Dynamic Positioning analysis and comfort assessment for the early design stage of large yachts

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In some specific environmentally protected areas, conventional mooring systems cannot be used by large yachts for stationing at anchor and therefore, the adoption of a dynamic positioning system is required. It becomes then necessary to evaluate the station keeping capabilities of a yacht since the early-design stage. Adopting a quasi-static approach, it is possible to perform a standard capability analysis, as commonly done for the offshore industry, obtaining a capability plot as output. However, capability plots are referring to specific wind-wave correlation that are not covering all the possible wave combinations present in a sea area. Here, it is proposed to use a scatter diagram approach for the dynamic positioning analysis of a large yacht, considering the specific sea areas where the yacht shall operate, in order to figure out the downtime period of the DP system per each sea area. The proposed method can be coupled with traditional ship motions analysis, leading to a combination between comfort assessment and DP predictions. In the present work, use has been made of a traditional displacement yacht 72 m long, comparing five different DP system configurations and evaluating an enhanced comfort ranking combining ISO AWI-22834 guidelines for large yachts with ISO AWI-22822 DP analysis.

Keywords: Large yachts, Comfort on-board, DP predictions, Early-design stage, Ship motions

1. Introduction

In the yacht industry, it is possible to subdivide pleasure craft into small crafts from 8 to 24 m and large yachts above 24 m, as referred by ISO/TC 8/SC 12. One of the most important targets in large yachts' design is the achievement of an adequate comfort level while cruising or stationing at anchor [1]. These aspects are related to a wide range of possible sources of discomfort, including also the effect of ship motions and accelerations in different sea states. In this sense, there is a lack of standards and criteria specific for the motions-related comfort on-board assessment of

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large yachts. Criteria are available in the literature for various kind of ships, as for example the Nordforsk ones [2], or specific studies on large cruise ships [3]. However, no one of them is specific for yachts or directly associated to leisure activities at anchor. To fill this gap, AWI-22834 working group led by MARIN has been established within ISO to produce a comparative scale of comfort among yachts that can be used for technical and commercial benefit [4] during the early design stage.

However, besides traditional seakeeping challenges, during stationing additional issues can be given by the mooring system. In case the yacht is expected to operate in environmentally protected areas, it can be required to provide the stationing of the vessel without traditional mooring lines, thus adopting a dynamic positioning (DP) system [5]. In such a case, several aspects that are not usually taken into account in large yacht design should be considered, such as a proper determination of the environmental loads acting on the vessel. Moreover, the necessity to use a DP system, allows the designer to investigate multiple possible solutions for the propulsive system and for the thruster devices to install on-board. To efficiently compare possible propulsive solutions since the early-design stage, it is necessary to provide a sufficiently reliable and fast calculation method to assess DP capability and rank the different design solutions. To this end, use can be made of quasi-static calculations, providing the necessary balance between reliability and calculation time for an initial design stage [6]. The traditional output of a quasi-static simulation is the so-called DP capability plot [7], reporting a maximum sustainable wind speed per each ship encounter angle. However, a capability plot is representative of standard environmental conditions which are based on offshore industry necessities.

For a large yacht, the working environment and the reference design loads are not comparable with offshore industry ones. Therefore, it is advisable to adopt a different approach for the DP capability prediction of such type of vessels. An appropriate set of environmental conditions for yacht DP analysis is still under discussion [8], and different possibilities may be chosen. Being yachts sailing and stationing at mostly in the Caribbean or Mediterranean Sea [9], it is possible to identify the characteristic working environment by means of the specific wave statistics of these areas. Then, the DP performances can be evaluated on a scatter diagram base [10], providing the downtime period of the DP system per each selected sea area. Adopting this approach, it is possible to rank the operability of the DP system according to an index of merit [4], comparing the DP capabilities of different yachts or different design solutions. With this approach it is possible to have both DP and seakeeping calculations for the same environmental conditions.

In this study, the MARIN yacht [11] has been chosen as reference hull, having at disposal wind loads measurements and seakeeping experiments. The original yacht propulsive configuration (propeller/rudder) has been analysed, considering different management of the rudders control. The results have been compared with other possible design solutions, including the adoption of a POD based propulsion system. The different DP system solutions are compared both in terms of standard capability plots and newly proposed downtime approach, providing, in this last case, a DP merit

index per each configuration. Besides, the MARIN yacht comfort has been analysed according to AWI-22834 guidelines for the stationing conditions. The DP analysis has been combined together with comfort criteria to verify whether the station keeping abilities may influence the comfort rating of the vessel. Two possible integration ways have been introduced and compared in terms of resulting comfort rating.

2. Comfort on-board of large yachts

In the design of a pleasure craft, the concept of comfort is of paramount importance, however a unique and complete definition of comfort does not exist as it includes *subjective* feelings of individuals. Moreover, the perception of comfort can be influenced by many factors, which are also dependent upon time to exposure, intensity of the phenomenon but also upon gender, age, previous experience and mental state of the subject. The most relevant factors for a yacht can be summarized as follows:

- *noise and vibrations*;
- *motions and postural stability*;
- *smell*;
- *on-board amenities, food and drink*;
- *other factors* (weather, temperature, humidity, etc.).

This study is focused on comfort related to ship motions, thus on the application of specific criteria associated to ship motions and acceleration. It is then necessary to identify the most relevant criteria associated to ship motions that can be referred to the judgement of comfort or discomfort on-board of a large yacht.

General criteria used for commercial vessels are available (an overview is given in Table 1), even though they were originally intended for certain operations on-board of either navy-vessels or passenger ships. The operations and the *life on-board* of a yacht are more similar to passenger ships ones rather than navy activity, therefore it is more reasonable to adopt criteria close to the one used for passenger vessels. However, specific criteria for passenger ships [3] adopted inside MARIN requires the calculation of the Motion Illness Rating (MIR), which adopts coefficients not available in the literature. Furthermore, its determination requires many parameters that could not be available in an early design stage.

To overcome this issue and to provide criteria of easy applicability for a large yacht, the AWI-22834 guidelines have been developed, to propose a framework for the determination of comfort levels for large yachts.

2.1. The AWI-22834 guidelines

To overcome the lack of precise standards and criteria specifically devoted for large yachts, ISO working group AWI 22834 led by MARIN has been established.

The main goal of this working group is to produce a comparative scale of comfort among yachts that can be used for technical and commercial benefit. The process goes through the following steps:

- identification of yacht specific criteria for comfort;
- environmental condition selection;
- operative condition selection (speed, encounter angle);
- identification of on board location of interest;
- evaluation of criteria satisfaction for all conditions.

As previously mentioned, available criteria for ship motion related comfort (Table 1) refer to other kind of vessels, therefore a selection of the most suitable criteria has been carried out. In the specific, Effective Gravity Angle (EGA) and Motion Sickness Index (MSI) have been chosen for the comfort assessment, adopting the following formulations:

$$EGA_L = \arctan \left(\frac{\ddot{\eta}_L}{\ddot{\zeta}_L + g} \right) \quad (1)$$

where low-case p denotes the calculation point, g is the gravity accelerations and $\ddot{\zeta}_L$ and $\ddot{\eta}_L$ are the absolute vertical and lateral acceleration in the calculation point. Equation (1) can be interpreted both in time domain and frequency domain; in the latter case, RMS values are considered.

For MSI, the following formulation has been taken into account [12]:

$$MSI_L = 100\Phi(Z_\zeta)\Phi(Z'_t) \quad (2)$$

$$Z_\zeta = 2.128 \log \ddot{\zeta}_p / g - 9.277 \log \hat{\omega}_\zeta - 5.809 \log \hat{\omega}_\zeta^2 - 1.851 \quad (3)$$

$$Z'_t = 1.134Z_\zeta + 1.989 \log T_e - 2.904 \quad (4)$$

$$\Phi(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^Z e^{-\frac{x^2}{2}} dx \quad (5)$$

where T_e is the exposure time in minutes and $\hat{\omega}_\zeta$ is the frequency in Hertz of the absolute vertical acceleration $\ddot{\zeta}$ spectrum' peak. This is a simplified version of MSI, taking into account only the vertical acceleration.

This choice has been made because of the necessity to have a right balance between the complexity of the criteria formulation and the need to have a sufficiently board indicator to describe comfort. According to the proposers, the combination between MSI and EGA makes it possible to have a single indicator covering both the need of people to look for support (but also for tipping or sliding of objects) and the percentage of people on-board that will suffer from seasickness after a certain exposure time.

The AWI working group proposes also the identification of the environmental conditions, the locations on-board and the fulfilment criteria for EGA and MSI. The selection of environmental conditions is based on the assumption that most of large yachts operates mostly in the Western Mediterranean and Caribbean Seas [9], using a combined wave scatter diagram of the two sea areas according to annual statistics. The analysis is limited to the wave heights between 1 and 2 meters: the waves with the higher occurrence in the combined scatter diagram, and ensuring a fair compromise with at anchor performances of vessels relatively short (less than about 60 m) and longer ones [22]. An overview of the resulting environmental conditions is given in Figure 1. All the irregular wave conditions refer to long crested sea approximation and are modelled with a JONSWAP wave spectrum.

The analysis should be carried out on 5 reference locations among the yacht, representative of 5 areas of interest for operations and leisure on-board:

1. Owners Cabin (OC);
2. Dining Area (DA);
3. Wheel House (WH);
4. Crew Area (CA);
5. Beach Club (BC).

Each of the above mentioned area should be identified by considering the geometrical centre of that space on-board, adding 1.2 meters to the reference deck height for the z coordinate. The analysis should be carried out for bow quartering seas over starboard, analysing also the mirrored position along longitudinal axis for points not located on the yacht diametral plane. Analysis should be carried out for two speeds: 0 and 12 knots. For all the mentioned conditions, the fulfilment criteria have been set to $EGA_P < 2$ deg and $MSI < 10\%$ with T_e equal to 1 hour.

Within this framework, it is then possible to identify the downtime period of the comfort criteria fulfilment at each speed V as follows:

$$OP_{comf_V} = \sum_{i=1}^{N_{T_z}} \sum_{j=1}^{N_L} p_{T_{zi}} p_{L_j} I_{comf_{ij}} \quad (6)$$

$$I_{comf} = \begin{cases} 1 & \text{if } MSI_L < 10\% \wedge EGA_L < 2 \text{ deg} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

where p_{T_z} is the marginal distribution of the wave periods as shown in Figure 1 and p_L is a weight function given at each location of interest. The preliminary AWI proposal is considering an equal weight within all the 5 locations (i.e. $N_L=5$). As final outcome, based on the values of OP_{comf_V} a rating is given on the base of a 5 stars scale. This relation is given in Table 2. The obtained rating can be global or local: in the latter case, it is sufficient to neglect the loop on locations from equation (6).

3. Dynamic positioning on large yachts

Dynamic positioning is a typical issue of offshore industry, where nowadays almost all vessel are requested to operate stationing in deep water environment with or without the aid of mooring lines. However this offshore technology can be applied also to other vessels, once they are required to autonomously keep a predetermined position, thus also on large yachts.

To determine the DP capabilities of a vessel, two different approaches can be followed: a dynamic approach or a quasi-static one. Dynamic simulations, even though they can be implemented also in simplified forms, are more oriented to the reproduction of the effective system mounted on-board [13], thus more indicated for an advanced design stage [14]. For an early-design stage, the quasi-static approach is preferable, giving the opportunity to analyse and compare multiple design solutions with a relatively short calculation time [15, 16]. These considerations made for offshore vessels can be shifted also to the yacht industry, therefore in this study a quasi-static approach has been selected for the analyses.

The quasi-static DP problem consists in the resolution of the equilibrium of forces and moments acting on the yacht on the horizontal plain. Considering the reference system of Figure 2, centred in the vessel midpoint O, the equilibrium is:

$$\begin{cases} \sum_{i=1}^{N_p} F_{X_{P_i}} &= F_{X_{ENV}} + F_{X_{EXT}} \\ \sum_{i=1}^{N_p} F_{Y_{P_i}} &= F_{Y_{ENV}} + F_{Y_{EXT}} \\ \sum_{i=1}^{N_p} (F_{Y_{P_i}} x_{P_i} - F_{X_{P_i}} y_{P_i}) &= M_{Z_{ENV}} + M_{Z_{EXT}} \end{cases} \quad (8)$$

where F_{X_p} and F_{Y_p} are the longitudinal and lateral forces provided by each of the N_p actuators installed on-board. x_p and y_p are the coordinates of the actuators (i.e. propulsors or tunnel thrusters) with respect to vessel midpoint O. In the right term of system (8), external and environmental forces appear. The external loads may be used to simulate any additional force or moment acting on a vessel, as for the case of a large yacht additional mooring lines, or can be neglected from the equilibrium. Here, aiming to study a stand-alone DP system, only environmental loads have been considered and are analysed in detail for the MARIN yacht test case.

3.1. Thrust allocation

The resolution of the quasi-static DP problem requires solving system (8) considering the actuator forces and directions as the problem unknowns. The resolution of system (8) is not an easy task to perform. Generally, the unknowns of the problem are $2N_{ST} + N_{TT}$ where N_{ST} is the number of steerable actuators (including the case of propeller plus rudder) and N_{TT} is the number of fixed tunnel thrusters.

Thus, having system (8) only 3 equations, the problem admits infinite possible feasible solutions. Therefore, it is necessary to adopt a suitable allocation procedure

to distribute the thrust with the correct orientation among the units to satisfy the equilibrium [17]. Here, a non-linear optimisation method has been used [18], considering the following non-linear objective function:

$$\begin{aligned} \min(z) &= \sum_{i=1}^{N_p} T_i^{\frac{2}{3}} = \sum_{i=1}^{N_p} \left(\sqrt{F_{X_{pi}}^2 + F_{Y_{pi}}^2} \right)^{\frac{2}{3}} = \\ &= \sum_{i=1}^{N_p} \left(\sqrt{(T_i \cos \alpha_i)^2 + (T_i \sin \alpha_i)^2} \right)^{\frac{2}{3}} \end{aligned} \quad (9)$$

This formulation is representative of the sum of absorbed power of each actuator, and can be written as a function of thrust components F_{X_p} , F_{Y_p} or as a function of thrust T and thrust orientation α . The non-linear optimization technique allows to manage also non-linear constraints, therefore, once the T, α unknowns setting is selected, system (8) becomes a set of non-linear constraints that suits with the adopted optimisation algorithm. In this study, use has been made of the T, α unknowns, because it suits better with the modelling adopted for the propeller/rudder, where the developed forces in x and y directions are described as follows:

$$F_{X_R} = T (1 - C_X \alpha^2) \quad (10)$$

$$F_{Y_R} = T C_Y \alpha \quad (11)$$

where C_X and C_Y are given by DNV regulations [19]. In such a way, the rudder angle becomes one of the unknowns and the differences between dependent and independent rudder control can be easily implemented in the resolution algorithm.

3.2. Capability plots approach

The standard way to represent DP calculations is by means of the so-called capability plots [7]. These diagrams are representative of the maximum sustainable wind speed V_W the DP system can face at each encounter angle χ using the on-board thrust devices. The capability plots are obtained by considering a specific wind-wave correlation curve, which is associating at each V_W a precise value of H_s and T_z . Current speed V_C is kept constant and collinear with wind and wave loads. To have a more reliable prediction, environmental loads are multiplied by a dynamic allowance coefficient (usually ranging between 1.20 and 1.25) to take into account dynamic effects in the quasi-static procedure. An example of capability plot is given in Figure 3, highlighting the maximum V_W at each χ ranging between 0° to 360° degrees for a sample vessel, using the IMCA wind-wave correlation.

Capability plots offer an easy way to compare capabilities of different DP configurations on the same vessel or compare DP systems mounted on-board of different

units. However, they refer to specific environmental conditions dictated by the wind-wave correlation adopted for the assessment. Therefore, this method is not suitable to match the same calculation conditions typical of comfort assessment analysis.

3.3. Scatter diagram approach

A different strategy to perform quasi-static calculation is the adoption of a scatter diagram approach [10]. This method allows a designer to have a more complete vision of the DP system performances in the sea environment of interest for the yacht. As mentioned, capability plots refer to a specific wind-wave correlation, thus they did not ensure that DP calculations cover all the possible combination of H_s and T_z that may occur in a sea area. By performing dedicated prediction in each cell of a wave scatter diagram, it is then sure that all the possible sea states have been analysed.

With this novel approach, the wind speed in each cell of the scatter diagram can be derived from the Pierson-Moskowitz wave spectrum, relating V_w to H_s and T_z . Therefore, each cell of the scatter diagram will have a different calculation wind speed. For the current loads, the same settings of the capability plots have been chosen considering a current speed of 0.75 m/s collinear with wind and waves. Being also scatter diagram approach a quasi-static method, a dynamic allowance coefficient can be applied to environmental loads.

This method allows to evaluate the downtime period for the DP system in a selected sea area by means of a DP operability index having the following form:

$$OP_{DP} = \sum_{k=1}^{N_\chi} p_{\chi_k} \sum_{i=1}^{N_{H_s}} \sum_{j=1}^{N_{T_z}} p_{w_{ij}} I_{DP_{ijk}} \quad (12)$$

$$I_{DP} = \begin{cases} 1 & \text{if position is kept} \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

where p_χ is the occurrence of each encounter angle the vessel is asked to keep and p_w is the joint probability of H_s and T_z given by the selected scatter diagram. In Figure 4 an example of the scatter diagram approach is reported for one heading condition, highlighting the differences with conditions used for the capability plots determination.

It can be observed that, considering only one heading and one H_s value, equation (12) has the same form of equation (6) adopted by AWI-22834 for comfort analysis. Therefore, the scatter diagram approach is capable to evaluate DP performance in the same environmental conditions of comfort analysis for large yachts.

4. The reference yacht

The vessel selected for this investigation is the MARIN yacht [11], a reference large yacht hull where the results of seakeeping tests and wind loads measurements are at disposal for research purposes. For such a reason, this yacht has been selected as basis platform for the performed explorative study on comfort analysis and DP system capabilities on large yachts. An overview of the main characteristics of the yacht is reported in Table 3. Hereafter, the preliminary ship motion calculations and the DP configurations considered for this study are given together with the environmental loads determination on the reference yacht as a starting point for the DP and comfort analysis.

4.1. Ship motion calculations

To evaluate the comfort assessment on a large yacht according to AWI-22834 guidelines (section 2.1), it is necessary to evaluate the ship motions of the vessel under analysis. There are several ways to predict ship motions, having different levels of accuracy and calculation/realisation time. The most accurate way possible to evaluate ship motion is still given by model tests, but it is almost impossible performing them in an early design stage. However, model test data on reference ship can be used to validate computational tools (like viscous CFD, diffraction or strip theory codes) that better suits for preliminary calculations.

This approach has been followed for the MARIN yacht, where experimental measurements are at disposal for ship motions. Calculations have been performed by means of Maxsurf 3D diffraction panel code, comparing motion RAOs with available experiments for beam and bow quartering seas, without the use of active stabilisers. Results are reported in Figure 5 for heave and roll motion, showing a good agreement between numerical and experimental curves, thus giving sufficient reliability to the ship motion analysis.

4.2. DP configurations

In this explorative study on large yachts, different DP configurations have been considered to study the system performance changes on the same base hull, in this case the MARIN yacht. The selected configurations are representative of standard propulsive layouts already present on-board of traditional large yachts, plus the addition of alternative solutions oriented to increase vessel low speed maneuverability, and therefore, probably more suitable to improve the station keeping ability of a yacht. Hereafter a brief description of the proposed configurations is given. It must be observed, that it is not possible to adopt a configuration fully derived from offshore applications (i.e. application of large azimuth thruster) to not compromise internal layout and yacht propulsive operative profile. An overview of the configurations is given in Figure 6, together with size and positioning of the thrust devices given according to reference system defined in Figure 2. The main details of the rudders used in conventional propulsive configurations are reported in Table 4.

4.2.1. *C1: conventional propulsion with dependent rudders and bow tunnel thruster*

This configuration (referred hereafter as C1 in the text) is a standard propulsive configuration for a twin screw large yacht. It is composed by a conventional propellers/rudders system and a tunnel thruster at the bow. The rudder control system allows to orientate the rudders only with the same angle. Configuration C1 is the simplest kind of DP system that can be implemented on-board, by simply using the same machinery installed for maneuvering and propulsion

4.2.2. *C2: conventional propulsion with dependent rudders and bow/stern tunnel thrusters*

This configuration (referred hereafter as C2 in the text) is a variation of configuration C1. The propulsion remains a conventional one for twin-screw yachts, considering dependent rudder management strategy. The main difference with respect to configuration C1 is related to the tunnel thrusters. In this specific case, instead of one bow tunnel thruster as in C1, 2 tunnels have been considered, one on the bow and one on the stern. The stern tunnel thruster can be integrated into the skeg, or, in case more space is needed can be of retractile type. In order to have the same amount of power installed on-board, the thruster sizes are reduced compared to previous configurations.

4.2.3. *C3: conventional propulsion with independent rudders and bow tunnel thruster*

This configuration (referred hereafter as C3 in the text) is a variation of previously described configuration C1. The yacht is still equipped with a conventional propulsion system. However, the rudder control is somewhat different, allowing to set different angles between the two rudders. The bow thruster mounted on-board is the same of configuration C1.

4.2.4. *C4: Conventional propulsion with independent rudders and bow/stern tunnel thrusters*

This configuration (referred hereafter as C4 in the text) is a variation of configuration C3. The propulsion remains a conventional one for twin-screw yachts, considering an independent rudder management strategy. As for configuration C2, an additional stern tunnel thruster has been considered, changing the size of the fixed thrusters.

4.2.5. *C5: Podded propulsion with bow tunnel thruster*

This last configuration (referred hereafter as C5 in the text) is representative of an unconventional propulsive solution for a large yacht. Instead of a conventional twin screw propulsion with conventional rudders, two steerable PODs are mounted on the vessel stern. Even though limitations are given for the maximum steering angle of a POD in sailing conditions, for zero speed application they can be oriented among all directions, avoiding mutual interactions with the adoption of forbidden zones in thrust allocation algorithm. The propulsive loads are the same of previous configuration, therefore, the pod maximum thrust has been considered comparable

with the standard propellers. At the bow, one tunnel thruster is present with the same characteristics of the one installed for configurations C1 and C2.

4.3. Environmental loads

The determination of environmental loads for the vessel under analysis is one of the most important steps for the DP predictions. In this study, environmental forces are given by the collinear and simultaneous action of wind, waves and current. The determination of such loads is not an easy task in an early design stage, especially for large yachts, due to the lack of specific simplified methods, that are available for offshore vessel forms only. Hereafter, the procedure adopted to determine the environmental loads is given, comparing also the force coefficients used for the MARIN yacht with simplified method derived from the offshore industry.

The wind loads are determined at each encounter angle χ on the bases of non-dimensional coefficients according to the following formulations:

$$F_{X_w} = \frac{1}{2} \rho_{air} A_F V_w^2 C_{X_w}(\chi) \quad (14)$$

$$F_{Y_w} = \frac{1}{2} \rho_{air} A_L V_w^2 C_{Y_w}(\chi) \quad (15)$$

$$M_{Z_w} = \frac{1}{2} \rho_{air} A_L L_{PP} V_w^2 C_{M_w}(\chi) \quad (16)$$

where A_F and A_L are the frontal and lateral area of the yacht superstructures, L_{PP} is the length between perpendiculars, V_w the wind speed in m/s and ρ_{air} the air density. The determination of wind loads coefficients for a large yachts in the early design stage, is not an easy task due to the lack of informations on the real yacht superstructures at disposal. It is possible to adopt model experiments on reference superstructures (like the Blendermann database [20]) or statistical methods based on wind data collections [21]. Another alternative could be the adoption of simplified methods derived from the offshore industry and applied by Classification Societies as reference for preliminary DP calculations [19]. For the MARIN yacht, wind tunnel measurements are available for the C_{X_w} , C_{Y_w} and C_{M_w} coefficients. In Figure 7 a comparison is given among the above mentioned methods, highlighting how measurements differs from simplified approaches for the C_{X_w} and C_{M_w} , while C_{Y_w} matches reasonably well.

The current loads are also determined starting from non-dimensional coefficients, using formulations analogue to (14), (15) and (16) to obtain dimensional loads. However, for current purposes, superstructure areas are substituted by wetted surface S , reference is made to current speed V_C and water density for salt water ρ_w . For current loads, really simple formulations are available in the literature [19, 22] referring to offshore applications. For the MARIN yacht geometry, current loads coefficients

have been determined by means of double body RANS calculations. In Figure 8 the coefficients obtained with CFD are compared with the DNV procedure for DP calculations. As previously observed for the wind, the C_{Y_C} coefficient is the only one having the same trend with both approaches, even though for current there is a difference above 30% on the maximum amplitude value.

For wave loads, irregular long crested sea conditions have been considered, starting from drift coefficients, derived from diffraction calculations as reported in section 4.1, and modelling the irregular waves with a spectrum:

$$F_{X_w} = \rho_w g \nabla^{\frac{1}{3}} \int_0^\infty C_{X_w}(\chi, \omega) S_\zeta(\omega) d\omega \quad (17)$$

$$F_{Y_w} = \rho_w g \nabla^{\frac{1}{3}} \int_0^\infty C_{Y_w}(\chi, \omega) S_\zeta(\omega) d\omega \quad (18)$$

$$M_{Z_w} = \rho_w g \nabla^{\frac{2}{3}} \int_0^\infty C_{M_w}(\chi, \omega) S_\zeta(\omega) d\omega \quad (19)$$

where ∇ is the vessel volume of displacement, g the acceleration of gravity and S_ζ is the wave amplitude spectrum expressed as a function of circular wave frequency ω . There are not simplified methods to directly determine frequency dependent drift force coefficients. Therefore, in an early-design stage, an alternative could be the application of simple methods to directly derive the forces [19, 22]. The general method given by DNV is suitable for short crested sea, which means the wave spectrum S_ζ is no more dependent only by ω but also by χ . In Figure 9 an example is given of the loads obtained applying DNV methods against the ones coming from diffraction coefficients for long or short crested irregular waves. The comparison is made with a JONSWAP spectrum for H_s of 1.5 metres and T_z of 6 seconds (the most probable according to AWI-22834 marginal distribution for T_z), using for short crested sea the parameters implemented in the DNV method. The wave forces generated with the DNV method are more conservative than direct calculation coming from diffraction theory also for the long crested sea case.

Despite the absence of simplified methods specific for large yachts, wind and current environmental loads can be estimated in an early design stage also by means of methods derived from the offshore industry. Wave loads are overestimated compared to direct calculations and this may lead to underestimation of DP capability performances. These considerations based on the MARIN yacht test case are not enough to derive a general guidelines, however highlight an issue that should be properly analysed with further investigations.

For such a case it has been decided to consider the loads coming from experiments and direct calculations for the DP analyses.

5. DP and comfort analysis for the MARIN yacht

Having defined the methods identified for the DP and comfort assessment in the early design stage of a large yacht, it is then possible to apply it on the MARIN yacht. The DP and comfort analysis will be firstly individually analysed; in a second phase, the two analyses are combined to obtain a single index of merit.

5.1. Comfort assessment

The comfort assessment for the MARIN yacht has been performed according to the AWI-22834 guidelines for the zero speed condition. The 5 locations for the comfort assessment are reported in Figure 10. Without having the effective internal layout, the selection of such coordinates for the calculation points has been decided based on MARIN internal statistics on the most recurrent calculation areas on yacht with comparable size.

In Figure 11 it is possible to observe the *MSI* and *EGA* variations in the five locations among the T_z considered by the guidelines. It can be observed that, for the MARIN yacht, the only limiting comfort criteria is related to the *MSI* in the crew area CA, for T_z around 6 seconds. The *EGA* criterion is always satisfied. This results in a top comfort rating according to AWI-22834 rating-system.

To have a comparison with other criteria related to comfort, the analysis has been carried out on the same environmental conditions, applying Nordforsk criteria for cruise liners (see Table 1). Here limits are given on vertical and lateral accelerations together with the RMS of roll motion. The study has been performed on the same locations used for AWI analysis. Figure 12 reports the criteria evaluation for the five locations. In this case the limitation is given by the vertical acceleration (which is related to *MSI*), however the limiting value of the Nordforsk criterion is more restrictive than the one given by AWI-22834 guidelines. In Table 5 the final rating obtained by the application of the two guidelines are given, highlighting the extremely restrictive nature of Nordforsk criteria for vertical acceleration. For the MARIN yacht, only the dining area DA satisfies the criteria, suggesting that the limiting vertical acceleration is probably too restrictive for large yacht.

5.2. DP calculations

The traditional analysis approach based on capability plots has been carried out as initial comparison among different DP system options. This standard capability analysis has been performed for the five DP system configurations and the obtained results are shown in Figure 13. For the calculations, IMCA wind-wave correlation has been used, a current speed of 0.75 m/s collinear with wind and waves and a dynamic allowance coefficient of 1.25. It can be noted that, globally, the higher capability is given by configuration C5. Configuration C1 is giving the lower capability envelope, being not extremely effective for beam and stern-quartering seas. It can be

observed that by introducing a stern thruster (config. C2) the capability of the vessel improves significantly throughout the whole encounter angles, having performance comparable with independent rudder (config. C3). The additional stern thruster is not really effective for the independent rudder configuration (config. C4), in fact, for stern-quartering seas, the capability envelope is quite lower than configuration C3, while for head seas they remain comparable.

The capability plot is for sure a valuable method to compare different DP design solutions. However, from the capability plot analysis it is not possible to clearly rank the five design solutions, because the effectiveness of the system is changing at each heading angle and only the maximum sustainable wind speed V_W can be addressed, without having a clear understanding of the DP system behaviour in the real working environment of the yacht.

For such a reason, the scatter diagram approach has been also applied to the five design solutions for the MARIN yacht. For the current loads, the same settings of the capability plots have been chosen considering a current speed of 0.75 m/s collinear with wind and waves. Being also scatter diagram approach a quasi-static method, a dynamic allowance coefficient of 1.25 has been also applied for these calculations. The irregular waves have been simulated with a JONSWAP spectrum, varying γ elongation parameter according to H_s and T_z combination. Moreover, it should be considered that a large yacht is not requested to keep a predefined heading while holding the position, therefore, it is more interesting to focus the analyses on the head seas, rather than on the whole 360 deg as in the capability plots. Therefore, scatter diagram calculations have been performed from the range of 0° to 60° degrees in steps of 15° . As already mentioned, the scatter diagram approach allows to identify the cells of a scatter diagram where the DP system is capable to hold the vessel in position, thus is dividing the sea area in two zones, one where the vessel can and another where cannot hold the position (according to I_{DP} defined in equation (13)).

The analysis can be applied to specific sea areas considering multiple headings (thus evaluating the OP_{DP} index according to equation (12)) or considering custom wave conditions for only one heading as in the AWI-22834 comfort assessment. In this study both approaches have been followed. In Figure 14 an example is given for Western Mediterranean sea; the figure shows the data relative to headings of 15° , 30° and 45° degrees. Head seas, 0° degrees, has been omitted because the DP system is always successful for all the five configurations. 60° degrees has been omitted because is not giving additional visual information compared to 45° degrees case. From the plotted data, it immediately appears that configuration C5 has the highest station keeping ability. The same comments given from the capability plot analyses can be also extended to the scatter diagram approach. Due to the intrinsic nature of this calculation approach, in case the same type of wave spectrum is used, the cells (i.e. the combination of H_s and T_z) where the DP system holds position remains the same among all possible sea areas. Therefore, by changing scatter diagram, only the joint occurrence p_w is changing, giving a different OP_{DP} value.

In Table 6 the value of the OP_{DP} index is reported for the different 5 configurations, considering the operation in Area 26 and Area 47 for all the calculated headings. Besides, also the operability index for the AWI-22834 condition is reported. All the data are given in terms of OP_{DP} index, with its relative correspondence with AWI-22834 star-rating system (Table 2).

The global data in Table 6 reports a higher OP_{DP} value for Area 26 compared to Area 47. The 5 tested DP system configurations are suffering for high wave heights and for high periods, therefore the operability of the system will reflect the joint wave distribution of each area. Area 47 is characterised by lower wave heights but higher periods compared to Area 26, having a higher wave density for wave-parameters combinations where DP system is not capable to hold position.

5.3. Combined analysis

The reported comfort and DP analyses are dissociated between each other. However, adopting a scatter diagram approach, it is possible to have DP and seakeeping calculations performed with the same environmental conditions. Moreover, the downtime-based rating system proposed by AWI-22834 guidelines well suits also for DP calculations. It is then possible to integrate the two analyses, leading to a global index of merit for a large yacht.

In this study, two possible integration methods are proposed, both based on comfort and DP analyses performed as described in the previous sections.

5.4. DP as an additional criterion

A first way to integrate DP into the comfort analysis framework proposed by AWI-22834 is to consider the DP assessment as an additional criteria for the determination of OP_{comf} parameter (equation (6)). In such a case, the parameter I_{comf} becomes:

$$I_{comf} = \begin{cases} 1 & \text{if } MSI_L < 10\% \wedge EGA_L < 2 \text{ deg} \wedge I_{DP} = 1 \\ 0 & \text{otherwise} \end{cases} \quad (20)$$

where I_{DP} is calculated for the AWI-22834 environmental conditions. This formulation is filtering out possible sea states where the comfort performances are satisfied but the vessel is not able to keep position.

Applying this method to the MARIN yacht, it results in eliminating from the acceptable H_s and T_z combinations sets found with the comfort analysis all the higher T_z cells, resulting in a lower OP_{comf} value. The obtained data are reported in Table 7. With this new notation, only configuration C5 maintain a comfort rating of five stars. All the other configuration have a reduced rating, especially C1, having a DP totally inefficient for AWI-22834 heading.

This way to include DP in the comfort analysis may be too much penalising for simple DP systems, giving too much impact to DP performances instead of intrinsic motions related comfort of the yacht. Therefore a second option has been analysed in the following section.

5.5. DP for optimal comfort heading

A second option for the integration of DP results into an early-design comfort analysis is to consider the DP system for its effective duty, which means to keep a desired heading leading to a more comfortable life on-board.

The previous proposal was forcing the DP system to keep the heading χ of 45° degrees, condition not 100% favourable for all the DP system configurations here presented. This results in a general down-rate of the global ranking of the vessel, especially for simple DP systems. However, being a large yacht not required to keep the predetermined position, it can be stated that a yacht with DP system mounted on-board can operate at a minimum motion heading, so increasing the comfort of the vessel. This can be achieved by introducing an additional calculation heading to the comfort and DP analyses.

By adopting the AWI-22834 guidelines for comfort rating, the conditions where *MSI* and *EGA* have less impact corresponds to head sea. Therefore the final OP_{comf} can be evaluated as follows:

$$OP_{comf} = \frac{OP_{comf}|_{\chi=45^\circ} + OP_{comf}|_{\chi=0^\circ}}{2} \quad (21)$$

In such a case, the values of OP_{comf} for 45° and 0° degrees should be inclusive of the DP analysis, thus with an I_{comf} evaluated according to equation 20. The results obtained applying this alternative inclusion method for DP are reported in Table 8. The final rating for the 5 configurations is still lowered compared to the pure motion ones, however there is a more fair comparison among different DP systems. Configurations C1 and C3 are the ones who benefit the most from this method with an increase of the rating by two additional stars. For the other configurations the improvement is more contained although still relevant.

6. Configuration ranking

As final consideration, the five tested DP configurations of the MARIN yacht can be ranked, based on the above described indices of merit. Being the motions related comfort evaluated with the AWI-22834 guidelines high for this large yacht, all the differences among the configuration are only related to DP system. For the analysed conditions, a final ranking can be summarised as follows:

- (1) *Configuration C5*: this configuration is without any doubt the most indicate to maximize the DP capability of a large yacht. The adoption of POD units increases the possibility to face the incoming loads by orienting the thrust with more freedom respect to a propeller/rudder system.
- (2) *Configurations C4 and C2*: these two configurations are the second-best option to have good station keeping capability on a large yacht. The installation of a stern thruster in combination with the independent or dependent rudder management is offering a good performance for the station keeping of the yacht. The system hold capacity is poor only for headings $> 45^\circ$ degrees, especially for high T_z .
- (3) *Configuration C3*: this configuration, with independent rudders and a single bow tunnel thruster, has lower station keeping ability respect to the previous one, but it can still be considered sufficient. The hold capacity is poor only at large heading angles.
- (4) *Configuration C1*: the standard propulsive configuration of a yacht has poor station keeping ability for both the tested sea areas. The system grants sufficient performances only for heading angle less than 30° degrees in all the tested scenarios.

This final ranking is subject to all the assumptions reported in the previous sections and to the adoption of the environmental loads specific for the MARIN yacht. However, this ranking is respecting the general trends observed for offshore industry, therefore the adoption of other environmental loads or the application on different yachts may lead to the same qualitative results, changing only the indexes magnitude.

7. Conclusions

In the present study, an explorative analysis has been performed on the MARIN yacht to evaluate the impact on station keeping capability of different possible DP system design solutions and its integration with AWI-22834 guidelines for comfort assessment. The tested configurations include standard propulsion layouts for a large yacht and more advanced ones, including different management of the rudder control, the addition of stern thrusters or the adoption of a podded propulsion.

For the comfort analysis, the AWI-22834 guidelines for large yachts have been followed, comparing the differences of the proposed limiting criteria with other available in literature on the same environmental conditions. The analysis highlights that the AWI criteria are less restrictive than others, but probably more suitable to establish a comparison between large yachts.

The DP analysis has been firstly performed with standard capability plots, stating that this method is not really suitable to analyse the system performances considering the effective sea environment the yacht will face during service. On the contrary a scatter diagram approach allows to analyse and compare multiple configurations

ranking it according to predefined merit index in different sea areas. The AWI ranking method based on stars has been used to obtain a homogeneous result with comfort analysis on yachts. This allows to integrate also the DP results with the comfort analysis. Two different methods have been presented and compared, showing that a fair integration can be achieved by considering more vessel headings in the combined analysis and using DP as additional limiting criterion for comfort.

The obtained results are specific for the tested case of the MARIN yacht, however the results of this explorative study may be a starting point for more general considerations. The ranking of the proposed configurations shows that the best configuration is the one with pods (C5), granting the maximum combined index of comfort. The traditional configuration (C1) with dependent rudders and bow tunnel thruster is the worse one. An attractive solution is given by the installation of a stern thruster as per the configuration C2 and C4. In fact, the adoption of a stern thruster is giving a larger improvement with respect to the selection between dependent or independent rudders.

This preliminary study highlights some aspects that needs to be further investigated for the establishment of a general procedure for DP and comfort assessment of large yacht in the early design stage. In the specific, a detailed study on the determination of general environmental loads is needed, together with a reliable criteria for acceptability for yacht DP performances. Besides, additional features can be incorporated, performing dedicated studies on power consumption, the energy management on board, the impact of vibration noise induced by different propulsion systems and underwater radiated noise.

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Fig. 1. Western Mediterranean (*top left*) and Caribbean Sea (*top right*) scatter diagram and combined marginal wave distribution (*bottom*) considered by AWI 22834.

Fig. 2. Reference system for DP and comfort analyses.

Fig. 3. Example of DP capability plot for a sample vessel.

Fig. 4. DP scatter diagram approach example (*left*) for a heading of 45° degrees and comparison with associated points on a capability plot (*right*) based on wind-wave correlations.

Fig. 5. Heave and Roll motion RAOs for the MARIN yacht: experimental and numerical values.

Fig. 6. Analysed DP system configurations for MARIN yacht.

Fig. 7. Wind loads coefficients for the MARIN yacht: experimental data and empiric-statistics methods.

Fig. 8. Current loads coefficients for the MARIN yacht: CFD calculations and empiric-statistics method.

Fig. 9. Wave loads for the MARIN yacht: diffraction calculations and empiric-statistics method.

Fig. 10. Locations for comfort analysis on the MARIN yacht.

Fig. 11. *MSI* and *EGA* evaluation for MARIN yacht according to AWI-22834 guidelines.

Fig. 12. Application of Nordforsk comfort criteria to the MARIN yacht for the AWI-22834 environmental conditions.

Fig. 13. Capability plots comparison between DP system configurations for MARIN yacht.

Fig. 14. Scatter diagram comparison between DP system configurations for MARIN yacht in area 26.

Table 1

Comfort related ship motion criteria applicable for passenger ships.

Criterion name	Quantity	Criteria fulfilment
Effective Gravity Angle	EGA	$RMS < 2deg$
ISO2631-1	MSI	$MSI < 10\%$
Comfort rating for passenger ships	MIR or CR	$MIR < 10$ (for passenger)
		$MIR < 20$ (for crew)
Nordforsk	Vertical acceleration	$RMS < 0.02g$
	Lateral acceleration	$RMS < 0.03g$
	roll	$RMS < 2 deg$
Vibration Dose Value	VDV	$VDV < 1$

Table 2

AWI 22834 star-rating system.

OP_{comf} (%)	stars
0-20	★ ★ ★ ★ ★
20-40	★ ★ ★ ★ ★
40-60	★ ★ ★ ★ ★
60-80	★ ★ ★ ★ ★
80-100	★ ★ ★ ★ ★

Table 3

MARIN yacht main characteristics.

Quantity	Value	Quantity	Value
Length between perpendiculars	L_{PP} 72.00 m	Displacement mass (salt water)	Δ 1730.1 t
Length on waterline	L_{WL} 73.35 m	Wetted surface (bare hull)	S 1094.7 m ²
Length overall submerged	L_{OS} 79.06 m	Frontal area (superstructures)	A_F 147.1 m ²
Breadth	B 12.40 m	Lateral area	A_L 854.1 m ²
Mean draught	T_M 3.312 m	Lateral area centre (from O)	x_W 3.49 m
Long. centre of gravity (from O)	x_G -1.88 m	Inertia radius around x axis	K_{xx} 4.64 m
Lat. centre of gravity (from O)	y_G 0.00 m	Inertia radius around y axis	K_{yy} 20.00 m
Vertical centre of gravity (from O)	z_G 2.30 m	Inertia radius around z axis	K_{zz} 20.52 m

Table 4
MARIN yacht rudders main characteristics.

Quantity	Value
Number of rudders	2
Average height	b_R 2.32 m
Average chord length	c_R 1.53 m
Geometric aspect ratio	λ_R 1.52
Projected area	A_R 3.55 m ²
Longitudinal position (from O)	x_R 0.00 m
Lateral offset (from O)	$ y_R $ 3.00 m
Maximum rudder angle	α_{MAX} 45.00 deg

Table 5
MARIN yacht comfort rating according to AWI-22384 and Nordforsk criteria.

Location	AWI-22834		Nordforsk	
	OP_{comf}	rating	OP_{comf}	rating
OC	100.00	★ ★ ★ ★ ★	1.96	★ ★ ★ ★ ★
DA	100.00	★ ★ ★ ★ ★	100.00	★ ★ ★ ★ ★
WH	100.00	★ ★ ★ ★ ★	1.96	★ ★ ★ ★ ★
CA	82.75	★ ★ ★ ★ ★	0.00	★ ★ ★ ★ ★
BC	100.00	★ ★ ★ ★ ★	1.96	★ ★ ★ ★ ★
GLOBAL	96.55	★ ★ ★ ★ ★	21.18	★ ★ ★ ★ ★

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Table 6
MARIN yacht configurations DP ratings.

Area 26 Western Mediterranean										
	$\chi = 0^\circ$ deg		$\chi = 15^\circ$ deg		$\chi = 30^\circ$ deg		$\chi = 45^\circ$ deg		$\chi = 60^\circ$ deg	
	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating
C1	100.00	*****	99.62	*****	23.34	*****	0.00	*****	0.00	*****
C2	100.00	*****	99.82	*****	92.09	*****	58.09	*****	23.34	*****
C3	100.00	*****	99.65	*****	88.46	*****	48.59	*****	19.81	*****
C4	100.00	*****	99.82	*****	92.48	*****	62.68	*****	31.28	*****
C5	100.00	*****	99.97	*****	97.10	*****	82.36	*****	66.13	*****
Area 47 Caribbean sea										
	$\chi = 0^\circ$ deg		$\chi = 15^\circ$ deg		$\chi = 30^\circ$ deg		$\chi = 45^\circ$ deg		$\chi = 60^\circ$ deg	
	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating
C1	100.00	*****	100.00	*****	5.54	*****	0.00	*****	0.00	*****
C2	100.00	*****	100.00	*****	84.77	*****	28.43	*****	5.54	*****
C3	100.00	*****	100.00	*****	73.70	*****	19.80	*****	4.63	*****
C4	100.00	*****	100.00	*****	85.76	*****	33.06	*****	8.94	*****
C5	100.00	*****	100.00	*****	96.54	*****	61.95	*****	38.10	*****
AWI-22834 conditions										
	$\chi = 0^\circ$ deg		$\chi = 15^\circ$ deg		$\chi = 30^\circ$ deg		$\chi = 45^\circ$ deg		$\chi = 60^\circ$ deg	
	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating	OP_{DP}	rating
C1							0.00	*****		
C2							54.84	*****		
C3							37.38	*****		
C4							61.88	*****		
C5							89.24	*****		

Table 7
MARIN yacht configurations global ratings considering DP as additional limiting criterion.

configuration	OP_{conf} (%)	rating
C1	0.00	★ ★ ★ ★ ★
C2	51.06	★ ★ ★ ★ ★
C3	33.41	★ ★ ★ ★ ★
C4	58.18	★ ★ ★ ★ ★
C5	85.83	★ ★ ★ ★ ★

Table 8
MARIN yacht configurations global ratings considering two headings.

configuration	OP_{conf} (%)	rating
C1	45.98	★ ★ ★ ★ ★
C2	71.51	★ ★ ★ ★ ★
C3	62.69	★ ★ ★ ★ ★
C4	75.07	★ ★ ★ ★ ★
C5	88.90	★ ★ ★ ★ ★

Fig. 2. Reference system for DP and comfort analyses.

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