# A Comparative Study on the Seakeeping Operability Performance of Naval Combatants

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**Abstract.** In this paper the seakeeping operability of three naval combatants, including a well documented design available in the literature, are compared. In order to accomplish this task, a new realistic operability index is proposed. The actual vessels under investigation are of different design philosophy. The designs were compared scaled down at the same length taking into account their original design condition. Their operability is examined at selected areas of the Eastern Mediterranean Sea for four missions, two speeds and three heading angles, taking into account given seakeeping criteria. Wind and Wave Atlas provides the necessary sea statistics. Plots were produced to quantify the operability of each hull form in a specified area at constant heading and speed. On the basis of the most probable ship's course in each area a component of the operability index is calculated. These indices are summed up to derive the overall seakeeping operability of each candidate. The derived results are discussed and conclusions are drawn.

**Keywords:** Seakeeping, operability, naval vessel, mission, criteria.
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## INTRODUCTION

During the last century a lot of computational methods to evaluate the seakeeping performance of ships in confused seas have been developed. Furthermore, criteria were established for the affordable dynamic responses that affect the ship integrity, the cargo (merchant ships), the crew and the passengers. As a reasonable consequence the capability of a ship to operate and accomplish her mission in a given sea environment could be quantified. Operability or operational effectiveness associates this capability with the percentage of time in which a ship does not violate any of imposed criteria (NATO, STANAG 4154, 2000).

To restrict ourselves in naval vessels, this capability is assessed by considering the various dynamic responses that affect the ship, the crew and its mission. The responses encompass both the basic ones (mainly heave, pitch and roll) and the derived ones, i.e. vertical and lateral velocities and accelerations along the vessel, as well as random events (slamming, deck wetness, propeller racing etc) at specific positions.

The seakeeping performance of a vessel is mainly affected by its size and its hull form geometrical parameters (main dimensions, block coefficient, prismatic coefficient, waterplane area coefficient, longitudinal and vertical location of the centre of buoyancy, longitudinal position of the center of waterplane area). It is essential to consider the same size when we compare alternative designs, that are expected to operate in the same areas. In this work the length of the vessel was considered as a size indicator. On the other hand, it is clear that the seakeeping operability should be examined in the preliminary ship design stage (Grigoropoulos, 2004), in order the designer to be able to take any necessary measures to improve it, in case some targets or specifications are not fulfilled. In general, the smaller the vessel is, the more sensitive it is in a specific sea environment. Nowadays, the trend is to build versatile, sophisticated and difficult to detect platforms, keeping their size small to reduce the building and maintenance cost, while innovations are also incorporated to improve specific capabilities, such as STEALTH property (VISBY Corvette, LAFAYETTE Frigate, DDG-1000 ZUMWALT Destroyer). In this paper we compare the seakeeping operability of the three candidate hull forms at the frigate size.

## OPERABILITY PERFORMANCE ASSESSMENT

Following NATO STANAG 4154 (2000) the seakeeping operability performance of naval ships is assessed in two ways:

- by comparison of the seakeeping performance of a specific design to another reference design with known (good) performance (Figure 1) or to a database of similar ships (Bales, 1980). This method is known as comparative and it is used extensively for hull form optimization for seakeeping (Grigoropoulos and Loukakis, 1990). This method uses quantitative as well as qualitative criteria.

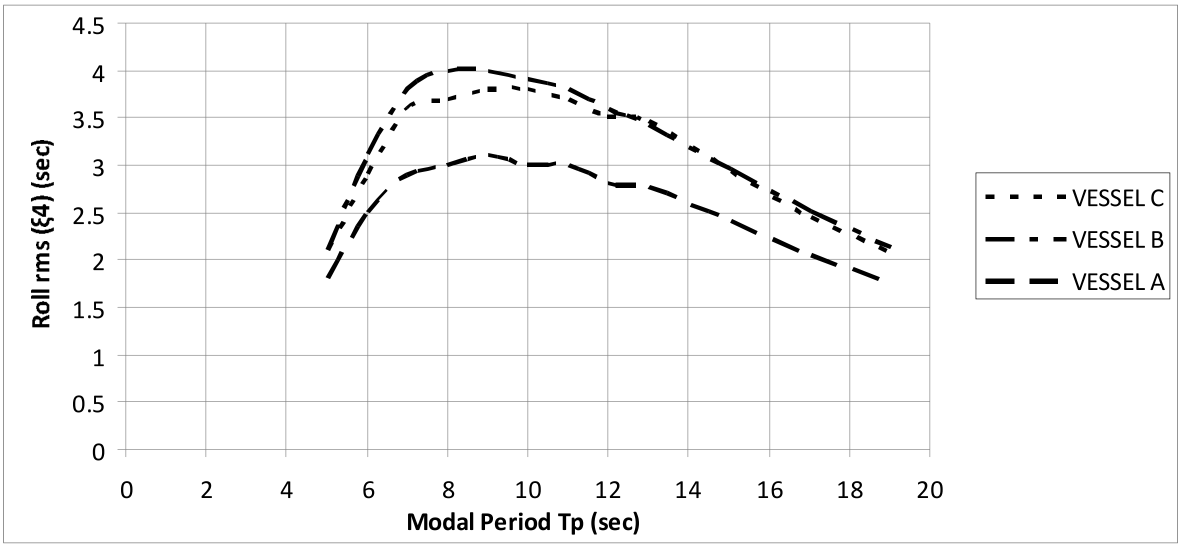


**FIGURE 1.** Comparative Method of Roll Evaluation. Three vessels sailing at a speed of 15 Kn, encounter beam seas with significant wave height $H_S$ = 3 m. Vessel A has the best performance.

- by direct calculation of the seakeeping performance and implementation of specific criteria. The latter are acceptable limits that are set to ship's responses based on crew and systems degradation. The vessel is evaluated according to these criteria (Figure 2) to derive the sea conditions where the ships is operable. Then, on the basis of the statistical percentage of time these conditions prevail, an operability index is derived (absolute method). This method uses only qualitative criteria.

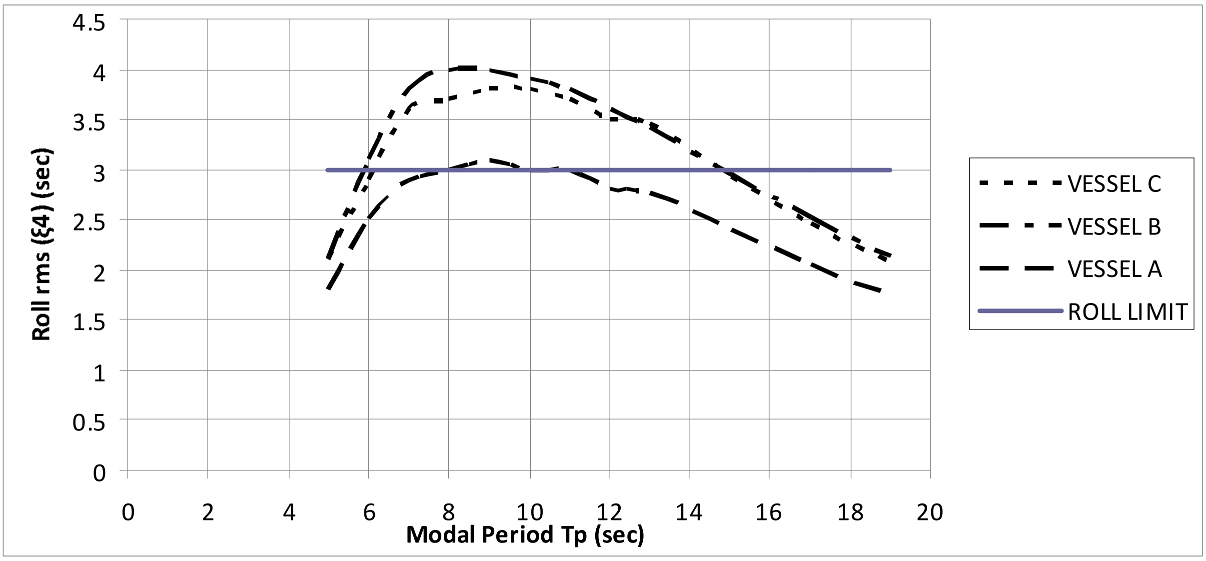


**FIGURE 2.** Absolute Method of Roll Evaluation. Three vessels sailing at a speed of 15 Kn, encounter beam seas with significant wave height $H_S$ = 3 m. Vessels B and C violate the roll limiting criterion for RMS roll (3 deg) for waves with Modal Period in the 6 to 15 sec range. Vessel A has the best performance, since its roll response exceeds the criterion for Modal Periods in the 8 to 10 sec range.

In the case of direct calculation belong also the polar plots proposed by Comstock and Keane (1980) which are used to derive the operability index of a naval vessel in a specific sea condition. Such a plot extracted from the PNA (1989) is shown in Figure 3. On this plot, which is based on the seakeeping criteria of Table 1, the operating (non-shaded) and non-operating (shaded) areas are depicted. The shaded area is defined by one or more responses that exceed the limiting values (criteria). The operability index in a specified Sea State, assuming that all headings are equally probable and the higher speeds are more probable than the lower ones, is the ratio of the non-shaded area to the whole circular area. In other words, the bigger the non-shaded area the better the seakeeping performance of the vessel. Thus, these plots don't take into account the effect of speed and heading profiles of the vessel in a rational way. Furthermore, they should be derived for all possible sea conditions encountered by a vessel throughout its mission or life to come up with a mission or a through-life operability index.

To be more specific, warships operate in various sea areas performing multiple tasks. Following STANAG (2000) there is long list of mission scenarios, such as Anti-Aircraft Warfare (AAW), Anti-Submarine Warfare (ASW) etc. Thus, in order to derive a realistic overall operability index the following components should be considered:

1. Definition of missions (AAW, ASW etc).
2. Sea environment description (Wind and Wave Atlas).
3. Responses calculation (computer or/ and model simulation).
4. Criteria application (STANAG 4154, NORDIC Project).
5. Data collection and evaluation in order to calculate the operability indices.

These components can only be combined within an absolute method of seakeeping performance evaluation, as the one proposed in this paper, which is also quite robust. Among the data to be collected under (5) in the above list of components is the operational profile of the vessel in accomplishing each of the assigned missions and the probability of encountering a restrictive sea condition with given heading, significant wave height and modal period. This information is not provided in either of Figures 1 or 2.

**TABLE 1.** Mission criteria sets.

| | | Roll [deg] | Pitch [deg] | Yaw [deg] | LOCATION-DEPENDENT CRITERIA | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | No. | Vacc [g] | Lacc [g] | Vvel [m/sec] |
| TAP | Deck Wetness | | | | 30 | | | |
| | Slamming | | | | 20 | | | |
| | Personnel, Bridge | 4 | 1.5 | | | 0.2 | 0.1 | |
| | Propeller Emergence | | | | 90 | | | |
| ASW | TAP Criteria AND … | | | | | | | |
| | Sonar Emergence | | | | 24 | | | |
| | Active SONAR | 7.5 | 2.5 | | | | | |
| AAW | TAP Criteria AND… | | | | | | | |
| | Fwd Gun | 3.8 | 3.8 | | | | | 0.5 |
| | Missile Launch from VLS | 8.8 | 1.5 | 0.8 | | 0,3 | 0.35 | |
| NAO | TAP Criteria AND… | | | | | | | |
| | Helicopter Landing | 2.5 | 1 | | | | | 1 |

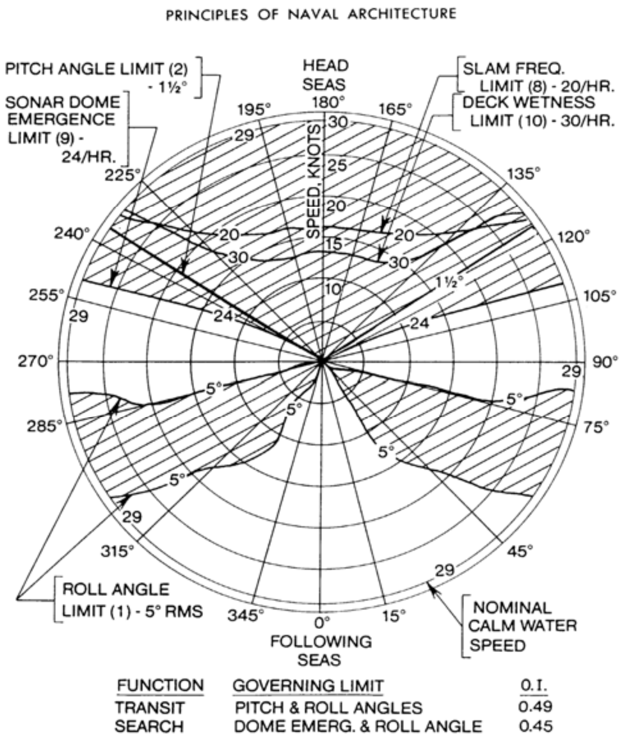


**FIGURE 3.** Polar Diagram for calculating the operability for TRANSIT and ASW operations at sea state 6 for all speeds and headings. The bigger the non-shaded area the better the seakeeping performance.

# MISSION AND SEAKEEPING BEHAVIOUR OF THE HULL FORMS

## Derivation of the Hull Forms

The prime scope of this paper is to present a rational comparison of three hull forms to be used as frigates serving Hellenic Navy and operating in the East Mediterranean sea region. Two of the selected hull forms, the ONR 5415M and the ONR 5613 hull forms were scaled down from the destroyer to the frigate size (Figure 4). The former one is a well documented design available in the literature. The third hull form (HULL C) was manipulated in its real dimensions and was considered as a guide for scaling the other two.

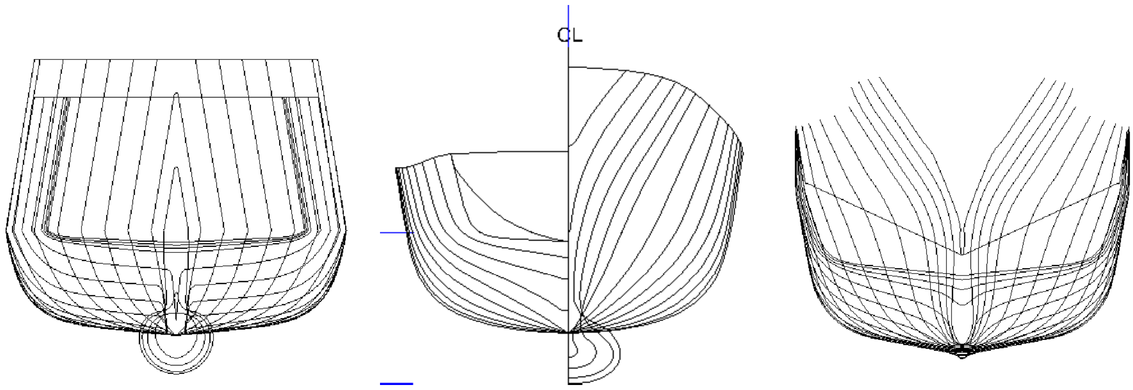


**FIGURE 4.** The investigated hull forms (HULL A, HULL B and HULL C)

**TABLE 2.** Main Particulars.

| MAIN PARTICULARS | HULL A (ONR 5613) | HULL B (5415 M) | HULL C |
|---|---|---|---|
| Length Between Perpendiculars, $L_{PP}$ [m] | 109 | 109 | 109 |
| Beam Amidships, B [m] | 13.29 | 14.62 | 13.96 |
| Draft Amidships, T [m] | 3.89 | 4.72 | 4.32 |
| Displacement in S.W. Δ [mt] | 3087.6 | 3898.4 | 3441.1 |
| Design Speed, V [kn] | 30 | 30 | 30 |
| Length/Beam Ratio L/B | 8.199 | 7.456 | 7.806 |
| Beam/Draft Ratio B/T | 3.418 | 3.099 | 3.233 |
| Draft/Beam Ratio T/B | 0.293 | 0.323 | 0.309 |
| Volume of Displ. / $(0.1L_{PP})^3$ | 2.325 | 2.934 | 2.59 |
| Froude Number (Fn) | 0.472 | 0.472 | 0.472 |
| Vert. Centre of Gravity (KG) [m] | 5.44 | 5.76 | 5.99 |
| Metacentric Height (GM) [m] | 1.41 | 1.46 | 1.41 |
| Wetted Surface, WS | 1590.2 | 1737.4 | 1619 |
| Block Coefficient $C_B$ | 0.534 | 0.506 | 0.51 |
| Prismatic Coefficient $C_P$ | 0.638 | 0.618 | 0.625 |

As reference for the scaling the length between perpendicular $L_{PP}$ was used, while the ratios of the main dimensions were kept constant. Thus, the resulting hulls possess the same length $L_{PP}$ but different displacement. Furthermore, the rest of the main dimensions are not the same (TABLE 2). The decision to compare the hull forms at their respective design conditions is based on the fact that the design condition is the most representative of each hull form, while the down-scaling of two of them was too mild to lead to un-realistic loading condition. In order to achieve greater accuracy, especially with roll response, the three hulls are examined with their appendages (Petropoulos, 2012).

## Mission Definition

Naval vessels are generally built as multi-tasking platforms. Their sensors and arsenal is oriented to one mission, but the platform has the ability to perform successfully a variety of different missions by fitting and / or replacing devices, sensors or systems while the platform remains the same (modular concept). In this work four missions are depicted: Transit And Patrol (TAP), Anti-Air Warfare (AAW), Anti-Submarine Warfare (ASW) and Naval-Air Operations (NAO).

The seakeeping operability of the three competitors is examined in four areas of the Eastern Mediterranean Sea assuming four missions specified in NATO STANAG 4154 (2000) along with their respective platform criteria. Two ship speeds and three wave heading angles are accounted for in the presented test case out of the five headings that could cover all instances. The Western European Armament Organization (WEAO) Wind and Wave Atlas (2004) provides the necessary sea statistics. Plots have been produced to quantify the operability of each hull form in a specified area at constant heading and speed.

## Sea Environment Description

In order to acquire reliable data for the sea environment, we use an Atlas. It is an edition where statistical data concerning wind speed, significant wave height, wave modal period, wind and wave directionality in various areas are gathered. The objective is to provide long term wind and wave statistics at specified points of a sea area (e.g. North Atlantic Ocean, Mediterranean Sea). For the purposes of this paper, the area of interest is focused on four points of the Eastern Mediterranean Sea (Figure 5). Statistical data related to the sea environment (wave direction, probability of occurrence, significant wave height and modal wave period) are derived from the WEAO Wind and Wave Atlas (2004).

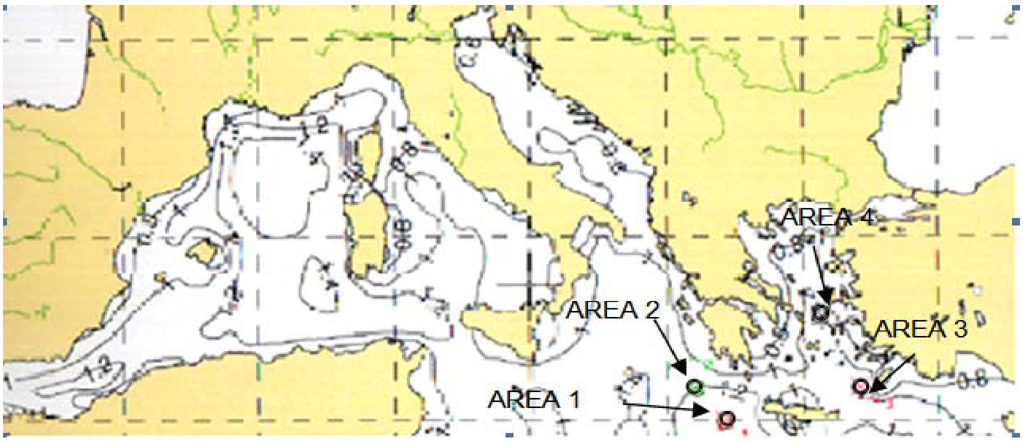


**FIGURE 5.** Areas of interest in the East Mediterranean sea region.

## Calculation of the Dynamic Responses

In order to estimate the ship responses, the Standard Ship Motion Program of US Navy SMP 93-PC (Smith and Meyers, 1994) is used. This code is a frequency domain, strip theory based program, able to calculate responses in all six degrees of freedom (surge, sway, heave, roll, pitch, yaw) as well as random events in irregular seas (long-crested and short-crested). Frank close-fit method is used to estimate the two-dimensional hydrodynamic characteristics (Frank, 1967). Up to ten sources are distributed on each half-section. A two-parameter Bretschneider spectrum is used. Roll response calculations make use of Tanaka's roll damping coefficients. Rigid body motions as well as derived responses and random events were calculated in various locations onboard the three vessels.

**TABLE 3.** Locations onboard ship. Station number starts at Forward Perpendicular. Y is the transverse distance from the vertical symmetry axis. Z is the vertical distance from the keel.

| NUMBER | NAME | STATION NR | Y [m] | Z [m] |
|---|---|---|---|---|
| | **HULL A** | | | |
| 1 | Helicopter Deck | 17.4711 | 0 | 10.325 |
| 2 | Bridge (Helmsman) | 6.6249 | 0 | 19.18 |
| 3 | FWD GMVLS Outer Corner | 6 | 4.399 | 11.738 |
| 4 | FWD Gun Barrel Tip | 5 | 0 | 11.738 |
| 5 | Slamming @ 3/20 $L_{PP}$ | 3 | 0 | 1.489 |
| 6 | Deck Wetness @ 1/10 $L_{PP}$ | 2 | 0.748 | 11.739 |
| 7 | Propeller Emergence | 18.44 | 2.898 | 3.38 |
| 8 | Sonar Dome Emergence | -0.0149 | 0 | 2.9 |
| | **HULL B** | | | |
| 1 | Helicopter Deck | 18.227 | 0 | 10.736 |
| 2 | Bridge (Helmsman) | 6.2 | 0 | 21.3014 |
| 3 | 5/54 Gun Barrel Tip | 1.8822 | 0 | 14.9687 |
| 4 | FWD GMVLS Outer Corner | 5 | 5.682 | 12.0457 |
| 5 | Slamming @ 3/20 $L_{PP}$ | 3 | 0 | 2.3186 |
| 6 | Deck Wetness @ 1/10 $L_{PP}$ | 2 | 5.7444 | 13.5076 |
| 7 | Propeller Emergence | 19 | 3.5668 | 4 |
| 8 | Sonar Dome Emergence | 0.5 | 0 | 3.7913 |
| | **HULL C** | | | |
| 1 | Helicopter Deck | 18.4954 | 0 | 10 |
| 2 | Bridge (Helmsman) | 5.5046 | 0 | 15.6 |
| 3 | 5/54 GUN Barrel Tip | 1.3211 | 0 | 10.3 |
| 4 | GMVLS Outer Corner | 12.6606 | 2.2 | 15.8 |
| 5 | Slamming @ 3/20 $L_{PP}$ | 3 | 0 | 0.6666 |
| 6 | Deck Wetness @ 1/10 $L_{PP}$ | 2 | 5.047 | 10.736 |
| 7 | Propeller Emergence | 18.935 | 3.25 | 2.8 |
| 8 | Sonar Dome Emergence | 3.5963 | 0 | 0.675 |

For the analysis described herein, the operating speeds are assumed to be 15 kn and 25 kn. Short-crested seas are considered. Calculations are made for eight locations onboard each ship (TABLE 3). The angles of wave encounter are $0^0$ (head seas), $45^0$ (bow seas) and $90^0$ (beam seas). These three headings have been selected as the worst cases out of the five headings to keep the number of plots to a minimum. The two additional headings refer to $135^o$ (stern waves) and $180^o$ (purely following waves). The body plans are derived as described by Petropoulos (2012) and fed to the code. For the purposes of the study, the appendages that affect roll response (skeg, non-retractable fins, rudders and bilge keels) are fed to the code. HULL A and HULL C are described by 25 stations, while HULL B is defined by 23 stations.

### Application of Seakeeping Criteria

The criteria are taken from NATO STANAG 4154 (2000) and concern the four aforementioned operations. Human Performance Degradation Criteria such as Motion Induced Interruptions as well as wind speed (for NAO operations) are omitted. Roll criterion used for NAO mission is the generic one, described in STANAG 4154. The decision to study simultaneously criteria referring to four missions arises from the fact that a naval ship is a multitasking platform. Thus, it is more realistic to use “multi-mission criteria sets” instead of single-mission criteria (Smith and Thomas, 1989), as depicted in TABLE 1 for the four missions under consideration. In case a response is used as criterion in more than one missions, only the stricter is taken under consideration. For instance, both TAP and NAO missions include roll RMS value as a criterion. But the RMS value for a NAO operation has a lower value than that of a TAP mission. Thus, the limiting criterion is considered to be the stricter one (Roll RMS value for NAO operations).

## A NEW METHOD TO ASSESS SEAKEEPING OPERABILITY

Following the discussion in the proceeding sections, the seakeeping operability of a naval vessel is directly related to a mission profile that actually constitutes its overall mission or at least the major part of it. The currently available methods either evaluate this property for a given sea condition (polar diagrams) or evaluate the upper limiting values of one or more responses for which the vessel is operable, disregarding the probability of encountering sea conditions for which the criteria are violated. Even the overall operability index derived by repetitive implementation of the polar diagrams for the long list of the sea conditions that the vessel may encounter during a year or through life is based on the statistics of the waves in one or more sea areas, without taking into account the mission profile and the associated speed and heading profiles for the specific naval ship.

In the present study, a different approach is used, based on the method recommended by Andrew, Loader and Penn (1984) in its simplified version as described by Lloyd (1989). The Operability Index for each ship sailing at a chosen area location, speed and angle of encounter over a year is graphically presented. The Modal Period $T_P$, and the Significant Wave Height $H_S$ are the abscissa and the ordinate of the plot, respectively. The wave probability of occurrence, taken from the WEAO Atlas is inserted and criteria of the four missions are plotted. The shaded area under the stricter criterion curve specifies the operable area for the ship at the specific pair of speed and heading angle. The operability index is the ratio of the shaded area to the area where there is a wave probability of occurrence. The probability of occurrence of each combination of $H_S$ and $T_P$ can be directly taken into account in whole or partly (if the respective parallelogram is crossed) as weighting in the evaluation of the operability index. Both the overall operability for all set criteria as well as the respective one for any single criterion or combination of criteria can be evaluated using the same plot.

In order to calculate the final operability of the vessel in the specific area, the course of the vessel to its mission in Cartesian Coordinates is combined with the directional wave statistics in the area to derive the probability of encountering specific headings. Then at each heading for which a plot like the one in Figure 6 is built, a weighting factor corresponding to the probability of encountering that heading is derived. The weighting factors are derived on the basis of TABLES 4 and 5. The former table presents the course of the vessel in the selected sea areas, while the latter one provides the probability of encountering waves with heading 0°, 45° and 90° in these areas.

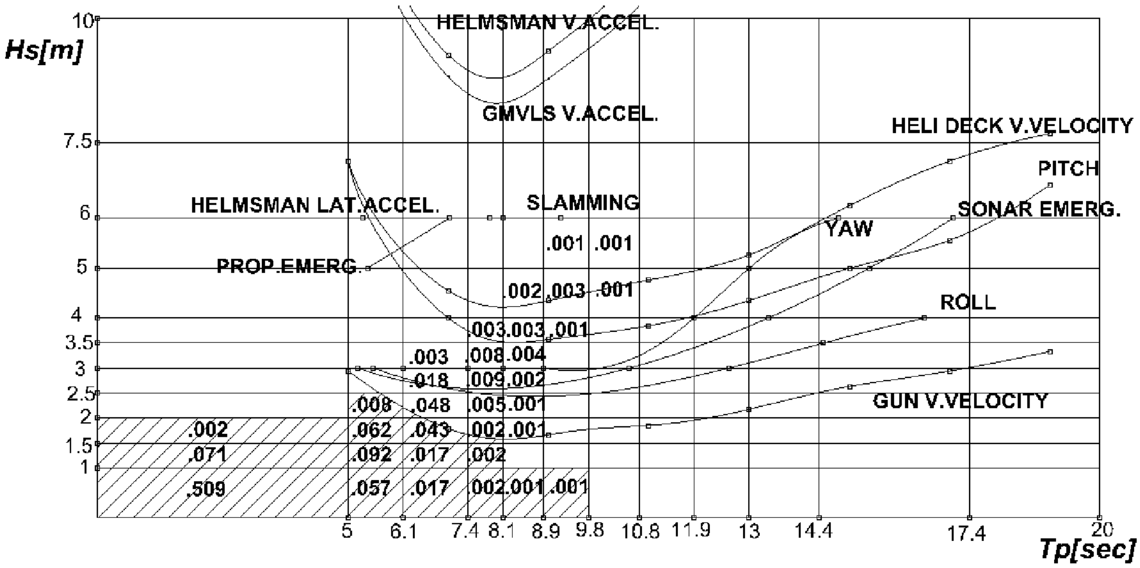


**FIGURE 6.** Operability calculation at a specific ship speed and wave heading and is based on the wave statistics of a specific area.. All criteria are plotted on a Cartesian coordinate system. Ship responses are calculated for a specific heading to derive the limiting ($T_P$, $H_S$) pairs. The shaded area represents the operability index for the specific area, ship, speed and heading.

**TABLE 4.** Ship's Course definition.

| Area | Ship Course (⁰) Relative to North |
|---|---|
| 1 (35N,22E) | 45 |
| 2 (36N,21E) | 90 |
| 3 (36N,27E) | 135 |
| 4 (38N,25.5E) | 0 |

**TABLE 5.** Wave Probability of Occurrence/ Directionality.

| Area | Course ($^0$) | Wave Probability of Occurrence/ Directionality ($^0$) | | |
|---|---|---|---|---|
| | | 0 | 45 | 90 |
| 1 | 45 | $0.1519/30^0 \div 60^0$ | $0.0835/345^0 \div 15^0$ | $0.3854/300^0 \div 330^0$ |
| 2 | 90 | $0.1013/75^0 \div 105^0$ | $0.0355/30^0 \div 60^0$ | $0.0578/345^0 \div 15^0$ |
| 3 | 135 | $0.0284/120^0 \div 150^0$ | $0.0396/165^0 \div 195^0$ | $0.0588/210^0 \div 240^0$ |
| 4 | 0 | $0{,}541/345^0 \div 15^0$ | $0.1074/300^0 \div 330^0$ | $0.0294/255^0 \div 285^0$ |

Finally, the operability indices for every speed, area and course are as follows (TABLE 6).

The overall operability performance assessment is calculated as the sum of the operability indices in all speeds, areas and courses. For simplicity reasons we may consider all ship speeds and areas as equally probable, otherwise we would have to make an assumption about their probabilities, thus we should insert weighting factors for each probability.

## DISCUSSION AND CONCLUSIONS

In this paper a different approach for assessing the operability of three naval ships is briefly described. The method makes use of Cartesian Coordinates, in which a mission criteria set for four missions is graphically represented. The curves are drawn for each vessel, traveling in four areas, at two speeds and three angles of wave encounter (five angles are needed to take into account the following seas as well). These plots have the advantage of giving information about the seakeeping operability performance in all probable waves encountered in that area. The use of mission criteria sets gives the opportunity to choose which area and which ship is more suitable for each mission or combination of missions. In that way mission performance can be optimized. In addition, if consequential locations are selected, plotted and the results combined, it is possible to optimize ship's route, thus saving time and budget. Moreover, ship owners or Navy can compare different designs and arrive at safe conclusions about what vessel suits best their needs.

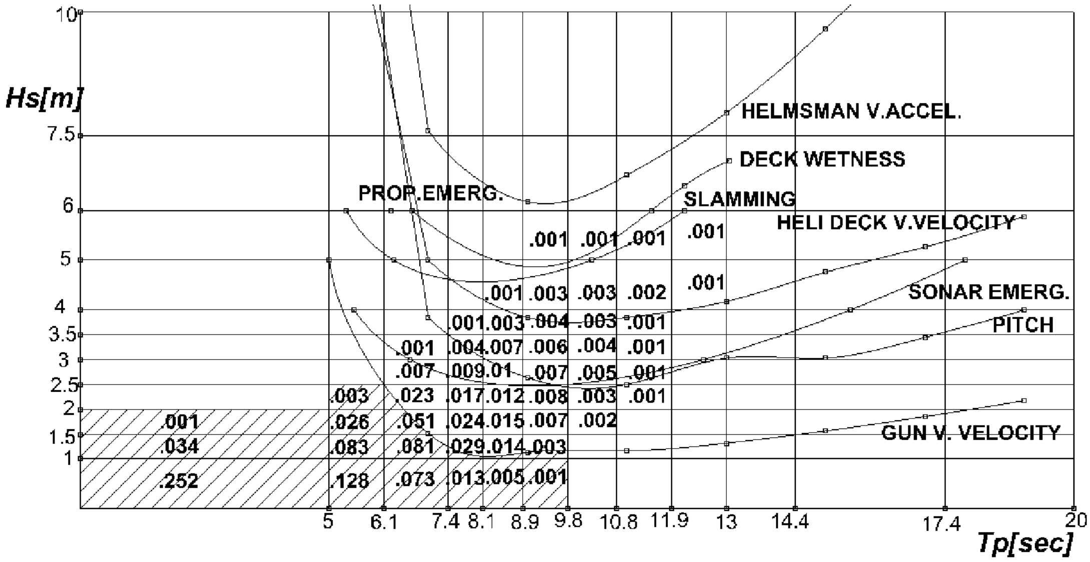


**FIGURE 7.** Altered 5415M plot for Area 1, at 15 kn in Head Seas. Criterion for gun barrel tip vertical velocity is the stricter of all.

**TABLE 6.** Final Operability Indices.

| Final Operability Indices | | | | |
|---|---|---|---|---|
| **Area 1 35 N, 22 E** | | | | |
| **Speed** | **Course ($^0$)** | **VESSEL A** | **VESSEL B** | **VESSEL C** |
| 15 | 45 | 80.72% | 75.42% | 70.04% |
| 25 | 45 | 78.91% | 76.45% | 70.94% |
| **Area 2 36 N, 21 E** | | | | |
| **Speed** | **Course ($^0$)** | **VESSEL A** | **VESSEL B** | **VESSEL C** |
| 15 | 90 | 82.30% | 77.78% | 73,67% |
| 25 | 90 | 81.30% | 79.18% | 74.17% |
| **Area 3 36 N, 27 E** | | | | |
| **Speed** | **Course ($^0$)** | **VESSEL A** | **VESSEL B** | **VESSEL C** |
| 15 | 135 | 86.34% | 81.79% | 77.86% |
| 25 | 135 | 85.43% | 83.11% | 78.25% |
| **Area 4 38 N, 25.5 E** | | | | |
| **Speed** | **Course ($^0$)** | **VESSEL A** | **VESSEL B** | **VESSEL C** |
| 15 | 0 | 88.53% | 86.11% | 83.99% |
| 25 | 0 | 89.54% | 89.05% | 84.97% |

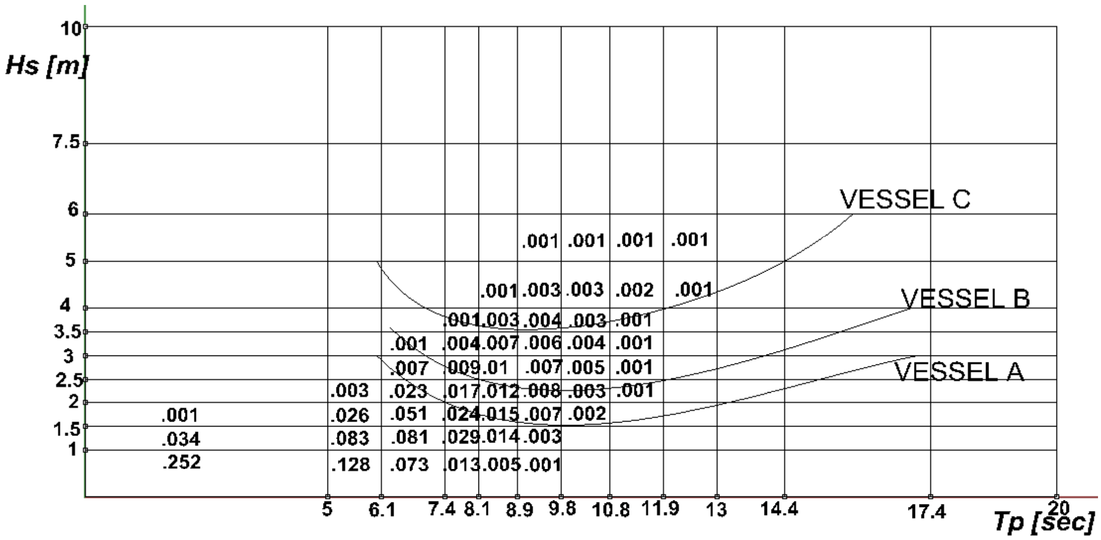


**FIGURE 8.** Sonar Emergence Criterion comparison for Area 1, at 25 kn in Head Seas. VESSEL C has a keel mounted sonar. The other two vessels have hull mounted sonars.

Following the results provided in graphical form, it is revealed that the gun barrel tip vertical velocity is the most limiting criterion (Figure 7). That was anticipated because the gun's location is close to the bow and thus exposed to large responses. On the other hand, keel mounted sonars suffer much less from sonar emergence than the hull mounted ones (Figure 8). Thus the designing trend to place keel mounted sonars in ships of that size is proved to be correct.

HULL A has the highest operability indices in every case. This may be due to:

1. The fact that the exact location of gun barrel tip wasn't known, thus an assumption had to be made. This is very important because the related criterion (gun barrel tip vertical velocity) is the stricter in every case examined.
2. The fact that this hull has an unconventional, wave piercing bow that moves through and not above waves.

It must be emphasized that all operability performance assessment methods use a large amount of data and require a high degree of automation, especially in the plotting process. The method described is more convenient in case we are interested in a few missions in a specific area. If we intend to investigate the performance for a long list of missions, at many speeds, sea areas and courses the results may give a more precise insight, but in that case the amount of data would be of considerable amount. Thus, the development of a code able to use all information in an automated way and plot the diagrams is of crucial importance to take full advance of the method.

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