UDC 629.5.015/017

Hamid ZERAATGAR[1],
Ali Bakhshandeh ROSTAMI[2]

An Investigation on Ship Operability versus Equipment Operability in Irregular Waves

Professional paper

A ship may have a certain function for which a set of appropriate equipment must perform their right functionalities. A ship is a total system composed of several subsystems. From a particular point of view, a naval ship as a total system may be divided into two subsystems such as the arms subsystem (guns, missiles, rockets and torpedoes) and the ship subsystem (includes everything except arms). The main goal of this study is to find out which subsystem of a ship fails to perform its functionality in harsh conditions of sea waves. For this purpose, a linear mathematical model for ship motions and dynamic behaviour such as accelerations, deck wetness, propeller emergence and so on is prepared. For the arms dynamics on the deck of the ship, a model based on motion of the ship as a solid object is considered. The criteria of the operability of the ship subsystem and the arms subsystem are collected from references and rearranged. A computer program is developed based on the mathematical model and the seakeeping criteria in irregular waves. A case study has been done for an existing frigate with a gun and a particular type of torpedo. Comparison of the range of operability of the arms subsystem and the ship subsystem shows that the gun has less operability than the ship.

Keywords: *operability, seakeeping, criteria, irregular waves, ship motions*

Istraživanje radne sposobnosti broda u odnosu na radnu sposobnost opreme pri gibanju na nepravilnim valovima

Stručni članak

Brod može imati određenu funkciju i za njeno ispunjavanje nužno je da određena skupina opreme mora izvodit svoje ispravne zadatke. Brod je totalan sustav koji je sastavljen iz više podsustava. Gledano s određenog stanovišta, ratni brod kao totalni sustav može se podijeliti u dva podsustava, a to su podsustav naoružanje (topovi, projektili, rakete i torpeda) i podsustav brod (tu je sve uključeno osim naoružanja). Glavni cilj ovog rada je da se ustanovi, koji će od brodskih podsustava zakazati u izvršavanju svojih zadataka pri ekstremnim uvjetima plovidbe na morskim valovima. U tu je svrhu pripremljen linearni model za gibanje broda na valovima i za određivanje raznih dinamičkih značajki kao što su to ubrzanja, zalijevanje palube, zakazivanje rada brodskog vijka i sl. Za potrebe analize dinamičkog ponašanja naoružanja na palubi broda razmatran je model koji se zasniva na gibanju broda kao krutog tijela. Kriteriji o učinkovitosti podsustava brod i podsustava naoružanje sakupljeni su iz literature i prilagođeni ovom problemu. Razvijen je program za elektroničko računalo koji se zasniva na matematičkom modelu i na kriterijima pomorstvenosti broda na nepravilnim valovima. Načinjen je praktični primjer za postojeću fregatu s topom i posebnim tipom torpeda. Usporedba razine učinkovitosti podsustava naoružanje i podsustava brod pokazuje da je učinkovitost topa manja u odnosu na onu od broda.

Ključne riječi: *učinkovitost, pomorstvenost broda, kriteriji, nepravilni valovi, gibanje broda*

Authors' Addresses (Adrese autora):
[1] Assistant Professor, *Amirkabir University of Technology*, Tehran, Iran
Email: hamidz@aut.ac.ir
Tel: +9821 64543110, +98 912 3353894
Fax: +9821 66412495
[2] M.Sc. in naval architecture, *Amirkabir University of Technology*, Tehran, Iran

Received (Primljeno): 2011-04-15
Accepted (Prihvaćeno): 2011-07-15
Open for discussion (Otvoreno za raspravu): 2013-03-31

Nomenclature

- ζ = wave amplitude
- k = wave number
- μ = angle of encounter
- ω_e = encounter frequency
- $\bar{\eta}_i$ = amplitude of motion of ship centre of gravity in six degrees
- δ = phase of motion of ship centre of gravity
- ε = phase of motion of points on ship
- ε_R = phase of relative motion
- $\bar{E}_i$ = amplitude of motion in points on ship
- $\bar{\dot{E}}_i$ = amplitude of velocity in points on ship
- $\bar{\ddot{E}}_i$ = amplitude of acceleration in points on ship
- $\bar{E}_R$ = amplitude of relative motion in points on ship
- $\bar{\dot{E}}_R$ = amplitude of relative velocity in points on ship
- Ω = angular motion in centre of gravity
- $\dot{\eta}$ = velocity of ship centre of gravity
- $\ddot{\eta}$ = acceleration of ship centre of gravity
- r = distance from centre of gravity to each point

1 Introduction

The main performance of a naval ship is to battle in the sea environment including the rough seas. A ship is a total system composed of several subsystems designed to perform some tasks and functions. From a particular point of view, a naval ship as a total system may be divided into two subsystems such as the arms subsystem (guns, missiles and torpedoes) and the ship subsystem (includes everything except arms).

When a naval ship is navigating in rough seas and using its arms to battle the enemy in the sea waves, one may expect that the arms subsystem and the ship subsystem provide their performance characteristics simultaneously. Certainly, it is not possible for these two subsystems to work properly in all sea wave conditions. When the wave height is rising, one of these systems would fail. The question is, "Which one fails earlier than the other?" Is it the ship subsystem or the arms subsystem?

St. Denis [1] has suggested an appropriate general measure for assessing ship's operational performance in a seaway, which he calls environmental operability. Aertssen [2] proposes different seakeeping criteria to measure the overall performance of different type of commercial vessels. Stark [3], Mandel [4] and Allen [5] propose seakeeping criteria for small high speed craft, Olson [6] and Comstock [7] propose seakeeping criteria for a naval mono-hull ship. The NATO defines standard criteria for operations of arms onboard naval vessels [8].

The intention of this paper is to show which subsystem is more sensitive to wave height and loses its operability when it encounters the sea waves. To do so, a linear mathematical model for the ship motions and dynamic behaviour such as accelerations, deck wetness, propeller emergence and so on has been considered. For the arms dynamics on the deck of the ship, a model based on the motion of the ship as a solid object is presented. The criteria of operability of the ship and the arms subsystems have been collected from literature. A computer program has been developed based on the mathematical model along with the seakeeping criteria in irregular waves. The program has been validated by comparison against the published results from other sources. Furthermore, a case study has been done for an existing frigate with several types of guns and a type of torpedo on its deck. The results are presented, discussed and some important conclusions are derived.

2 The mathematical model and the computer program

2.1 Calculation of ship motion in regular waves

If a ship is hit by the sinusoidal wave:

$$\zeta = \zeta_a \cos\left(kx\cos\mu + ky\sin\mu - \omega_e t\right) \tag{1}$$

then the ship moves in six degrees of freedom as follows:

$$\eta_i = \bar{\eta}_i \cos(\omega_e t + \delta_i) \;\; i = 1,...,6 \tag{2}$$

The ship centre of gravity assumes the following velocities and accelerations:

$$\dot{\eta}_i = -\omega_e \bar{\eta}_i \sin(\omega_e t + \delta_i) \tag{3}$$
$$\ddot{\eta}_i = -\omega_e^2 \bar{\eta}_i \cos(\omega_e t + \delta_i) \;\; i = 1,...,6$$

The motion of a point on the ship could be derived as:

$$\vec{E} = \vec{\eta} + \vec{\Omega} \times \vec{r}$$

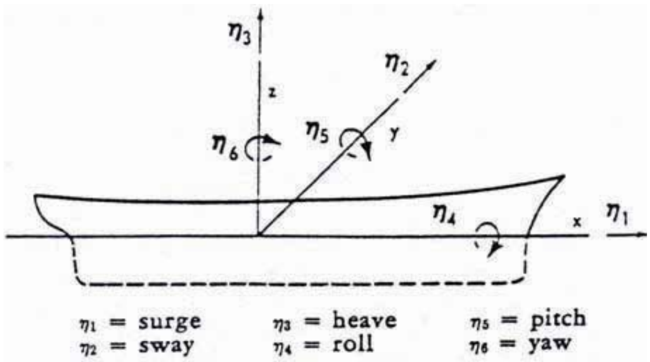


Figure 1 **Definition of ship motions and their positive directions**
Slika 1 **Definicija gibanja broda**

where:

$$\vec{\eta} = \eta_1 \hat{i} + \eta_2 \hat{j} + \eta_3 \hat{k}$$
$$\vec{\Omega} = \eta_4 \hat{i} + \eta_5 \hat{j} + \eta_6 \hat{k}$$
$$\vec{r} = x.\hat{i} + y.\hat{j} + z.\hat{k}$$
$$\vec{E} = E_1 \hat{i} + E_2 \hat{j} + E_3 \hat{k}.$$

The three linear motions of a point on a ship, taking into account Figure 1, may be written as:

$$E_1 = \eta_1 - y.\eta_6 + z.\eta_5 = \bar{E}_1.\cos(\omega_e t + \varepsilon_1) \tag{4}$$

$$E_2 = \eta_2 - z.\eta_4 + x.\eta_6 = \bar{E}_2.\cos(\omega_e t + \varepsilon_2) \tag{5}$$

$$E_3 = \eta_3 - x.\eta_5 + y.\eta_4 = \bar{E}_3.\cos(\omega_e t + \varepsilon_3) \tag{6}$$

For the velocities and accelerations of a point on a ship, one may further write:

$$\dot{E}_1 = -\omega_e \bar{E}_1.\sin(\omega_e t + \varepsilon_1) \tag{7}$$

$$\dot{E}_2 = -\omega_e \bar{E}_2.\sin(\omega_e t + \varepsilon_2) \tag{8}$$

$$\dot{E}_3 = -\omega_e \bar{E}_3.\sin(\omega_e t + \varepsilon_3) \tag{9}$$

$$\ddot{E}_1 = -\omega_e^2 \bar{E}_1.\cos(\omega_e t + \varepsilon_1) \tag{10}$$

$$\ddot{E}_2 = -\omega_e^2 \bar{E}_2.\cos(\omega_e t + \varepsilon_2) \tag{11}$$

$$\ddot{E}_3 = -\omega_e^2 \bar{E}_3.\cos(\omega_e t + \varepsilon_3) \tag{12}$$

The vertical relative motion and relative velocity of a point on the ship i.e. $P(x, y, z)$ and the wave profile would then be as follows:

$$E_{3R} = \eta_3 - x.\eta_5 + y.\eta_4 - \zeta = \bar{E}_{3R}.\cos(\omega_e t + \varepsilon_{3R}) \tag{13}$$

$$\dot{E}_{3R} = -\omega_e.\bar{E}_{3R}.\sin(\omega_e t + \varepsilon_{3R}) \tag{14}$$

2.2 Calculation of dynamic phenomena in irregular waves

An irregular wave in time domain can be defined in frequency domain by its spectrum. Having assumed a normal probability density function for the wave profile and a Rayleigh density function for wave maxima (or minima), any phenomena induced by ship motions in irregular waves have the probability density functions as follows:

Normal density function:

$$p(\eta) = \frac{1}{\sqrt{2\pi E_\eta}} \exp\left[-\frac{\eta^2}{2E_\eta}\right] \tag{15}$$

Rayleigh density function:

$$p(\overline{\eta}) = \frac{\overline{\eta}}{E_\eta} \exp\left(\frac{-\overline{\eta}^2}{2E_\eta}\right) \tag{16}$$

where:

$\overline{\eta}$: Amplitude of the maxima or minima

E_η: Energy (standard deviation) of the ship irregular motion (or phenomenon)

$p(\eta)$: Probability density function of the ship irregular motion (or phenomenon)

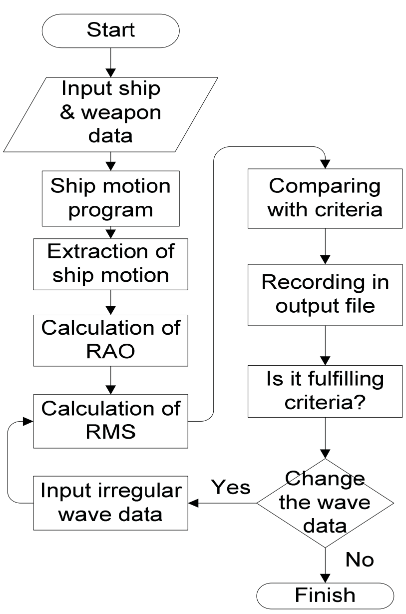
$p(\overline{\eta})$: Probability density function of the amplitude of the ship's irregular motion (or phenomenon)

By the above probability density function, it may be concluded that the mean ship motion amplitude, significant amplitude, and mean one tenth of the highest amplitudes are $\overline{\eta}_{mean} = 1.25E_\eta^{1/2}$, $\eta_{1/3} = 2.0E_\eta^{1/2}$ and $\eta_{1/10} = 2.55E_\eta^{1/2}$ respectively.

2.3 The computer program

A computer program, called SHIPDYNA, has been developed on the basis of linear motion. The SHIPDYNA takes the ship specifications as well as offset tables, arms specifications and their position on a ship deck as input. The type of wave spectrum and the wave severity, ship speed, and relative wave directions are the other inputs. Then, SHIPDYNA runs a standard ship dynamic program, called STATEK, and takes the motion amplitude and the phase leg. In the next stage, it calculates all phenomena caused by ship motions such as displacements, velocities, accelerations, slamming, deck wetness, sonar emergences, propeller emergences among others. Finally, it checks whether any dynamic phenomenon has exceeded the criteria or not. Figure 2 indicates flowchart of the SHIPDYNA.

Figure 2 **The SHIPDYNA computer program flowchart**
Slika 2 **Dijagram toka računalnog programa SHIPDYNA**



3 The case study

3.1 The input data

A frigate with the main particulars as in Table 1 is used for the case study. Table 2 shows the arms and their position on the decks of the ship (see also Figure 2). Table 3 and Table 4 show the range of the seakeeping criteria for the ship subsystem [9] and the arms subsystem respectively [10],[11].

Table 1 **Main particulars of the frigate**
Tablica 1 **Glavne značajke fregate**

Parameter	Magnitude	**Dimensions**
Length Overall	94.49	**meters**
Length Between Perpendiculars	88.39	**meters**
Maximum Breadth	11.10	**meters**
Height	7.62	**meters**
Max. Displacement	1550	**tons**
Draught	**3.5**	**meters**

Table 2 **The type of guns and their position onboard the frigate**
Tablica 2 **Tip topova i njihov razmještaj na fregati**

Arm Name	Gun Position on frigate		
	x(from AP)	y(from CL)	z(above BL)
Gun MK 75/62 OTO Melara	71.3	0	7.62
Gun MK-15 /CIWS	51.42	0	12.18
Gun OTO Melara 40/70 Bofors	21.76	0	9.96
Torpedo MK-32	25.15	4.5	9.96

Table 3 **The seakeeping criteria for the ship subsystem**
Tablica 3 **Kriteriji pomorstvenosti za podsustav brod**

Phenomena	Criteria	**Magnitude**
Slamming	Number per Hour	**20**
Deck Wetness	Number per Hour	**100**
Sonar Emergence	**Number per Hour**	**24**

Table 4 **The seakeeping criteria for the arms subsystem**
Tablica 4 **Kriteriji pomorstvenosti za podsustav naoružanje**

Arms	Criteria	**Magnitude**
Gun	Vertical Velocity RMS (m/s)	**1.**
Torpedo	Roll RMS (deg.)	**3.8**
	Pitch RMS (deg.)	**3.8**

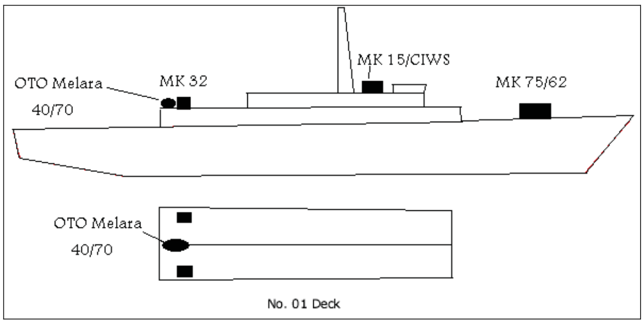


Figure 3 **Arrangement of arms onboard the frigate**
Slika 3 **Razmještaj naoružanja na palubi fregate**

The said frigate navigates in long-crested irregular waves of the ITTC two-parameter spectrum type at a speed of 28 knots and different wave heading angles. The results of calculation by SHIPDYNA are shown in Tables 4 and 5 and plotted in Figure 4. The pairs of significant wave height of 1 meter to 6 meters with wave characteristic period of 7 seconds are the irregular wave parameters.

3.2 Calculation results for the arms subsystem and the ship subsystem

The sign "√" means fulfilling the criteria, while the sign "×" means exceeding the relevant criteria. Tables 5 and 6 show the gun, torpedo and ship subsystem performances in irregular waves. In case of a heading angle of 120 degrees, the ship is operable up to the wave height of 4 meters, while the gun operability is limited to the wave height of 2 meters. For the heading angles of 135, 150 and 180 degrees the gun fails to work for the wave height larger than 1 meter, while the ship is operable up to the wave height of 3 meters. Except for the heading angle of 180 degrees, it is somehow impossible to keep exactly 180 degrees, the torpedo is not operable for the wave height larger than 1 meter.

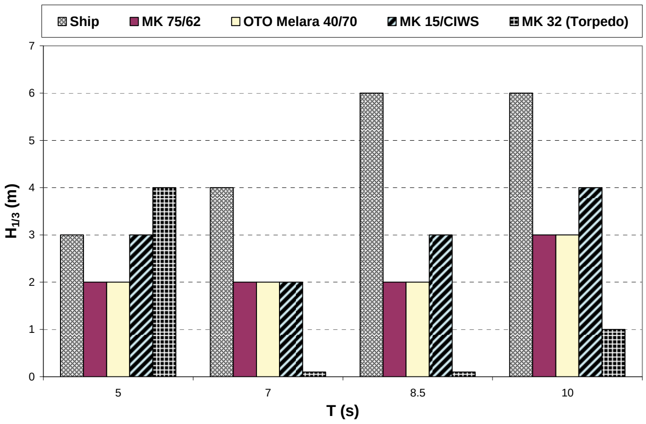


Figure 4 **Operability range for the ship and the arms subsystems in irregular waves**
Slika 4 **Razina učinkovitosti podsustava brod i podsustava naoružanje pri gibanju na nepravilnim valovima**

Table 5 **Loss of effectiveness of gun MK 75/62 versus ship in irregular waves**
Tablica 5 **Gubitak učinkovitosti topa MK 75/62 u odnosu na brod pri gibanju na nepravilnim valovima**

Heading		120		135		150		180	
T1	$h_{1/3}$	ship	gun	ship	gun	ship	gun	ship	gun
5	1	√	√	√	√	√	√	√	√
5	2	√	√	√	√	√	√	√	√
5	3	√	×	√	√	√	√	√	√
5	4	×	×	√	×	√	√	√	√
5	5	×	×	×	×	√	×	√	√
5	6	×	×	×	×	×	×	×	√

Table 6 **Loss of effectiveness of Torpedo MK 32 versus ship in irregular waves**
Tablica 6 **Gubitak učinkovitosti torpeda MK 32 u odnosu na brod pri gibanju na nepravilnim valovima**

Heading		120		135		150		180	
T1	$h_{1/3}$	ship	gun	ship	gun	ship	gun	ship	gun
5	1	√	√	√	√	√	√	√	√
5	2	√	√	√	√	√	√	√	√
5	3	√	×	√	√	√	√	√	√
5	4	×	×	√	×	√	√	√	√
5	5	×	×	×	×	√	√	√	√
5	6	×	×	×	×	×	×	×	√

4 Discussion

The behaviour of the subsystems would form the behaviour of the total system. From the dynamic point of view in the rough seas, when one of these system loses its effectiveness, then the total system, let's say the naval ship, loses its effectiveness, too.

Tables 5 and Figure 4 show the behaviour of the gun and the ship at wave period of 7 seconds. For all practical heading angles, the gun loses its performance earlier than the ship.

Table 6 and Figure 4 show the ship and the torpedo behaviour in the rough seas. In head sea condition, the ship mostly loses its performance much earlier than the torpedo. However, as soon as a small deviation from head sea condition occurs, which is inevitable in practical conditions, the torpedo sharply losses its effectiveness. In other heading angles, the torpedo loses its performance much earlier than the ship. It is interesting that, for instance, at wave period of 7 seconds and wave heading of 120 degrees, the torpedo should not be launched even at the significant wave height of 1 meter, while the ship is capable to operate properly at the significant wave height of 4 meters.

The fire control system and the arms system together define the dynamic criteria of the gun system. It is clear that if the range of operability of a naval ship is to be extended in rough sea conditions, the gun and the torpedo subsystems need to be optimized rather than the ship subsystem.

The authors as naval architects, without any knowledge of the arms system, emphasize that the torpedo needs much more development to reach the same operability as that of the ship.

5 Conclusions

This is a study of the range of operability of the arms subsystem and the ship subsystem making together a naval ship as a total system. Based on the calculations of the range of operability of the arms subsystem compared with the range of operability of the ship subsystem the following conclusions are drawn:

1. The ship subsystem has wider range of operability than the gun subsystem. To improve the operability of a naval ship it is recommended to improve the gun subsystem rather than the ship subsystem.
2. The ship subsystem has much wider range of operability than the torpedo subsystem. It is, therefore, highly recommended to improve the torpedo subsystem in order to improve the naval ship operability.

6 References

[1] ST. DENIS, M.: "On the environmental operability of seagoing systems", SNAME T&R Bulletin, No. 1-32, (1976).

[2] AERTSSEN G., van SLUIJS, M.F.: "Service performance and seakeeping trials on a large container ship ", Transactions RINA, London, Vol. 114, (1972).

[3] STARK, D.A.: "Hydrofoil control and dynamics criteria (Technical Substantiation)", A Boeing Marine System Report BMS D321-51313-2, Vol. III (1977).

[4] MANDEL, P.: "Seagoing box scores and seakeeping criteria for monohull, SWATH, planning hydrofoil, surface effect ships and air cushion vehicles", DTRC Report SPD-79/1, (1979).

[5] ALLEN, R.G., JONES, R.R.: "Structural design-limit pressures on high performance marine vehicles", AIAA and SNAME Advanced Marine Vehicles Conference, (1980).

[6] OLSON, S.R.: "A seakeeping evaluation of four naval monohulls and a 3250 ton SWATH", Center for Naval Analysis Memorandum 77-0640, (1977).

[7] COMSTOCK, E.N., BALES, S.L., KEAN, R.G.: "Sea keeping in ship Operations", SNAME STAR Symposium, San Diego, (1980).

[8] EEFSEN, T. et al.: "Development of frigate designs with good seakeeping characteristics", 9th Symposium on Practical Design of Ships and Other Floating Structures, Luebeck-Travemuende, Germany © Schiffbautechnische Gesellschaft e.V, (2004).

[9] CROSSLAND, P.: "The effect of roll-stabilization controllers on warship operational performance", Control Engineering Practice 11, p.423–431, (2003).

[10] LEWIS E, V.: "Motion in waves and controllability", Society of Naval Architectures and Marine Engineers, Principles of Naval Architecture, second revision, Vol. III, (1989).

[11] …: "Common procedures for seakeeping in the ship design process", NATO Standardization Agreement, STANAG 4154 (edition 3), Document AC/141 (NG6)D/13. NATO Unclassified, (1998).