

Modeling the physical properties of wave generated by turbulent wake of submarine in the Persian Gulf and the Gulf of Oman

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In this paper internal waves generated by turbulent wake of a submarine were modelled with MIT-gcm and were compared with the results of modeling by COHERENS. By using these models, detection of a submarine using its magnetic induced wake is investigated. The results show that the height of these internal waves could be an order of submarine diameter and its wavelength could be more than 10 times greater than its length depending on its speed. The speed of these generated waves, could be exceeded the speed of submarine.

[Keywords: Turbulent wake, modeling, MIT-gcm, COHERENS, Persian Gulf, Gulf of Oman]

Introduction

Different turbulence models has been developed by many researchers to model turbulent flows (e.g. I. B. Celik¹ and M. Jahanmiri²). Subsurface vehicle may move between two environments: first, a medium with stratification and the second an environment with no stratification. In both cases, a different turbulent wake is created (e.g. A. M. Abdilghanie³, H. E. Gilreath⁴ and K. W. Kaulum⁵). Turbulent wake of subsurface vehicle may be near or far from it⁶. These wakes are examined by some researcher (e.g. S. Hassid⁷, A. Onufriev⁸ and A. A. Bidokhti⁹). The subsurface object may be towed or a self-propeller one. The aim of the study was to investigate the principles of physics and engineering applications should be avoided. The turbulent wake creates a magnetic field that could be used to detect submarines in the range of less than 10 km. The collapse of turbulent wake creates internal waves that could be moved hundreds of kilometers¹⁰. These generated waves have a specific height, period, speed and wave length. The generated waves are linear wave. The characteristics of these waves were investigated using MIT-gcm and COHERENS 3-D numerical models. Merritt experimentally investigated the momentum less turbulent wake in a linear stratified fluid. He showed that the most important parameter is the Froude number. Horizontal and vertical

components of turbulent wake was done experimentally in a linear stratified environment by Lin and Pao¹¹. Gilreath and Brandt performed experiments that considered the internal waves generated by a self-propelled moving object in a linear stratified fluid.

Since, the turbulent wake is under the influence of sea currents, the effects of flow on the turbulent wake were modeled, using oceanic models. In this phase, amplitude, speed, wavelength and period of internal waves generated by submarine in the Persian Gulf and the Gulf of Oman were extracted at different speeds. The distribution of submarine turbulent wake in the vertical and horizontal and interval that it is detectable were evaluated using numerical models. This feature hasn't been extracted in the Persian Gulf and the Gulf of Oman.

Materials and Methods

Figure 1 shows the study region and the bathymetry of it.

The region of interest for this study is the Persian Gulf, the Gulf of Oman and Strait of Hormuz. Which is enclosed between the lengths of approximately 48 to 59 degrees east longitude and 23 to 31 degrees north latitude. Gulf of Oman with the triangular shape is located between Iran, Oman and Pakistan. The maximum length is 950 km from the North West

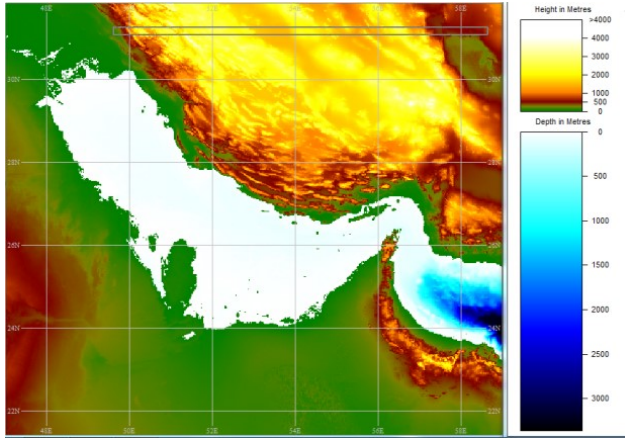


Figure 1 — The topography of the study area

to the South East and a maximum width of about 340 kilometers North East to South West. The Persian Gulf is a Mediterranean gulf in Western Asia. An extension of the Indian Ocean (Gulf of Oman) through the Strait of Hormuz, it lies between Iran to the northeast and the Arabian Peninsula to the southwest.

Due to the increased computing power in recent years and usage of computers that can perform a high volume of calculations in a short time, numerical methods for the prediction of ocean phenomena is the best way. These methods have been significant advances in recent years, and many studies have been conducted by these methods¹². Two dimensionless numbers are considered in turbulence modeling: Reynolds number and Froude number¹³.

For simplicity, we assume that submarine is move in the x-direction and during modeling does not change its direction and the move is to alternate. The gravity force is act in the Z direction.

The equations are as follows¹⁴:

$$\frac{\partial w^*}{\partial z^*} = 0 \quad \dots (1)$$

$$\frac{\partial u^*}{\partial t^*} + \frac{\partial(w^*u^*)}{\partial z^*} = -\frac{1}{\rho} \frac{\partial p^*}{\partial x^*} + \nu \frac{\partial^2 u^*}{\partial z^* \partial z^*} - \rho^* F_x^* \quad \dots (2)$$

$$\frac{\partial \rho^*}{\partial t^*} + w^* \frac{\partial \rho^*}{\partial z^*} = \kappa \frac{\partial^2 \rho^*}{\partial z^* \partial z^*} \quad \dots (3)$$

Density can be considered in the form of a fixed amount plus a small deviation. This deviation is divided into two parts, the average value and the amount of swinging. That is:

$$\rho^* = \rho_0 + \langle \rho^* \rangle(z^*) + \rho'^*(x^*, t^*) \quad \dots (4)$$

So the equation of momentum is as follows:

$$\frac{\partial u^*}{\partial t^*} + \frac{\partial(w^*u^*)}{\partial z^*} = -\frac{\partial p^*}{\partial x^*} + \nu \frac{\partial^2 u^*}{\partial z^* \partial z^*} - \rho'^* g \delta_z \quad \dots (5)$$

Dimensionless quantities are defined as follows:

$$t = \frac{t^* U}{L}, x = \frac{x^*}{L}, u = \frac{u^*}{U}, \rho' = \frac{\rho'^*}{\Delta \rho}, p = \frac{p^*}{\rho_0 U^2} \quad \dots (6)$$

The dimensionless equations can be obtained as follows:

$$\frac{\partial w}{\partial z} = 0 \quad \dots (7)$$

$$\frac{\partial u}{\partial t} + \frac{\partial(wu)}{\partial z} = -\frac{\partial p'}{\partial x} + \frac{1}{Re} \frac{\partial^2 u}{\partial z \partial z} - \frac{\Delta \rho g L}{\rho_0 U^2} \rho' \delta_z \quad \dots (8)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho w)}{\partial z} = \frac{1}{Pr Re} \frac{\partial^2 \rho}{\partial z \partial z} \quad \dots (9)$$

In these equations:

$$Ri = \frac{g \Delta \rho D}{\rho_0 U^2} = \frac{N^2}{(\frac{\partial u}{\partial z})^2} \quad \dots (10)$$

If the N value is fixed in a fluid we can write:

$$Fr = \frac{U}{ND} \quad \dots (11)$$

$$N = \left[-\frac{g}{\rho_0} \frac{d(\rho^*)}{dz^*} \right]^{\frac{1}{2}} \quad \dots (12)$$

The condition of generating internal waves by submarine is as follows¹⁵:

$$\frac{(\rho_2 - \rho_1) g H}{\rho_0 (u_1 - u_2)^2} < \frac{1}{4} \quad \dots (13)$$

This relationship suggests that if the medium is unstratified, internal waves may still be formed by submarine passage.

Waves generated by turbulent wake are depend to Brunt-Väisälä frequency. The collapse of turbulent wake is a third of it¹⁶.

The detection range of wake, period, height, speed and wavelength of waves was extracted everywhere in the Persian Gulf and the Gulf of Oman and the submarine different positions at various depths.

Results

Figure 2 shows the distance that the turbulent wake of submarine is detectable for a submarine at a speed of 10 meters per second and the length of 35 meters and a diameter of 5 meters at a depth of 100 meters and 65 meters in the Gulf of Oman. This distance is determined using the magnetic field caused by turbulent wake of submarine. These are the results of measured values and modeling.

Figures 3 to 8 show the wavelength, height, and speed of the waves caused by the movement of

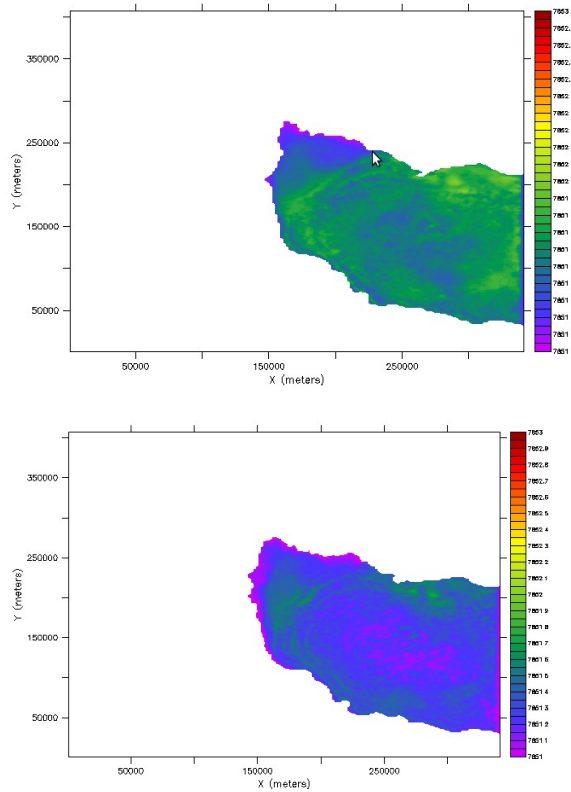


Figure 2 — The distance that the turbulent wake of submarine is detectable for a submarine at a speed of 10 meters per second and the length of 35 meters and a diameter of 5 meters at a depth of 100 meters(up) and 65 meters(down) in the Gulf of Oman

submarines for a submarine at a speed of 5 m/s and 10 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm and COHERENS in the Persian Gulf and the Gulf of Oman. The figures show that the speed of wave produced by turbulent wake may be greater than the speed of the submarine that induced it. Also the wavelength of wave produced by turbulent wake may be greater than the length of the submarine that created it.

Figure 9 shows the collapse of the horizontal turbulent wake caused by the movement of submarines for a submarine at a speed of 10 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm and the collapse of the vertical turbulent wake using COHERENS in the Persian Gulf and the Gulf of Oman.

Figure 10 shows the measured results of vertical and horizontal components of turbulent wake by the movement of submarines at speed of 5 and 10 m/s with a diameter of 5, 6.8 and 8 meters in the Gulf of Oman. The vertical component was modeled with

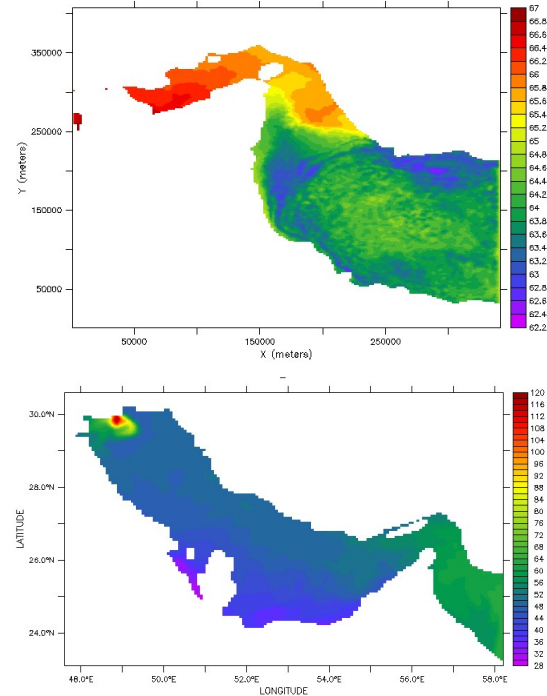


Figure 3 — The wavelength of the waves caused by the movement of submarines for a submarine at a speed of 5 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS(down) in the Persian Gulf and the Gulf of Oman

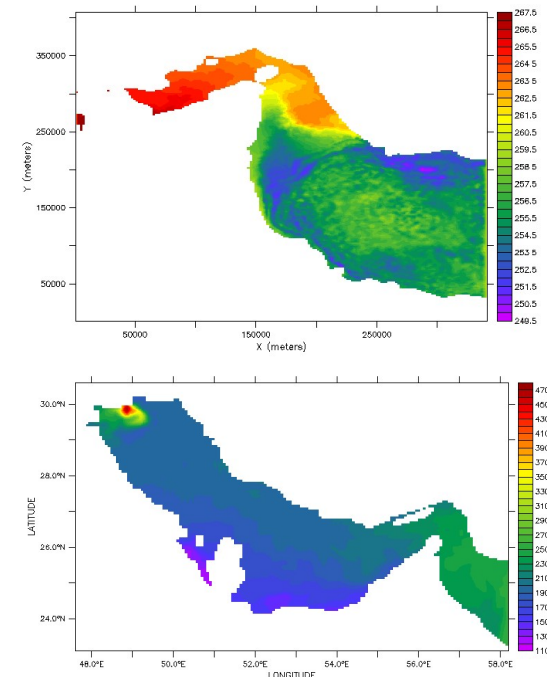


Figure 4 — The wavelength of the waves caused by the movement of submarines for a submarine at a speed of 10 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS (down) in the Persian Gulf and the Gulf of Oman

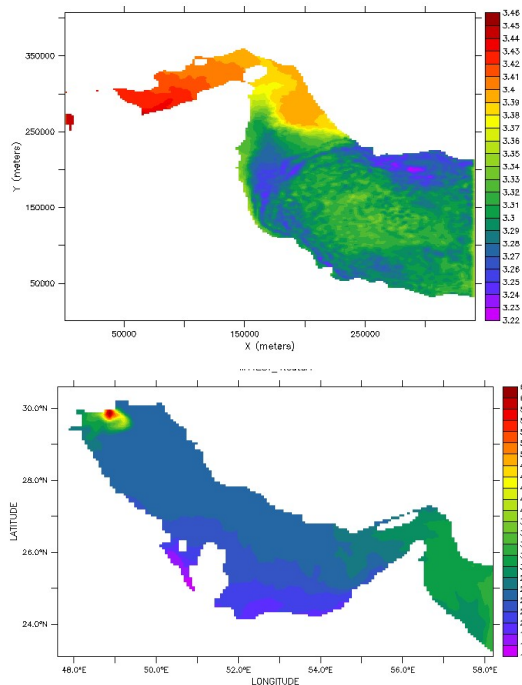


Figure 5 — The height of the waves caused by the movement of submarines for a submarine at a speed of 5 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS(down) in the Persian Gulf and the Gulf of Oman

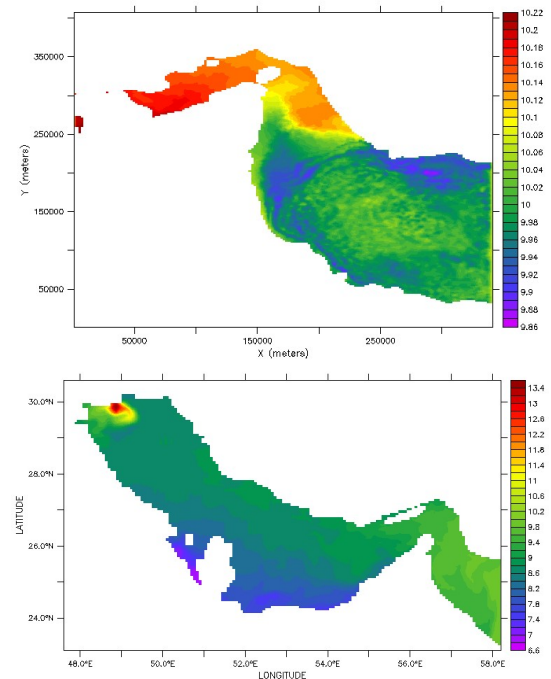


Figure 7 — The speed of the waves caused by the movement of submarines for a submarine at a speed of 5 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS(down) in the Persian Gulf and the Gulf of Oman

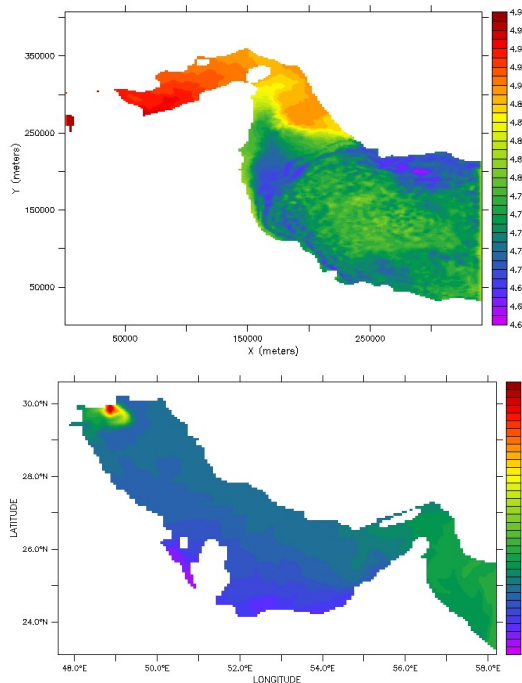


Figure 6 — The height of the waves caused by the movement of submarines for a submarine at a speed of 10 m/s and the length of 57.3 meters and a diameter of 6.8 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS (down) in the Persian Gulf and the Gulf of Oman

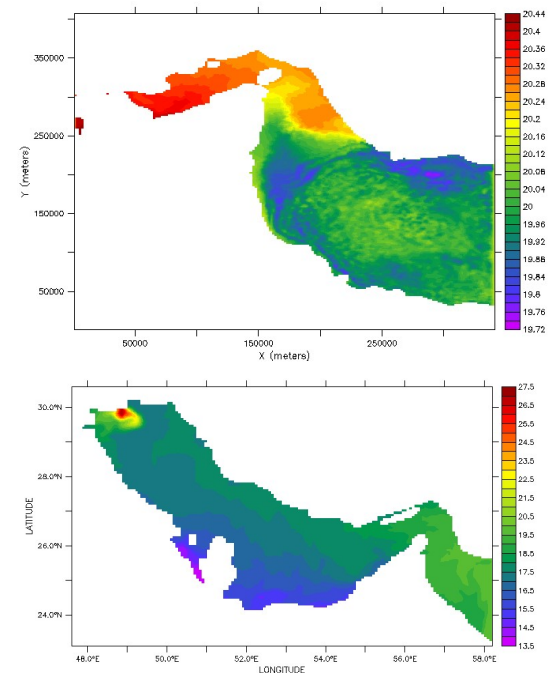


Figure 8 — The speed of the waves caused by the movement of submarines for a submarine at a speed of 10 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and COHERENS(down) in the Persian Gulf and the Gulf of Oman

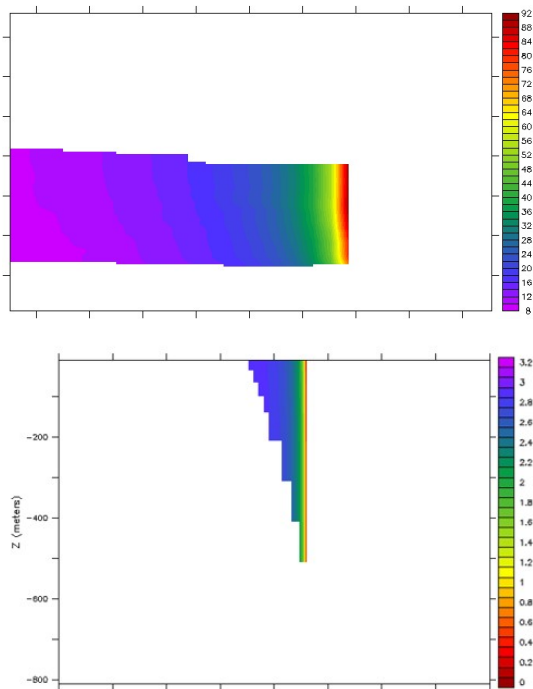


Figure 9 — The collapse of the horizontal turbulent wake caused by the movement of submarines for a submarine at a speed of 10 m/s and the length of 30 meters and a diameter of 5 meters at a depth of 65 meters using MIT-gcm(up) and The collapse of the vertical turbulent wake using COHERENS(down) in the Persian Gulf and the Gulf of Oman

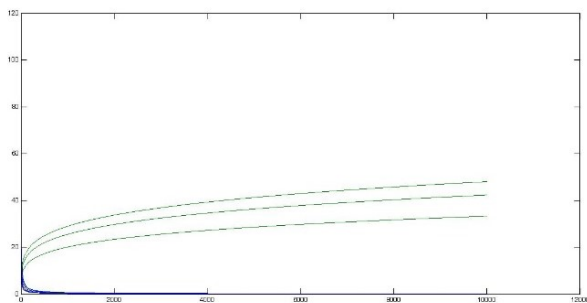


Figure 10 — The measured results of vertical and horizontal components of turbulent wake by the movement of submarines at speed of 5 and 10 m/s with a diameter of 5, 6.8 and 8 meters in the Gulf of Oman (The horizontal component is marked with green color and the vertical component is marked with blue)

MIT-gcm and the horizontal component was modeled with COHERENS. As shown in figure, vertical component of turbulent wake collapse at a distance less than 100 meters from the submarine. At this point, the internal waves are formed.

Figure 11 shows the magnetic field caused by the turbulent wake of submarine near it. This magnetic field is related to the turbulent wake of submarine and is not related to the magnetic field of the hull.

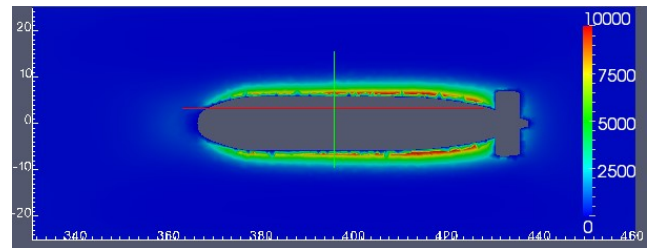


Figure 11 — The magnetic field caused by the turbulent wake of submarine near it

Discussion

Internal waves caused by movement of submarines numerically investigated in three dimensions in the Persian Gulf and the Gulf of Oman. The results showed that internal waves created by movement have a wavelength on the order of ten times of the submarines length in a stratified medium. Waves caused by submarine motion depends on the speed and dimension of it. The wavelength of the waves also depends on the size of the submarine and the speed of its movement. The results related to the collapsing of turbulent wake also corresponded with theoretical results and is a third of Brunt-Väisälä frequency. Numerical modeling results showed that crossing of a submarine at a speed of 5 meters per second and 30 meters in length and 5 meters diameter can produce internal waves with height of less than 5 meters (less than the diameter of the submarine) and a wavelength of about 300 meters (More than 10 times the length of the submarine) with a speed of more than 5 meters per second (more than speed of submarine), which have been detected from a distance of about 7 kilometers. By studying the waves created by turbulent wake of submarine and internal waves caused by tides and bottom slope, this is clear that the period and height of these waves are quite different. So we can filter these waves by a filtering software. Due to the lack of studies in this field, two numerical model was used for modeling these parameters. Common points of two models are the Persian Gulf, the Strait of Hormuz and Gulf of Oman that are located between 54.5 to 56.5 East Longitude. Due to the time of collapse of turbulent wake and the physical properties of these waves, the location of submarine could be determined. The vertical and horizontal components of turbulent wake was investigated and it was found that the vertical component of turbulent wake within 100 meters of the submarine reaches about 2 meters. It Corresponded with experimental results and field studies¹⁷.

The results show that the magnetic field caused by the turbulent wake of submarine is a very big amount that is about 10 micro-Tesla. The measurement results show that the magnetic field induced by submarine is about 10 micro-tesla.

Conclusion

The present study showed that internal waves created by movement of a submarine have a wavelength on the order of ten times of the submarines length in a stratified medium.

Amplitude, wavelength and period of these waves, depends on submarine dimension and its depth.

The results have a good agreement with the results of experimental and theoretical results.

The results of two numerical models have a good agreement with each other.

References

- 1 I. B. Celik, Introductory Turbulence Modeling, West Virginia University, 1999.
- 2 M. Jahanmiri, The phenomenon of turbulence in fluids, Tehran: Sarvnegar, 2010.
- 3 A. M. Abdilghanie, "A Numerical Investigation of Turbulence-Driven and Forced Generation of Internal Gravity Waves in Stratified Mid-Water," Cornell University, Egypt, 2011.
- 4 H. E. Gilreath and A. Brandt, "Experiments on the generation of internal waves in a stratified Fluid," *AIAA*, vol. 17, pp. 83-100, 1983.
- 5 K. W. Kaulum, "PREDICTIONS OF SUBMARINE WAKE SIZE AND CONTAMINANT CONCENTRATIONS IN AN OCEAN ENVIRONMENT," Nuclear Monitoring Research Office Defense Advanced Research Projects Agency, California, 1972.
- 6 C. E. Meritt, "Wake growth in stratified Flow," *AIAA*, vol. 12, pp. 940-949, 1974.
- 7 S. Hassid, "Collapse of turbulent wakes in stable stratified media," *Hydronautics*, vol. 14, pp. 25-32, 1980.
- 8 A. Onufriev, "Turbulent wake in a stratified medium," *Zhurn Prikl Mekhaniki i Tehnich Fiziki*, vol. 5, pp. 68-72, 1970.
- 9 A. A. Bidokhti, "Flow Visualization of Internal Waves and Wakes of a Streamlined Body in a Stratified Fluid," vol. 9, no. 2, pp. 635-641, 2014.
- 10 G. G. Chernykh, N. N. Fedorova and N. P. Moshkin, "Numerical simulation of turbulent wakes," *Russian J Theoret Appl Mech*, vol. 2, pp. 295-304, 1992.
- 11 J. T. Lin and Y. H. Pao, "Wakes in stratified Fluids," *Annu Rev Fluid Mech*, vol. 11, pp. 317-338, 1979.
- 12 J. Kampf, Advanced Ocean modeling using open-source software, vol. first, London: Springer, 2010.
- 13 G. Chernykh, "Numerical simulation of turbulent wakes," *Russian J Theoret Appl Mech*, vol. 2, pp. 295-304, 1992.
- 14 Y. D. Chashechkin, "Internal waves, vortices and turbulence in a wake past a bluff body in a continuously stratified liquid," Grenoble, 1994.
- 15 E. Tuck, Submarine internal waves, University of Adelaide, 1993.
- 16 S. K. S. & D. Prof.Tatavarti, "Non-acoustic Detection of Moving Submerged Bodies In Ocean," *International Journal of Innovative Research & Development*, vol. 10, pp. 361-372, 2012.
- 17 M. Moonsan, Comprehensive engineering, naval architecture book, Tehran: Malek ashtar University, 2012.