March 2019

Limiting environment determination for an offshore vessel

Luca BRAIDOTTI [a], Ubaldo LA MONACA [a], Alberto MARINÒ [a] and Vittorio BUCCI [a,1]

[a] *University of Trieste, Department of Engineering and Architecture, Via Valerio 10, 34127, Trieste.*

Abstract. The design of an offshore vessel requires the combination of multiple aspects typical of naval architecture and marine engineering. Between them, the definition of environmental loads and excitation is relevant, since it is required to evaluate motion operability, dynamic positioning capability and structure dimensions. These three topics traditionally refer to independent analyses and are treated in separate design stages. Moreover, the techniques and the calculations performed to asses the performances of the vessel under design differ topic by topic, referring to different limiting environmental conditions. This paper presents a comparison between the different limiting environment determination for the assessment of ship motion, dynamic positioning and maximum design loads for structures. In particular, advanced analysis methods are applied on a reference vessel to highlight the differences between station keeping, sea keeping and structural loads limiting environment. A combined representation of station keeping and seakeeping data is then used to compare the vessel operability issues with recommended design loads.

Keywords. Extreme loads, Dynamic positioning, Wave modelling, Vessel operability, Extreme value theory

1. Introduction

The design process of an offshore vessel is somewhat different from merchant ship one. The peculiarities and necessities of the Oil & Gas industry require to operate in more severe environments, giving to topic related to seakeeping and station keeping more relevance compared to standard issues like resistance and propulsion [1]. Besides vessel dynamics, also structural strength is of primary importance and, for an offshore vessel, corresponds with the determination of a maximum load associated with maximum wave height [2]. For such a reason, the selection of a working environment is of primary importance, resulting in the dimensioning of the structures, but also in the correct dimensioning of the dynamic positioning (DP) system or of the motion reduction devices.

The mentioned topics require the resolution of specific issues that need to be solved by the adoption of specialistic methods and procedures like the extreme value theory for the maximum wave determination [3,4] or non-linear optimisation procedures for DP capability predictions [5,6]. However, these kinds of analyses remain dissociated during

[1]Corresponding Author: University of Trieste; E-mail: vbucci@units.it.

the vessel design process. As an example, the prediction of ship motions and DP capability differ for the selection of the working environment [7]. Moreover, the design loads for the structures involved in offshore operations (i.e. the whole ship or significant appendages like stingers) is not matching the real operability of the vessel [8].

The present paper presents an approach to combine the operability due to ship motions and DP [9], highlighting the differences between the maximum survival wave for vessel dynamics and the one considered for vessel and auxiliary structures dimensioning. A test case is reported on a Pipe Lay Crane Vessel (PLCV) to highlight the differences between the multiple analysis outcomes.

2. Analysis methods

Prior to the application of a combined method involving seakeeping and station keeping, it is necessary to individually describe the theories and the assumptions on the base of the standard DP and motions calculations. Besides, the maximum wave height determination, based on the extreme value theory, will be described to have a complete overview of the methods adopted through this study.

2.1. Seakeeping analysis

The performance assessment of an offshore vessel in a specific working environment depends on the following factors:

- Wave response characteristics;
- Sea environment;
- Vessel heading χ and speed (encounter conditions);
- Criteria for crew and vesel operation safety.

Model experiments can be carried out to determine the vessel wave response characteristics, obtaining frequency-dependent Relative Amplitude Operators (RAO) or transfer functions for the vessel six degrees of freedom (DOF). In alternative 2D or 3D analytical methods allows the estimation of the RAOs, provided that the adopted code as sufficient reliability for the analysed vessel type. The main difficulty for the evaluation of seakeeping performances is the determination of the responses limiting values, which will cause performance degradation [10]. These criteria have to be supplied by the operators and typically refer to root mean square (RMS) or maximum single amplitude values of a quantity. Then it is possible to represent the limiting criteria with critical curves on a diagram having the significant wave height $H_{1/3}$ as ordinate and the zero crossing wave period T_z as abscissa. Here, each limiting curve corresponds to a specific heading and speed and allows to evaluate the vessel operability by using wave statistics in a scatter diagram form.

The RMS value of a generic x_i motion results as from spectral integration:

$$x_{irms} = \int_0^\infty S_\zeta(\omega) RAO^2(\omega)\, \mathrm{d}\omega \qquad (1)$$

where ω is the wave circular frequency and S_ζ is the wave spectrum amplitude of the analysed sea state. It has to be noted that equation (1) is valid in case the RAO is obtained dividing the analysed quantity with the wave amplitude.

2.2. DP capability

Two possible approaches can be followed to determine the capability of a DP system in an early design stage [11]: a quasi-steady method and a time domain one [12]. Generally, time-domain resolutions require a more detailed modelling of the vessel and are more time-consuming compared to quasi-steady methods. Here a quasi-steady approach has been used to solve the DP issue. In this sense, the following 3 DOF equilibrium system on the horizontal plane describes the equilibrium of the forces:

$$\begin{cases} \sum_{i=1}^{n_T} F_{x_{T_i}} + F_{x_{env}} + F_{x_{ext}} & = 0 \\ \sum_{i=1}^{n_T} F_{y_{T_i}} + F_{y_{env}} + F_{y_{ext}} & = 0 \\ \sum_{i=1}^{n_T} M_{z_{T_i}} + M_{z_{env}} + M_{z_{ext}} & = 0 \end{cases} \tag{2}$$

where n_T is the number of actuators and the subscripts $_T$, $_{env}$ and $_{ext}$ denote the actuators, environmental and external forces and moments components. System (2) has 3 equations with $2n_T$ unknowns, thus it admits infinite possible solutions. The resolution is achieved adopting an optimisation algorithm, aimed to minimise the following objective function:

$$\min(Z) = \sum_{i=1}^{n_T} \left(F_{x_{T_i}}^2 + F_{y_{T_i}}^2 \right) \tag{3}$$

Equation (3) is representative of the square of the total thrust delivered by the actuators [13]. System (2) becomes a set of equality constraints limiting the search of the optimum. Besides the equilibrium equation, additional constraints are needed to ensure that the thruster will be not overloaded and to consider the *forbidden zones*. This leads to a non-linear optimisation problem, that can be solved adopting proper techniques [14]. It is well known that quasi-steady predictions are overestimating the DP capability compared to time domain simulations [15]. To reduce this effect, a dynamic allowance is considered, increasing the environmental loads of 25%.

The final DP capability of the vessel is determined estimating the maximum sustainable wind that the system can face at each encounter heading, considering all the environmental loads (wind, wave and current) concurrent. The final results are then reported on the so-called *capability plots*.

2.3. Maximum wave height determination

During the design process of an offshore vessel/structure, the estimation and prediction of extreme loads and motions in harsh condition are extremely important. In both cases, the analysis includes data series relative to an almost short time compared to the vessel/structure life cycle. Moreover, the extreme values lies in a region above the maximum value of the sample data [16]. On this purpose it is necessary to use extreme value theory to properly identify the limiting distributions that are more suitable to describe the data in extreme regions. Previous studies highlights that mixed distributions can be used to reproduce the data sample once all the peaks are included in the analysis [17].

Another option is given by use data only above a selected threshold value [18]. Here, this second option has been used, adopting a Generalised Pareto Distribution (GED) to fit the extreme wave data and evaluate the extreme $H_{1/3}$ associated to the probability of occurrence p of 0.1%.

3. Combined station keeping and seakeeping predictions

In the previous section, the individual analysis related to sekeeping and DP are presented. However, it is the opinion that the two topic are strongly related and should be then considered in a combined approach. The operating conditions for offshore vessels are determined by motion or acceleration limitations for certain on-board equipment (crane, derrick, stinger, etc.). As described in the previous section, the critical curve for a certain motion can be obtained and plotted in diagrams as function of T_z and $H_{1/3}$. Station-keeping calculations are not considering all the possible combinations of $H_{1/3}$ and T_z, but refers to a wind-wave correlation, associating to a wind speed V_w a specific couple of $H_{1/3}$ and T_z. It is then consequential that, once seakeeping and DP calculation refers to the adoption of the same wave spectrum, there is a correspondence of input data only for the point laying on the wind-wave correlation curve. At this point, intersecting the critical curves with the wind-wave correlation one, it is possible to determine a maximum wind speed for the selected criteria per each vessel heading and represent it on the DP capability plot.

3.1. Common reference system

To ensure that the combined analysis effectively corresponds to the same condition for seakeeping and DP, it is convenient to adopt the same reference system for the individual calculations. In the specific, the reference system for DP is adopted also for seakeeping calculation. With reference to Figure 1, the system is centred in the vessel midpoint O, considering rotation positive in clockwise direction. The encounter angle between vessel and concurrent loads is named χ with 0° corresponding to the bow and 180° to the stern.

4. Test case

To investigate the combined prediction between station keeping and DP performances, use has been made of a reference PLCV (Fig. 2). The vessel has a length overall L_{OA} of 165 metres, a breadth B of 38 metres and an operative draught T of 5 metrs, corresponding to a displacement Δ of 24000 tonnes. The vessel is equipped with six azimuth thrusters and a fixed bow tunnel thruster disposed as shown in Figure 3. The PLCV is predisposed for S-lay operation, having a stinger fitted to the aft-ship in asymmetrical position. To consider the presence of the stinger during DP calculation, an additional external load of 150 tonnes in longitudinal has been added to the environmental loads. This vessel is extremely interesting due to the presence of a fully asymmetrical thruster disposition and the presence of the stinger. The stinger has to be properly dimensioned according to the maximum loads that may occur in the junctions between the structure and the vessel. On this purpose, it is necessary to determine the wave height to use for the

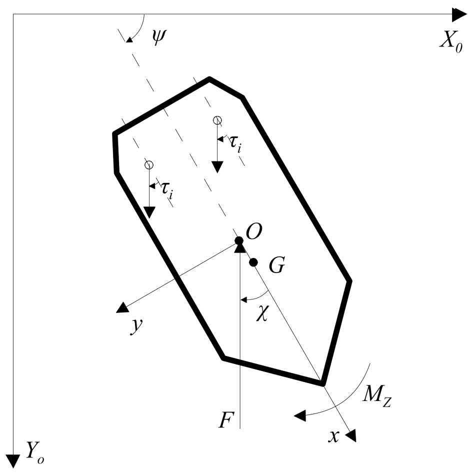

Figure 1. Reference system for combined analysis

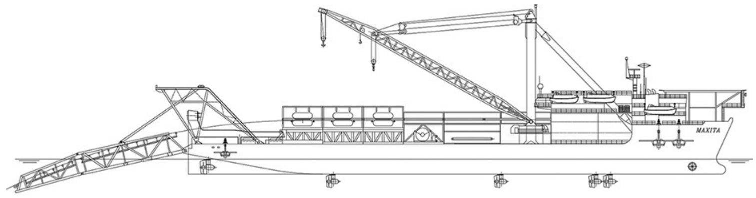

Figure 2. PLCV profile

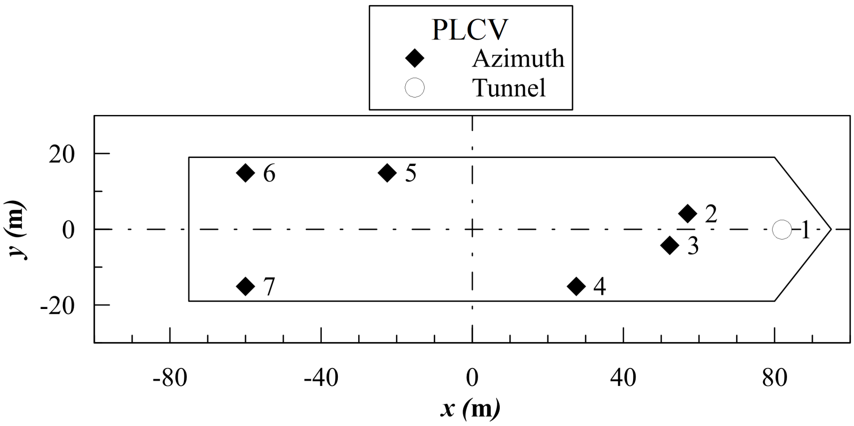

Figure 3. PLCV thrusters layout

design. To properly determine the design $H_{1/3}$, use has been made of the SHIPREL [19] (Reliability Methods for Ship Structural Design) wave scatter diagram [20] describing the North Atlantic sea environment.

Besides the limiting $H_{1/3}$ it is necessary to define also the limiting motion criteria. According to operators, for an S-lay operation the limiting criteria are associated to pitch

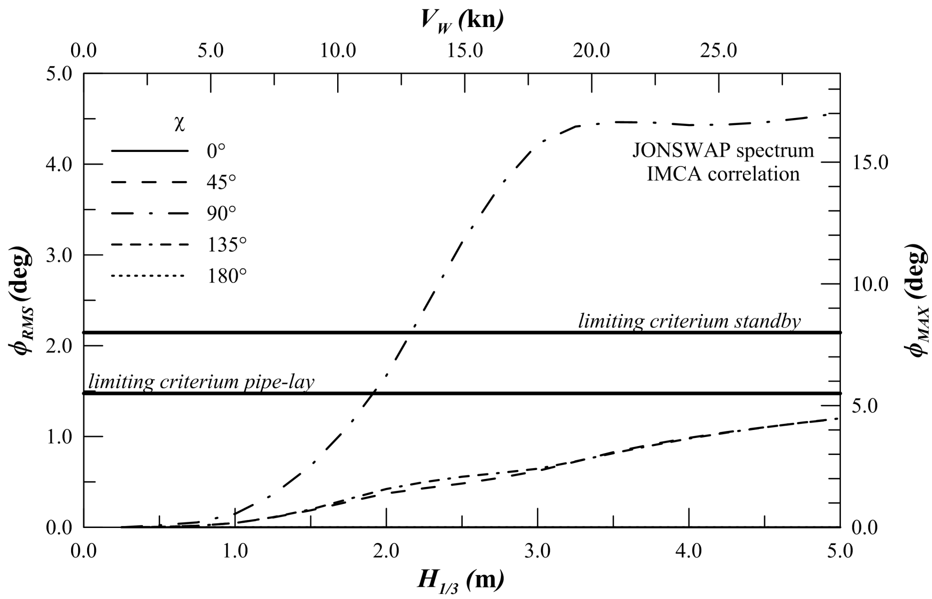

Figure 4. Roll RMS at zero speed for multiple headings

and roll motions, considering 1.0° of pitch and 5.5° of roll in maximum single amplitude. During standby, the limits may increase to 1.5° of pitch and 8.0° for roll. To determine the combined analysis use has been made of the JONSWAP spectrum with a cosine squared spread function, to be compliant with IMCA wind-wave correlation adopted for DP calculations. For the selected vessel the RAO were measured during model experiments and the environmental forces also, increasing the reliability of the presented results.

5. Results and discussion

On the reference PLCV, the standard seakeeping analysis has been performed, considering the above-mentioned criteria for roll and pitch motions. By considering the use of a JONSWAP spectrum and making reference to the IMCA wind-wave correlation, it is possible to perform seakeeping calculations directly on the specific couple $H_{1/3}$, T_z corresponding to the selected wind-wave correlation. Then, instead to plot the limiting curve on a scatter diagram, it is possible to visualize the criteria on the RMS and maximum amplitude value directly as a function of the $H_{1/3}$ only, since the T_z changes accordingly the correlation. In Figure 4 it is possible to observe the RMS of roll motion as a function of the $H_{1/3}$. Here the limiting criteria are given for the pipe lay operations and standby conditions are represented by the two tick horizontal lines, noting that the low $H_{1/3}$ limiting values are obtained for χ= 90° only. For the other headings, roll is not a limiting issue.

With reference to the pitch motion, the situation is different, since, due to the small allowable single amplitude values (1.0 and 1.5 degrees), the limiting $H_{1/3}$ is relatively low with respect to roll motion. This can be better visualised in Figure 5, where it can be noticed that, despite for beam seas (where the pitch motion is almost close to zero), all

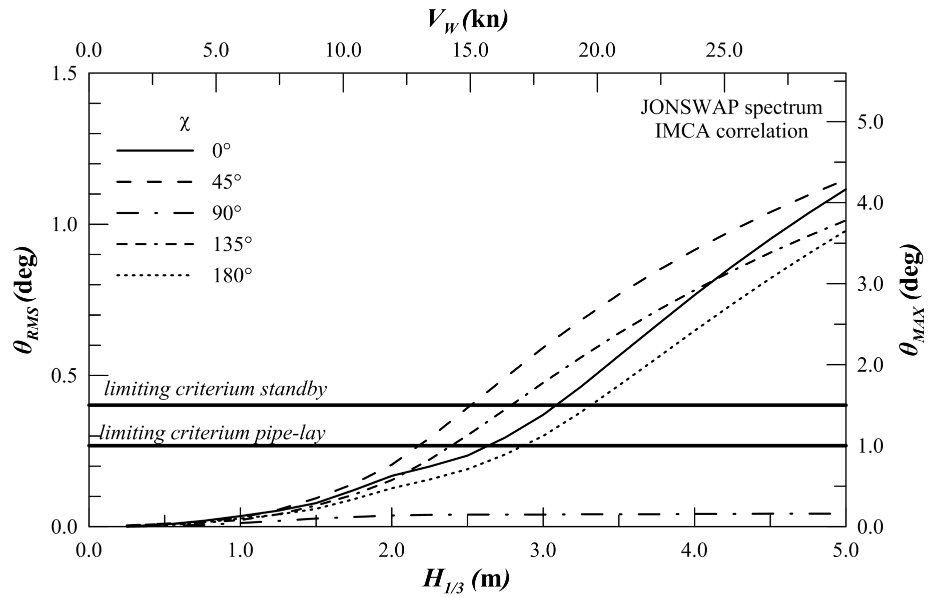

Figure 5. Pitch RMS at zero speed for multiple headings

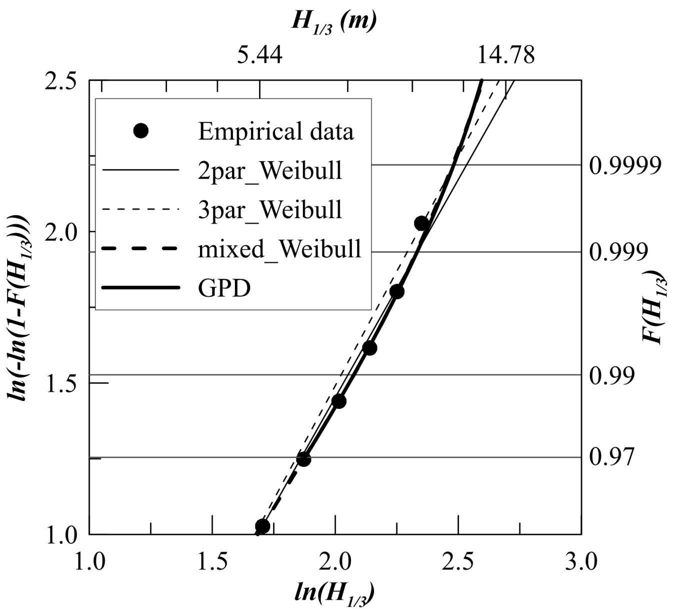

Figure 6. Extreme wave height determination for SHIPREL data

the intersections between criteria and RMS curves are below 4.0 meters of $H_{1/3}$.

Besides the seakeeping calculations, the estimation of the maximum design wave height has been performed. As mentioned, the analysis method used is based on the extreme value theory using a GPD distribution. To determine the extreme values, the inverse cumulative distribution (quantile) of the limiting law should be used, that in case of a GPD, has the following form:

$$Q(p,u,\eta,\beta) = u + \frac{\beta}{\eta}\left[1-\left(\frac{n}{N_u}(1-p)\right)^{\beta}\right] \tag{4}$$

where u is the threshold value, η is the scale parameter (defined in $(0,+\infty)$), β is the shape parameter (defined in $(-\infty,+\infty)$), n represents the total number of observations and N_u is the number of observations exceeding the threshold value u.

Considering the SHIPREL data, the threshold limit evaluated according the mean exceed function technique is 5.5 meters. So, applying equation (4) with a p=0.01, the extreme wave height results to be 10.14 meters. In Figure 6 the tale of the distribution is represented on the Weibull plot, highlighting the differences between the GPD and other limiting distributions for the analysed data set. By considering a maximum wave height of 10.14 m, according to IMCA correlation, the corresponding wind speed results to be of 50.23 knots.

As last analysis, DP calculations have been performed on the PLCV. Calculations are not referring only to intact conditions (means with all active thrusters), but also to multiple failure levels. In fact, it is common practice to group DP system into three equipment classes. In class 1, the position can be lost in case of one failure. Class 2 (named also DP2) states that the vessel should keep position in event of one failure. Class 3 (named also DP3) imply the ability to keep position in case of loss of one compartment of on-board power (for the PLCV it corresponds to the loss of two thrusters). All the possible combinations have been evaluated, representing the minimum envelop of each class in terms of maximum sustainable wind per each vessel heading.

At this point each analysis has given a maximum wave height (associated to a wind speed V_w) as heading dependent limiting value for the vessel operations. In fact, the motion limits are representative of the operability in therms of pipe-laying operation, the DP limits indicate the vessel station-keeping ability and the design wave gives an indication of safety for the stinger structure dimensioned according to the extreme wave for North Atlantic. All these limits can be plotted on the same diagram. Figure 7 shows all these limits together. It can be immediately noticed that the motion limitations are the most restrictive with regards to the operability itself, stating that pipe lay operations can be executed up to a wind speed of about 20 knots. In case this threshold is exceeded, then the vessel can operate in standby condition, means with the stinger in water and the pipe connected with the vessel. Here limitations are given by the DP system close to beam seas and by the structural strength for head and following conditions. It is interesting to observe that the pip-laying operations can be executed with the half of the power installed on-board. In fact, DP3 envelope is similar to the motion one. This analysis highlights that it is necessary to consider multiple criteria to establish the effective limiting environment for an offshore ship.

6. Conclusions

Through this paper the standard analysis methods for ship motions, station keeping ability and design wave height determination have been presented and discussed. Besides, the possibility to consider comparable and coherent inputs for the multiple analysis has

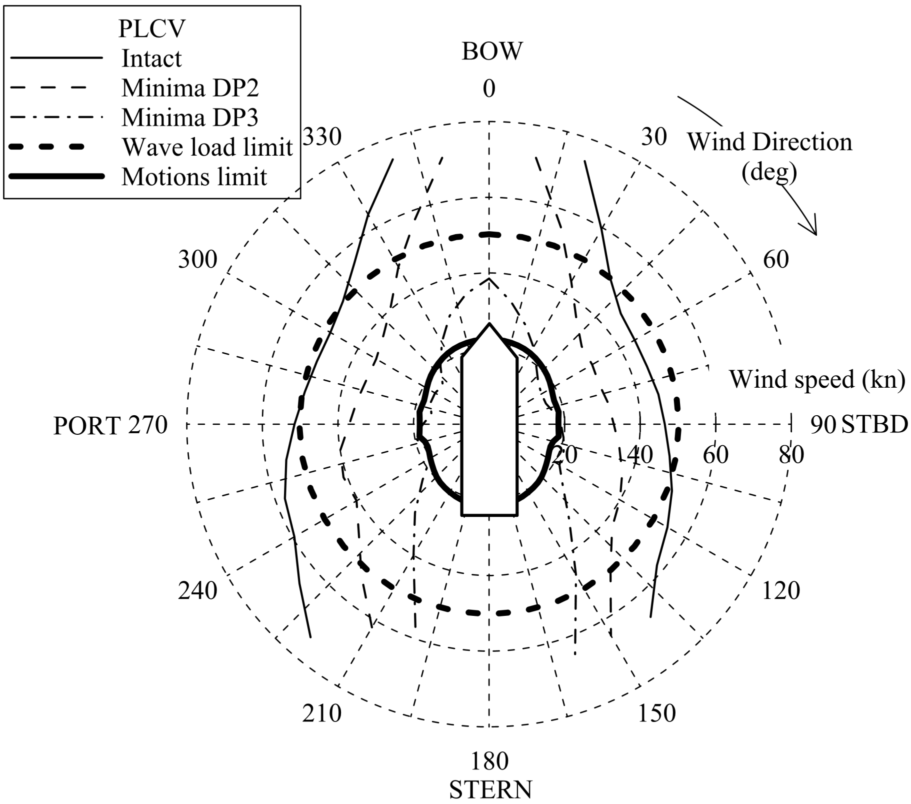

Figure 7. Limiting environments on a DP capability plot

been investigated, obtaining comparable limiting environments from the individual analysis methods. In particular the combined station keeping and seakeeping analysis allow to select a suitable wind-wave correlation that can be then used also for the conversion of the design wave in maximum wind speed. For the maximum design wave, use has been made of GPD distribution, applied to specific values of the North Atlantic. The implemented procedure highlight that each individual analysis is giving a different limiting environment, considering different operational issues. Motions are limiting for the operation itself, while DP and structural strength deals more with survival condition. Since the analysis highlights that for the considered vessel the installed power is too high for the operation purposes, than this method can give to designers an indication on how to reduce power installed on-board or to change the thrusters layout to optimise the vessel operability.

References

[1] R. Nabergoj, Station-keeping and seakeeping in offshore vessel design, *Proceedings of 1st INT-NAM 2011*, Istanbul, 2011.

[2] DNV, Rules for the classification of ships, *Det Norske Veritas*, 2011.

[3] C.G. Soares, Z. Cherneva, E. Antao, Characteristic of abnormal waves in the North Sea storm sea states, *Applied Ocean research* **25** (2003), 337-344.

[4] F. Mauro, J. Prpić-Oršić, L. Braidotti, Extreme loads estimation using genetic algorithm approach, *Trends in the Analysis and Design of Marine Structures*, MARSTRUCT 2019, Dubrovnik, 2019.
[5] F. Mauro, R. Nabergoj, Smart thrust allocation procedures in early design stage dynamic positioning predictions, *Proceedings of the 18th International Conference on Ships and Shipping Research NAV 2015*, Lecco, 2015.
[6] F. Mauro, R. Nabergoj, Advantages and Disadvantages of of thrusters allocation procedures in preliminary dynamic positioning predictions, *Ocean Engineering* **123** (2016), 96-102.
[7] F. Mauro, R. Nabergoj, Optimal thruster location on offshore DP vessels, *International Shipbuilding Progress* **Pre-press** (2019), 1-18.
[8] F. Mauro, L. Braidotti, U. la Monaca, R. Nabergoj, Extreme loads determination on complex slender structures, *International Shipbuilding Progress* **66**(1) (2019), 57-76.
[9] F. Mauro, R. Nabergoj, Integrated station-keeping and seakeeping predictions, *16th International congress of the International Maritime Association of the Mediterranean IMAM 2015*, Pula, 2015.
[10] Nordforsk, Assessment of Ship Performance on a Seaway: The Nordic Cooperative Project: "Seakeeping Performance of Ships", *Norforsk*, 1987.
[11] F. Mauro, F. Gaudiano, Station-keeping calculations in early design stage: two possible approaches, *Proceedings of NAV 2018 Conference*, Trieste, 2018.
[12] J.J. Serraris, Time-domain analysis for DP simulations, *Proceedings of OMAE Conference*, Honolulu, Hawaii, 2009.
[13] F. Mauro, E. Duranti, Effect of propeller modelling on station keeping thruster allocation strategy, *Proceedings of NAV 2018 Conference*, Trieste, 2018.
[14] E. van Daalen, H. Cozijn, C. Loussuran, P. Hemker, A generic optimisation algorithm for the allocation of DP actuators, *Proceedings of OMAE 2011 Conference*, Rotterdam, 2011.
[15] O. Smogeli, N. Trong, B. Borhaug, L. Pivano, The next level DP capability analysis, *Proceedings of Dynamic Positioning Conference*, 2013.
[16] F. Mauro, M. Monacolli, Evaluation of extreme wave loads for slender tubular structures, *Proceedings of NAV 2018 Conference*, Trieste, 2018.
[17] F. Mauro, R. Nabergoj, Extreme value calculation of Multi-Modal Peak Distributions, *Proceedings of EM 2016*, Svratka, 2016.
[18] F. Mauro, R. Nabergoj, An Enhanced Method for Extreme Loads Analysis, *Brodogradnja* **68**(2) (2016), 79-92.
[19] C.G. Soares, M. Dogliani, O. Ostergaard, G. Permentier, P.T. Pedersen, Reliability Based Ship Structural Design, *SNAME Transactions* **104** (1996), 357-389.
[20] N. Hogben, N. Dacunha, G. Olliver, Global Wave Statistics, *British Maritime Technology Limited*, 1986.