DOI 10.15589/jnn20180103
УДК 629.58:532.51
M90

SUBMARINE MOTIONS AT A NEAR-SURFACE DEPTH UNDER IRREGULAR OCEAN WAVES

РУХ ПІДВОДНОГО ЧОВНА БІЛЯ ПОВЕРХНІ ПІД ДІЄЮ НЕРЕГУЛЯРНИХ ХВИЛЬ

Mohammad Moonesun
m.moonesun@gmail.com
ORCID: 0000-0001-6507-0956

Мухамед Мунесан,
асп.

Admiral Makarov National University of Shipbuilding, Mykolaiv
Національний університет кораблебудування імені адмірала Макарова, м. Миколаїв

Abstract. This research aims to study the seakeeping behavior of a submarine close to the sea water surface. At the depths close to the sea level, the submarine experiences the effect of ocean waves. Due to these dynamic effects, small and medium submarines cannot perform the snorting operation in rough and stormy sea properly. This study is based on the numerical method. For verification of the results, some experiments are carried out in the towing tank of the Admiral Makarov National University of Shipbuilding. As a result of this study enabling the small and medium submarines to navigate and snort in rough ocean waves, the unique innovative system “Moon-Korol” is presented as a new patent.

Keywords: submarine; snorkel; seakeeping; wave spectrum; pitch; heave.

Аннотация. Это исследование посвящено изучению мореходности подводной лодки, движущейся на малой глубине в условиях морского волнения. Из-за этих динамических эффектов на малых и средних подводных лодках нельзя должным образом осуществить нормальную работу шноркеля на волнении. В основу исследования положен численный метод. Для проверки результатов некоторые эксперименты проводились в опытовом бассейне НУК имени адмирала Макарова. Практическим результатом этого исследования является патент уникальной инновационной системы «Moon-Korol”, обеспечивающей работу перископа и шноркеля малых и средних подводных лодок на волнении.

Ключевые слова: подводная лодка; шноркель; мореходность; волновой спектр; угол наклона; перемещение.

Анотація. Це дослідження присвячено вивченню морехідності підводного човна, який рухається на малій глибині в умовах морського хвилювання. Із-за цих динамічних ефектів на малих та середніх підводних човнах неможливо належним чином здійснити нормальну роботу шноркеля на хвилюванні. В основу дослідження покладено чисельний метод. Для перевірки результатів деякі експерименти виконувалися в НУК імені адмірала Макарова. Практичним результатом цього дослідження є патент унікальної інноваційної системи «Moon-Korol”, що забезпечує роботу перископу і шноркеля на хвилюванні.

Ключові слова: підводний човен; шноркель; морехідність; хвильовий спектр; кут нахилу; переміщення.

REFERENCES

[1] Thurman H.V., Trujillo A. P. Essentials of oceanography. Edition 5, Prentice Hall, 2001, pp. 240–243.

[2] Dean W. R. On the reflection of surface waves by a submerged circular cylinder. ProcCamb Phil Soc., 1948, vol. 44, pp. 483–491.

[3] Ursell F. Surface waves in the presence of a submerged circular cylinder. I and II ProcCamb Phil Soc., 1949, vol. 46, pp. 141–158.

[4] Ogilvie T. F. First and second order forces on a cylinder submerged under a free surface. J Fluid Mech., 1963, vol. 16, pp. 451–472.

[5] Chaplin J. R. nonlinear forces on a horizontal cylinder beneath waves. J Fluid Mech., 1984, vol. 147, pp. 449–464.

[6] Etienne G., Benoit M., Grilli S. T., Buvat C. Modeling of fully nonlinear wave interactions with moving submerged structures. Proceedings of the Twentieth International Offshore and Polar Engineering Conference, Beijing, China, 2010, pp. 529–536.

[7] Wu G. X. Hydrodynamic forces on a submerged circular cylinder undergoing large-amplitude motion. J Fluid Mech., 1993, vol. 254, pp. 41–58.

[8] Hannan M. A., Bai W., Ang K. K. Modeling of fully nonlinear wave radiation by submerged moving structures using the higher order boundary element method. Journal of Marine Science and Application, 2014, vol. 13, pp. 1–10.

[9] Evans D. V., Jeffrey D. C., Salter S. H., Taylor J. R. M. Submerged Cylinder Wave Energy Device: theory and experiment. Applied Ocean Research, 1979, vol. 1, no. 1, pp. 3–12.

[10] Dessi D., Carcaterra A., Diodati G. Experimental investigation versus numerical simulation of the dynamic response of a moored floating structure to waves. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, September 1, 2004, vol. 218, pp. 153–165.

PROBLEM STATEMENT

When a submarine is near the water surface, its motions are intense, making its operation difficult. To solve this problem, submarine depth should be increased. Yet, when increasing the depth, the waves effects and submarine motions decrease, in turn increases the seaworthiness.

LATEST RESEARCH AND PUBLICATIONS ANALYSIS

The hydrodynamic forces of ocean surface waves on submerged bodies have been studied in several different fields of engineering. Some examples are as follows. Offshore engineering considers wave impacts on vertical and horizontal fixed cylinders as the structural members of a platform leg. Several extended studies have been conducted to analyze the diffraction around a submerged fixed cylinder. Thus, Dean (1948) [1, 2] made use of the linearized potential theory to demonstrate the effects of reflection. Ursell (1949) [3] and later Ogilvie (1963) [4] presented the formulation of wave steepness up to the second order. Using experiment as a method, Chaplin (1984) [5] measured the nonlinear force on a fixed horizontal cylinder beneath the waves. He analyzed the influence of the Keulegan-Carpenter number value on the harmonics of the applied force

This subject is also relevant in Wave Energy Converters (WEC). Here, attention is paid to wave effects on the moored or prescribed motions of cylinders of energy converters just near the surface. This study is noteworthy if applied to offshore engineering for moored semi-submersibles [6-10]. Wu (1993) presented a formulation for calculating the forces exerted on a submerged cylinder undergoing large-amplitude motions. When the free surface condition is linearized, the body surface condition is satisfied in its immediate position. The solution for the potential is stated as a multi-pole expansion. Wu obtained results for a circular cylinder in a purely vertical motion and clock-wise circular motion in a wave field [7].

Moreover, wave effects on the non-moored free submerged body near the free surface and at the snorkel depth are considered in submarine and submersible design. This is the category that this study pursues. In this work, we intend to determine a safe depth for calm and stable motions of a submarine. This safe depth is not necessarily equal to wave base.

In this study, a submarine design is analyzed at several depths accompanied by regular surface waves. For executing the next stages and gaining and more effective and accurate results, precise 3D submarine models and numerical prediction of the CFD method can serve as a good option. The latter methods are more time-consuming than the analytical ones, but yield better results. There are several CFD software tools capable of modeling the ocean waves (regular or irregular waves), for instance, Flow-3D [10], IOWA and Open FOAM. Accordingly, the focus and preference of the study would be the Panel method implemented via simulation in Maxsurf [10].

THE ARTICLE AIM is to establish the optimal immersion depth of a submarine near the water surface to keep the normal seaworthiness.

BASIC MATERIAL

The study employs three methods: numerical (CFD), experimental (model test in a towing tank), and analytical (Panel) methods. The point of application of each of these methods in the process of research is shown in Fig. 1.

Governing Equations. This section of the thesis presented by this publication includes the following topics: irregular wave spectrum, seakeeping formulations, CFD formulations, and Panel method formulation.

Wave and Response Spectrum. The ship motion in an irregular seaway is determined by means of the following steps:

1. A suitable wave spectrum is chosen for a particular seaway in which the vessel is to operate.

2. The wave spectrum is transformed into a spectrum where the frequency of encounter is considered instead of the absolute wave frequency (Fig. 2).

3. A plot is obtained in which the ordinates represent the amplitude of motion (either pitch, roll or heave) to a base of encountering frequency distribution.

4. The diagram obtained in step 3 is modified so that the ordinates represent the ratio of the square of the motion amplitude to the square of the wave amplitude. This diagram is dubbed as the response amplitude operators (RAO) or simply the “transform spectrum”.

5. The motion amplitude spectrum is obtained by multiplying the ordinates of the transformed wave spec-

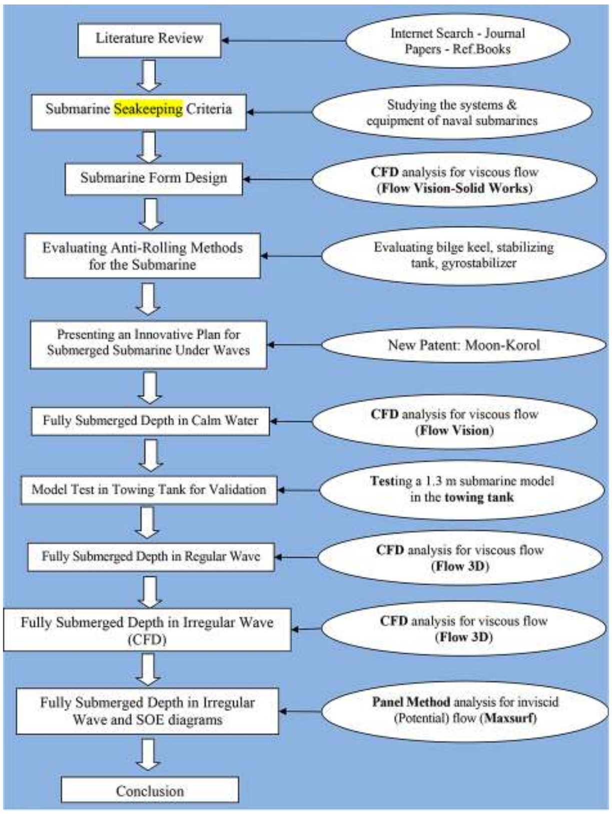


Fig. 1. Methodology applied in the process of research

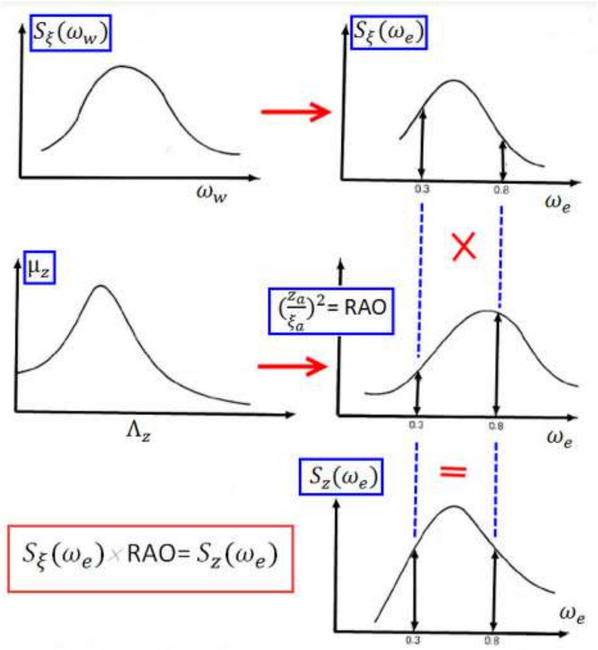


Fig. 2. Prediction of ship motion in an irregular seaway via Wave spectrum, Encountering wave spectrum, Response in regular waves, Response Amplitude Operator (RAO) and Response spectrum

trum by the ordinates of the RAO for the corresponding frequencies of encounter.

6. Finally, the area under the motion amplitude spectrum is determined in order to obtain the necessary motion characteristics.

CFD formulation. To solve the governing equations of fluid flow, Flow-3D solves a modification of the commonly used Reynolds-average Navier-Stokes (RANS) equations. The modifications include algorithms to track the free surface. The modified RANS equations have the following form:

Continuity:

$$\frac{\partial}{\partial x}(uA_x)+\frac{\partial}{\partial y}(vA_y)+\frac{\partial}{\partial y}(wA_z)=0$$

Momentum:

$$\frac{\partial U_i}{\partial t}+\frac{1}{V_F}\left(U_j A_j \frac{\partial U_i}{\partial x_j}\right)=\frac{1}{\rho}\frac{\partial P'}{\partial x_i}+g_i+f_i$$

Theory of Panel Method. In order to apply the Panel method, the wave height and steepness are also assumed to be so small that the use can be made of the linear wave theory. The fluid is considered to be inviscid and incompressible. The flow is assumed irrotational. Thus, the flow field can be stated by a velocity potential gradient, which is governed by the Laplace equation and simultaneously should satisfy the proper boundary conditions.

Verification of Numerical Studies

Experimental tests have been performed on the model Persia-110 in the towing tank of the Admiral Makarov National University of Shipbuilding. The tank has the length of 33 m, width of 2.5 m and draft of 1.3 m (Fig. 3).

Evaluation of Stabilizing Methods for Submarines

First, several different stabilizing methods have been studied in order to enable submarines to navigate in rough seas. The predicted stabilizing effects and disadvantages of each method are listed in Table 1.

Accordingly, a completely different and more effective method has to be introduced. The above studies have shown that there is only one practical and realistic way of doing this, which is to increase the distance from the submarine to the water surface and waves. However, as discussed earlier, the height of the snorkel mast has a serious limitation because it causes a severe hydrodynamic resistance, high vibration and structural problems. Our innovative solution to get out of this deadlock is to present an inventive design called the Moon-Korol system. The Moon-Korol system, or the Snorting Buoy, is an engineering plan which was unveiled by M. Moonesun and U. Korol in 2013. This patent was registered in Ukraine and Iran.

The main advantage of this system resides in enabling small and medium submarines to snort in rough ocean waves. Currently, small and medium submarines cannot perform the snorting operation in rough and stormy sea because they have weak stability and seakeeping specifi-

Fig. 3. Persia-110 model in the marine laboratory of the Admiral Makarov National University of Shipbuilding

Table 1. Main disadvantages of stabilizing methods

1	Bilge Keel	There is no effect reducing the pitch motion.
2	Stabilizing Tank	Existing tanks cannot be used properly. It is impossible to set some new tanks.
3	Fin Stabilizer	Large dimensions of hydroplanes lead to a drop in speed and thus the heave increase.
4	Gyrostabilizer	The large weight causes inappropriate arrangement and placing.

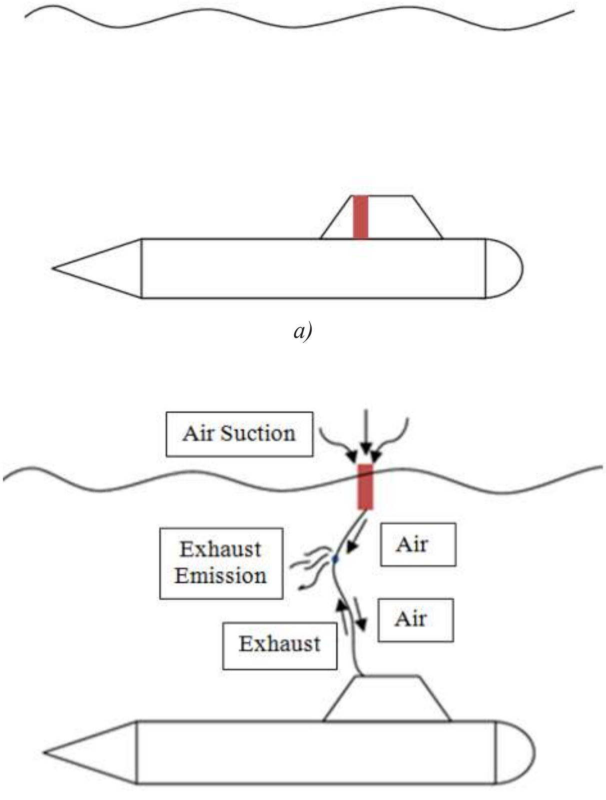


Fig. 4. Schematic of the Moon-Korol snorting system:

a — Moon-Korol is mounted in after a part of the sailing; *b* — Moon-Korol is released to sea level for fresh air suction and exhaust emission

cations. The defect was covered by this innovative plan. First, the Moon-Korol system was designed for installing on the medium-size submarines of Iranian Navy.

The main advantages of the Snorting Buoy are as follows.

1. Small and medium submarines are capable of snorting in rough waves.
2. There are fewer movements at snorting operation.
3. There are fewer risks of aerial bombing attack.
4. The SONAR hearing is improved as there is less ambient noise from the waves.
5. Forward speed at snorting operation can be near zero.

As shown in Fig. 4, this buoy is mounted inside the sailing and will be released at a safe depth beneath the sea water level. This safe depth, as mentioned above, should not be less than 0.1λ. The inside arrangement of the Snorting Buoy is presented in Fig.4.

CFD and Panel Method Results and Analysis

Fig. 5 renders the variations of total resistance versus depth for Model-A in the modeling under calm water. The graph shows that the fully submerged depth is registered at H* = 4.5 or h = 4.5D. A sharp decline in resistance occurs from just near surface (H* = 0) to the H* = 1, with wave resistance decreasing by 80%. This is referred to as "Milestone depth". The Milestone depth in Model-A is at H* = 1, or h = D, or h = 0.12L. Next, we have performed the modeling under calm water with the use of the CFD method in the Flow Vision software.

For our next step, we performed the modeling under regular and irregular waves via the CFD method in the Flow-3D software. The general configurations and dimensions of domain are shown in Fig. 6. The length and width are 12 and 2.6 m, respectively, while the depth is 4 m (3.5 for draft and 0.5 for freeboard). The boundary conditions are as follows: input "wave", output "specified pressure and other sides are symmetry". The model is situated at different depths of "h" according to Fig. 6 *a*. There are two mesh blocks: one block for the total domain with coarse meshes and the other block for fine meshes around the object body. The accuracy of the body shape depends on the fine meshes (Fig. 6 *b*). To produce the wave, the input boundary condition is "Wave"; Flow-3D can generate regular and irregular waves. The generated wave and the position of the object under waves are shown in Fig. 6 *c*.

For studying the wave effects on the submarine, several depths for submarine situation (h) are considered according to Fig. 6 *a* and Table 2.

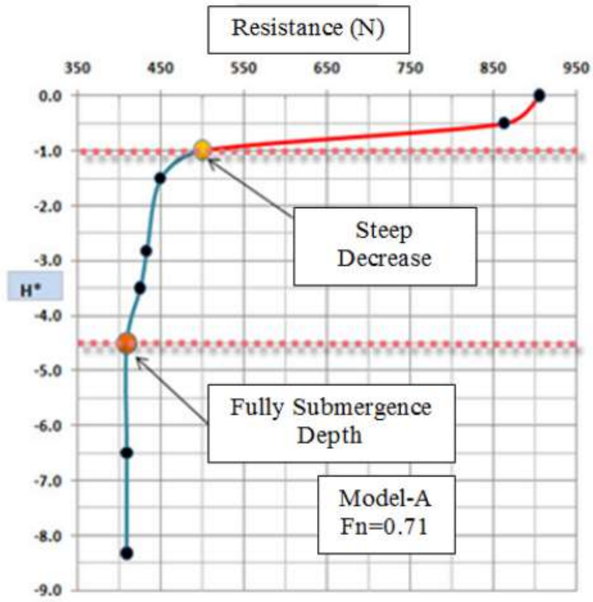
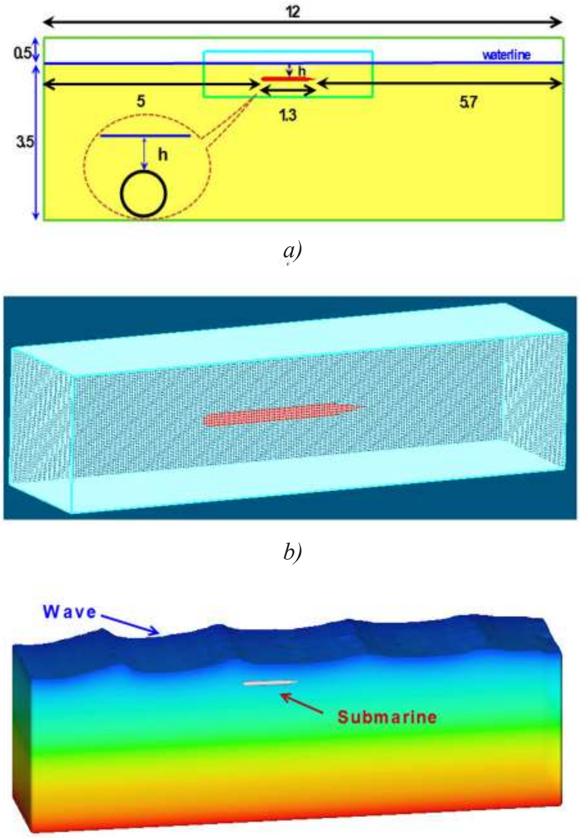


Fig. 5. Variations of total resistance versus depth in Model-A



a)

b)

c)

Fig. 6. Wave simulation by means of CFD tools (Flow-3D): *a* — dimensions of domain (in meters); *b* — fine meshes in Mesh Block2; *c* — generated wave and position of submarine

Table 2. Considered conditions for analyses

	Submarine depth (m)	Description vs wave length (equivalent to)
1	0	Body tangent to free surface
2	0.05	R_s (or) 0.03λ
3	0.1	D_s (or) 0.06λ
4	0.15	1.5D_s (or) 0.09λ
5	0.25	2.5D_s (or) 0.16λ
6	0.35	3.5D_s (or) 0.22λ
7	0.55	5.5D_s (or) 0.35λ
8	0.75	7.5D_s (or) 0.48λ
9	0.95	9.5D_s (or) 0.61λ
10	1.6	≅λ
11	2.4	≅ 1.5λ
12	3	≅ 3λ

In conclusion, the results could be abstracted in the Fig. 7, which fairly shows the gradient of movements versus depth of submergence. Depth of λ/2 could be considered an absolutely calm depth, but the depth of 0.1λ could be recommended as an operational safe and approximately calm depth for submarines.

The next step for more extensive studies is application of the Panel method via Maxsurf software. There are two main options of numerical methods for the study based on the Potential flow: Strip Theory and Panel Method. The Strip Theory is quite common and applicable for surface crafts and ships, but it has no applicability for submerged bodies. This can be ascribed to a Conformal Mapping basis, which requires a water plane area. Hence, only the Panel Method can be employed in order to study the dynamics of submerged bodies like submarines through the Potential flow. The main disadvantage of this method is an almost zero forward speed.

This study is performed via Maxsurf Motions. Only CFD methods based on solving RANS equations are utilized in order to simulate a submerged submarine at viscous fluid and at non zero speed. This method is more accurate, but also more time-consuming with regard to solving and more complicated in terms of programming.

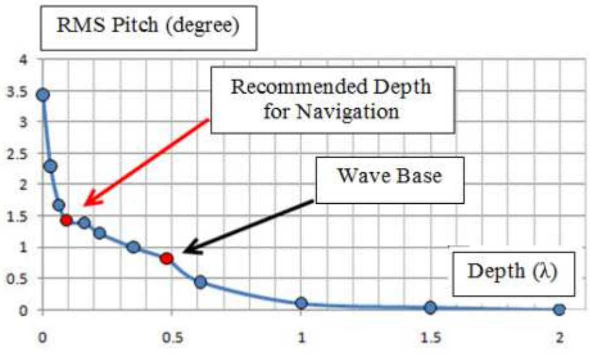
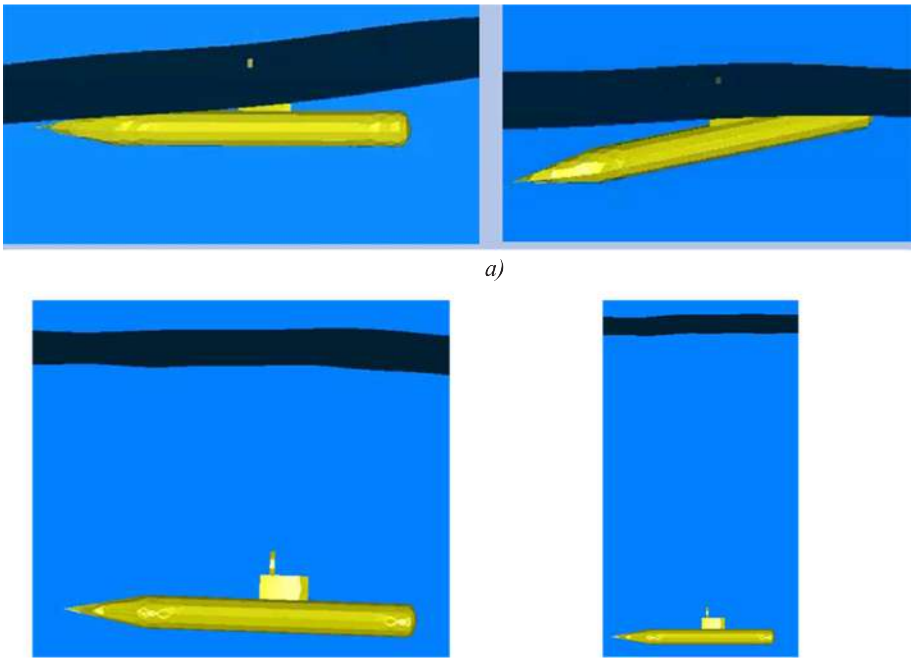


Fig.7. Gradient of RMS pitch versus submergence depth of a submarine



a)

b)

c)

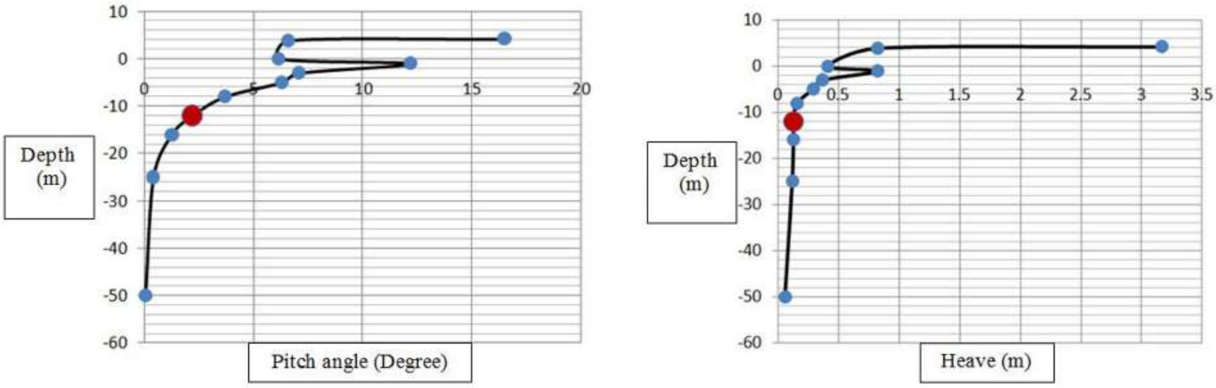
Fig. 8. Dynamic simulation of a submarine under non-linear wave (JONSWAP spectrum):
a — at the snorkel depth; *b* — at the depth of 16 m; *c* — at the depth of 50 m

The visualized results of simulations for submarine motions and irregular wave surface are rendered in Fig. 8. As it can be seen, by increasing the depth of submergence, there occurs a decrease in motion amplitude.

With consideration to other cases, it becomes clear that by increasing the depth there occurs a fast decrease in RMS values (Fig. 9). This decreasing trend shows that at the depth of 8 meters (λ/12.5), RMS pitch is only 30% of a 1-meter depth (λ/100). Also, at the depth of 8 meters (λ/12.5), RMS heave is only 20% of a 1-meter depth (λ/100). This is the major result of the present study, revealing the depth about 0.1λ can be recommended as an operationally calm, stable, and safe for naval or research submarines. The depth of 50 meters (λ/2 equal wave base depth) is absolutely calm; however, it may be inaccessible for small and medium submarines. Thus, a logical and accessibly recommended depth for all submarine types is 0.1λ.

As shown in Fig. 10 and 11, when the submarine is near the water surface, the motions are intense. Therefore, the hatched area is large, and the submarine operation becomes difficult. To solve this problem, the submarine depth is increased, which in turn decreases the waves effects and submarine motions decreases, as well as reduces the hatched area. This means that with an increasing immersion depth, the seaworthiness increases.

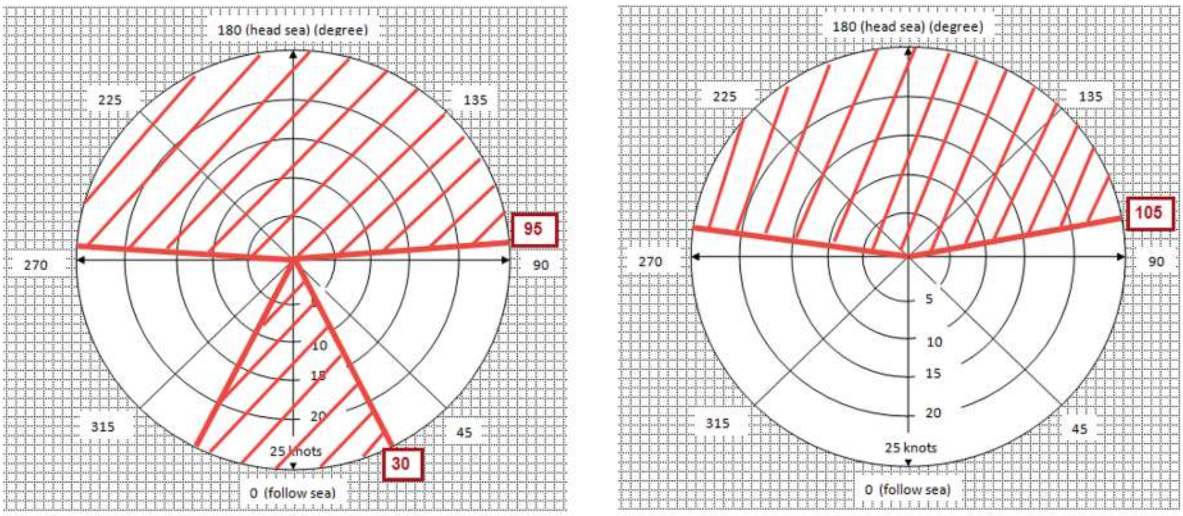
Fig. 12 shows the result of modeling at the initial depth of 40 m. The horizontal axis is the time (mea-



a)

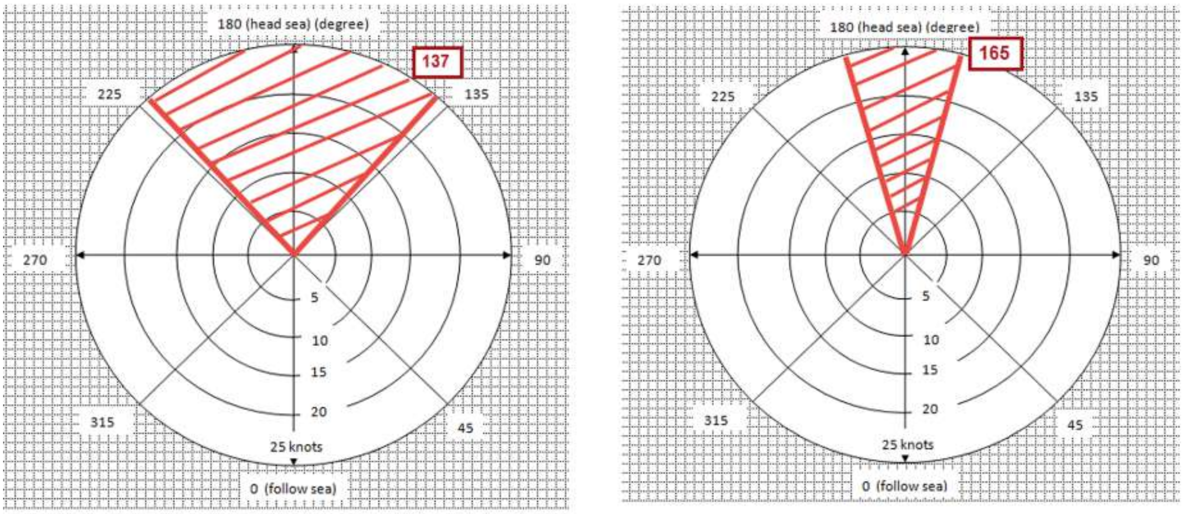
b)

Fig. 9. RMS values of motions at different depths:
a — pitch angle at heading 180 degree; *b* — heave at heading 180 degree



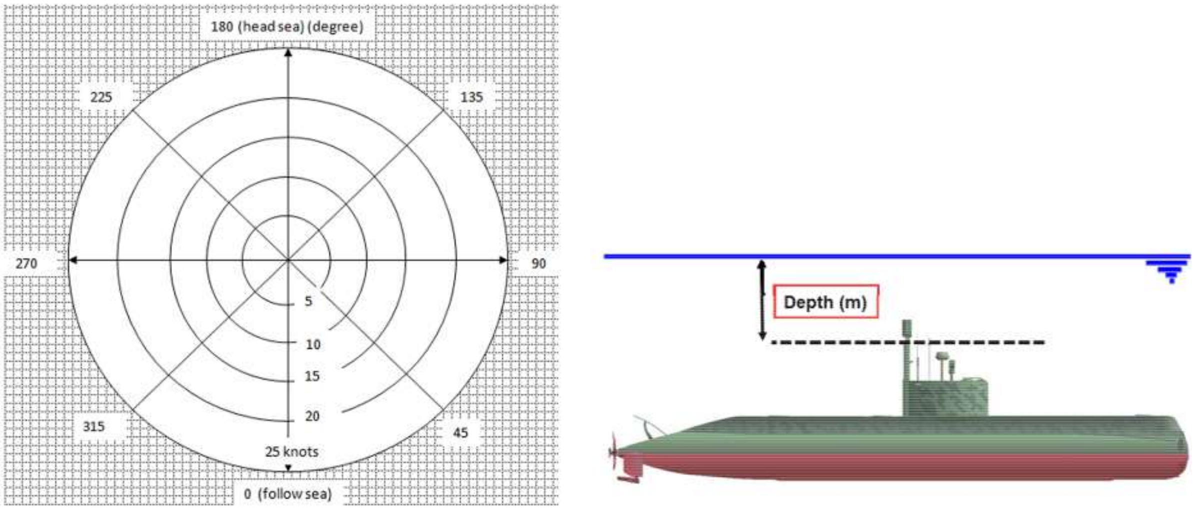
Depth: 3 m (λ/33), O.I = 56%

Depth: 5 m (λ/20), O.I = 64%



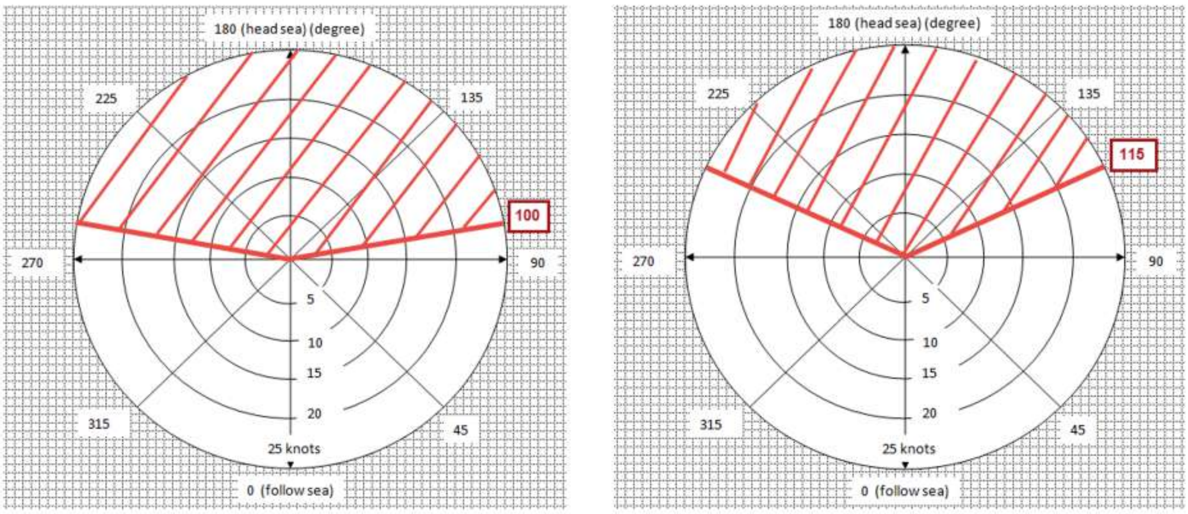
Depth: 8 m (λ/12.5), O.I = 83%

Depth: 12 m (λ/8.3), O.I = 97%



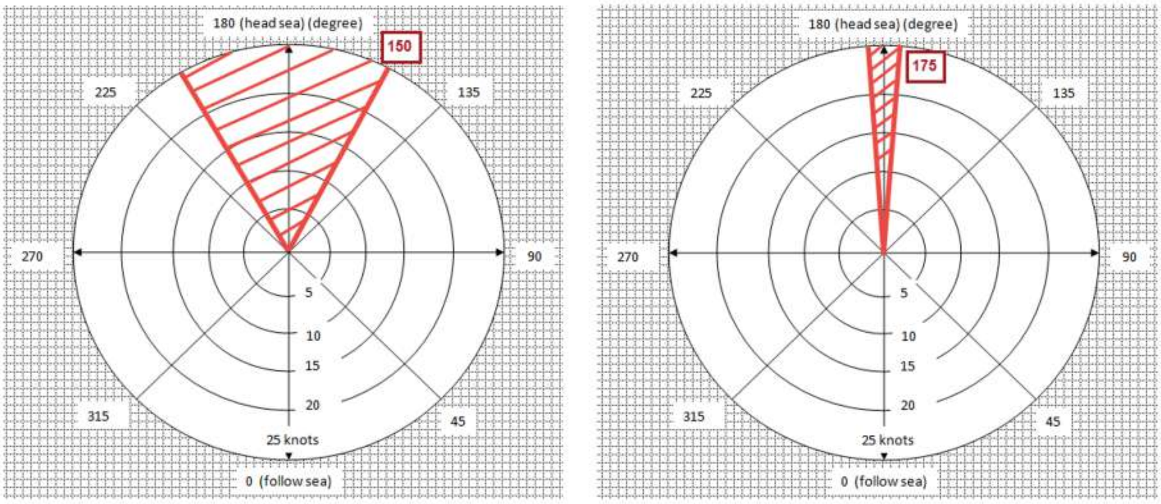
Depth: 16 m (λ/6.25), O.I = 100%

Fig. 10. SOE diagram for the pitch angle (limit value of 2.5 degree): submarine at snorting condition, JONSWAP spectrum, significant wave height of 2 m



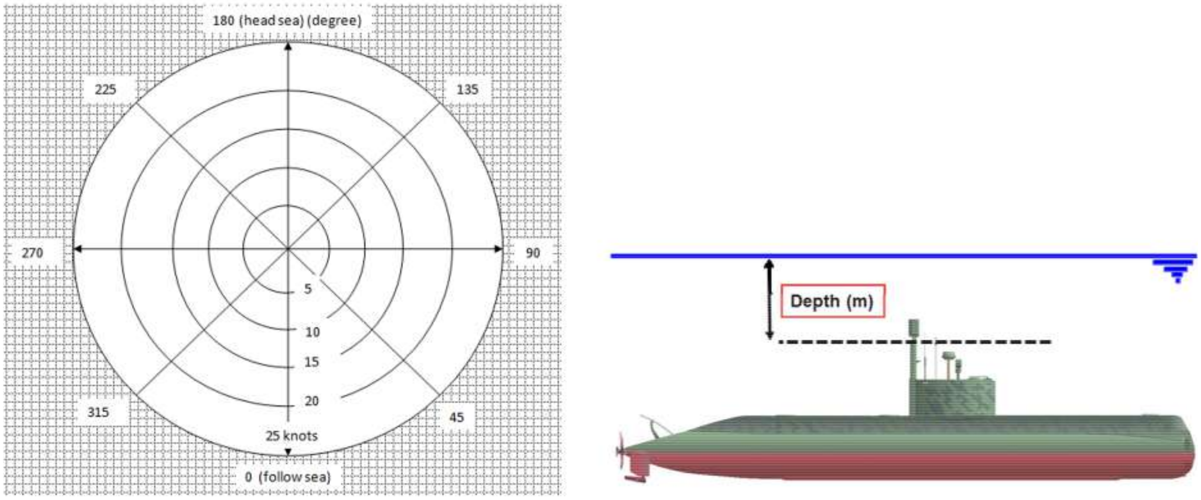
Depth: 3 m (λ/33), O.I = 36%

Depth: 5 m (λ/20), O.I = 58%



Depth: 8 m (λ/12.5), O.I = 76%

Depth: 12 m (λ/8.3), O.I = 92%



Depth: 16 m (λ/6.25), O.I = 100%

Fig. 11. SOE diagram for RMS Vertical Acceleration (limit value of 0.2 g): submarine at the snorting condition, JONSWAP spectrum, significant wave height: 2 m

Fig. 12. Depth change due to the suction force from surface waves. Initial depth: 40 m, speed: 5 knots, regular waves height: 2.5 m, period: 8 sec, wave length: 103 m

sured in seconds) and vertical axis is the depth of submergence (measured in meters). The suction force of the wave causes the submarine to move upward. It is obvious that the slope of depth change is not always constant: the closer to the water surface, the more suction effects will be observed. The diagram of Fig.14 demonstrates that at the initial depth of 40 m (0.4λ), the slope of the depth change is small, being equal to 0.0288. From the depth of 35 m (0.35λ), the slope of depth change is slightly higher, 0.0475. From the depth of 20 m (0.2λ) onwards, the slope of the change is very sharp and equal to 0.2431. This suggests that at depths less than 20 m (0.2λ), the amount of suction effects and depth variations is very high, and if the submarine cannot control the depth, there occurs the Broach phenomenon.

CONCLUSIONS. None of the existing stabilizing methods are suitable for the use on naval submarines. Accordingly, a completely different and more effective method has to be introduced. The above studies have shown that there is only one practical and realistic way for solve this problem, which is to increase the distance from the submarine to the free surface of water and waves. Yet, as discussed earlier, the height of the Snorkel mast has a serious limitation because it causes severe hydrodynamic resistance, high vibration and structural problems. Our innovative solution to get out of this deadlock is to present an inventive design called the Moon-Korol system. This buoy is mounted inside the sailing and will be released at a safe depth beneath the sea water level. This depth should not be less than 0.1λ. It has been established that this method could be effective for increasing submarine navigation capabilities in rough seas. A conceptual design has been done for the snorting buoy detailed systems, which indicates that it is quite possible to arrange the buoy in the submarine. The total weight of this system is acceptable, consequently, its installation on top of the submarine body does not result in a negative metacentric height and instability. Our studies have shown that this system has no adverse effects on other submarine systems.

© Мухамед Мунесан
Надійшла до редколегії 19.03.2018
Статтю рекомендує до друку член редколегії ЗНП НУК
д-р техн. наук, проф. *В. О. Нєкрасов*