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Evaluation of Naval Submarine Seakeeping Criteria

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Abstract This paper proposes some new criteria for seakeeping performance of naval submarine seaworthiness behavior. For ships, there are twelve criteria for seaway performance analysis. The scope of mission, systems and device's restrictions, hull shape, hydrostatics and stability properties of ships and submarines are essentially different. In snorkel condition, only snorkel mast is above the water surface. In submerged condition, the submarine is far from the sea surface and ocean waves so that seakeeping is not important and is not discussed. Seakeeping criteria for several kinds of ships such as merchant and Naval ship, single hull and multi-hull ships with different operations, are separately defined but there had not been any obvious criteria for submarines specially for Naval submarines. This paper, by a restatement and review on twelve criteria for ships, proposes some new criteria for naval submarines. These criteria are separately presented for surface condition and snorkel condition because the missions and operational systems, propulsion system, stability condition, draft and wave moments in these two conditions are different. Thus, there are two separate criteria for two conditions. Methodology in this paper is based upon the experiences of authors and a group of specialists in submarine design, and test in the sea, a knowledge on the submarine devices and systems. Computer modeling of seakeeping is performed in Paramarine and Flow Vision software.

Keywords Submarine seakeeping, seaway, motion, submerge, snorkel, RAO, SOE, criteria.

Introduction

The first step in the assessment of seakeeping performance is usually to determine the wave spectrum for a seaway [1-3]. The emphasis is often on wave heights rather than wave periods, and information on directionality and wave spectrum forms is rare [4-6]. In seakeeping analysis, until design of RAO (Response Amplitude Operation) diagrams, there is not any need for design criteria but for extraction of SOE (Seakeeping Operating Envelope) polar diagrams [7-8] and submarine seaworthiness abilities, there is an urgent need for some clear and technical criteria according to the submarine technical specifications. The characteristics of submarine systems are presented in literature [9-13]. Knowledge of these systems is urgent for seakeeping performance evaluation. A simplified method of presenting the seakeeping performance of specific design is to plot a polar diagram [15-16]. In SOE diagrams the restrictions of submarine operations or Operability Index (O.I) in several sea states are evaluated. The seakeeping performance of a ship can either be predicted using computer codes or measured in a seakeeping basin [17].

Performing all expected missions in rough seas can be accepted for a ship as an indication for a good seakeeping [18]. Ship motions at sea have always been a problem for the naval architect [8]. Whilst the introduction of ride controls has somewhat reduced the severity of motions in some cases, there has been considerable interest in the underlying effect of hull form on the ship motions [18]. Ships are partially submerged objects with six degrees of freedom for their motion (with constraints related to its interaction with water) [19]. Seakeeping properties and motion of ships and submarines are different in several aspects of views [20-23]. The shape and navigation mode of submarines are very different from ships, some origins of submarine hydrodynamic. Extensive discussions about hydrodynamic characteristics of the shape of submarine are discussed [24-34] and IHSS (Iranian Hydrodynamic Series of Submarine). Seakeeping performance index is a term used to assess the motion and dynamic effects for a given sea state, direction of heading angle and speed of transit [35]. Dynamic stability or capsizing of ships can also be investigated in detail as the cause–effect chain can be analyzed in a deterministic, repeatable wave train at different interaction positions [36]. Submarine can dive from the sea surface into the depth of sea in three conditions: surface, snorkel and submerge condition. In snorkel condition, the total volume of submarine is under the water surface but very near to the surface so that only snorkel mast is out of water (Fig.1). Snorkel mast causes suction of air for starting and operating of diesel engine and air compressor. Diesel engine causes batteries charging and air compressor can charge high pressure air capsules.

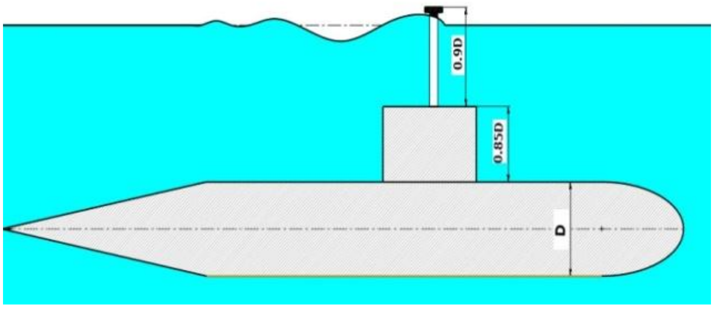
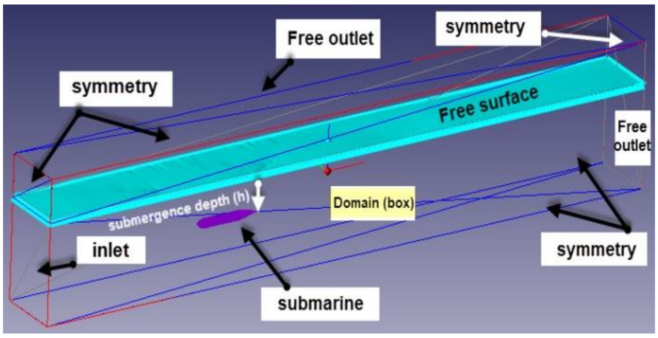


Figure 1: Snorkel depth in naval submarines

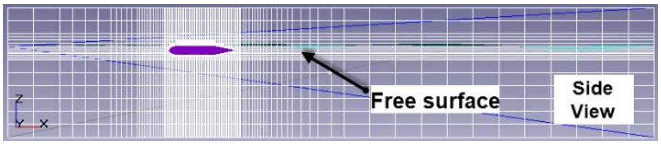
After a restricted time, batteries and capsules have been charged and diesel–generator and compressor are turned off and submarine is ready to dive and go to submerged condition. In submerged condition, submarine is fully submerged and is far from the sea surface and waves. In this situation, sea waves don't have any influence on the submarine motion so that seakeeping studies are ignored in submerged mode and are only evaluated for surface and snorkel condition. Static stability and GZ curve parameters in snorkel are very weak compared with the surface condition because water plane area is almost zero. Transverse and longitudinal metacentric height in snorkel mode is equal to each other and very smaller than the metacentric height in surface condition. Therefore, stability in snorkel condition is very weak and submarine is still under wave moment. It means more critical and sensible condition compared to surface condition because of minimum stability and strong wave heeling and pitching moments. Wave action in snorkel is less than surface waves because of more drafts and distance from the water surface, but it is considerable for snorkel stability condition. In this paper two conditions for seakeeping criteria are presented; surface and snorkel condition and each of them have three categories;

1. People
2. Mission systems
3.platform system (Lewis, 1989).

People category is related to human health and performance for doing their duties. It is the same for surface and snorkel condition. Mission system is related to the operational systems that are urgent for doing the mission such as sonar search, battery charging and snorkeling. It is different for surface and snorkel condition because of that each mission is different. Platform systems are related to the general system and devices that must be kept safe and intact in the submarine life period such as diesel, generator, electric motor, piping and installation. It is different in surface and snorkel because some systems are turned off in each condition. According to these differences, different criteria must be regarded. This paper, firstly, identifies the new proposed parameters that are based on authors' experiences on submarine design and data acquisition in sea trials. Other data are achieved from modeling in Paramarine and Flow Vision software (Fig.2). Hence some quantities are proposed for each parameter. Another part in this paper is removing some parameters from twelve parameters of ships that are not belonged to submarines and are special for ships. The final step is providing a table of seakeeping criteria special for submarines that could be the basis of extraction of submarine SOE diagrams.



(a)



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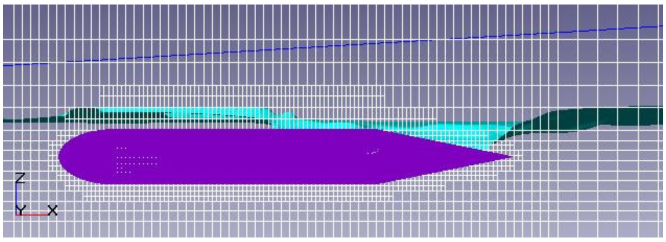

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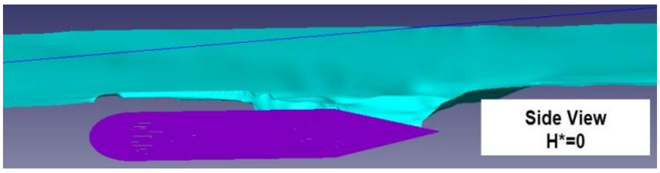

(d)

Figure 2: (a) Domain and structured grid (b) tiny cell around free surface (c)Very tiny cells near the wall for boundary layer modeling and keeping y+ about 30 (d) Half modeling because of axis-symmetry and free surface variations

Ship and submarine seakeeping behavior comparison

The performance of a hull forms, both in calm and rough water is a major concern for the naval architect. No single parameter can be used to define the seakeeping performance of a design. There are twelve parameters for ship seakeeping behavior according to table 1. (Lewis, 1989).

Table 1: Twelve seakeeping performance criteria for ships [8]

No.	Seaway performance criteria	Affected elements	Performance degradation
(a) Absolute Motion Amplitudes			
1.	Roll angle	People, Mission and Platform Systems	Personnel injury, reduced task proficiency and mission and hull system degradation
2.	Pitch angle		
3.	Vertical displacement of points on flight deck	{ People Mission Systems	Injury to personnel handling aircraft, inability to safely launch or recover aircraft
(b) Absolute Velocities and Accelerations			
4.	Vertical acceleration	People and Mission Systems	Personnel fatigue, reduced task proficiency and mission system degradation
5.	Lateral acceleration		
6.	Motion sickness incidence (MSI)	People	Reduced task proficiency
7.	Slam acceleration (vibratory, vertical)	People, Mission and Platform Systems	Personnel fatigue, injury, reduced task proficiency and mission and hull system degradation. Preclusion of towed sonar operation.
(c) Motions Relative to Sea			
8.	Frequency of slamming. (Simultaneus bow reimmersion & exceedance of a threshold vertical velocity)	{ Mission Systems Platform Systems	Hull whipping stresses and damage to sensors on the masts. Slamming damage to bottom forward hull structure
9.	Frequency of emergence of a sonar dome	Mission Systems	Reduced efficiency of sonar
10.	Frequency of deck wetness (submergence if the main deck forward)	{ People Mission Systems	Injury or drowning of personnel. Damage to deck-mounted equipment
11.	Probability of propeller emergence	Platform Systems	Damage to the main propulsion plant
(d) Motions relative to aircraft			
12.	Vertical velocity of aircraft relative to the flight deck	Mission Systems	Damage to aircraft landing gear and/or loss of aircraft

From table 1, some of these parameters are not related to submarine and must be omitted so as:

1-Vertical displacement of points on flight deck: It is according to criterion No.3 in table 1 and is omitted because the flight deck, there are not on a submarine.

2-Vertical velocity of aircraft relative to the flight deck: It is according to criterion No.12 in table 1 and is omitted because the flight deck, there is not on a submarine.

Frequency of deck wetness; according to criterion No.10 table 1 this parameter is also omitted because the submarine hull is cylindrical and completely watertight. Moreover, all devices on submarines hull are designed for sea water condition and in the depth of water. Thus deck wetness cannot cause any damage to submarine stability and devices. The shape with circular cross section such as a cylinder has constant stability parameters in all roll angles and also the range of stability in GZ curve for submarine is to 180 degrees. According to these conditions, deck wetness is not important for submarines and is omitted. Therefore, three criteria are removed from table 1, and other three criteria are added that are belonged to submarine:

1-Sonar acoustic deafness: Submarine in submerged and snorkel condition doesn't have radar detection and direct vision (maybe only periscope in snorkel depth). Several sonars are eyes of submarine that prevent damage to the fixed barriers and mobile objects. Criterion No.9 of table 1 is only concentrated on the emergence of the sonar dome, but this parameter is not sufficient and clear for submarine detection because in most conditions, sonar emergence doesn't occur, but sonar becomes deaf. Its reason is a high level of ambient noise because of sea waves and stiff motions of the bow. In high sea states, moving and breaking of wave produces some troublous noises. In this condition, submarine may clash to underwater hills and barriers and other submarines and ship. Submarine has several kinds of sonars such as active, passive, conformal, flank, back looking and towing sonar array. In bad sea conditions and high sea forces, submarine is in dangerous condition. For getting a safe condition, submarine must go into the depth of water so that ambient noise be suitable and all sonars be efficient. Main restriction in this seakeeping parameter is related to the situation of sonar and acoustic sensors. This criterion is important for both surface and snorkel condition, especially in snorkel depth that sonar must be applicable for detection. As shown in Fig.3, waves move near the sonar, and their effects can cause a reduction in sonar efficiency. There is an ideal or optimum sonar draft in calm water than the sonar efficiency is maximum. In operational sea state, there is a safe sonar navigation draft as shown in Fig.3. In this draft, sonar efficiency isn't ideal but submarine can navigate safely. In high sea state, there is an unsafe sonar navigation draft which sonar efficiency is minimum, and it is dangerous condition for navigation at near the surface. This condition is important for forward hydroplanes too. As shown in Fig.3, location B for sonar and hydroplanes is better than location A as regarding wave ambient noise. This parameter presents as percentage. This percentage is the ratio of the time that sonar is deaf and the total time (that is regarded 1 hour or 60 minutes).

$$P_1(\%) = \frac{t_1(\text{time that sonar is deaf})}{t_0(\text{total time} = 60 \text{ min})}$$

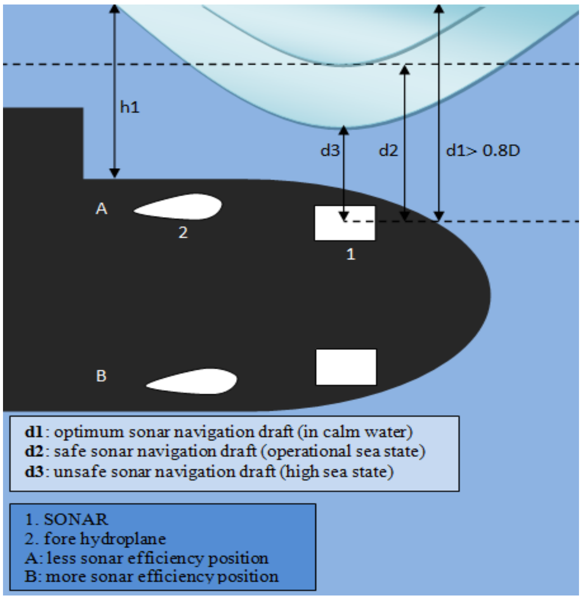

Figure 3: Ideal, safe and unsafe draft for sonar efficiency (and hydroplanes) in snorkel condition- location B as a advised position

2-Snorkel mast flooding: When a submarine is in snorkel depth, only snorkel mast is above the water surface for suction the atmosphere air (Fig.4). This mast has an automatic head valve. This head valve has a sensor that, if it be wetted, it will be closed immediately for preventing the water entrance to inside the submarine and preventing flooding and suffering damage in the diesel engine. The wetting of head valve is due to relative motion of sea wave and submarine as shown in Fig.4.

Defined sea state for submarine operations is very important in snorkel condition. In Fig.4, the safe wave amplitude h_2 is related to standard sea state for submarine and h_3 is related to high sea states that causes a steep fall in snorkeling. For this reason, the automatic head valve will be interval opened and closed. There are two important parameters in submarine naval architecture design: the height h_0 is the usual height of snorkel mast from pressure hull and h_1 is a usual draft. Quantities are shown on Fig.4. All these parameters should be regarded with together. This interval action of head valve causes quick fall in the inlet air flux. As in snorkel depth, the diesel engine is turned on and consuming the air inside the hull, if the head valve be closed for long time, it will cause a quick fall of inside pressure or vacuum condition inside the pressure hull. Vacuum condition is very dangerous for human and machineries such as audience and breathing problems for human and water leakage into the pressure hull (because of intense pressure difference) and closing and jamming of the bulkhead door. Then the time of continuous operation of head valve is very important. This criterion is important only for snorkel condition and is presented by percentage as so:

$$P_2(\%) = \frac{(t_0 - t_2)}{t_0} \times 100$$

t_2: the time that head valve is open (in minutes), t_0: the total time that is regarded 60 minutes.

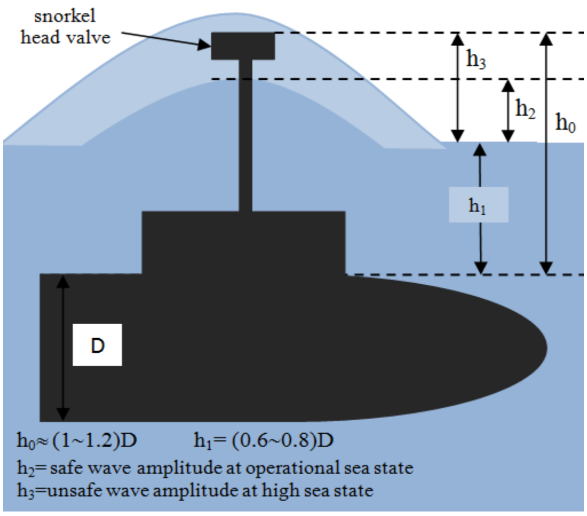

Figure 4: Main parameters in submarine architecture for improvement of snorkel mast flooding

Thus in this criterion, the wave height and sea force (sea state) is very important. Snorkel mast there is in ordinary diesel–electric submarine for air intake and charging the batteries but in submarines that are equipped with air independent propulsion (AIP) system such as nuclear propulsion, this criterion is not important because they don't have snorkel mast.

3-Battery performance disruption: Submarines have 200 to 400 battery cells dependent upon the voltage level. Duty of these batteries is providing electric energy for propulsion (electric motor) and hotel load (lighting, air conditioning, etc.) then their continuous operation is vital. Sealed batteries are not influenced by submarine motions but non-sealed batteries such as lead-acid batteries are influenced by the submarine motions. Vertical accelerations on batteries and amplitude of roll and pitch motion are very effective on battery efficiency. For example, acid inside the battery is important for battery exercise and acid spillage cause battery disruption. Acid spillage can cause producing toxic gases and pressure hull corrosion and other damages to submarines. Thus battery performance is significant in submarine seakeeping behavior. This criterion is important both in surface and snorkel condition. This criterion is presented by percentage. This percentage defines as:

$$P_3(\%) = \frac{(t_0 - t_3)}{t_0} \times 100$$

t_3: battery exercise in minutes. t_0: total time (60 minutes).

Battery is important in diesel-electric submarines and is not important for submarines that are equipped with AIP systems, and this criterion will be ignored. Thus after omitting three criteria (for ships) and adding three criteria (special for submarines), there will be twelve criteria for evaluation of submarine seakeeping behavior that is presented in table 2.

Table 2: Twelve seakeeping performance criteria for submarines

No.	Seaway performance criteria	Affected elements	Performance degradation
(a) Absolute Motion Amplitudes			
1. 2.	**Roll angle Pitch angle**	People, Mission and Platform Systems	Personnel injury, reduced task proficiency and mission and hull system degradation
(b) Absolute Velocities and Accelerations			
3. 4.	**Vertical acceleration Lateral acceleration**	People and Mission Systems	Personnel fatigue, reduced task proficiency and mission system degradation
5.	**Motion sickness incidence (MSI)**	People	Reduced task proficiency
6.	**Slam acceleration (vibratory, vertical)**	People, Mission and Platform Systems	Personnel fatigue, injury, reduced task proficiency and mission and hull system degradation. Preclusion of towed sonar operation.
(c) Motions Relative to Sea			
7.	**Frequency of slamming. (Simultaneus bow reimmersion & exceedance of a threshold vertical velocity)**	Mission Systems Platform Systems	Hull whipping stresses and damage to sensors on the masts. Slamming damage to bottom forward hull structure
8.	**Frequency of emergence of a sonar dome**	Mission Systems	Reduced efficiency of sonar
9.	**Sonar acoustic deafness**	Mission Systems	Reduced efficiency of sonar and detection abilities
10.	**Probability of propeller emergence**	Platform Systems	Damage to the main propulsion plant
11.	**Batteries performance disruption**	Mission Systems Platform Systems	Interruption in electric energy support, reduction in speed, acid spillage and damage to battery cell
12.	**Snorkel mast flooding**	People, Mission and Platform Systems	Vacuum and pressure fall, audience and breathing problems, disruption in snorkeling, damage to diesel engine and compressor, water leakage

Seakeeping performance values

The hydrodynamic design based on clear definitions of operability requirements, and mission criteria have made seakeeping and maneuvering oriented design decisions easier through a quantitative description of performance throughout the design process. After introduction of seakeeping parameters of submarines, the values of each parameter can be determined. These are important for identifying safe and unsafe operating envelope or the polar diagrams of SOE. These suggested quantities are presented for two conditions; surface and snorkel (table 3).

Table 3: Quantities of seakeeping performance criteria for submarines in surface & snorkel condition

No.	Seaway performance criteria	Surface condition	Snorkel condition
1	**Roll angle (degree)**	9.6	9.6
2	**Pitch angle (degree)**	1.5	2.5
3	**Vertical acceleration (g)**	0.25	0.2
4	**Lateral acceleration (g)**	0.1	0.1
5	**Motion sickness incidence (MSI) (% in 2 hours)**	20% in 2 hours	25% in 2 hours
6	**Slam acceleration (vibratory, vertical) (g)**	0.2	0.05
7	**Frequency of slamming (Simultaneous bow re-immersion & exceeding of a threshold vertical velocity) (%)**	3	0.5
8	**Frequency of emergence of a sonar dome**	60 in 1 hr	20 in 1 hr
9	**Sonar acoustic deafness (%)**	10	5
10	**Probability of propeller emergence (%)**	25	8
11	**Batteries performance disruption (%)**	5	5
12	**Snorkel mast flooding (%)**	-	25

By comparison between two conditions (surface and snorkel) it can be seen:

1- criterion of roll angle doesn't change in surface and snorkel because of constant relation between transverse stability and heeling moments.

2- Criterion of pitch angle is different between two conditions because of intensive fall of longitudinal metacentric height in snorkel condition and more motions.

3- Absolute vertical acceleration in snorkel is less than surface condition.

4- Absolute lateral acceleration is the same for two conditions.

5- Motion sickness incidence (MSI) in snorkel is more than the surface condition because of more intensive motions.

6- Usually, slamming loads are much larger than other wave loads. Slamming acceleration in snorkel is very less than surface because the draft in snorkel is more than surface condition. The snorkel draft is about two times of the surface draft.

7- Frequency of slamming in snorkel is very less than surface because of the same reason stated in criterion No.6.

8- Frequency of emergence of the sonar dome in snorkel is very less than surface because of the same stated in criterion No.6. Sonar dome is provided for passive sonar that is located at the front of hull, above or beneath the bow axis.

9- Sonar acoustic deafness and ambient noise in snorkel are less than surface condition because in snorkel draft, sonar has more distances from sea-surface waves.

10- Probability of propeller emergence in snorkel is lesser than the surface condition because of more draft, and more distance of propeller from the water surface.

11- Battery performance disruption is the same for both conditions.

12- Snorkel mast flooding is only important to snorkel condition and isn't important in surface condition.

Conclusion

For analyzing the seakeeping behavior of submarine and design of SOE polar diagram (that shows the safe and unsafe operation zone), some limitation and restrictions must be defined as seakeeping criteria. These criteria must be special for submarines because there is remarkable different between submarine and ship missions and machineries. Submarine has three conditions: surface, snorkel and submerge mode. For submerged mode, seakeeping criteria don't defined because it is far from sea waves. In comparison with snorkel and surface condition, in some cases, snorkel is more critical and in other cases, surface parameters are critical. There are some obvious differences between snorkel and surface condition such as stability, draft, wave action, turn off/on machineries and their missions. Three parameters that are only for ship, are discussed and omitted and other additional three parameters that are special for submarine are identified and defined. Therefore, in this paper twelve parameters were presented and suggested for submarine seakeeping analyzing.

Nomenclature

p_1	Percentage of Sonar acoustic deafness
p_2	Percentage of Snorkel mast flooding
p_3	Percentage of Battery performance disruption
t_0	total time that is regarded 60 minutes
t_1	Sonar deafness time in minutes
t_2	the time that head valve is open in minutes
t_3	battery exercise in minutes

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