OPERATIONAL BEHAVIOUR OF AN OFFSHORE MULTIPURPOSE SUPPORT VESSEL IN THE EASTERN MEDITERRANEAN SEA

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SUMMARY

The objective of this work is to analyse the operational behaviour of an offshore multipurpose support vessel designed to operate in the Eastern Mediterranean Sea. First, the seakeeping analysis is performed in a regular wave condition for different heading angles estimating heave and pitch motions through the strip theory. After that, the effects of the vertical acceleration on the bow, occurrence of slamming or hydrodynamic impact of the hull on the surface of the water; wetted deck, occurrence or invasion of water on the deck of the vessel and propeller emersion, motion sickness and wave-induced additional resistance are analysed. The present analysis is extended in an irregular sea condition, and the estimated seakeeping criteria are compared to the acceptable levels. In defining the most suitable operational mode of the offshore support vessels, multi-criteria decision techniques and probabilistic approach are employed to perform an adequate evaluation of the seakeeping performance accounting for different hazardous events through the service life.

1. INTRODUCTION

New challenges in the Mediterranean Sea have been risen in the last decades, including the offshore oil and gas exploration and installation, and operation of renewable energy offshore wind turbine installations. The new defined natural gas fields in the Eastern Mediterranean are shown in Figure 1.

The seakeeping performance of ships is an essential characteristic in predicting the ship behaviour in regular and irregular waves and stochastic conditions and many approaches to estimate the wave-induced impact on the ship were developed. Series of studies with this respect have been performed based on numerical and experimental approaches (Blok & Beukelman, 1984, Jensen et al., 1994, Fonseca & Guedes Soares, 1998, Prpić-Oršić & Faltinsen, 2012).

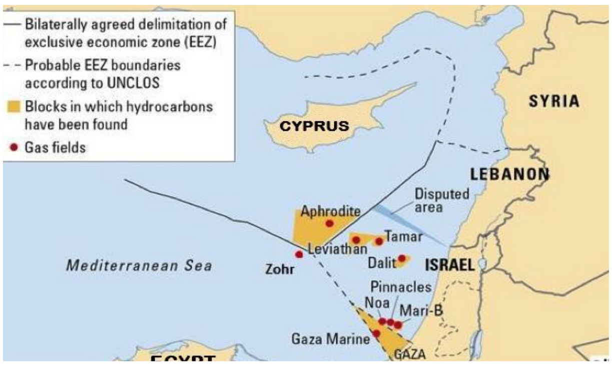

Figure 1: Natural gas fields in the Eastern Mediterranean (Zughayar, 2016)

Following the current design regulations (IACS, 2018) and specific requirements, an offshore multipurpose support vessel, as a part of an offshore support fleet for a maintenance operation at offshore wind farms, transportation of people and patrol operation was initially designed and presented in (Almany et al., 2018). Recently this ship was updated with respect to the main dimensions and the seakeeping performance of the most updated design solution of that ship is analysed here.

2. DYNAMIC BEHAVIOUR

The main characteristics of the analysed offshore multipurpose supporting vessel (Almany et al., 2018) are: L_{pp} =42m, B= 7.6m; d= 2.5mervice speed of v=23 knots (v_{max}=25 knots) as can be seen in Figure 2.

Figure 2: Offshore multipurpose support vessel

The vessel may accommodate up to 20 crew members and has an option of taking 20 technicians or castaways to the nearest port for one week at sea, and the ship mission autonomy is about 1,000 miles.

This type of vessels may cover a variety of multifunction including survey, platform supply, offshore construction, support, inspection, maintenance and repairs and also patrol operations.

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The motion of the vessel in regular sea is estimated, then extrapolated for real situations of the irregular sea. The characteristics that quantify the behaviour of the ship are obtained through the Strip theory (Gerritsman & Beukelman, 1964).

The movements in six degrees of freedom of a ship advancing at a constant speed with an angle of arbitrary direction are estimated. The amplitudes and phases for the movements of the ship in regular sinusoidal waves are calculated using as an input the strip-wise geometry of the ship hull (see Figure 3).

The employed procedure is based on the strip theory and according to which the ship hull is divided into transversal slices and the movement of each of the slices is computed independently of the other being linearized.

The amplitudes of waves and movements are assumed small relative to the equilibrium point. It is also assumed that the movements are linear and harmonic and that the flow on each slice is two-dimensional.

The vertical movement of each segment is considered as a combination of the heave and pitch movements of the vessel, and the ship motion is defined:

$$\zeta_i = a_i \cos(\omega_e t - \varepsilon_i),\ i = 1 \ldots 6 \qquad (1)$$

where ω_e is the encounter frequency, a_i is the amplitude of the motion, ε_i is the phase angle that expresses the delay of the motion about the peak of the wave. The response movement of the ship in the wave is given in the frequency of the encounter, ω_e, which is defined as:

$$\omega_e = \omega - k\, v_s \cos(\mu) \qquad (2)$$

where $\omega = \sqrt{(2\pi g/\lambda)}$ is the wave frequency, λ is the wavelength, g is the acceleration of gravity, k is the wave number and μ is the heading angle.

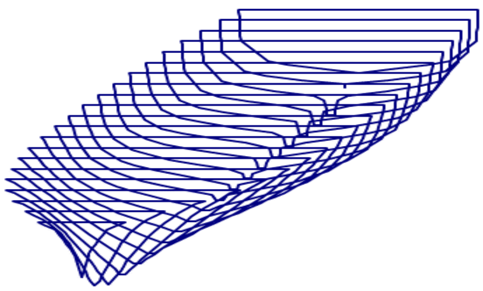


Figure 3: Strip-wise geometry description of ship

Assuming that the motion responses are linear and harmonic, the ship movements may be defined as (Salvesen et al., 1970):

$$\sum_k [(M_{jk} + A_{jk})\ddot{\zeta}_k + B_{jk}\dot{\zeta}_k + C_{jk}\zeta_k] = F_j e^{i\omega_e t}\ ;\ j = 1 \ldots 6 \qquad (3)$$

where M_{jk} is the components of the mass matrix, A_{jk} and B_{jk} are the coefficients of the additional mass and damping, C_{jk} is the hydrostatic restoration coefficients, and F_j is the amplitudes of the forces and moments of excitation. The heave and pitch movements required for the present analysis are decoupled from the sway, yaw, roll and surge motions.

The ship motion coefficients are defined as a function of the encounter frequencies employing the Frank Close-Fit method, which initially was developed by (Frank, 1967) and is valid for any type of cross sections, which are partly or fully submerged.

The additional mass and damping coefficients are computed assuming the two-dimensional problem of a cylinder section in the same shape as the individual sections that oscillate on the free surface. Once hull sections are fed, the hydrostatic characteristics and the additional mass and damping coefficients are computed, then the movements for the specific conditions of the heading angle, μ, velocity, v and sea states, $H_{1/3}$ and T_z are defined.

Within a year, the Mediterranean Sea is dominated by wave heights of 1 to 2m with a probability of 40 to 50%. From March to November, almost altogether along with significant wave heights of 1 to 2m, comparatively frequent are the heights of waves of less than 1 m; their probability is 25 to 35% in the western part of the Mediterranean Sea and 20 to 25% in the eastern part. Wave heights of 2 to 3m are the most likely in the eastern part of the sea, where their occurrence from December to February reaches 25 to 30%, in the rest of the year it is about 20%. In the western part of the sea, the probability of wave heights of 2 to 3m is 15 to 20% during the whole year. Wave heights of 3m and more are more commonly observed from December to February.

The analysed vessel is designed as a part of the service group G6, unrestricted (Almany et al., 2018). The maximum operational freedom for the sea state with a significant wave height of $H_{1/3}$ = 4m is assumed here (Zughayar, 2016).

The available wave data are based on collected visual wave observations, and the sea surface is divided into zones (Hogben et al., 1986), where these geographic areas represent the fairly uniform wave conditions. The relative rate of occurrences of different sea states is defined by the significant wave height $H_{1/3}$ and zero crossing period T_z.

The occurrence of the sea states in the Eastern Mediterranean areas, where the analysed ship is operating, is shown by a scatter diagram, which is a function of the significant wave height, $H_{1/3}$, which is the average of the highest one third of the wave heights and zero crossing period, T_z, as given in Figure 4.

It is assumed that the sea states are described by a single peaked spectrum, which is well modelled by the parametric form of the Pierson and Moskowitz (1964) spectrum.

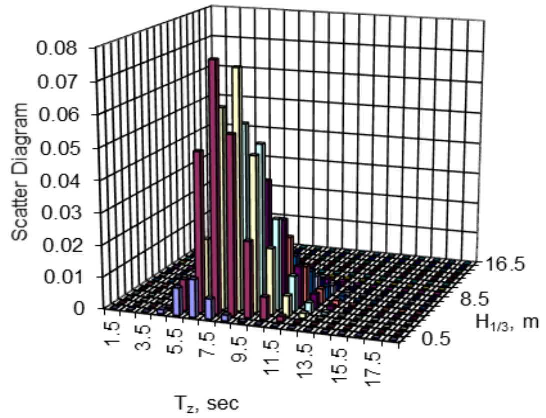


Figure 4: Scatter diagram of the Eastern Mediterranean sea

The PM spectrum is used in the short-term spectral analysis for the rendezvous probability and the significant wave height as:

$$S_\xi(\omega|H_{1/3},T_z)=171H_{1/3}^2T_z(\omega T_z)^{-5}\text{Exp}[-685.76(\omega T_z)^{-4}] \tag{4}$$

With the heave, $\eta_3 = z_a/\xi_a$ and pitch, $\eta_5 = \theta_a/\xi_a$ amplitudes, where ξ_a is the wave amplitude, and their respective phase angles, $\varepsilon_3 = \varepsilon_z$ and $\varepsilon_5 = \varepsilon_\theta$ the heaving and pitching motions in a regular seaway are defined as:

$$z(t) = z_a \cos(\omega_e t + \varepsilon_z) \tag{5}$$

$$\theta(t)\theta_a \cos(\omega_e t + \varepsilon_\theta) \tag{6}$$

The motion at the point of interest x= ξ when ξ_a =1m and assuming that the rotating angles (for instance pitch) is small, which leads to sinθ≈θ, and permits to write the relationships in a linear form is defined as (Journee & Massie, 2001):

$$z_x = z_a + \xi\theta_a = z_{xa}\cos(\omega_e t + \varepsilon_{zx})$$

where ξ is the distance of at the point of interest x from the centre of gravity of the ship, z_{xa} is the vertical motion amplitude, ε_x is the phase defined as:

$$z_{xa}=\sqrt{[(z_a)^2 + (\xi\theta_a)^2 + 2 z_a \xi\theta_a \cos(\varepsilon_z - \varepsilon_\theta)]} \tag{7}$$

$$\tan(\varepsilon_{zx}) = [z_a \sin(\varepsilon_z) + \xi\theta_a \sin(\varepsilon_\theta)]/[z_a \cos(\varepsilon_z) + \xi\theta_a \cos(\varepsilon_\theta)] \tag{8}$$

When the ship is heading into waves, the water elevation at the point of interest x= ξ is given as:

$$\xi_x(t) = \xi_a \cos(\omega_e t - k_e\xi) \tag{9}$$

where $k_e = (\omega_e^2)/g$ and ξ_a is the wave amplitude.

The relative vertical motion at the point of interest x about the surface of the wave is defined by:

$$s_x = z_x - \xi_x \tag{10}$$

$$s_x = z_{xa}\cos(\omega_e t + \varepsilon_{zx}) - \xi_a \cos(\omega_e t - k_e\xi) \tag{11}$$

$$s_x = s_{xa}\cos(\omega_e t + \varepsilon_{sx}\sigma) \tag{12}$$

where the amplitude, s_{xa} and phase, ε_{sx} are calculated as:

$$s_{xa}=\sqrt{[(z_x)^2 + (\xi_a)^2 - 2z_{xa}\xi_a\cos(\omega_e t - k_e\xi)]} \tag{13}$$

$$\tan(\varepsilon_{sx}) = [\xi_a \sin(k_e\xi - \omega_e t) - z_a \sin(\varepsilon_{zx})] / [\xi_a \cos(\omega_e t - k_e\xi) - z_{xa}\cos(\varepsilon_{zx})] \quad \tan(\varepsilon_{sx}) = \tag{14}$$

The amplitude of the relative vertical velocity and acceleration are calculated as:

$$v_{xa} = \omega_e s_{xa} \tag{15}$$

$$a_{xa} = \omega_e^2 s_{xa} \tag{16}$$

The energy density response spectrum, $S_R(\omega_e)$ is defined as:

$$S_R(\omega_e) = S_\xi(\omega_e|H(\omega_e)|^2 \tag{17}$$

where $S_R(\omega_e)$ is the wave spectrum and $|H(\omega_e)|^2$ is the RAO as a function of the encounter frequency, ω_e. In the case of the pitching motion, RAO=$(\theta_a/\xi_a)^2$ and for heaving motion, RAO=$(z_a/\xi_a)^2$.

The objective here is to evaluate the dynamic behaviour of the vessel when faces certain sea states that characterise the region of the Eastern Mediterranean Sea. The vertical movement, composed of the ship's pitch and heave movements, is responsible for the dynamic effects that may compromise the performance of the vessel if occurring in sufficient quantities. Therefore, it is necessary to evaluate the phenomena of the seakeeping, including the effects of the vertical acceleration on the bow, occurrence of the slamming or hydrodynamic impact of the hull on the surface of the water; wetted deck, occurrence or invasion of water on the deck of the vessel and propeller emersion, motion sickness and wave-induced additional resistance.

The response of the vessel in the regular-sea is defined, and it is extrapolated to real situations of the irregular sea. The analysis is performed for the ship movements for specific conditions of the angle of headings, $\mu \in [0, 360°]$ with a step of 30º for a ship velocity v $\in[0, 25°]$ knots with a step of 5 knots, sea states defined by a wave frequency of $\omega \in [0.1, 3.1]$ rad/s and a significant wave height of $H_{1/3} \in [0.5, 4]$ m with a step of 0.5m.

The seakeeping phenomena are evaluated through statistical procedures, where the sea wave is represented by a spectrum of energy as well as the response of the ship.

Assuming that the waves follow the Rayleigh probability distribution, the probability of occurrence of a specific event is estimated as (Bhattacharyya, 1978):

$$P[z>z_c]=\exp[-z_c^2/(2\ m_{oz})] \qquad (18)$$

where m_{oz} is the zero spectral moment, and z_c is the critical value representing the acceptance criterion.

The number of responses per second is approximately calculated as:

$$n_z=1/(2\pi)\sqrt{(m_{2z}/m_{oz})} \qquad (19)$$

where m_{2z} is the second spectral moment.

To estimate the acceptable vertical acceleration on a board in an open sea agitated water ISO2631-1 (2010) may be used. The criteria adopted here for evaluating the occurrence of seakeeping phenomena are defined for the bow thrust is the RMS acceleration greater than 0.2g resulting in a probability of 5%, for the green water the probability of displacement higher than the freeboard of 5%. For slamming a criterion is adopted, which represents the probability of velocity higher than the critical velocity as defined by Ochi and Motter (1974):

$$v_c = 0.093\sqrt{(L_{pp}\ g)} \qquad (20)$$

where v_c is the critical relative velocity, and L is the length of the ship resulting in 5% of probability.

The probability of the relative height of the point of the longitudinal position under analysis is higher than its draft, d_b in the point. The probability of propeller emersion is limited to 15%.

The motion sickness acceptable index is defined as 10% for an exposure time of 8 hours.

2.1 DECK WETNESS

The incidence of water on the deck can cause disasters for many types of ships. Seawater may enter the ship and flood one or more compartments, causing a progressive flood. It may also cause damage to the mooring and other equipment on the deck.

The vertical displacement is defined as:

$$S(X_{FP}) = Z - X_{FP}\theta - \xi(X_{FP}) \qquad (21)$$

where z is the heave displacement, θ is the pitch angle and $\xi(x_{FP})$ is the wave elevation at x_{FP}. The dynamic effects of the interaction of the bow with the rising wave changes depending on the shape of the bow.

Ochi and Motter (1974) defined a limiting probability of 0.05, which is used to calculated m_{os}:

$$P\ [s(x_{FP}) > f(x_{FP})] < 0.05 \qquad (22)$$

where $f(x_{FP})$ is the effective freeboard. Assuming that this event follows the Rayleigh distribution, the probability that $s(x_{FP}) > f(x_{FP})$ at x_{FP} is defined as:

$$P\ [s(x_{FP}) > f(x_{FP})]= \exp[-f(x_{FP})^2/(2\ m_{osFP})] \qquad (23)$$

where m_{osFP} is the zero response spectral moment for the relative vertical motion at the forward perpendicular, x_{FP}.

2.2 PROPELLER EMERSION

When the propeller emersion occurs, it loses its efficiency, failing to provide the thrust required to maintain the speed of service of the vessel. To ensure propulsion efficiency, the propeller must be submerged. In the case of an excessive emersion, in addition to provoking greater mechanical demands, inducing more wear of its components, the propeller can also wear when working in a cavitation regime.

Knowing that the probability of the relative vertical movement at the point of the tip of the propeller in exceeding the draft of the propeller should be less than 5 %. Assuming that this event follows the Rayleigh distribution, the probability that $s(x_P)> d_P$, and the depth of the tip of the propeller is d_P = 1.5m, is defined as:

$$P[s(x_P)>d_P]=\exp[-d_P^2/(2\ m_{osP})] \qquad (24)$$

2.3 VERTICAL ACCELERATION

High vertical accelerations along the hull can cause discomfort and poor performance to the crew, invalidate some equipment, and depend on the magnitude, can make human work impossible. It is assumed that the bow of the vessel is located at x_B = 19.9m from the longitudinal centre of gravity, which is the location of the hull where the most substantial vertical accelerations occur due to the combination of heave and pitch movements.

The assumed criterion here, which evaluates the criticality of this event is:

$$P[a_s(x_B)> a_c] < 0.05 \qquad (25)$$

Assuming that this event follows the Rayleigh distribution, where the probability that $a_s(x_B) > a_c$ is defined as:

$$P[a_s(x_b)>a_c]=\exp[-a_c^2/(2\, m_{osb})] \quad (26)$$

2.4 HYDRODYNAMIC IMPACT

The impact of the wave with the bow of the ship, known as slamming, in addition to the fact that is causing high local stresses, due to induced vibrations may generate additional stresses that in combination to the bending moment increases the total stresses.

The parameters defining the hydrodynamic effect are related to the frequency, the time interval of the occurrence, impact strength and speed where the slamming is developed.

The condition for the bow, at section x_B in exceeding the ship's draft, d_B can be defined by:

$$\left[d_B - s(X_B)\right] < 0 \quad (27)$$

$$S(X_B) = Z - X_B\theta - \xi(X_B) \quad (28)$$

where d_B is the draft of the vessel at the bow section, z, θ are the heave and pitch, and $\zeta(x_B)$ is the wave amplitude.

Ochi and Motter (1974) defined the limiting probability values of slamming as 5%. Knowing that the probability of relative vertical motion at the bow in exceeding the ship's draft and that the probability of the vertical relative velocity at point x_B exceeding the critical velocity should be less than 5%, then m_{ovB} and m_{osB} required from their respective criteria, for studied loading cases are defined as:

$$P[s(x_B)> d_B \cap v_s(x_B)> v_c]< 0.05 \quad (29)$$

The probability of slamming is given as defined by Ochi and Motter (1974):

$$P[s(x_B)>d_B \cap v_s(x_B)>v_c]= \exp[-d_B^2/(2\, m_{osB}) - v_c^2/(2\, m_{ovB})] \quad (30)$$

where m_{osB} is the zero spectral moment of the relative vertical motion, and m_{ovB} is the zero spectral moment of the relative vertical velocity at x_B.

2.5 ADDITIONAL POWER

To maintain the service speed at sea, the vessel needs additional power due to the presence of waves. The additional resistance at sea can be represented either by an increase in the power required to maintain the speed or by a reduction in speed for a given constant power of service (Kim et al., 2017).

In the initial phase of the design, where the powertrain was selected, a 3% rotational speed margin, a sea margin of 15 % and a motor margin of 10% were added to the required power in still water, to achieve the service speed in the various sea conditions with a certain margin of safety.

The additional resistance calculation as a part of the total BHP has the purpose of verifying if the installed power margin can be considered as satisfactory:

$$2m_o(BHP)>BHP_{installed} \quad (31)$$

The installed engine power, $BHP_{installed}$ is 2,880kW.

The spectrum of the encountered added resistance of the ship in an irregular seaway:

$$S_{Raw} = S\xi\left(\omega_e \middle| H_{1/3}, T_Z\right) R_{aw} / \xi_a^2 \quad (32)$$

The event that prevents the ship from increasing the probability of maintaining its service speed is the emersion of the propeller, which means that the ship should decrease its speed of service when it is sailing in waves with waves above a specific speed to keep the propeller immersed. Therefore, there is excessive power in some sea state conditions because the maximum available power of the ship cannot maintain the speed of service.

The needed power calculated here is based on the approach developed by Joosen (1966) and discussed in (Bhattacharyya, 1978).

2.6 MOTION SICKNESS INDEX

The motion sickness index is defined based on the concept developed by O'Hanlon and McCauley (1974), and following ISO2631-1 (2010), MSI has to be smaller than 10%:

$$MSI(\%) = 100\ \Phi(a, t) < 10\% \quad (33)$$

$$\Phi(a, t) = \Phi(z_a)\ \Phi(z_t') \quad (34)$$

$$z_a=2.128 \operatorname{Log}_{10}(|a_v|/g) - 9.277 \operatorname{Log}_{10}|\omega_e/2\pi| - 5.809 \operatorname{Log}_{10}|\omega_e/2\pi|^2 - 1.851 \quad (35)$$

$$z_t'=1.134z_a+1.989\operatorname{Log}_{10}(t_{exp})-2.904 \quad (36)$$

$$a_v=0.798 \sqrt{(m_{oa})} \quad (37)$$

where Φ(.) is the standard cumulative Normal distribution function with a zero mean and unity standard deviation, t_{exp} is the exposure time given in minutes, ω_e is in Hz and $|a_v|/g$ represents RMS magnitude of the vertical acceleration.

3. SEAKEEPING ANALYSIS

3.1 SHIP OPERABILITY

The operability constraints are defined based on some criteria that were already defined in the previous section and the operability criteria as has been discussed by Nordenstrom (1971), Hutchison (1981), Naito et al. (2006), Ghaemi and Olszewski (2017).

The ship operational limitation is defined by the maximum significant wave height that the ship operates normally, without restriction, concerning any individual criterion related to the deck wetness, hydrodynamic impact (slamming), propeller emersion, motion sickness, wave-induced water resistance and vertical acceleration or a combination of them. Figure 5 shows the maximum significant wave height for $\mu \in [0, 360°]$ and v= 25 knots in the case of any individual operational criterion where the ship may operate without restrictions. Figure 6 shows the maximum significant wave height for $\mu \in [0, 360°]$, $v \in [0, 25]$ knots, in the case of the combined criterion, where the ship may simultaneously operate through all criteria. Figure 7 shows the maximum significant wave height for $\mu \in [0, 360°]$ in the case of the global criterion, where the ship may simultaneously operate without restrictions accounting for all criteria and ship speeds.

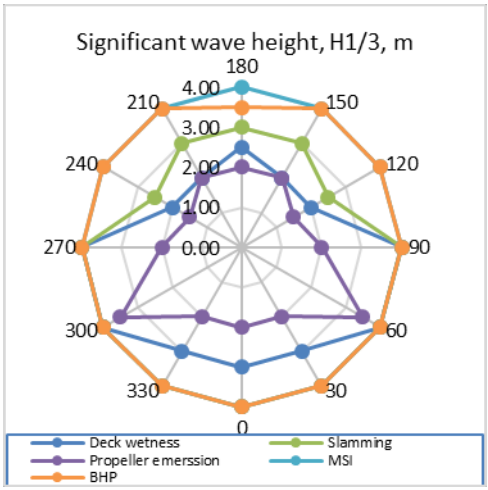


Figure 5: Maximum significant wave height, v= 25 knots, individual criterion.

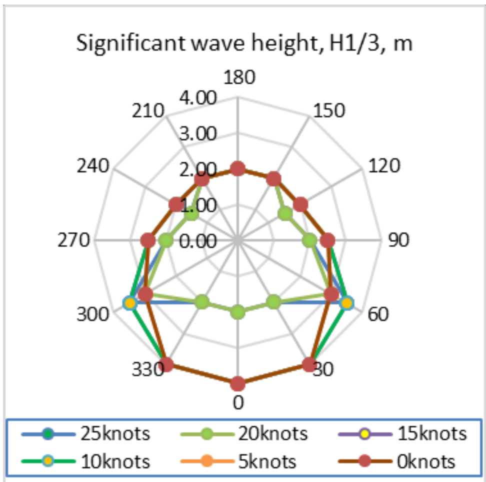


Figure 6: Maximum significant wave height, $v \in [0, 25]$ knots, combined criterion.

It can be noticed that the analysed ship can operate in an acceptable operational level up to the significant wave height of 2m. However, the event that prevents the ship from increasing the probability of maintaining its service speed is the emersion of the propeller, studied here for a 10% provision loading condition, which means that the ship should decrease its speed of service when it is sailing in waves with a significant wave height above 2m to keep the propeller immersed.

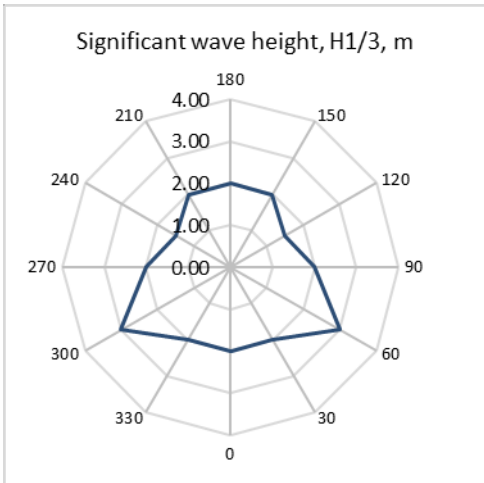


Figure 7 Maximum significant wave height, global criterion.

3.2 MULTI-PURPOSE NAVIGATION

In defining the most suitable scenarios in the multipurpose design application of the offshore support vessels, several objectives are considered, employing multi-criteria decision techniques. A long-term forecast of different seakeeping criteria is developed to perform an adequate evaluation of the seakeeping quality, allowing the designed ship to work in the prescribed conditions.

From the estimated RAOs, the probabilistic distribution of the seakeeping criteria in each stationary short-term period may be estimated by using the spectral response moments. Based on the assumption of a stationary zero-mean Gaussian wave elevation process, within each short-term period, the response process for a linear system is also a stationary zero-mean Gaussian process (Garbatov & Guedes Soares, 2012).

During the service life of a ship, a wide range of weather conditions and sea states may be encountered. The total time of the service life may be regarded as a large number of short intervals, each of a few hours' duration, in which the sea state remains constant.

The significant wave height, $H_{1/3}$ calculated for any short-term intervals along the service life of a ship is characterised by distribution or probability density functions, where the short-term responses are combined taking into account of exposure to the various levels of sea severity.

Any most expected seakeeping criterion, E_i, during the service life of the ship, is calculated as a weighted sum of the various short-term estimates, each of which is for a particular combination of the seas state and operational conditions and accounts for the relative probability of that particular combination:

$$E_i = \frac{\sum_{i=1}^{6}\sum_{k=1}^{12}\sum_{l=1}^{8}\left(w_{state_{l_i}}\, w_{\mu_{k_i}}\, C_{j_i}\right)}{\sum_{k=0}^{12}\sum_{l=1}^{8}\left(w_{state_{l_i}}\, w_{\mu_{k_i}}\right)} \quad (38)$$

where i ∈ [1, 6] is the number of operational scenarios (or navigation modes), j ∈ [1, 6] is the number of criteria, k ∈ [1, 12] is the number of heading angles, l ∈ [1, 8] is the number of sea states (expressed by significant wave heights), C_{ji} is the value of j^{th} criterion, $w_{state\ lj}$ is the weighting factor for a sea state, $w_{\mu\ ki}$ is the weighting factor for a heading for a given loading condition.

Employing the approach developed in (Moore et al., 1978), two artificial alternatives are analysed including the ideal alternative, which has the best scores for all seakeeping criteria considered and the ideal harmful alternative considers the worst criteria scores. The analysis leads to an alternative that is the closest to the ideal positive solution, and it is the farthest from the harmful ideal alternative.

The analysis includes six alternatives operational scenarios: D_1: Patrol Navigation; D_2: Steady Navigation; D_3: Confident Navigation; D_4: Sustainable Navigation, D_5: Navigation in Comfort and D_6: Multipurpose Navigation and six criteria: Deck wetness, C_1, Hydrodynamic impact (Slamming), C_2, Propeller emersion, C_3, Motion sickness, C_4, Wave-induced water resistance, C_5, Ship speed, C_6.

Any operational scenario, i=1, …, 6 is a function of the criteria, which is scored, x_{ij} concerning the criterion j=1, …, m, where a matrix $\mathbf{X} = (x_{ij})$ of n×m is developed. C_1 to C_6 are defined based on the seakeeping analysis.

J^+ is the set of benefit criteria, where the more significant score represents a better condition. J^- is the set of negative criteria, where the less score represents the better condition.

The first step in the analysis is to construct a normalized decision matrix, where the criterion dimensions are transformed into non-dimensional ones (Moore et al., 1978):

$$r_{ij} = x_{ij} / \sqrt{(\Sigma x^2_{ij})},\ \text{for } i = 1, \ldots, n;\ j = 1, \ldots, m \quad (39)$$

Next, the weighted normalized decision matrix is constructed using a set of weights for each criteria w_j, where each column of the normalized decision matrix is multiplied by its associated weight:

$$v_{ij} = w_j\, r_{ij} \quad (40)$$

The positive ideal solution is defined by:

$$A^* = \{v_1^*, \ldots, v_m^*\} \quad (41)$$

where $v_j^* = \{\max(v_{ij}) \text{ if } j \in J^+, \min(v_{ij}) \text{ if } j \in J^{+'}\}$ and the negative ideal solution is defined as:

$$A' = \{v_1', \ldots, v_m'\} \quad (42)$$

where $v' = \{\min(v_{ij}) \text{ if } j \in J^-, \max(v_{ij}) \text{ if } j \in J^{-'}\}$.

The separation measures for each alternative is defined as:

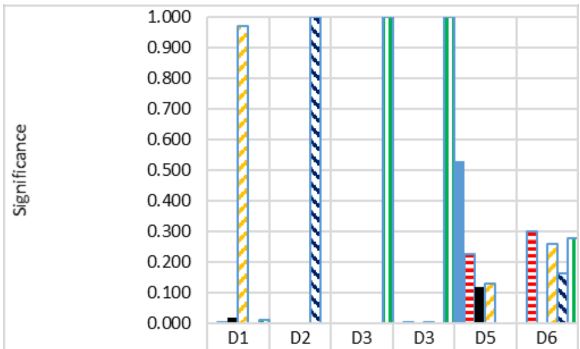
$$S_i^* = [\Sigma\,(v_j^* - v_{ij})^2],\ i = 1, \ldots, n \quad (43)$$

$$S'_i = [\Sigma\,(v_j' - v_{ij})^2],\ i = 1, \ldots, n \quad (44)$$

The relative closeness to the ideal solution C_i^* is calculated as:

$$C_i^* = S^*_i / (S_i^* + S'_i),\ \text{for } 0 < C_i^* < 1 \quad (45)$$

The option with C_i^* that is closest to 1 is the best-suited solution. The significance of different criteria for the maximum relative closeness to the ideal solution, for the analysed different operational scenarios, are presented in Figure 8.



	D1	D2	D3	D3	D5	D6
Wetness	0.002	0.000	0.000	0.000	0.529	0.000
Slamming	0.001	0.000	0.000	0.000	0.225	0.299
Propeller emersion	0.018	0.000	0.000	0.000	0.117	0.000
MSI	0.969	0.000	0.000	0.000	0.129	0.260
BHP	0.000	1.000	0.000	0.000	0.000	0.163
Speed	0.010	0.000	1.000	1.000	0.000	0.278

Figure 8: Significance of seakeeping criterion, S^*_i for different operational scenarios.

As can be seen from Figure 8, the best-suited seakeeping criteria to be kept for patrolling navigation, D_1, results in a significance of MSI=.97, propeller emersion=0.02 and speed of 0.01. In the case of steady navigation, D_2, the BHP significance is 1.0; for a confident navigation, D_3, the speed significance is 1.0; for a sustainable navigation, D_4, the speed significance is 1.0; for a navigation in comfort, D_5, the deck wetness significance is 0.53; slamming significance is 0.22, propeller emersion significance is

0.12 and MSI is 0.13 and finally for the multipurpose navigation, D_6, the significance for slamming is 0.3, MSI=0.26, BHP=0.16 and for speed is 0.28.

It can be pointed out that the approach employed here clearly identify the most crucial sea keeping criteria for any specific navigation mode of operation of the analysed ship.

3.3 SAFETY NAVIGATION

The safety navigation is defined here as the assurance that the ship operates and maintains a specified seakeeping performance through the service life. Safety also depends on the probability of non-violating the seakeeping criteria acceptance and its measure is defined by controlling the existing hazardous events to be at an acceptable level, as low as reasonably possible.

The hazardous events analysed here are related to the probability of violating the seakeeping criterion $C_1 - C_6$.

A serial system of correlated events of a different significance is assumed to represent the seakeeping performance of the ship, and six operational scenarios D_1-D_6 are analysed.

The probability of failure, which is defined as a probability of not satisfying any seakeeping criterion is defined by:

$$P_{fi} = 1 - S^*_i \Phi(\beta_i) \quad (46)$$

where P_{fi} is the probability of failure, which can be measured by the Beta index, β_i and S^*_i is the significance of any individual seakeeping criterion (see Figure 19).

The serial system fails if only one of the elements fails, which leads to:

$$P_{f^s} = 1 - \Phi_m(\beta; \rho; S*) \quad (47)$$

where Φ_m is the m-dimensional normal cumulative distribution function and ρ is the correlation coefficient between any two events (see Table 1).

A formal generalised series system beta index is defined as:

$$\beta^s = -\Phi^{-1}\left(P_{f^s}\right) \ . \quad (48)$$

To evaluate the serial system, the second order Ditlevsen bounds (Ditlevsen, 1979), which has been proven to be a good tool in different structural analyses (Garbatov & Guedes Soares, 2011), are employed here:

$$\Phi\left(-\beta^s\right) \le \sum_{i=1}^{m} \Phi\left(-\beta_i\right) - \sum_{i=2}^{m} max\left\{\Phi\left(-\beta_i, -\beta_j; \rho_{ij}\right)\right\} \quad (49)$$

Table 1 Correlation coefficient between any two events

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1.000	0.915	0.800	0.963	0.932	0.887
C_2	0.915	1.000	0.951	0.980	0.997	0.993
C_3	0.800	0.951	1.000	0.877	0.953	0.980
C_4	0.963	0.980	0.877	1.000	0.981	0.953
C_5	0.932	0.997	0.953	0.981	1.000	0.992
C_6	0.887	0.993	0.980	0.953	0.992	1.000

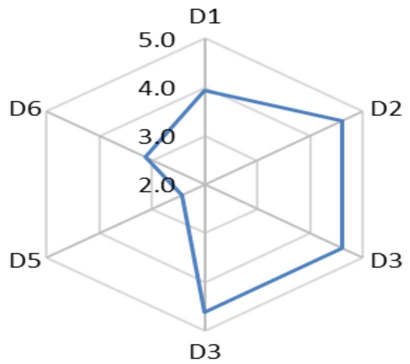


Figure 9: Beta index of navigational scenarios.

As can be seen from Figure 9, the lower beta index is defined for the operational “Navigation in Comfort”, $\beta(D_5)$=2.426, followed by the scenario of “Multipurpose Navigation”, $\beta(D_6)$ = 3.14, and “Patrol Navigation”, $\beta(D_1)$=3.937. Scenarios D_2 - D_4 demonstrate the best performance, $\beta(D_{2\text{-}4})$=4.611, which is explained with the fact that in the speed range of 10 to 20 knots, the criterion of BHP and steady speed is well achieved. However, it has to be noticed that the analysed seakeeping criterion are highly correlated and that effects the results.

4. CONCLUSION

This work analysed the operational behaviour of an offshore multipurpose support vessel, design to operate in the Eastern Mediterranean Sea. First, the seakeeping analysis was performed in a regular wave condition of different heading angles estimating heave and pitch motions through the Strip theory. After that, the effects of vertical acceleration on the bow, occurrence of slamming, wetted deck, propeller emersion, motion sickness and wave-induced ship resistance were analysed. The present study was also conducted in an irregular sea condition, and the estimated seakeeping criteria were compared to the acceptable levels as stipulated by the existing standards. Multi-criteria decision techniques were employed, including the long-term forecast of different seakeeping criteria to perform an adequate evaluation of the seakeeping operational modes, allowing to identify the most significant criteria to be accounted in the design so that ship may operate in the prescribed service conditions. Employing the second order Ditlevsen bounds, which accounts for different correlated hazardous events, originated from the non-satisfying the seakeeping criterion, the best suitable mode of operation was identified.

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