$.

Rosen and Garme (2004) and Camilleri et al. (2018) highlighted the impact pressure distribution on the bottom of planing craft in waves.

In De Luca, F and Pensa, C. (2012), the effects of the conventional and unconventional interceptors on the performances in regular waves have been presented. The tests have been carried out on monohedral hulls in the speed range $Fr_\nabla = 1.1–3.3$.

2. Models tested and experimental plan

The models of the *NSS*, published in F. De Luca & C. Pensa (2017), are hard chine hulls characterized by five affine stretched models, build with warped bottom and $A_T/A_X < 1$.

The models where tested in the Towing Tank of the *DII* of the *Università degli Studi di Napoli* "*Federico II*" whose main characteristics are: length 136.0 m, width 9.0 m and deep 4.5 m; maximum speed of the carriage 10.0 m/s. The tests were performed in ranges Fr = 0.5–1.6 and $Fr_\nabla = 1.1–4.3$. Therefore, the hulls are affected by a high dynamic lift. The series is composed by 5 geometries and 7 models: the two geometries with lower L/B ratios – C1 and C2 - have been built in two scales of reduction: the smaller models have been built to overcome instrumentation limits in seakeeping tests. These smaller models are indicated in Table 1 with C1s and C2s.

One displacement and mass configuration for each model were tested in waves. Tables 1 and 2 show the experimental plan.

As suggested by Fridsma (1971), the dynamic behavior in rough water was detected by testing the models at a constant speed because little or no surge motion arises for this kind of planing craft.

The study of unsteady phenomena needs a great number of tests to make reliable the statistical approach necessary to analyse the data logged. A large experimental campaign, introduces the critical issue of the comparability of tests performed in different moments and on different models. Particular care was taken of data acquisition and analysis of models set up and wave generations.

Table 1
Main dimensions and speed range of tests.

Model		C1s	C2s	C3	C4	C5
L_{OA}	(m)	1.567	1.567	2.611	2.611	2.611
L_{WL}	(m)	1.440	1.440	2.400	2.400	2.400
B_{WL}	(m)	0.446	0.396	0.577	0.493	0.41
L_{CG} ($\tau_S = 0$)	(m)	0.567	0.567	0.945	0.945	0.945
Δ	(kg)	26.52	20.91	73.93	54.12	37.4
Ⓜ		4.83	5.23	5.72	6.34	7.18
A_T/A_X		0.94	0.94	0.94	0.94	0.94
L_{WL}/B_{WL}		3.23	3.64	4.16	4.87	5.85
B_{WL}/T		4.12	4.12	4.12	4.12	4.12
V_{CG}/B_{WL}		0.50	0.50	0.50	0.50	0.50
K_{44}/B_{WL}		0.40	0.40	0.40	0.40	0.40
K_{55}/L_{WL}		0.25	0.25	0.25	0.25	0.25
β_T	deg	13.2	13.2	13.2	13.2	13.2
$\beta_{0.5}$	deg	22.3	22.3	22.3	22.3	22.3
$\beta_{0.75}$	deg	38.5	38.5	38.5	38.5	38.5
Fr	Test n° 1–2 - 3	0.720	0.720	0.720	0.720	0.720
	Test n° 7–8 - 9	0.928	0.928	0.928	0.928	0.928
	Test n° 13-14-15		1.197			0.515

Table 2
Sea state and spectrum parameters tested.

test n°	Spectrum	γ	Hs (m)	Tp (s)	f_p (1/s)
1-7-13	JONSWAP	3.3	0.045	1.176	0.850
2-8-14	JONSWAP	3.3	0.060	1.356	0.737
3-9-15	JONSWAP	3.3	0.075	1.52	0.660

2.1. Set-up of models

The first goal is to set the CG position. The L_{CG} position is chosen to have no trim in static condition. V_{CG} is set to make V_{CG}/B_{WL} ratio constant for all the models. To obtain the desired L_{CG} and V_{CG}, the models were suspended on a pivot free to pitch and roll shown in Fig. 1. The models were positioned to have the pivot at the desired CG and the mobile mass was disposed to obtain the zero trim. Then a procedure like an inclining test was made to calculate V_{CG}. Differently to the standard inclining test the model is constrained to rotate around a fixed point (the pivot) so large angles are allowed overcoming the limit of the metacentric method and the uncertainty due to the calculation of KM.

The ITTC, 2011 procedures to perform sea keeping tests in Towing

Fig. 1. Setting of L_{CG}, V_{CG} and radii of gyration.

Tank suggest the evaluation of the real values of radii of gyration of ship. If they are preliminary unknown, a value of 0.25 L_{OA} for pitch or yaw and a value between 0.35B and 0.40B for transverse radius of gyration could be considered.

Since the models tested in towing tank can be referred to hull with different L_{OA}/L_{WL} and B_{OA}/B_{WL}, to compare the performances of the five models, it was considered appropriate to refer to WL instead OA dimensions.

To obtain the desired radii of gyration, the models were suspended at the same pivot shown in Fig. 1 and oscillated. The frequencies and angles measured made possible to evaluate the achieved radii of gyration.

2.2. Gauges settings

The acquisition of the accelerations has been carried out by two triaxial accelerometer Cross Bow CXL04GP3-R-AL, the characteristics of which are: Input Range (g)$\pm$ 4, Sensitivity (mV/g) 500 $\pm$ 15, Noise (mg rms) 10 and Bandwidth (Hz) DC -100. One accelerometer is positioned at the center of mass G, the other at 0.5 L_{WL} forward of G.

The Towing system (TC system) used allows controlling the thrust direction through a laser tracking. For the entire series the angle of shaft line was fixed to 8 deg and the vertical component of the thrust has been considered to take in to account the effects of this on lift and trim.

As shown in Fig. 2, the resistances of the models were measured by a HBM Load cell (PW115AH 20 kg, accuracy Class III) fixed on the forward end of the controlled shaft. The aim of the control was the constancy of the thrust direction.

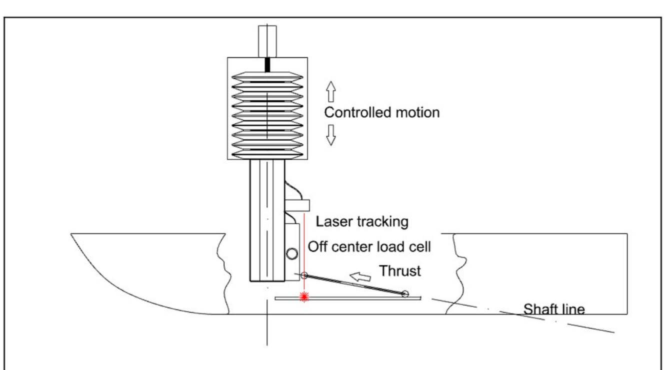

Fig. 2. Description of the towing system.

The measurement of body motion was made with *Qualisys Motion Capture System* that is known as a high-quality optical system for position tracking in engineering applications, allowing sub-millimeter accuracy.

To verify the waves profile achieved with the wave-maker, two different kind of sensors were used: two capacitive probes ACAMINA AWP-24-2 Wave Height Gauges and four ultrasonic probes Baumer UNDK 30U6103. The capacitive probes, more precise, have been fixed to the towing tank, the ultrasonic probes were fixed to the carriage and, therefore, were following the models during the tests.

2.3. Data analysis

The data were sampled at a frequency of 500 Hz. To overcome the aliasing problems, the oversampling techniques were applied. Subsequently the data were filtered with a Butterworth bandpass filter of the fifth order 0.05–20 Hz according to g *method* guidelines Riley et al. (2016).

The mean value of accelerations, heave and pitch, have been removed from the measured data. To reach a sufficient number of encounters (about 200) several tests (not less than 15) have been concatenated overlapping the extreme values of the acquisitions on the zero up crossing.

Fig. 3 shows an example of data with and without the application of the Butterworth filter. The positive maxima accelerations refer to the impact on the water (see Fig. 4).

To estimate online the wave spectrum and ensure the good fit to the target the Welch method has been adopted, Welch (1967), that is a refinement of the Bartlett method, Bartlett, 1948. The Welch method reduces the large fluctuations of the periodogram splitting up the available sample of N observations into equal subsamples of M observations each, and then averages the periodograms obtained from the subsamples for each value of frequency. The Welch method enhances the Bartlett method through two ways: first, the data segments in the Welch method are allowed in windows partially overlapped; second, each data segment is windowed prior to computing the periodogram. Finally, the power spectral density, PSD, is determined by averaging the windowed periodograms. In this work, the data were split in windows of about 4000 samples and the overlapping was of 60%.

The reductions of the large fluctuations of the periodograms obtained by the overlapping suggested by the Welch procedure, ensure an effective smoothing between each window and a high control over the bias resolution properties of the estimated PSD.

2.4. Wave generation

All the models were tested in three different sea state (SS) irregular head sea. The SSs taken into account are shown in Table 2. The SSs have been chosen considering the main goal of the hull C 954 that is the geometry from which the *NSS* was developed for. The model C 954 was designed to sail in coastal route in waves well characterized by JONSWAP spectra. Moreover, the SSs were chosen considering the need to compare the behaviours of the five models. This need has led to some considerations on the scale factors. In particular, due to the wide range of slenderness ratios of the models, the ship dimension of reference of the models is significantly different. In particular, the C1 and C2 models, whose Ⓜ are smaller, refer to ships dramatically smaller than those of C5 and quite different respect to C4. For these reasons, to compare the seakeeping behavior of all the models, C1 and C2 geometries have been built also in smaller scale: 0.6 in respect to C1 and C2. These new models have been named C1s and C2s.

With these new scale factors, it is possible to compare the tests performed respectively in test 3 and 7 on models C3, C4, C5 with tests performed in tests 1 and 9 on models C1s and C2s.

To ensure meaningful comparisons, it has been necessary to refer the behaviours of all the models, strictly to the same wave spectra and, therefore, to the same nominal spectra. In operational terms, the

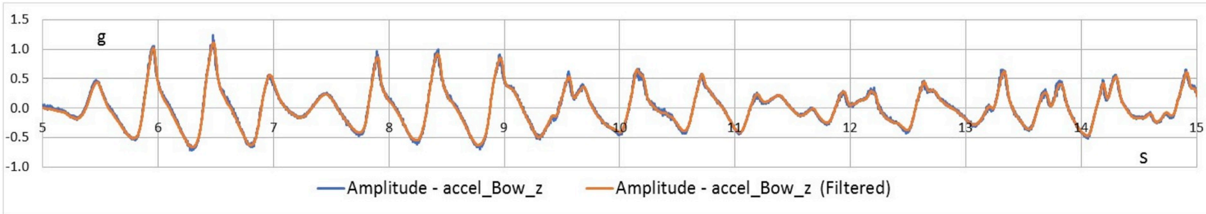

Fig. 3. Example of filtering of the acceleration signal.

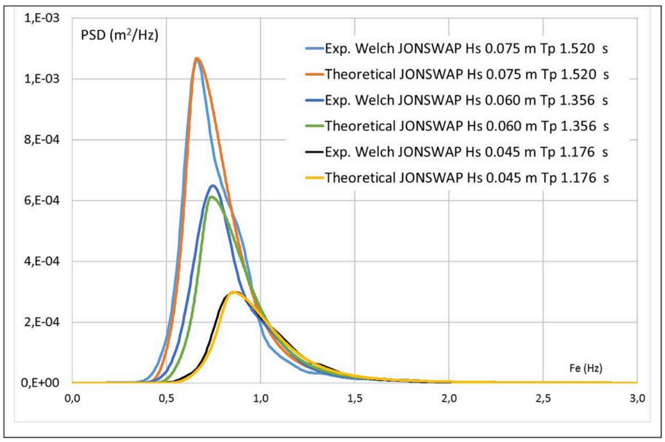

Fig. 4. Comparison between experimental and theoretical spectra.

problem ended up controlling the wave maker actions. In detail, the heights of the generated wave have been measured through capacitive probes arranged in three longitudinal positions of the tank and the following operations have been carried out:

1) irregular sea generation and measurement with reference to capacitive probes;
2) comparison between the theoretical spectrum and the realized spectrum;
3) creation of an ad hoc transfer function;
4) verification of the generated spectrum (three acquisitions of at least 200 encounters).

This procedure has been carried out at the beginning of the experimentation of each model. By each new wave calibration, the transfer functions have been verified for every experimental session.

3. Results

For all the models and all the sailing conditions, heave, pitch and vertical accelerations have been measured logging the instantaneous values, whereas the resistances have been presented as mean values.

The data has been analysed both in time and frequency domain. To improve the analysis quality of the results in time domain, heave, pitch and accelerations have been synchronized with the wave profile measured at the G. Due to the great amount of data, only some examples of time traces have been shown in graphic form. Fig. 5 shows the synchronized patterns of all the physical quantity measured.

The following Fig. 6 shows the response of the hull C1s in frequency domain for all test conditions. The response spectra are expressed in terms of spectral density (rms^2 per hertz unit) respect to the encounter frequency.

Table 3 shows, for each test performed, the wave resistance ratio expressed as RT_{Mw}/RT_M.

To highlight the influence of the speed on the resistance in wave, in the following Fig. 7 the same data given in Table 3 are classified by Fr.

To read correctly Fig. 7, referring to Tables 1 and 2, it is important to remark that:

- tests from 13 to 15 for model C2s refer to Fr 1.197, differently, for C5 model refer to Fr = 0.515.
- C1s and C2s are on a smaller scale, and it is possible to compare the tests performed respectively in test 3 and 7 on models C3, C4, C5 with tests performed in 1 and 9 on models C1s and C2s.

Anyway, histogram is aligned to simplifying the comparisons.
It is possible to notice that (Fig. 7):

- the higher the speed the lower the increasing of resistance for all the models, in all the three SSs tested, the phenomenon is amplified for the higher slenderness ratio.
- the resistance increases from model C2s to C5 together with the increase of Ⓜ and L/B
- the trend changes for the C1s model

All the statistics on results of the tests have been shown in tabular form in Appendix II. Nevertheless, to facilitate the overview of the behaviours of the models, the synopsis of motions heights and accelerations maxima has been shown, by the following Figs. 8 to 11, only for the mean of 1/3 highest values. The histograms are arranged using the same logic of Fig. 7.

For a correct interpretation of the histograms above shown (Figs. 7 to 11), it is well to remember that the four models derived from the parent hull C1 were developed by scaling depth and breadth by the same reduction factors, maintaining homothetic forms of all the transversal sections. These transformations, increasing both L/B and Ⓜ, imply that the different models, even if they are of the same length, are characterized by different displacements. For this reason, for example, the slenderest model C5 have to be considered a significantly smaller model respect to the C1s or C2s ones and, consequently, the worst performances, in terms of motion and accelerations, are mainly to relate with the different absolute dimension of the ships.

On this basis, to avoid misunderstanding in the interpretations of the histograms, it is suggested to compare the performances varying speed and sea state on the same models. Following this way, it is possible to observe that:

- for high slenderness ratio (C4 and C5), with the increasing of the Fr the pitch angles decrease;
- for intermediate or low slenderness ratio, the dependencies of the pitch angles on the Fr is not monotonic;
- the same tendencies are observable in the Heave histograms;
- regarding the accelerations, for each sea states, the speed is a significant influencing factor.

4. Data representation

To provide an agile tool to represent the results, the data has also been fitted with statistical distributions.

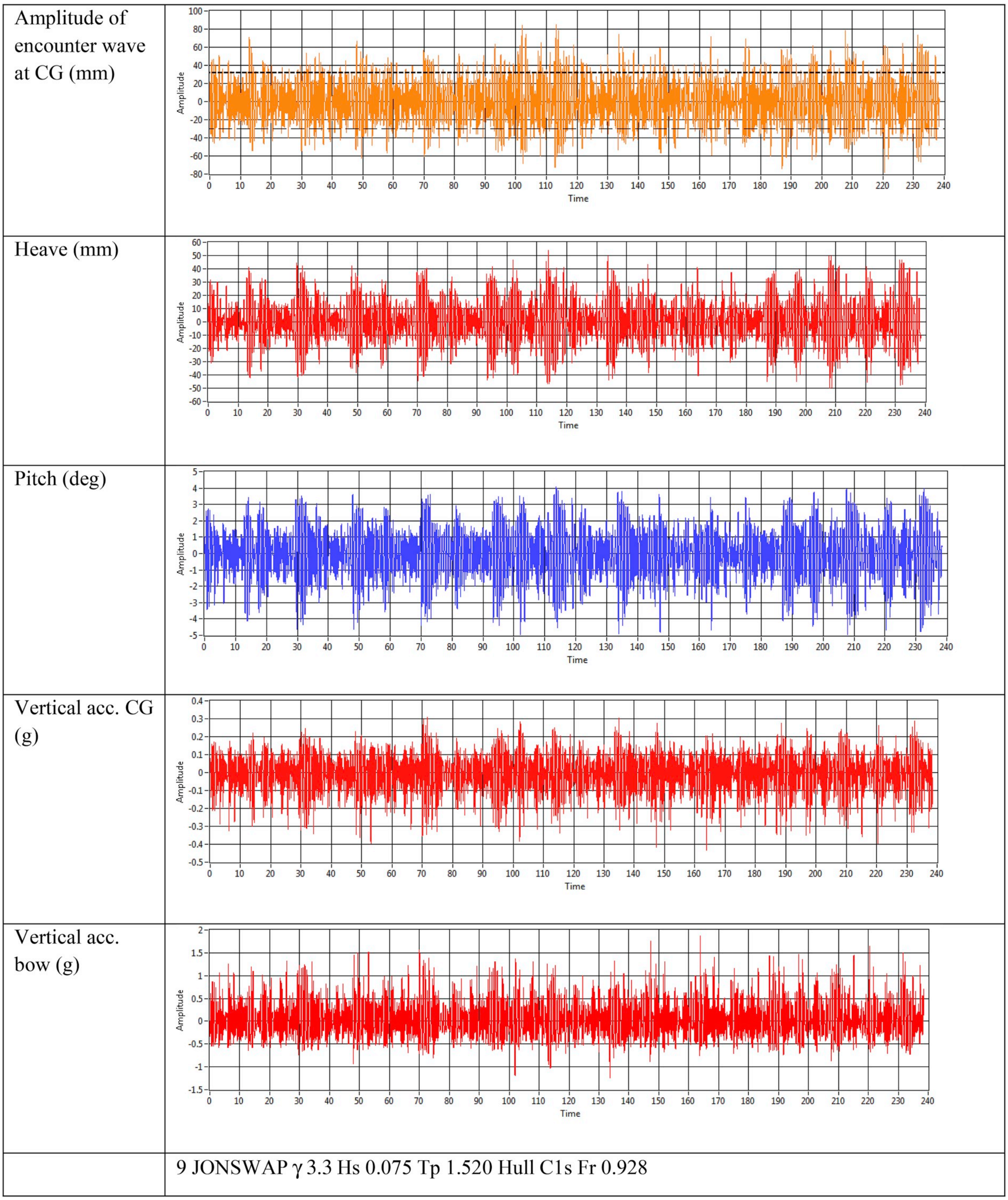

Fig. 5. Synchronized patterns of signals acquired.

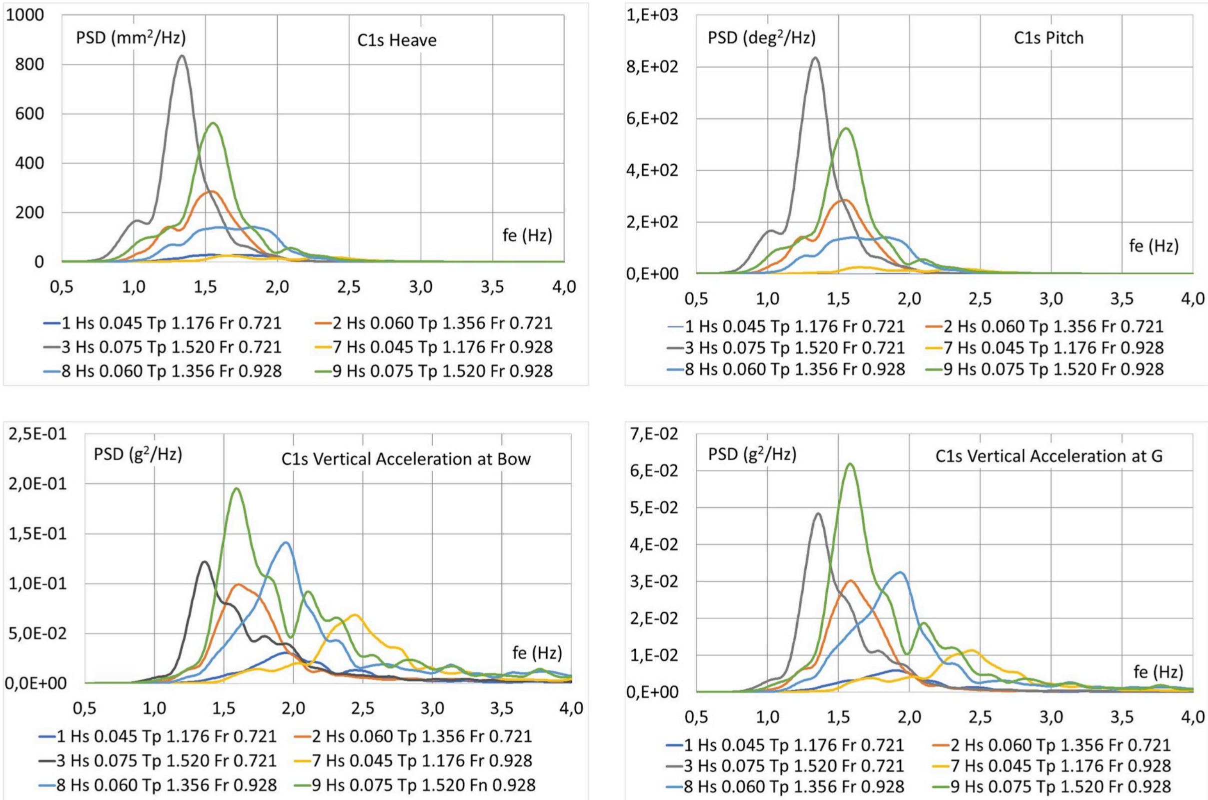

Fig. 6. Response spectra for C1s model.

Table 3
Wave resistance ratio.

Test	C1s	C2s	C3	C4	C5
1	1.03	1.01	1.01	1.02	1.03
2	1.05	1.02	1.01	1.03	1.06
3	1.05	1.03	1.03	1.06	1.07
7	1.04	1.02	1.01	1.00	1.01
8	1.04	1.02	1.02	1.02	1.02
9	1.04	1.02	1.03	1.04	1.05
13		1.02			1.07
14		1.02			1.08
15		1.02			1.10

The magnitudes under consideration are maximum and minimum of pitch and heave; and the maximums (impacts) of vertical accelerations at the centre of gravity and at the bow.

The PDF functions used are the following:

Normal:

$$\text{PDF: } f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{x-\mu}{2\sigma^2}} \tag{1}$$

Were x is the continuous random variable normalized by the process RMS, μ the mean value and σ the standard deviation of the quantile.

Extreme:

$$\text{PDF: } f(x) = \frac{1}{\beta} e^{\left(-\frac{x-\alpha}{\beta}\right)} e^{\left(-e^{\left(-\frac{x-\alpha}{\beta}\right)}\right)} \tag{2}$$

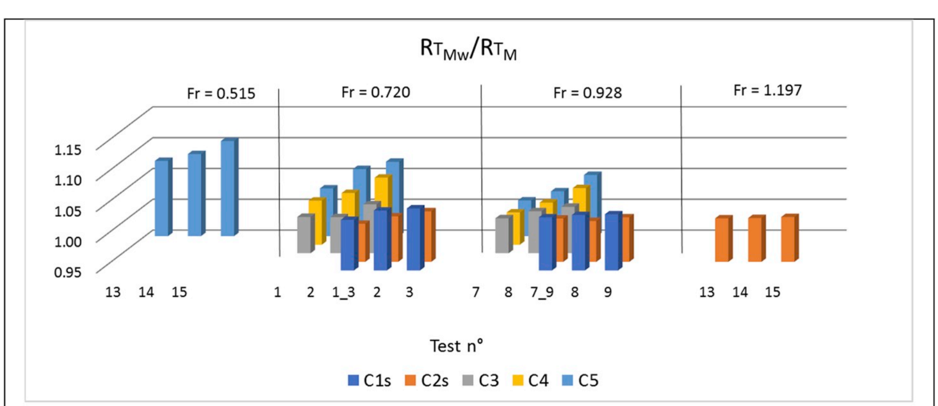

Fig. 7. Wave resistance ratio.

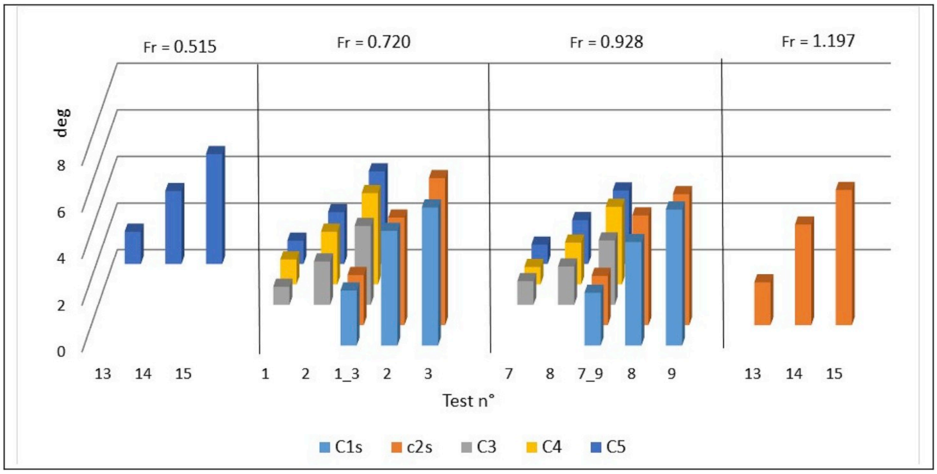

Fig. 8. 1/3 significant pitch motion.

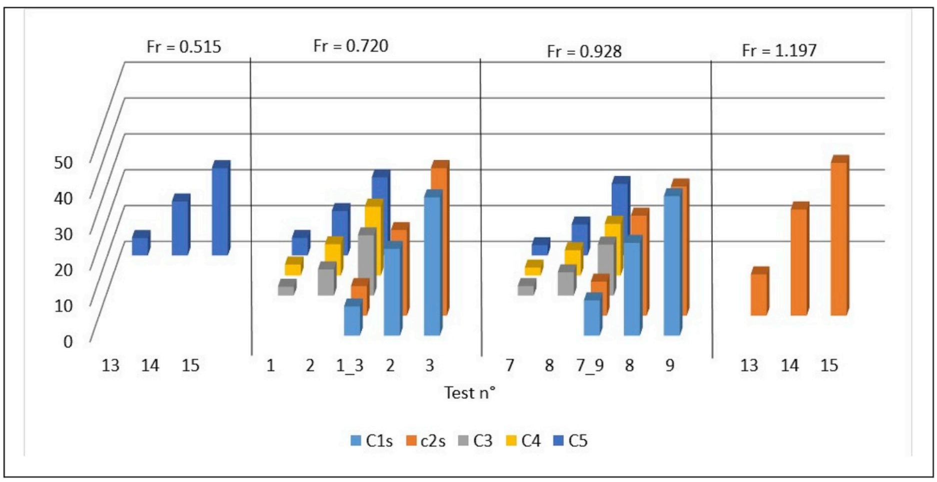

Fig. 9. Non-Dimensional $H_{1/3}$ significant heave ($H_{1/3}/L_{WL}$).

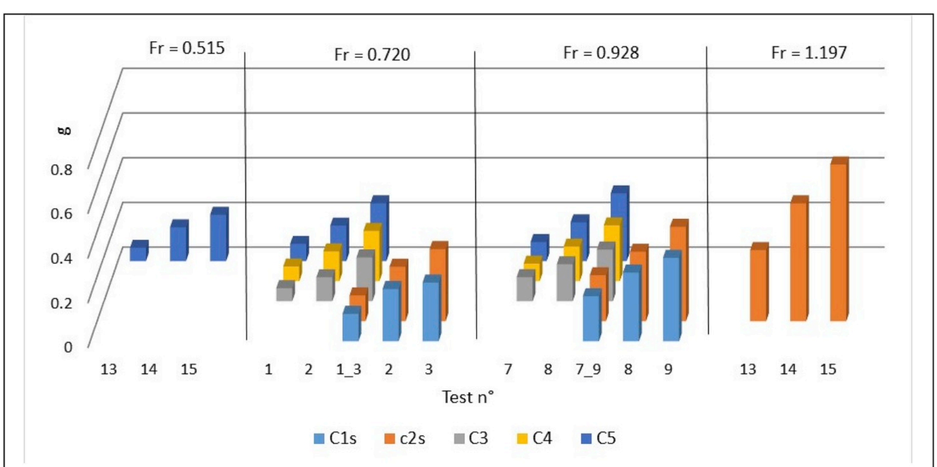

Fig. 10. Vertical acceleration maxima at G.

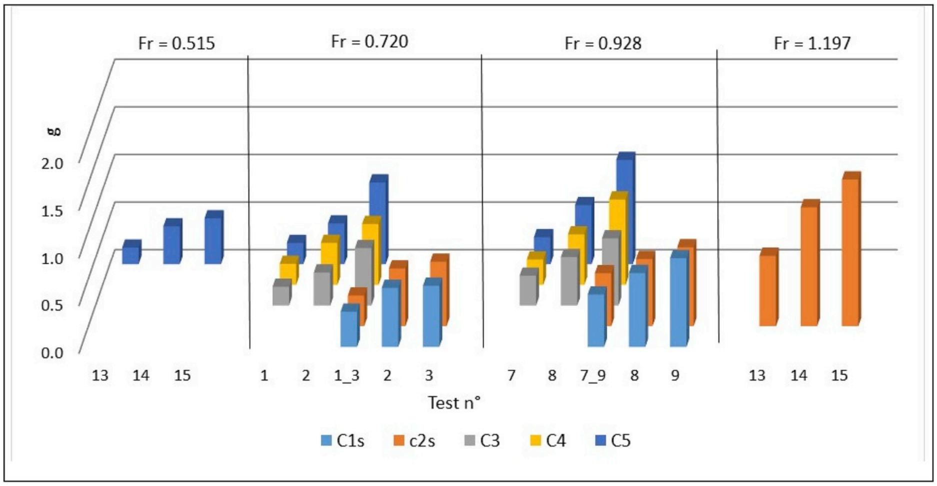

Fig. 11. Vertical acceleration maxima at bow (0.5 L_{WL} fwd G).

Where α is the location parameter and β is the scale parameter.

Cartwright Longuet Higgins, CLH, Cartwright and Longuet-Higgins, 1956:

$$\text{PDF: } f(x) = \frac{1}{\sqrt{2\pi}}\left[\varepsilon e^{-\frac{x^2}{2\varepsilon^2}} + x\sqrt{1-\varepsilon^2}\, e^{-\frac{x^2}{2}} \int_{-\infty}^{x\sqrt{1-\varepsilon^2}/\varepsilon} e^{-\frac{y^2}{2}} dy\right] \tag{3}$$

$$\varepsilon^2 = 1 - (1-2r)^2$$

Where ε is the bandwidth parameter and r is the determined proportion of negative maxima to total maxima.

Gamma:

$$\text{PDF: } f(x) = \left(x/_{\alpha}\right)^{\beta-1} e^{-x/_{\alpha}} \Big/ \alpha\Gamma(\beta) \tag{4}$$

where.

α is the scale parameter of the random variable
β is the shape parameter of the random variable
$\Gamma(\beta)$ is the gamma function of β.

The CLH, Extreme and Normal was used to represent pitch and heave maxima and minima.

Differently from what reported in Begovic et al. (2016) and in Taunton et al. (2011), the residues shown in Appendix III highlights that Extreme PDF returns a better fitting than CLH.

To represent maxima of accelerations, Gamma function were fitted following the literature knowledge but noticing the relevant presence of negative maxima, Extreme PDF was also adopted on acceleration returning the best fit for the test performed.

The Levenberg-Marquardt method, L.M. has been used to fit probability density function on experimental data. It is fully described in Nocedal, Jorge at al. (2006). It consists in a non-linear curve fitting method to calculate the best-fit parameters that minimize the weighted mean square error between the observations Y and the best nonlinear fit y.

$$y[i] = f(x[i], a_0, a_1, a_2, \ldots) \tag{5}$$

Where a_0, a_1, a_2, …are the Parameters.

The L.M. method is an evolution of Gauss-Newton method; the main difference consists in a positive definite diagonal matrix added to the Hessian matrix to avoid the weakness of the singular Hessian matrix.

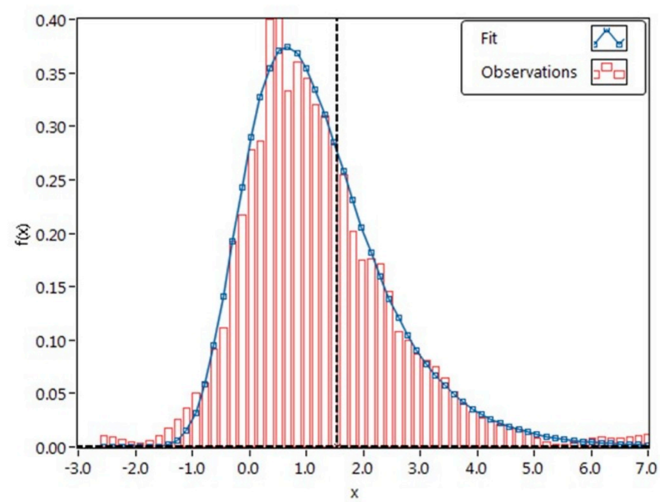

Fig. 12. Example distribution of bow acceleration maxima, TEST 02 c2s. Exstreme distribution, RMS = 0.241086, Residue 0.000290 (x = acc bow max/RMS).

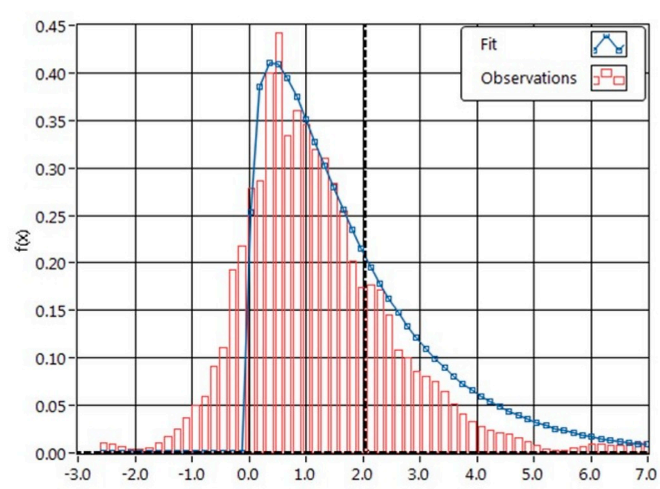

Fig. 13. Example distribution of bow acceleration maxima, TEST 02 c2s. Gamma distribution RMS = 0.241086 Residue = 0.002483 (x = acc bow max/RMS).

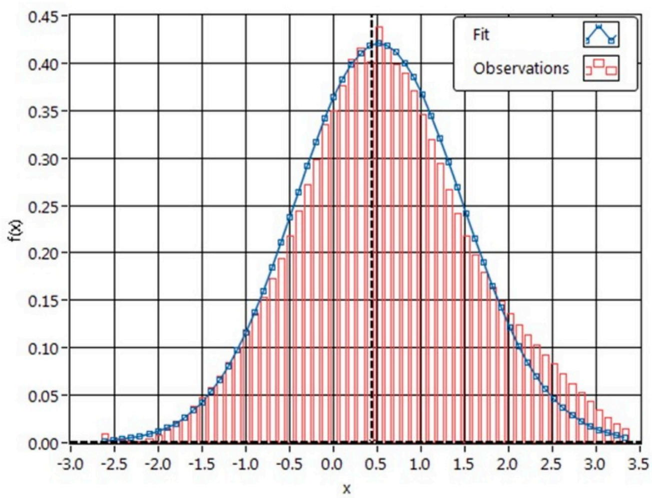

Fig. 14. Example distribution of heave maxima, TEST 02 c2s. Cartwright Longuet Higgins distribution RMS = 11.907722 Residue = 0.000301 (heave max/RMS); $\varepsilon = 0.909$.

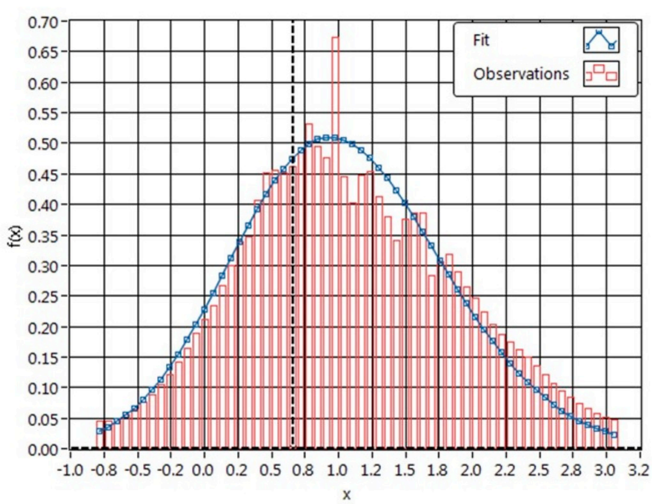

Fig. 15. Example distribution of pitch maxima, TEST 02 c2s. Cartwright Longuet Higgins distribution, RMS = 1.149339, Residue = 0.001427 (pitch max/RMS); $\varepsilon = 0.574$.

To evaluate the goodness of fitting the residue has been shown. They are defined as the mean square error between the best non-linear fit and the observations.

For the Normal PDF a direct estimation of the function is possible evaluating average and standard deviation on the data. Also Cartwright Longuet Higgins can be estimated directly following the procedure proposed in Taunton et al. (2011). The direct estimates have been made and the values have been compared with the derived output of the fitting through L.M. method without finding substantial differences, confirming the goodness of the use of the L.M. method.

The Figs. 8 to15 show some examples of fitting of accelerations, heave and pitch.

5. Conclusions

This paper shows the results of the experimentation performed on the models of the systematic series NSS, in irregular sea.

It completes the performance representation of the systematic series presented in the previous article De Luca, F, Pensa, C., (2017) where the data relating to calm water were provided.

Overall the five models were tested in about forty conditions, varying speed and sea state. To guarantee an adequate number of wave encounters, each condition was tested for no less than fifteen runs.

JONSWAP spectra (γ 3.3) were chosen because they are suitable for characterizing the weather conditions for which the hulls have been designed.

Model sizes and sea states take into account the different probable dimensions of the ships to which the individual models refer: the slender the model the bigger the ship.

The tests show a strong dependence on the slenderness factor Ⓜ. This dependence must be well interpreted remembering that the more elongated models refer to lighter ships. In other words, referring to the same wave heights, the more elongated models have been tested at same values $H_{1/3}/L_{WL}$ but at higher values of $H_{1/3}/\nabla^{1/3}$.

Appendix I. Example of application

To facilitate the designer work, the following example shows the procedure for the evaluation of the performances of a model of the NSS in a known SS.

It is assumed that we want to predict the vertical accelerations, on the bow, to evaluate the level of comfort on board of a C2s shaped craft with $LWL_S = 21.6$ m. This length implies a scale factor $LWL_S/LWL_M = 15$.

From Tables 1 and 2 we deduce the sailing conditions available on the C2s model:

Considering the *Test 09* of model C2s, we refer to the hardest context tested in Towing Tank. In particular, referring to the scale factor 15, we analyse the behavior of the craft at $V_S = 20.4$ kn (Fr = 0.928) and waves characterized by Hs = 1.125 m, Tp = 3.9 s and JONSWAP $\gamma = 3.3$ (Douglas SS3).

To compute the $A_{1/n}$ of interest, the Extreme Value PDF, 1, and his Cumulative Probability Function (F(x)), 2, have been taken into account. (Fig. 16 shows the fitting of the PDF function vs. the observation).

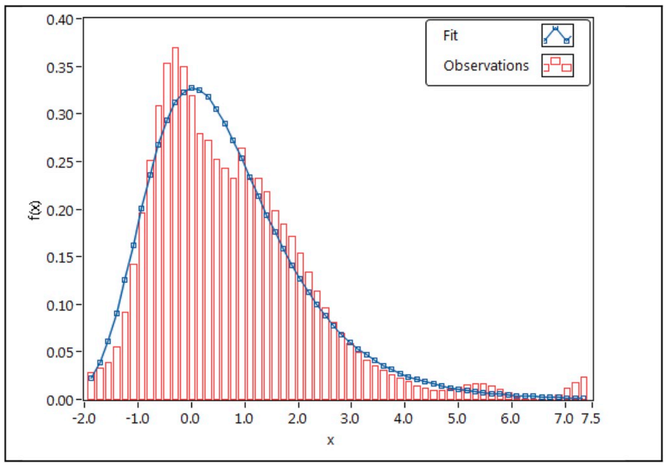

Fig. 16. Extreme distribution of bow acceleration maxima (*Test 09* of model C2s).

$$\text{PDF: } f(x) = \frac{1}{\beta} e^{\left(-\frac{x-\alpha}{\beta}\right)} e^{\left(-e^{\left(-\frac{x-\alpha}{\beta}\right)}\right)} \tag{6}$$

$$\text{CDF: } F(x) = e^{\left(-e^{\left(-\frac{x-\alpha}{\beta}\right)}\right)} \tag{7}$$

Where x is normalized by the process RMS: $x = $ acc./RMS.

In Appendix III the coefficients α and β are indicated. In this case (*Test 9 C2s)* they are: $\alpha = 0.024503$ and $\beta = 1.12437$. The same Appendix reports that RMS = 0.383.

The first step of the procedure is the evaluation of the limit value $x_{1/n}$ that is the lower bound of the Right-Tailed Area having 1/n exceeding probability. The limit value $x_{1/n}$ is calculated evaluating the inverse of the CDF function, F^{-1}, in the point (1-1/n):

$$x_{1/n} = F^{-1}(1\text{-}1/n) \tag{8}$$

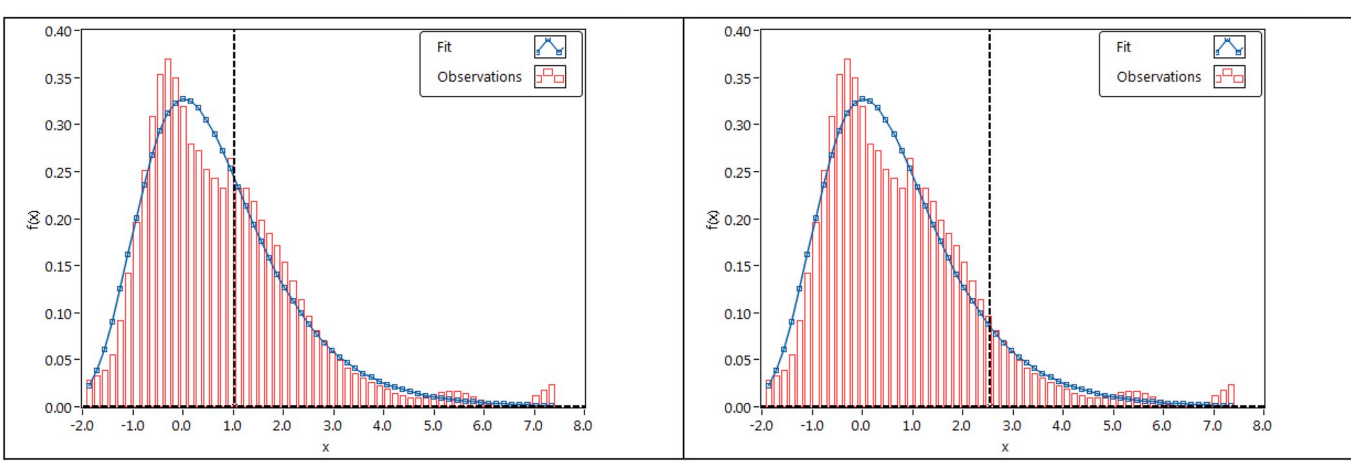

Fig. 17. Exstreme PDF of Acc Bow (*Test 09*-C2s) with limit value 1/3 and 1/10 of exceedance probability.

Whose values are shown in Table 4, both in non-dimensional and dimensional form, and with the vertical dashed lines in the Fig. 17, for n = 2 and 3.

Table 4
Limit values to varying of the exceedance probability

Exceedance probability	Limit value
1/n	$x_{1/n}$
1/100	4.41
1/50	5.20
1/10	2.55
1/3	1.04
1/2	0.44

To evaluate the mean of the nth highest maxima of accelerations, $A_{1/n}$, equation (4) have to be applied.

$$A_{1/n} = RMS \int_{x_{1/n}}^{\infty} n\, z \cdot f(z) dz = RMS \cdot n \int_{x_{1/n}}^{\infty} z\, \frac{1}{\beta} e^{\left(-\frac{z-\alpha}{\beta}\right)} e^{\left(-e^{\left(-\frac{z-\alpha}{\beta}\right)}\right)} dz \tag{9}$$

where *RMS* could be found in Appendix III.

Table 5 shows the results of the proposed procedure and, for validation, the experimental data collected in the tank.

Table 5
Maxima bow accelerations

$A_{1/n}$	PDF (g)	Experimental (g)
$A_{1/100}$	2.40	2.30
$A_{1/50}$	2.10	2.00
$A_{1/10}$	1.40	1.30
$A_{1/3}$	0.88	0.83
$A_{1/2}$	0.68	0.65

Appendix II. Statistics on experimental data

Next tables show statistics of data measure in terms of pitch, heave and vertical acceleration.

	Hull	C1s		Pitch				Heave				Vertical acc. CG				Vertical acc. bow			
	JONSWAP γ 3.3		Speed	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$
n°	Tp	Hs	Fr	deg	deg	deg	deg	mm	mm	mm	mm	g	g	g	g	g	g	g	g
1	1.176	0.045	0.721	1.4	2.4	3.2	4.1	6	12	17	23	0.07	0.12	0.17	0.24	0.19	0.37	0.53	0.85
2	1.356	0.060	0.721	3.0	4.9	6.1	7.5	18	35	47	61	0.14	0.23	0.30	0.38	0.33	0.62	0.86	1.18
3	1.520	0.075	0.721	3.7	5.9	7.6	9.3	25	56	79	99	0.16	0.26	0.34	0.42	0.35	0.64	0.87	1.17
7	1.176	0.045	0.928	1.4	2.3	2.8	3.5	7	14	20	25	0.11	0.20	0.27	0.37	0.29	0.55	0.76	1.07
8	1.356	0.060	0.928	2.7	4.4	5.8	7.1	18	37	51	65	0.16	0.31	0.43	0.70	0.38	0.78	1.15	1.93
9	1.520	0.075	0.928	3.6	5.8	7.4	8.6	28	56	78	97	0.21	0.37	0.48	0.60	0.48	0.93	1.28	1.64

	Hull	**C2s**		**Pitch**				**Heave**				**Vertical acc. CG**				**Vertical acc. bow**			
	JONSWAP γ 3.3		**Speed**	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$
n°	**Tp**	**Hs**	**Fr**	**deg**	**deg**	**deg**	**deg**	**mm**	**mm**	**mm**	**mm**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
1	1.176	0.045	0.721	1.2	2.2	3.0	4.1	5	12	19	27	0.06	0.12	0.16	0.22	0.16	0.32	0.48	0.78
2	1.356	0.060	0.721	2.7	4.6	6.0	7.6	14	34	51	68	0.14	0.24	0.31	0.41	0.29	0.61	0.91	1.47
3	1.520	0.075	0.721	3.6	6.3	8.1	10.1	30	59	82	107	0.19	0.32	0.41	0.51	0.29	0.68	0.99	1.48
7	1.176	0.045	0.928	1.2	2.1	2.8	3.5	7	14	19	27	0.11	0.21	0.28	0.38	0.26	0.56	0.78	1.14
8	1.356	0.060	0.928	2.9	4.7	5.9	7.9	19	40	53	64	0.17	0.31	0.40	0.53	0.26	0.71	1.02	1.44
9	1.520	0.075	0.928	3.4	5.6	7.2	8.7	26	52	73	93	0.22	0.42	0.58	0.85	0.26	0.83	1.31	2.25
13	1.176	0.045	1.197	1.0	1.8	2.3	3.0	8	17	22	27	0.17	0.32	0.43	0.59	0.38	0.74	1.00	1.38
14	1.356	0.060	1.197	2.8	4.3	5.3	6.1	26	43	53	62	0.29	0.53	0.68	0.85	0.55	1.25	1.66	2.17
15	1.520	0.075	1.197	3.6	5.8	7.3	8.4	29	61	80	95	0.36	0.70	1.07	1.63	0.62	1.54	2.42	3.47

	Hull	**C3**		**Pitch**				**Heave**				**Vertical acc. CG**				**Vertical acc. bow**			
	JONSWAP γ 3.3		**Speed**	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$
n°	**Tp**	**Hs**	**Fr**	**deg**	**deg**	**deg**	**deg**	**mm**	**mm**	**mm**	**mm**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
1	1.176	0.045	0.721	0.4	0.8	1.0	1.2	2	6	9	11	0.03	0.06	0.08	0.09	0.10	0.20	0.26	0.34
2	1.356	0.060	0.721	1.0	1.9	2.4	2.8	8	18	25	32	0.05	0.11	0.14	0.17	0.17	0.35	0.49	0.67
3	1.520	0.075	0.721	2.1	3.4	4.2	4.8	24	40	50	57	0.11	0.20	0.25	0.30	0.31	0.60	0.87	1.12
7	1.176	0.045	0.928	0.6	1.0	1.3	1.8	3	6	10	13	0.06	0.11	0.14	0.20	0.16	0.31	0.43	0.60
8	1.356	0.060	0.928	1.0	1.6	2.0	2.4	9	16	19	23	0.09	0.17	0.21	0.25	0.26	0.51	0.65	0.84
9	1.520	0.075	0.928	1.7	2.8	3.3	3.6	20	34	41	48	0.12	0.23	0.30	0.39	0.35	0.70	0.97	1.31

	Hull	**C4**		**Pitch**				**Heave**				**Vertical acc. CG**				**Vertical acc. bow**			
	JONSWAP γ 3.3		**Speed**	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$
n°	**Tp**	**Hs**	**Fr**	**deg**	**deg**	**deg**	**deg**	**mm**	**mm**	**mm**	**mm**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
1	1.176	0.045	0.721	0.6	1.1	1.6	1.6	3	7	12	29	0.03	0.07	0.10	0.16	0.09	0.22	0.33	0.60
2	1.356	0.060	0.721	1.3	2.3	2.9	3.2	10	21	28	35	0.06	0.13	0.17	0.21	0.21	0.44	0.62	0.84
3	1.520	0.075	0.721	2.4	3.9	4.9	5.5	22	46	60	68	0.11	0.22	0.29	0.36	0.26	0.64	1.00	1.52
7	1.176	0.045	0.928	0.4	0.7	0.9	1.1	3	5	8	9	0.04	0.08	0.11	0.15	0.13	0.27	0.37	0.51
8	1.356	0.060	0.928	1.1	1.8	2.2	2.5	7	17	23	27	0.08	0.15	0.20	0.28	0.26	0.53	0.69	0.92
9	1.520	0.075	0.928	2.0	3.3	4.0	4.4	18	35	43	49	0.12	0.25	0.33	0.44	0.44	0.90	1.28	1.60

	Hull	**C5**		**Pitch**				**Heave**				**Vertical acc. CG**				**Vertical acc. bow**			
	JONSWAP γ 3.3		**Speed**	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	H_{mean}	$H_{1/3}$	$H_{1/10}$	$H_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$	A_{mean}	$A_{1/3}$	$A_{1/10}$	$A_{1/100}$
n°	**Tp**	**Hs**	**Fr**	**deg**	**deg**	**deg**	**deg**	**mm**	**mm**	**mm**	**mm**	**g**	**g**	**g**	**g**	**g**	**g**	**g**	**g**
1	1.176	0.045	0.721	0.7	1.0	1.2	1.5	7	12	14	18	0.04	0.08	0.10	0.11	0.14	0.22	0.32	0.38
2	1.356	0.060	0.721	1.5	2.2	3.1	3.5	19	30	36	43	0.09	0.16	0.19	0.23	0.30	0.43	0.66	0.84
3	1.520	0.075	0.721	2.5	4.0	5.1	6.1	34	52	66	80	0.15	0.26	0.33	0.41	0.47	0.86	1.28	1.68
7	1.176	0.045	0.928	0.5	0.8	1.1	1.3	3	7	10	14	0.04	0.09	0.10	0.12	0.13	0.28	0.37	0.48
8	1.356	0.060	0.928	1.2	1.9	2.6	3.0	11	21	26	33	0.10	0.17	0.21	0.27	0.29	0.62	0.81	1.08
9	1.520	0.075	0.928	2.1	3.2	4.4	4.9	26	48	57	63	0.17	0.30	0.38	0.51	0.46	1.09	1.55	2.22
13	1.176	0.045	0.515	0.9	1.4	1.9	2.1	8	12	14	17	0.03	0.06	0.07	0.09	0.11	0.17	0.24	0.30
14	1.356	0.060	0.515	2.2	3.1	4.3	5.1	23	36	45	55	0.08	0.15	0.18	0.22	0.30	0.40	0.66	0.87
15	1.520	0.075	0.515	3.3	4.7	6.7	7.5	38	58	68	76	0.12	0.21	0.26	0.31	0.33	0.48	0.75	0.92

Appendix III. PDF parameters

The next tables show the coefficients of PDF, described in the paragraph "Data Representation", fitted on the observations.

C1s pitch (deg)					Cartwright Longuet Higgins				Normal						Extreme value					
	JONSWAP γ 3.3				Maxima		Minima		Maxima			Minima			Maxima			Minima		
n°	Tp (s)	Hs (mm)	Fr	RMS	ε	residue	ε	residue	μ	σ	residue	μ	σ	residue	α	β	residue	α	β	residue
1	1.176	0.045	0.721	0.613	0.586	5.4E-04	0.571	4.4E-04	0.964	0.784	7.4E-04	0.992	0.805	7.3E-04	0.775	0.722	1.0E-03	0.805	0.737	2.0E-04
2	1.356	0.060	0.721	1.255	0.431	3.8E-04	0.440	1.2E-03	1.087	0.748	5.4E-04	1.161	0.818	6.7E-04	0.898	0.683	1.1E-03	0.956	0.751	2.9E-04
3	1.520	0.075	0.721	1.545	0.336	9.9E-04	0.430	1.4E-03	1.106	0.688	1.0E-03	1.157	0.796	4.8E-04	0.949	0.632	1.6E-03	0.970	0.735	9.6E-04
7	1.176	0.045	0.928	0.594	0.467	7.2E-04	0.505	2.1E-03	1.111	0.770	7.8E-05	1.154	0.848	4.5E-04	0.923	0.728	1.8E-03	0.959	0.798	1.4E-03
8	1.356	0.060	0.928	1.146	0.406	1.0E-03	0.505	1.4E-03	1.088	0.717	9.7E-04	1.123	0.857	7.3E-04	0.934	0.661	1.7E-03	0.922	0.777	3.2E-04
9	1.520	0.075	0.928	1.527	0.391	2.9E-03	0.497	1.9E-03	1.020	0.683	3.5E-03	1.129	0.851	8.8E-04	0.879	0.616	2.3E-03	0.945	0.779	7.8E-04
C2s pitch (deg)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.555	0.631	9.2E-04	0.656	7.5E-04	0.892	0.768	1.0E-03	0.915	0.837	8.5E-04	0.717	0.700	2.3E-04	0.741	0.768	7.9E-04
2	1.356	0.060	0.721	1.149	0.574	1.4E-03	0.608	2.4E-03	1.006	0.822	1.6E-03	1.066	0.945	9.0E-04	0.812	0.751	1.3E-03	0.865	0.846	3.2E-04
3	1.520	0.075	0.721	1.627	0.603	1.3E-03	0.656	2.3E-03	1.010	0.843	9.9E-04	1.038	0.975	6.1E-04	0.812	0.793	2.1E-03	0.807	0.887	4.6E-04
7	1.176	0.045	0.928	0.579	0.606	2.1E-04	0.607	8.5E-04	0.980	0.815	1.6E-04	1.027	0.868	2.3E-04	0.781	0.764	1.4E-03	0.813	0.809	1.3E-03
8	1.356	0.060	0.928	1.220	0.272	9.3E-04	0.492	3.0E-03	1.093	0.655	1.1E-03	1.202	0.884	3.5E-04	0.933	0.595	1.2E-03	0.985	0.815	7.1E-04
9	1.520	0.075	0.928	1.529	0.500	5.1E-04	0.569	2.8E-03	0.992	0.711	2.0E-04	1.167	0.950	3.7E-04	0.828	0.665	1.4E-03	0.953	0.883	6.8E-04
13	1.176	0.045	1.197	0.506	0.665	1.1E-03	0.665	2.5E-03	0.973	0.893	4.7E-04	1.028	0.960	3.8E-04	0.744	0.839	1.8E-03	0.800	0.904	1.5E-03
14	1.356	0.060	1.197	1.134	0.354	1.8E-03	0.519	6.2E-03	1.133	0.691	7.4E-04	1.252	0.929	4.5E-04	0.975	0.656	3.4E-03	1.036	0.875	1.6E-03
15	1.520	0.075	1.197	1.528	0.413	1.4E-03	0.551	3.5E-03	1.085	0.697	8.3E-04	1.208	0.961	5.4E-04	0.899	0.657	3.3E-03	0.997	0.894	6.6E-04
C3 pitch (deg)					Cartwright Longuet Higgins				Normal						Extreme value					
	JONSWAP γ 3.3				Maxima		Minima		Maxima			Minima			Maxima			Minima		
n°	Tp (s)	Hs (mm)	Fr	RMS	ε	residue	ε	residue	μ	σ	residue	μ	σ	residue	α	β	residue	α	β	residue
1	1.176	0.045	0.721	0.210	0.635	8.8E-04	0.636	1.6E-03	1.005	0.888	1.5E-04	1.045	0.928	9.8E-05	0.800	0.833	1.1E-03	0.829	0.872	9.4E-04
2	1.356	0.060	0.721	0.481	0.689	2.0E-03	0.675	1.8E-03	0.946	0.936	1.2E-03	0.955	0.923	1.4E-03	0.738	0.846	8.7E-04	0.741	0.832	4.3E-04
3	1.520	0.075	0.721	0.870	0.625	5.6E-03	0.609	5.9E-03	1.070	0.915	3.1E-03	1.162	1.008	1.1E-03	0.847	0.863	5.4E-03	0.938	0.925	1.3E-03
7	1.176	0.045	0.928	0.285	0.706	8.6E-04	0.683	1.5E-03	0.862	0.856	1.0E-03	0.982	0.940	3.7E-04	0.673	0.770	6.8E-04	0.751	0.886	1.6E-03
8	1.356	0.060	0.928	0.439	0.589	8.0E-04	0.623	3.4E-03	1.030	0.849	3.4E-04	1.111	0.971	1.9E-04	0.824	0.790	1.3E-03	0.885	0.912	1.1E-03
9	1.520	0.075	0.928	0.725	0.364	1.6E-03	0.580	8.3E-03	1.155	0.719	5.1E-04	1.261	1.005	6.6E-04	0.990	0.679	2.5E-03	1.026	0.948	1.9E-03
C4 pitch (deg)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.296	0.685	2.0E-03	0.664	2.3E-03	0.814	0.711	7.8E-04	0.823	0.718	1.7E-03	0.661	0.666	1.4E-03	0.657	0.657	1.1E-03
2	1.356	0.060	0.721	0.588	0.523	7.1E-04	0.608	2.7E-03	1.051	0.786	4.8E-04	1.096	0.943	3.3E-04	0.878	0.737	1.8E-03	0.880	0.878	9.0E-04
3	1.520	0.075	0.721	0.995	0.470	5.6E-04	0.523	3.0E-03	1.094	0.768	2.2E-04	1.151	0.893	1.8E-03	0.912	0.726	1.4E-03	0.930	0.818	1.2E-03
7	1.176	0.045	0.928	0.199	0.618	1.5E-03	0.625	2.5E-03	1.034	0.888	4.0E-04	1.081	0.949	3.2E-04	0.835	0.837	1.7E-03	0.859	0.888	1.2E-03
8	1.356	0.060	0.928	0.478	0.542	3.2E-03	0.536	3.3E-03	1.110	0.839	1.3E-03	1.169	0.903	3.4E-04	0.923	0.804	4.0E-03	0.958	0.843	1.1E-03
9	1.520	0.075	0.928	0.836	0.533	2.8E-03	0.560	4.9E-03	1.042	0.817	3.1E-03	1.184	0.946	7.1E-04	0.847	0.736	2.4E-03	0.965	0.879	1.4E-03
C5 pitch (deg)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.272	0.370	5.8E-04	0.397	2.0E-03	1.115	0.735	8.4E-04	1.174	0.790	7.8E-04	0.945	0.676	1.1E-03	0.996	0.726	1.1E-03

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C3 pitch (deg)					Cartwright Longuet Higgins				Normal						Extreme value					
	JONSWAP γ 3.3				Maxima		Minima		Maxima			Minima			Maxima			Minima		
n°	Tp (s)	Hs (mm)	Fr	RMS	ε	residue	ε	residue	μ	σ	residue	μ	σ	residue	α	β	residue	α	β	residue
2	1.356	0.060	0.721	0.634	0.467	1.1E-03	0.542	2.3E-03	1.069	0.750	1.1E-03	1.114	0.876	5.9E-04	0.895	0.704	2.3E-03	0.913	0.811	1.2E-03
3	1.520	0.075	0.721	1.025	0.381	1.5E-03	0.514	3.4E-03	1.091	0.755	2.2E-03	1.128	0.901	2.4E-03	0.934	0.675	1.2E-03	0.925	0.799	6.3E-04
7	1.176	0.045	0.928	0.224	0.529	3.1E-04	0.601	3.3E-03	1.038	0.783	2.3E-04	1.125	0.941	1.7E-04	0.848	0.731	1.5E-03	0.902	0.892	1.5E-03
8	1.356	0.060	0.928	0.527	0.528	9.9E-04	0.535	3.2E-03	1.069	0.798	3.2E-04	1.147	0.880	8.5E-04	0.888	0.759	2.4E-03	0.945	0.828	1.9E-03
9	1.520	0.075	0.928	0.893	0.496	9.8E-04	0.601	3.7E-03	1.021	0.746	1.2E-03	1.176	0.993	2.7E-04	0.855	0.687	1.7E-03	0.939	0.924	5.0E-04
13	1.176	0.045	0.515	0.375	0.442	9.6E-04	0.519	2.1E-03	1.077	0.767	1.6E-03	1.081	0.849	1.6E-03	0.893	0.697	6.3E-04	0.900	0.762	8.7E-04
14	1.356	0.060	0.515	0.897	0.417	2.0E-03	0.470	4.2E-03	1.143	0.773	1.1E-03	1.176	0.865	1.8E-03	0.965	0.719	2.2E-03	0.990	0.783	1.5E-03
15	1.520	0.075	0.515	1.347	0.546	2.2E-03	0.528	4.2E-03	1.092	0.846	8.7E-04	1.119	0.895	2.6E-03	0.910	0.794	2.5E-03	0.931	0.802	1.8E-03

C1s heave (mm)					Cartwright Longuet Higgins				Normal						Extreme value					
	JONSWAP γ 3.3				Maxima		Minima		Maxima			Minima			Maxima			Minima		
n°	Tp (s)	Hs (mm)	Fr	RMS	ε	residue	ε	residue	μ	σ	residue	μ	σ	residue	α	β	residue	α	β	residue
1	1.176	0.045	0.721	4.867	0.958	1.8E-04	0.938	2.0E-04	0.358	0.979	1.8E-04	0.422	0.926	1.5E-04	0.131	0.908	6.9E-04	0.203	0.856	7.2E-04
2	1.356	0.060	0.721	12.109	0.907	8.6E-04	0.878	2.6E-04	0.577	1.084	1.0E-04	0.619	0.996	6.3E-05	0.310	1.026	8.4E-04	0.391	0.943	9.1E-04
3	1.520	0.075	0.721	17.731	0.877	9.9E-04	0.827	1.1E-03	0.656	1.070	1.9E-04	0.692	0.905	1.1E-03	0.398	1.020	1.0E-03	0.514	0.849	2.1E-03
7	1.176	0.045	0.928	4.758	0.893	1.3E-03	0.822	6.4E-04	0.625	1.106	9.1E-05	0.732	0.966	3.8E-04	0.360	1.054	1.1E-03	0.516	0.922	2.0E-03
8	1.356	0.060	0.928	10.812	0.759	9.4E-04	0.780	8.3E-04	0.817	0.901	8.5E-04	0.828	0.981	1.7E-04	0.630	0.849	2.2E-03	0.601	0.922	1.2E-03
9	1.520	0.075	0.928	16.003	0.771	8.4E-04	0.744	1.2E-03	0.801	0.918	8.1E-04	0.812	0.861	1.3E-03	0.611	0.848	1.0E-03	0.632	0.797	1.8E-03

C2s heave (mm)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	4.546	0.961	2.0E-04	0.957	1.8E-04	0.336	0.932	1.3E-04	0.359	0.956	4.5E+00	0.118	0.864	4.8E-04	0.148	0.885	6.5E-04
2	1.356	0.060	0.721	11.908	0.909	3.0E-04	0.924	4.1E-04	0.532	0.991	2.5E-04	0.491	0.998	1.2E+01	0.310	0.920	6.0E-04	0.249	0.932	6.8E-04
3	1.520	0.075	0.721	19.735	0.887	1.3E-03	0.871	5.6E-04	0.630	1.060	7.2E-04	0.647	1.020	2.0E+01	0.367	1.003	1.3E-03	0.411	0.959	9.2E-04
7	1.176	0.045	0.928	4.779	0.885	3.6E-04	0.887	3.7E-04	0.587	0.960	3.4E-04	0.608	1.017	4.8E+00	0.371	0.892	8.4E-04	0.357	0.960	7.5E-04
8	1.356	0.060	0.928	11.589	0.778	1.5E-03	0.755	5.7E-04	0.855	1.012	3.2E-04	0.852	0.941	1.2E+01	0.626	0.956	1.4E-03	0.637	0.886	1.2E-03
9	1.520	0.075	0.928	18.081	0.905	5.1E-04	0.896	5.4E-04	0.565	1.049	3.2E-05	0.585	1.036	1.8E+01	0.321	0.990	9.2E-04	0.348	0.974	9.8E-04
13	1.176	0.045	1.197	4.976	0.793	4.7E-04	0.839	1.3E-03	0.782	0.939	3.2E-04	0.750	1.059	5.0E+00	0.547	0.878	1.1E-03	0.497	0.997	8.8E-04
14	1.356	0.060	1.197	12.060	0.640	2.7E-03	0.607	2.0E-03	1.061	0.942	4.5E-04	1.074	0.904	1.2E+01	0.861	0.898	2.3E-03	0.871	0.859	1.7E-03
15	1.520	0.075	1.197	18.109	0.776	1.3E-03	0.822	2.1E-03	0.851	1.003	1.9E-04	0.799	1.086	1.8E+01	0.635	0.951	1.5E-03	0.564	1.024	1.3E-03

C3 heave (mm)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	2.294	0.944	5.2E-04	0.925	5.6E-04	0.445	1.084	3.9E-05	0.510	1.073	4.7E-05	0.180	1.020	7.8E-04	0.245	1.017	9.1E-04
2	1.356	0.060	0.721	5.781	0.933	2.1E-03	0.905	2.5E-03	0.449	0.971	2.1E-03	0.493	0.879	2.3E-03	0.237	0.856	9.1E-04	0.292	0.771	7.2E-04
3	1.520	0.075	0.721	11.920	0.686	4.7E-03	0.707	3.8E-03	1.037	0.998	1.5E-03	1.006	1.020	9.5E-04	0.833	0.954	4.1E-03	0.789	0.969	2.5E-03
7	1.176	0.045	0.928	2.281	0.920	9.7E-04	0.907	5.9E-04	0.490	0.962	9.8E-04	0.529	0.962	5.9E-04	0.261	0.880	1.2E-03	0.294	0.893	1.3E-03
8	1.356	0.060	0.928	5.125	0.817	2.2E-03	0.754	2.1E-03	0.812	1.072	3.8E-04	0.855	0.937	1.7E-03	0.561	1.022	1.5E-03	0.619	0.880	3.0E-03
9	1.520	0.075	0.928	9.467	0.594	3.8E-03	0.568	2.2E-03	1.140	0.931	7.0E-04	1.096	0.858	7.1E-04	0.923	0.891	2.4E-03	0.903	0.829	2.5E-03

C4 heave (mm)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	3.428	0.961	2.2E-03	0.978	1.7E-03	0.307	0.759	4.5E-04	0.230	0.800	3.7E-04	0.140	0.701	1.1E-03	0.051	0.732	7.1E-04
2	1.356	0.060	0.721	7.178	0.892	9.4E-04	0.899	6.8E-04	0.608	1.049	4.4E-04	0.592	1.057	1.1E-04	0.369	0.986	9.2E-04	0.342	0.998	7.4E-04
3	1.520	0.075	0.721	13.386	0.822	2.4E-03	0.829	1.2E-03	0.797	1.074	7.9E-04	0.764	1.043	2.4E-04	0.567	1.008	1.8E-03	0.537	0.974	9.4E-04
7	1.176	0.045	0.928	2.090	0.965	7.1E-04	0.943	2.4E-04	0.362	1.116	6.2E-05	0.432	1.032	6.8E-05	0.088	1.047	7.3E-04	0.185	0.972	9.8E-04
8	1.356	0.060	0.928	5.458	0.864	1.6E-03	0.880	1.9E-03	0.693	1.083	5.0E-04	0.681	1.132	1.8E-04	0.473	1.008	1.3E-03	0.417	1.079	1.1E-03
9	1.520	0.075	0.928	10.624	0.828	2.1E-03	0.784	1.4E-03	0.800	1.088	3.6E-04	0.830	0.982	7.4E-04	0.551	1.027	1.1E-03	0.599	0.926	1.3E-03

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C1s heave (mm)					Cartwright Longuet Higgins				Normal						Extreme value					
	JONSWAP γ 3.3				Maxima		Minima		Maxima			Minima			Maxima			Minima		
n°	Tp (s)	Hs (mm)	Fr	RMS	ε	residue	ε	residue	μ	σ	residue	μ	σ	residue	α	β	residue	α	β	residue
C5 heave (mm)					**Cartwright Longuet Higgins**				**Normal**						**Extreme value**					
	JONSWAP γ 3.3				**Maxima**		**Minima**		**Maxima**			**Minima**			**Maxima**			**Minima**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS**	**ε**	**residue**	**ε**	**residue**	**μ**	**σ**	**residue**	**μ**	**σ**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	3.259	0.588	1.8E-03	0.591	1.2E-03	1.093	0.902	3.1E-04	1.057	0.875	1.4E-04	0.873	0.844	8.9E-04	0.851	0.822	1.2E-03
2	1.356	0.060	0.721	8.136	0.569	3.1E-03	0.611	3.0E-03	1.126	0.906	4.7E-04	1.058	0.903	1.2E-03	0.924	0.853	1.7E-03	0.850	0.847	2.6E-03
3	1.520	0.075	0.721	14.635	0.569	2.6E-03	0.605	9.9E-04	1.103	0.907	9.6E-04	0.997	0.858	9.4E-04	0.902	0.831	1.0E-03	0.802	0.784	5.3E-04
7	1.176	0.045	0.928	2.694	0.956	5.1E-04	0.932	2.7E-04	0.395	1.089	2.9E-05	0.468	1.006	1.9E-04	0.131	1.020	7.1E-04	0.213	0.939	9.5E-04
8	1.356	0.060	0.928	6.667	0.863	2.1E-03	0.838	1.0E-03	0.720	1.123	2.2E-04	0.732	1.022	2.6E-04	0.474	1.057	1.1E-03	0.497	0.968	1.3E-03
9	1.520	0.075	0.928	13.001	0.679	2.0E-03	0.703	2.3E-03	1.002	0.957	2.9E-04	0.957	0.949	1.2E-03	0.787	0.901	1.4E-03	0.743	0.891	2.2E-03
13	1.176	0.045	0.515	3.547	0.607	2.0E-03	0.626	1.1E-03	1.056	0.915	9.1E-04	1.039	0.911	1.1E-04	0.848	0.834	6.8E-04	0.830	0.850	6.8E-04
14	1.356	0.060	0.515	9.587	0.486	2.1E-03	0.511	6.3E-04	1.151	0.835	3.8E-04	1.074	0.793	4.0E-04	0.956	0.780	1.3E-03	0.882	0.750	1.2E-03
15	1.520	0.075	0.515	15.765	0.570	2.2E-03	0.538	1.3E-03	1.074	0.888	1.0E-03	1.031	0.820	1.5E-03	0.880	0.813	9.5E-04	0.856	0.741	8.2E-04

C1s Vertical acceleration (g)						Gamma						Extreme value					
	JONSWAP γ 3.3					Maxima G			Maxima bow			Maxima G			Maxima bow		
n°	Tp (s)	Hs (mm)	Fr	RMS $_G$	RMS $_{Bow}$	α	β	residue	α	β	residue	α	β	residue	α	β	residue
1	1.176	0.045	0.721	0.162	0.613	1.724	0.801	4.6E-03	1.616	0.967	2.4E-03	0.702	0.744	7.2E-04	0.776	0.840	4.6E-04
2	1.356	0.060	0.721	0.250	1.255	2.138	0.658	2.3E-03	1.726	1.019	2.3E-03	0.839	0.726	8.7E-04	0.890	0.949	1.6E-04
3	1.520	0.075	0.721	0.270	1.545	3.289	0.403	3.8E-03	1.906	0.926	3.2E-03	0.941	0.603	2.5E-03	0.930	0.956	7.0E-04
7	1.176	0.045	0.928	0.241	0.594	1.963	0.779	3.9E-03	1.782	0.924	3.3E-03	0.829	0.822	7.3E-04	0.844	0.892	5.3E-04
8	1.356	0.060	0.928	0.327	1.146	1.633	0.919	3.4E-03	1.535	1.095	2.7E-03	0.733	0.812	4.2E-04	0.719	0.926	3.4E-04
9	1.520	0.075	0.928	0.378	1.527	2.070	0.741	2.9E-03	1.495	1.338	3.5E-03	0.884	0.797	6.1E-04	0.855	1.096	3.5E-04
C2s Vertical acceleration (g)						**Gamma**						**Extreme value**					
	JONSWAP γ 3.3					**Maxima G**			**Maxima bow**			**Maxima G**			**Maxima bow**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS $_G$**	**RMS $_{Bow}$**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.063	0.142	1.484	0.960	4.9E-03	1.524	0.997	3.8E-03	0.642	0.765	6.3E-02	0.670	0.820	8.2E-04
2	1.356	0.060	0.721	0.128	0.241	1.827	0.807	5.3E-03	1.291	1.408	2.5E-03	0.780	0.788	1.3E-01	0.660	0.983	2.9E-04
3	1.520	0.075	0.721	0.172	0.295	1.949	0.718	2.8E-03	1.325	1.457	4.0E-03	0.804	0.723	1.7E-01	0.622	1.094	8.1E-04
7	1.176	0.045	0.928	0.100	0.248	1.655	0.940	3.8E-03	1.352	1.433	4.8E-03	0.755	0.855	1.0E-01	0.649	1.082	2.7E-04
8	1.356	0.060	0.928	0.159	0.323	1.811	0.855	4.4E-03	1.077	2.360	9.4E-03	0.802	0.835	1.6E-01	0.292	1.228	3.1E-04
9	1.520	0.075	0.928	0.208	0.383	1.956	0.780	3.2E-03	0.994	3.034	1.2E-02	0.826	0.818	2.1E-01	0.025	1.124	5.0E-04
13	1.176	0.045	1.197	0.149	0.326	1.652	0.984	3.8E-03	1.430	1.302	3.5E-03	0.790	0.888	1.5E-01	0.784	1.019	3.2E-04
14	1.356	0.060	1.197	0.230	0.464	1.750	1.049	2.5E-03	1.209	2.188	5.1E-03	0.943	0.977	2.3E-01	0.703	1.387	4.3E-04
15	1.520	0.075	1.197	0.293	0.565	1.749	0.974	2.9E-03	1.083	2.511	7.5E-03	0.853	0.920	2.9E-01	0.417	1.311	4.3E-04
C3 Vertical acceleration (g)						**Gamma**						**Extreme value**					
	JONSWAP γ 3.3					**Maxima G**			**Maxima bow**			**Maxima G**			**Maxima bow**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS $_G$**	**RMS $_{Bow}$**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.030	0.089	1.599	1.037	6.2E-03	1.587	1.138	4.7E-03	0.735	0.902	8.9E-04	0.813	0.987	7.6E-04
2	1.356	0.060	0.721	0.060	0.155	1.423	1.073	5.7E-03	1.317	1.352	3.8E-03	0.618	0.816	3.4E-04	0.683	0.953	1.5E-04
3	1.520	0.075	0.721	0.109	0.249	1.880	0.858	6.6E-03	1.416	1.393	4.3E-03	0.838	0.859	1.9E-03	0.775	1.071	2.6E-04
7	1.176	0.045	0.928	0.051	0.146	1.525	1.139	5.6E-03	1.491	1.152	4.9E-03	0.758	0.941	5.5E-04	0.718	0.946	4.3E-04
8	1.356	0.060	0.928	0.082	0.219	1.741	0.945	5.7E-03	1.324	1.493	4.9E-03	0.807	0.895	1.0E-03	0.750	1.050	4.3E-04
9	1.520	0.075	0.928	0.119	0.290	1.617	1.041	5.3E-03	1.383	1.397	4.8E-03	0.755	0.925	8.5E-04	0.709	1.050	1.2E-04
C4 Vertical acceleration (g)						**Gamma**						**Extreme value**					
	JONSWAP γ 3.3					**Maxima G**			**Maxima bow**			**Maxima G**			**Maxima bow**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS $_G$**	**RMS $_{Bow}$**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.043	0.111	1.152	1.343	1.1E-02	1.323	1.187	5.7E-03	0.286	0.827	5.9E-04	0.471	0.879	8.0E-04

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(*continued*)

C1s Vertical acceleration (g)						Gamma						Extreme value					
	JONSWAP γ 3.3					Maxima G			Maxima bow			Maxima G			Maxima bow		
n°	Tp (s)	Hs (mm)	Fr	RMS_G	RMS_{Bow}	α	β	residue	α	β	residue	α	β	residue	α	β	residue
2	1.356	0.060	0.721	0.082	0.195	1.405	1.129	9.4E-03	1.229	1.643	5.4E-03	0.516	0.863	9.5E-04	0.646	1.078	4.1E-04
3	1.520	0.075	0.721	0.136	0.250	1.675	0.877	6.3E-03	1.032	2.831	1.7E-02	0.648	0.811	1.2E-03	0.388	1.145	7.6E-03
7	1.176	0.045	0.928	0.042	0.122	1.354	1.224	7.4E-03	1.347	1.347	5.2E-03	0.523	0.931	6.7E-04	0.659	0.992	4.2E-04
8	1.356	0.060	0.928	0.086	0.220	1.628	0.976	6.8E-03	1.423	1.504	5.4E-03	0.671	0.904	1.8E-03	0.768	1.180	4.6E-04
9	1.520	0.075	0.928	0.142	0.254	1.776	0.817	5.1E-03	1.378	2.187	2.4E-03	0.702	0.795	1.1E-03	1.053	1.639	7.8E-05
C5 Vertical acceleration (g)						**Gamma**						**Extreme value**					
	JONSWAP γ 3.3					**Maxima G**			**Maxima bow**			**Maxima G**			**Maxima bow**		
n°	**Tp (s)**	**Hs (mm)**	**Fr**	**RMS_G**	**RMS_{Bow}**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**	**α**	**β**	**residue**
1	1.176	0.045	0.721	0.107	0.107	2.305	0.616	4.0E-03	2.090	0.768	2.2E-03	0.867	0.720	1.5E-03	0.955	0.816	5.4E-04
2	1.356	0.060	0.721	0.217	0.217	2.232	0.572	5.1E-03	2.204	0.716	1.4E-03	0.781	0.645	1.9E-03	0.981	0.780	6.7E-04
3	1.520	0.075	0.721	0.326	0.326	1.914	0.675	7.7E-03	1.795	0.906	1.9E-03	0.725	0.669	4.4E-03	0.902	0.828	9.0E-04
7	1.176	0.045	0.928	0.119	0.119	1.613	1.028	7.3E-03	1.308	1.413	5.4E-03	0.729	0.905	1.2E-03	0.637	0.997	3.3E-04
8	1.356	0.060	0.928	0.234	0.234	2.213	0.643	6.7E-03	1.472	1.386	3.7E-03	0.840	0.737	2.6E-03	0.807	1.126	4.3E-04
9	1.520	0.075	0.928	0.375	0.375	2.232	0.588	2.6E-03	1.223	1.766	4.4E-03	0.796	0.671	7.3E-04	0.621	1.142	1.6E-04
13	1.176	0.045	0.515	0.095	0.095	2.416	0.535	3.0E-03	2.243	0.633	3.0E-03	0.833	0.633	1.2E-03	0.873	0.716	5.5E-04
14	1.356	0.060	0.515	0.232	0.232	2.342	0.534	2.9E-03	2.222	0.690	1.6E-03	0.789	0.619	1.2E-03	0.945	0.769	6.4E-04
15	1.520	0.075	0.515	0.270	0.270	1.997	0.696	5.0E-03	2.005	0.773	3.5E-03	0.802	0.707	1.2E-03	0.902	0.786	9.1E-04

Appendix J. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2019.106620.

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