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DESIGN PARAMETERS FOR INCREASED OPERABILITY OF OFFSHORE CRANE VESSELS

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ABSTRACT

Marine subsea operations are performed by highly specialized ships, referred to as Inspection, Maintenance, and Repair (IMR) and Offshore Construction Vessels (OCV). Although the ships and their on-board equipment are designed to operate in harsh environmental conditions, the current practice often is to terminate operations when a rigid and conservative weather limitation is reached, often specified in terms of the significant wave height as the exclusive criterion. Such general limitations do not account for vessel specific motion behavior. Since the offshore industry is aiming for all-year-round safe subsea operations, there is a strong interest amongst ship designers, owners and operators to establish vessel and task specific criteria. The project Vessel Performance within the Norwegian Centre for Research-based Innovation on Marine Operations (SFI MOVE), is developing response-based procedures, that are leading to case-specific operational ranges. This approach enables the full exploitation of vessel performance capabilities for safe and efficient offshore operations. Two methods with different complexity levels are proposed. Firstly, on the higher level, detailed operability analysis for a fleet and sea area of interest are performed by means of numerical tools. This level can be used to obtain detailed results for existing ships, but the procedure can also be applied as guidance in the design stage. Secondly, on the lower level, generic diagrams can be used to estimate and compare the operational performance of different vessels based on fact sheet parameters. This is especially relevant for decision making processes where a detailed study cannot be performed.

INTRODUCTION

All-year-round marine operations are currently the focus of many oil companies, as a consequence of increased efforts and investments to prolong production from mature fields. This implies installation and maintenance of complex equipment also during the winter season (80% availability typically implies North Atlantic operations in significant wave heights up to 4.5 m or 5.0 m [1]) and hence high availability. Such operations require special weather insensitive handling equipment and more precise data for hydrodynamic loads on both the vessel hull and the complex module structure that is subject to strongly transient and non-linear processes when lowered through the splash zone [2].

The vessels being used in different types of marine operations have different capacities (crane- and winch capacity, deck area, dead weight, etc.), equipment and safety barriers (redundancies, freeboard and protection of working

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deck, de-icing, etc.). The type of marine operation and the geographical operation area imply different vessel requirements, and a performance evaluation will thus be dependent on operation type and location.

In order to assess the overall performance of a vessel (including technical, communication, and human aspects) for a certain marine operation, the research in SFI MOVE aims to contribute to the establishment of a set of operation based criteria and key parameters, describing and quantifying the ability of an offshore work vessel to perform its predefined work tasks effectively. Key Performance Indicators (KPI), eventually combined with balanced score cards, are often used to define and measure how well various levels of an organization succeeds in meeting operational and strategic goals. The definition of a KPI can be simple or complex, either express the gross result from a process or include balanced measures of several more or less easily quantifiable contributions to an over-all evaluation of success, e.g. the public opinion of the enterprise's social responsibility. The use of KPIs in the maritime sector is not new, the Shipping KPI Standard as a result of the EU-supported flagship project provides a methodology and platform to measure ship operation performance for merchant vessels by establishing KPIs, extracted from historical data, that are merged into higher level Shipping Performance Indi-

performance evaluation of marine lifting operations over the vessel side, which represent a significant part within subsea construction activities. The different parties involved in the overall performance of a vessel in marine lifting operations typically are ship designers, ship owners, operators, and oil companies. Each of them have a different view on operational performance and different priorities. From the designers perspective, research has been carried out in this field over the last years. The System Based Design (SBD) concept for ships has been introduced by Levander [5] for cruise ships and ferries. In this approach, the ship is divided into task/function-related systems and information from the existing fleet is used to estimate volumes and areas for a feasible new concept in an early design stage. Erikstad and Levander [6] extended this methodology later also to offshore vessels. The decomposition of vessel design aspects into sub-functions allows individual weighting of characteristic parameters. A similar methodology appears promising to assess the overall performance of a complex offshore operation where the well-tuned interaction of humans and technical sub-systems becomes crucial for success.

The areas influencing the overall operational performance cover more than just design-related issues. Among the most critical are human factors (including level of education, personal skills, well-being, communication, and project planning), as well as vessel motion behavior, technical performance of on-board equipment, and environmental aspects. The selected parameters listed in Fig. 1 are interlinked and will influence the overall performance of a marine lifting operation. Ebrahimi et. al proposed

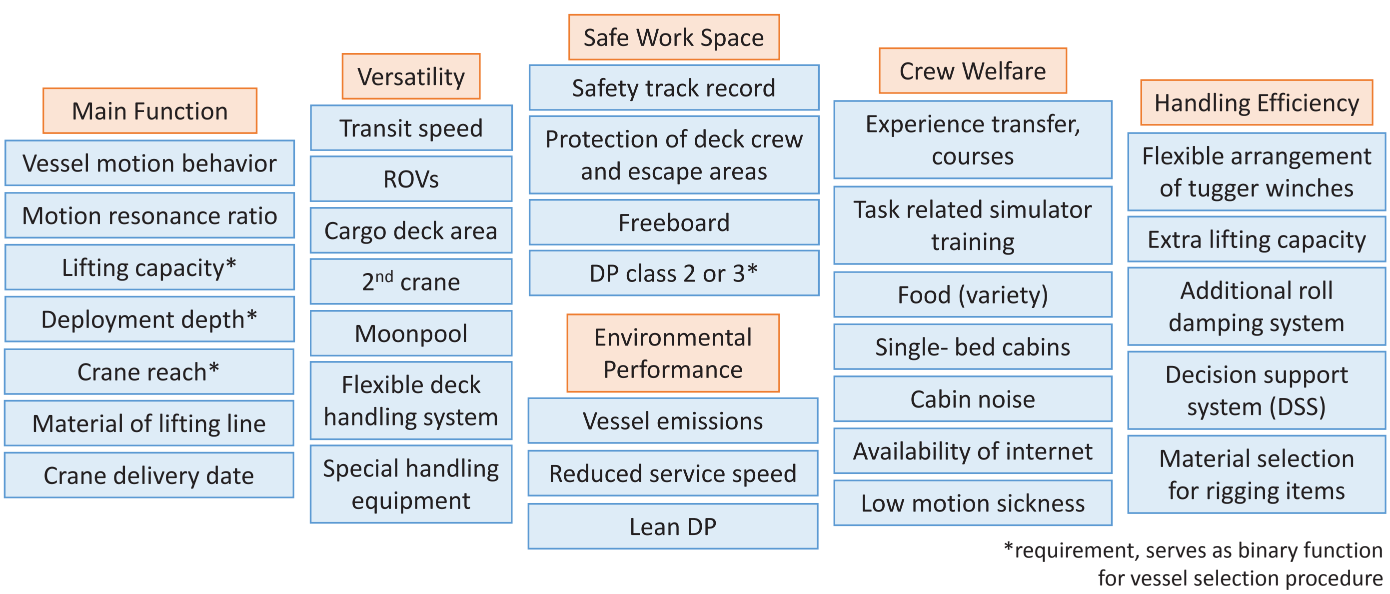

FIGURE 1. Selection of parameters, indicating performance for offshore lifting operations over the vessel's side.

Performance Indicators (PI) to account for technical, operational and commercial aspects of the decision making process in an early design phase of offshore vessels [7]. However, the philosophy behind the approach presented in this paper is to keep economical aspects outside the set of parameters. A cost/benefit analysis shall be introduced as a subsequent step within the evaluation process.

This paper focuses on the establishment of the performance measure for *Vessel motion behavior* (sub-item of *Main Function* in Fig. 1). Instead of a method that is based on regression of existing designs, a parametric variation study is performed to establish a generic database for a wide range of main particulars, with the aim to estimate a response-based vessel performance index in order to investigate operability beyond the limitations of existing vessels in an unique and broad sense. The proposed indicator shall contribute to improve vessel performance from different perspectives: it shall offer a rating method for existing vessels, which is relevant for owners, operators, and oil companies and it shall provide guidance for designers to tailor future hulls to maximize operability, which shall not necessarily be by default the largest and most expensive ship. Since the full hydrodynamic task- and location-specific assessment of vessel operability is complex and often not applicable in practice, a simplified evaluation approach is presented.

METHODOLOGY

A marine lifting operation can be sub-divided into six operational phases as illustrated in Tab. 1. Each phase is associated with specific criticalities, which have to be identified during the planning process and kept within an acceptable limit. For modules of larger weight, such as sub-sea templates, the vertical crane tip motion when crossing the splash zone (phase 4 in Tab. 1) is often considered as the most critical, while for tall objects of relatively low weight, such as suction anchors, pendulum motions occurring when the object is hanging in air (phase 3 in Tab. 1) may be more relevant. The pendulum motions are caused by horizontal crane tip motions and their magnitude is mainly depending on the ratio of the vessel's roll resonance period to the natural pendulum period of the system crane line and lifted object.

Considering all phases of a lifting operation, the location of the crane tip will vary strongly. Possible typical crane tip locations are shown in Fig. 2. In this paper, a generic lifting operation is investigated where the crossing of the splash zone is assumed to be the most critical phase. For example a typical crane position, while an object on the crane hook is crossing the splash-zone over the ship side, is location #6 in Fig. 2. A vessel heading of 15° off head sea is used, which reflects practical offshore experience, since this heading provides a good compromise between low wave-induced roll motions and sheltering effects for the lifting operation over lee ship side. In reality, this heading might

PREPARATION

Phase	Selected Hazards
(De-) Mobilization	Time/availability
	Unexpected vessel list during lift off from quayside
	Hot welding work
Transit	Loads on sea-fastenings
	Crew comfort (motion sickness)
	Slamming and green water
	Speed loss

OPERATION

#	Phase	Selected Hazards
1	Lift preparations	Hot work (cut-off of sea-fastenings leads to thermal exposure and damage to fiber rigging)
		Pendulum motions of crane hook (damage to structure and personnel injury)
		Work at height
2	Lift-off from deck	Unexpected tension in lifting wire
		Unexpected horizontal motion due to misalignment of object and crane tip position
		Poor communication
3	Object in air	Unexpected horizontal pendulum motions
		Unexpected rotational motions
		Collision of object with ship structure or personnel
		Wire entanglement
		Human errors related to operation of tugger winches
		Poor communication
		Unexpected vessel list during over-boarding
4	Crossing of splash zone	Relative vertical crane tip motions
		Strongly varying forces
		Line slack and snatch peak loads due to negative dynamic hook load*
		Violation of max. crane load*
		Violation of max. rigging capacity*
		Violation of max. hook load of object*
		Collision of object with vessel hull
		Floating and dropping of loose objects in a basket
5	Lowering through water column	Increasing vertical responses, approaching resonance
		Violation of max. crane load due to additional weight of lifting line
6	Landing on seabed	Visibility
		Current
		Capability of automatic heave compensation (AHC)
		Accuracy of orientation and positioning of object

TABLE 1. Phases of a marine lifting operation

*Typical limiting criteria for determination of max. sea state

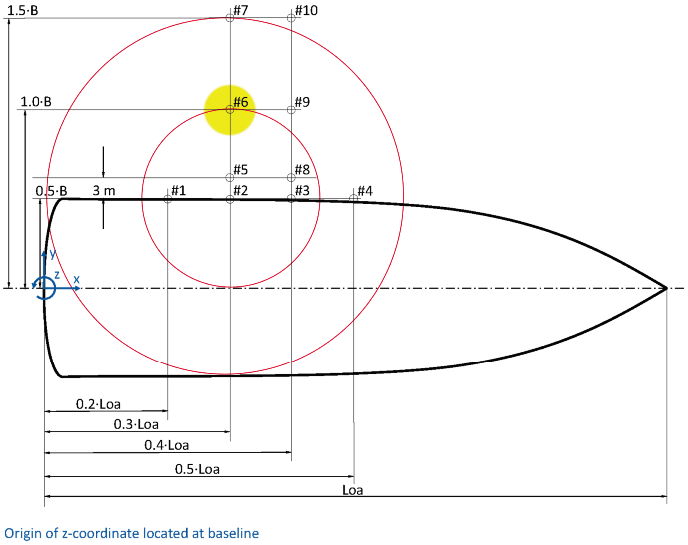

FIGURE 2. Typical crane tip locations during an offshore lifting operation.

not be possible when the vessel is operating in close proximity to an offshore structure or in cross-seas, when waves are propagating from different directions.

In the early design phase of an offshore vessel or initial planning phases of a marine lifting operation, detailed hydrodynamic calculations are usually not feasible, either due to a lack of information or required expert knowledge of involved personnel. Since it is nevertheless critical to have a good estimate of the motion characteristics and hence the response-based performance of a vessel for a specific operation, a generic database has been developed. With simple input parameters such as vessel hull length (L), beam (B), draught (D), and metacentric height (GM_T) a performance prognosis is returned based on interpolation.

In order to establish this database, a large number of frequency-domain vessel response calculations has been performed with SINTEF Ocean's code VERES, which is based on strip theory [8], [9]. A base case geometry of a modern offshore vessel design, from which generic variants are created in five different length classes, 80 m, 100 m, 120 m, 140 m, and 160 m (hull length) with realistic average length to beam ratios for this vessel type. In each of the five length classes, the parameters beam, draught, GM_T, and the radius of gyration for roll (r_{44}) have been varied within a typical range. Since the height of the meta-center is defined by the characteristics of the cross sectional geometry, the vertical position of the center of gravity above keel (KG) was adjusted in order to achieve the desired GM_T value. In order to isolate the influence of each variable, the other parameters have been kept constant if applicable or else adapted as shown in Tab. 2. For example, the variation of the hull length (L) implies an adaption of the displacement (∇) and of the radius of gyration for pitch (r_{55}) in order to keep the ratio r_{55}/L at a constant value of 0.25. Similarly for variation of beam (B), the ratio r_{44}/B was kept at a constant value of 0.35. Both values can be considered as typical mean values for vessel motion analysis [9].

varied	constant	adapted
L	D, GM_T, KG, r_{44}, r_{55}/L	∇
B	D, GM_T, L, r_{44}/B, r_{55}	KG, ∇
D	GM_T, L, r_{44}, r_{55}	KG, ∇
GM_T	B, D, ∇, L, r_{44}, r_{55}	KG
r_{44}	B, D, ∇, GM_T, L, KG, r_{55}	

TABLE 2. Overview of varied parameters (left column) and parameters that are kept constant (center column) and are adapted (right column) for each variation case.

Definition of the Vessel Response Measure

For each of the 85 hull variants that have been created, a frequency domain response calculation at 15° wave heading is performed using VERES. Frictional damping caused by skin friction stressed on the hull [10], eddy damping from pressure variation on the naked hull [11], lift damping [12], the damping contributions due to normal forces on the bilge keels [13], and hull pressure [14] are included in the vessel response calculations, based on a significant wave height of 2 m. The result of the numerical calculations are displacement, velocity and acceleration RAOs in six degrees of freedom at center of gravity and at the crane tip location #6. Assuming long-crested sea and using the JONSWAP (Joint North Sea Wave Project) wave spectrum formulation with variable peakedness parameter γ as proposed by DNV GL [1] to represent wave conditions as predominately found along the Norwegian continental shelf and in the North Sea, short-term statistics in terms of Root Mean Square (RMS) values are calculated for relevant motion components.

Equipment and safety related vessel motion limitation criteria can vary significantly, and the appropriate choice of limits will finally determine vessel operability. In this study, literature values were used to present a general approach. Besides vertical crane tip displacement limitations, global motion criteria, related to roll and pitch motions are considered. The NATO Standardization Agreement on seakeeping in the ship design process (STANAG, [15]) defines limiting RMS values for roll- and pitch angles of 2.2° and 1.5°, respectively, for replenishment operations at sea (with reference to pallet slip angle). Further, maximum tolerable

RMS values of 1.5 m for vertical displacement, 1.5 m/s for vertical velocity, and 1.0 m/s^2 for vertical acceleration are assumed. The assessment of operability for different limitation criteria will be essential in further analysis.

In order to evaluate percentage operability, annual wave scatter diagrams for the North Atlantic (area 4), based on Global Wave Statistics [16], were used. It has to be mentioned that the GWS data were gathered by ship-based observations between 1854 and 1984 and do not represent high accuracy data, since partly poor accuracy with regards to wave periods and the seasonal influences was identified [17]. However, the statistical data is considered to be sufficient for the intended purpose of this study. In order to quantify response-based vessel performance, a new parameter, denoted Integrated Operability Factor (IOF) is introduced that shall serve the purpose of a PI. The IOF describes the ratio of the area enclosed by the percentage operational performance $P_{Op}{}^{\beta}$ between zero and a maximum tolerable operational limit OP_{max} to the area defined by the maximum possible operability, which is represented by the product of OP_{max} and 100% operability. This is illustrated in Fig. 3 for an exemplary variation of GM_T. A division of the light blue area below the green curve by the rectangle from 0° to 2.2° on the x-axis and 0% to 100% on the y-axis would give the IOF as a performance indicator for the vessel with $GM_T = 2.0$ m; or, as a more general expression

$$IOF = \frac{\int_0^{OP_{max}} P_{OP}^{\beta}(OP_{tol})\, dOP_{tol}}{OP_{max} \cdot 100} \quad (1)$$

It is apparent that the choice of the upper limit OP_{max} will affect the level of the derived IOF value and its sensitivity regarding design variations. While the percentage operability for increasing motion limitations rapidly approaches 100% operability, the convergence of the IOF will approach 100% slower and therefore is capable to show differences of the vessel behavior even for higher operational limits. Nevertheless, since the influence of a parametric variation mostly effect operability when the limitation criteria are low, a reduction of OP_{max} will result in a lower value and an increased variance of the IOF. This will have no influence on the ranking of the results as long as the respective OP_{max} is applied consistently for all designs analyzed in a comparative study.

Without doubt, the determination of percentage operability for one defined limitation criterion (e.g. as a result of maximum tolerable loads on on-board equipment) is important to assess vessel performance for a marine operation. However, in order to rank the operational performance of different vessel designs, the assessment of operability over a broader range of maximum tolerable response levels is advantageous. Compared to one single percentage operability value, as in the classical assessment, the IOF gives additional information on the operation quality of a vessel in a broader sense. The higher the IOF, the faster the convergence of the $P_{Op}{}^{\beta}$ curve towards 100% operability.

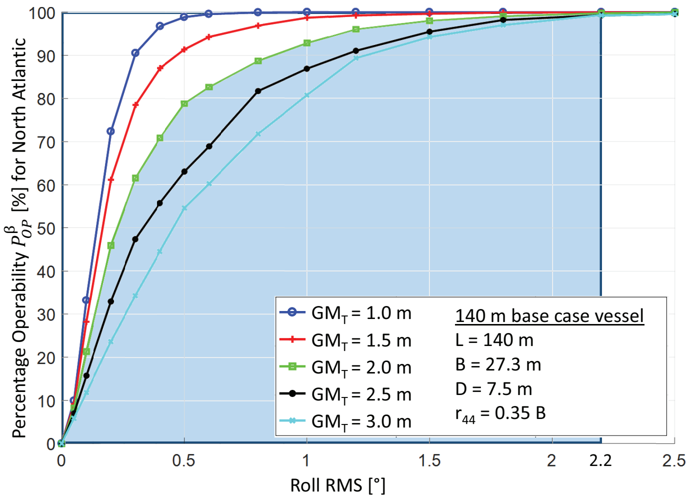

FIGURE 3. Determination of roll motion performance measure for vessels with different GM_T values.

PARAMETRIC VARIATION STUDY

A hull design of a modern OCV, in operation since 2015 was used as the base case for the parametric study, varying hull length (L), beam (B), draught (D), metacentric height (GM_T), and the radius of gyration of roll (r_{44}). The results in terms of IOF values are shown in Fig. 4, where the top graph contains results from beam variation, the second for draught variation, the third for variation of GM_T, and the bottom graph shows the results of variation of r_{44}. The five columns in each graph represent the five vessel length classes from 80 m (left columns) to 160 m (right columns). The color of the lines indicate the different motion components of interest for the selected scenario. Global roll motions are shown by the yellow lines and global pitch motions by the green lines. The IOF for the vertical motions at the crane tip position (location # 6, see Fig. 2) are indicated by red lines (displacement [m]), purple lines (velocities [m/s]) and blue lines (acceleration [m/s^2]). In each column and figure, the respective variation parameter increases is given from left (lowest value) to right (highest value) so that the base case for each length class can be found in the middle of each presented hull length.

Generally, the vessel response performance, expressed in terms of the IOF, is increasing with hull length and vessel size (displacement), respectively. This tendency is ex-

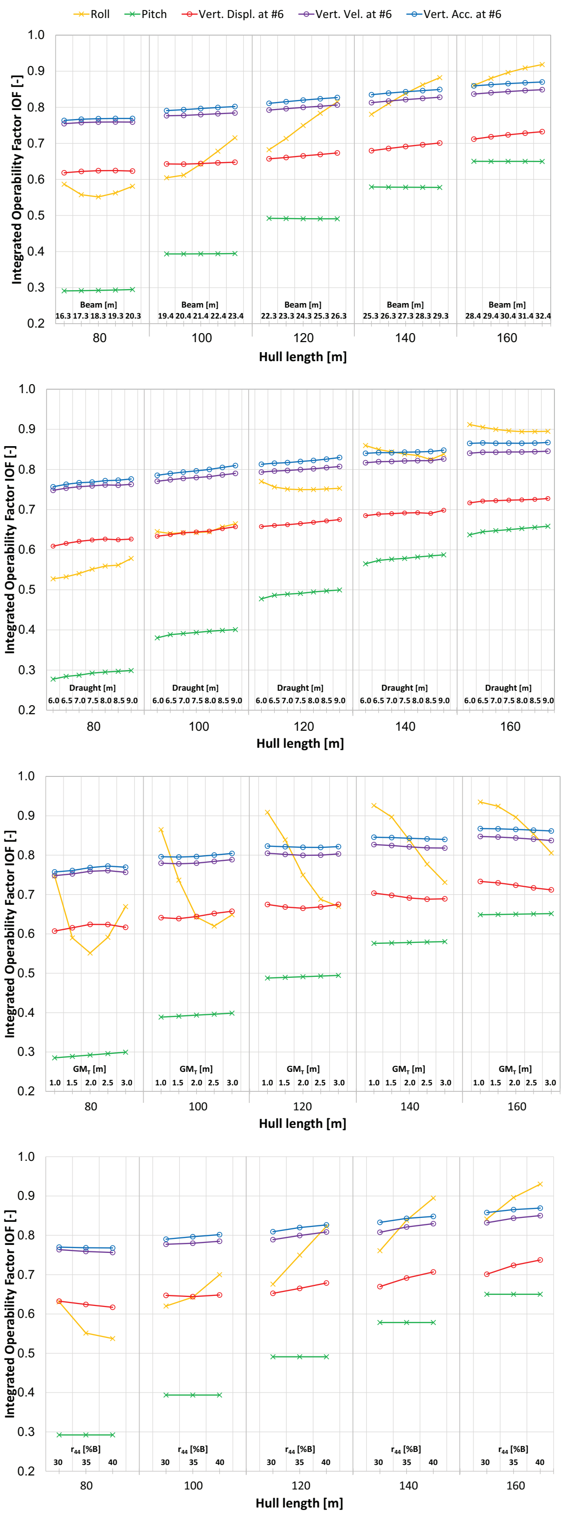

FIGURE 4. IOF obtained from the parametric variation study, varying beam, draught, GM_T and r_{44} (top to bottom).

pected, especially since beam and displacement are increasing proportionally to the hull length, as explained above. Roll appears to be the most sensitive motion component for almost all performed parametric variations. While, for the variation of beam, GM_T and r_{44} shows a significant impact on the IOF for roll motion behavior (top, third and fourth graph in Fig. 4), the influence from the variation of draught is rather small (second graph in Fig. 4). The IOF for roll is significantly rising with increasing beam (note that KG is adapted in this case in order to keep GM_T constant and the ratio of r_{44}/B is kept constant at 0.35, see Tab. 2), whereas the IOF for pitch is not affected. Vertical motions at the crane tip location #6 are marginally rising with increasing beam.

The variation of the vessel draught reveals a slight increase of all IOFs with increasing draught (note that KG is adapted in this case in order to keep GM_T constant, see Tab. 2), with the exception of an effect of increased draught on the roll motion for hull length classes of 120 m and above. Here the tendency is reversed, i.e. the roll IOF decreases with increasing draught. Depending on the loading condition, the choice of draught and GM_T during the vessel design process will typically be within the range that has been applied for the parametric variation.

Compared to all performed parametric variations the variation of GM_T shows the largest impact on the IOF, especially for the roll motion. According to the results, the impact of a low GM_T on the roll motion behavior seems to be higher than the effect of selecting a larger vessel. For example, the roll-related operability of a vessel of the 120 m length class with a GM_T = 1.5 m is higher than the roll-related operability of a 160 m long vessel with a GM_T of GM_T = 3.0 m. Nevertheless, since the length of the vessel has a large impact on the pitch behavior, the influence of the variation of the GM_T on the other selected motion components is negligible compared to the effect of choosing a vessel from another length class. The fact that draught and GM_T are dependent on the loading condition implies that the adjustment of the loading condition can be used to enhance operability. This could for example be achieved through decision support systems providing assistance with regards to ballasting during marine operations.

The variation of r_{44} shows a significant impact on the IOF for roll and, slightly less pronounced, for the vertical motions at the selected crane tip location #6 (see Fig. 2). Since r_{44} is neither measurable at full scale nor fully controllable during the design process, the uncertainty of this input value has a direct and noticeable impact on the results of the vessel response behavior. Which even more cause concern, since generally, this value may vary significantly between 30% and 45% of the vessel beam [9]. Nevertheless, based on the experience of a Norwegian ship designer and project partner, for modern offshore construction vessels, the r_{44} value might be assumed to be relatively close to the value of 33% of the vessel's beam.

Influence of Local Geometry Variations

In order to assess the influence of local geometric features of the hull shape, the variation procedure and response calculation has been performed for five different hull geometries from different designers, creating a 120 m long base case for each ship. The results are summarized in Fig. 5. The lines represent the mean IOF values from all five hull designs and the vertical bars at each variant represent its standard deviation. The same colors as before are used to indicate the different motion components. It is obvious that local geometric variations have a large influence on the roll motion behavior of a vessel, where the maximum standard deviation is 7.7% of the mean value. To some reduced extend the pitch motion behavior is also influenced by a standard deviation of 3.3% of the mean IOF. Interestingly, the variance of vertical motions at the crane tip location #6 is significantly smaller. A maximum standard deviation corresponding to 1.8% of the mean IOF value is observed for vertical displacements, while for vertical velocities and accelerations even smaller standard deviations of 0.9% are calculated.

Taking into consideration that the chosen hull geometries are representing a wide range of design philosophies, a deviation of a few percent in the IOF value, representing a performance indicator for vessel operability, opens possibilities to develop a generic methodology, where the estimation of operational performance in marine operations appears to be possible without the detailed knowledge of the hull geometry.

In order to explain the deviations that occur for roll and pitch motions of the five different hull designs, some hull data has to be utilized. From the available data, it appears that the vessel that feature a larger block coefficient and a larger water plane area coefficient and subsequently a slightly larger displacement and buoyancy (while keeping the same main particulars) show higher IOF values than the more slender designs. This can be attributed to increased vertical damping effects, leading to reduced heave motions. A further explanation could be a possible deviation in the longitudinal distribution of volume: reduced pitch motion responses due to increased damping could be an effect of larger buoyancy at the forward and aft hull section. Another noticeable difference of the hull designs is the bilge radius. A smaller bilge radius and consequently an increased distance between the bilge keels and the ship center line, or more precisely the center of roll motion creates a larger lever and hence additional roll damping. Since

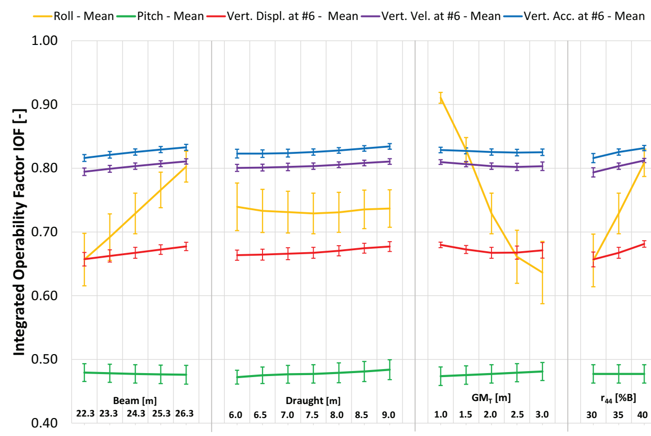

FIGURE 5. Mean values and standard deviation of IOF obtained for five hulls of identical main particulars but local geometric variations.

vertical motion at location #6 consists of a phase shifted superposition of roll, pitch, and local heave motions the differences in IOF are not as pronounced as for the global motions roll and pitch. It is also apparent that the older vessel designs show less favorable results. Due to the limited number of cases, this might be a coincidence, but it could also be a result of operability-oriented hull design in the last years.

CONCLUSIONS AND PERSPECTIVE

Parametric design variations for hull length, beam, draught, metacentric height, and roll radius of gyration were performed for a generic offshore vessel hull design in five different length classes to evaluate the isolated impact of each parameter on vessel operability. In order to evaluate and compare operational performance, a new performance indicator for marine operations, the Integrated Operability Factor (IOF), is introduced. Compared to the criterion of absolute percentage operability for a single operational limit, the IOF additionally includes information of operational performance over a broad range of limitation criteria, which provides a more global impression of vessel response behavior for a specific marine operation.

The presented study is based on a generic marine lifting operation over the vessel side. It can be observed that the IOF is higher with increasing vessel displacement for all considered motion criteria. Nevertheless, the roll motion behavior appears to be the parameter that is most affected by design modifications. While the variation of beam, GM_T, and r_{44} show a significant impact on the roll motion behavior in all vessel length classes, the variation of draught has a rather small influence.

The comparison of parametric variations for five hull designs of identical main particulars but local geometrical deviations indicates a favorable impact on operational performance for a fuller hull designs, i.e. for larger block and water plane area coefficients and smaller bilge radius and consequently slightly increased displacement. However, considering the entire operation including the transit phase, where speed loss and fuel consumption (also important performance indicators) are considered, other hull designs might be favorable. Compared to global vessel motions, the maximum variance of the IOF related to vertical motions at a selected crane tip location has been significantly smaller.

Keeping in mind that the five hull geometries represent a wide range of design variables, a maximum deviation of the IOF of a few percentage is within an order of magnitude that opens possibilities to develop a generic methodology, where the estimation of operational performance in marine operations appears to be possible without the detailed knowledge of the hull geometry. Based on a database of characteristic vessel response data (RAOs) for various parametric vessel designs and headings, an interpolation procedure shall be developed to predict operability for arbitrary limitation criteria valid at arbitrary coordinates, sea area, and season without the requirement of detailed hull information. Further, within the scope of SFI MOVE, a set of performance measures for marine lifting operations, as shown in Fig. 1 shall be established. For this objective, the IOF will be an important contributing parameter.

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