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Analysis of Dynamic Stability of a Fast Single Craft Being Chased

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Abstract: Several important factors such as the metacenter point, the center of gravity and the center of buoyancy that is prevented from rolling unexpectedly need to be considered to create stability in the ship. In this paper, a fast single craft that can move at the maximum speed of 120 kilometers per hour is investigated and analyzed in terms of design and dynamics stability. According to the results of simulation, the drag and lift coefficients are 8.96×10^5 and 1.46×10^6 in the motion of single craft respectively. Also the results are desirable if the lift to drag ratio be more than one (Accordingly this ratio is calculated 1.62 in this paper). In the analysis of the movement of the vessels based on the drag and lift coefficients as 2.48×10^5 and 8.39×10^5 respectively, the ratio of the two coefficients is 3.38 which indicates the accuracy of the results.

Keywords: Dynamic Analysis, Craft, Simulation, Fluent Software, Drag Coefficient

1. Introduction

Today, the design and manufacture of fast crafts (particularly in the naval industry) that have high maneuverability, speed and dynamic stability is of particular importance. Accordingly many researchers have conducted studies in this field and have achieved different results. Moghoomi et al [1] in “a comparative study of laminar and turbulent flows of the vessels’ rudder with IFS 61-TR 25 and NACA0020 profile (by FLUENT software)" while investigating the lift, drag and momentum coefficients of both profiles concluded that this type of NACA0020 profile is inappropriate for laminar and appropriate for turbulent flows. Michio Uno and Yoshiaki Tokada [2] in “the effects of rudder and modified velocity on testing the ship mode” compared two new and classic methods in which they established the rate of propeller rotation and rudder effectiveness modifier factor in a new way and approached their model to the actual value which is much more accurate than the previous methods. Widmore and Perkovic [3] in “optimizing sailing against the wind by rudder rotor system” Concluded that the use of rudder torsion (bending) can reduce angle of inclination and the angle of sailing against the wind and provide good conditions for the deflector. Ben Jiu et al [4] in “Instable numerical simulation of turbulent flow cavitation around the propeller slopes” investigated the pressure created during the formation of cavitation and pressure at the propeller surface the laboratory results of which are the same as the experimental results. John Vandam et al [5] in “modeling a vessel by hydrodynamic smooth particles” studied the effect of water, hydrodynamic forces, fluid motion, and the motion of objects on the entry and exit of object in a case study that according to them the results are consistent with experimental studies. Montazeri et al [6] studied the effect of reducing the role of rudder on the moving object. In this study assuming a body with two degrees of freedom the mathematical model with second and fifth attenuation is analyzed for the rudder equations in the water and the results indicated that controlling the rudder increases its stability. Apostolos [7] in “optimization of ship design" examined a comprehensive approach to ship design and concludes that it is necessary to choose a multiple approach to design that can lead to improved and innovative design with increased bearing capacity and safety and reducing energy that finally improves environmental protection. Yosoke Tahara et al [8] in “multi-objective optimization method by CFD for ship design” studied three parts of the design based on the computational fluid dynamics. Also in his study as two types of optimization algorithms such as non-linear optimization algorithms and genetic algorithm were investigated that the genetic algorithm was more appropriate in terms of hydrodynamic performance. Alan Brown and John Salkdo [9] in “multi-objective optimization of navy ships” proposed a software program to design warships with systematic approach multi-objective based on mission effectiveness and life cycle.

2. Method

In this article first, a fast craft was analyzed by introducing the engineering relations of hydro-dynamic flow of marine crafts. Then using the FLUENT software (FLUENT 16.00 & Gambit 2.4.6) the boundary layer flows and other important factors were analyzed for the movement of a craft alone or when chased by the enemy.

2.1. Engineering Relations

In the floating objects if the metacenter point (M) is higher than the center of gravity, i.e. the GM distance is positive (metacentric height), the object will be stable and on the other hand if the metacenter point M is lower than the center of gravity, i.e. the GM distance is negative, the object will be unstable. In the designed mechanism first GM must be calculated according to this issue. Therefore, equation (1) determines the metacentric height. BM also represents the distance from the center of the buoyancy to the floating object’s center of gravity. Figure 1 presents the metacentric gravity and center of buoyancy points.

$$GM = BM - BG = \frac{1}{\Delta} - BG \quad (1)$$

In this equation I is the moment of inertia of the floating object’s section at the interface with water around the horizontal axis that spins around its axis and Δ is the fluid displaced by the object.

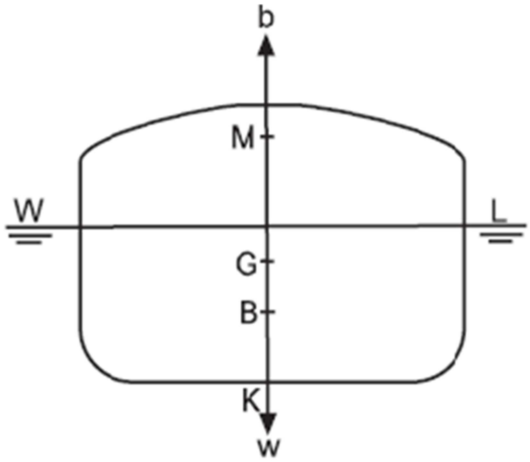

Fig. 1. *Metacenter, center of gravity and center of buoyancy points.*

If the angle between the lines is the buoyancy before and after the rotation is θ as shown in Fig. (2), the amount of momentum required to rotate an object as much as θ is obtained by equation (2).

$$M = W.GM.\sin(\theta) \quad (2)$$

Where: M is the momentum required to rotate the floater and W is its weight. Also, if the applied momentum on the floating object is removed, the floater will float around the rotation axis. Figure 2 presents the rotation caused by the momentum on the floater. In this Figure the momentum on the displacement of the center of gravity, buoyancy and metacenter points and roll angle created by the momentum are observed.

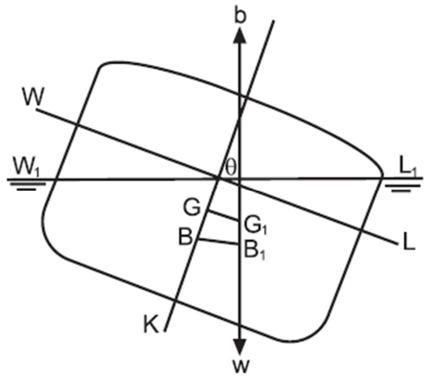

Fig. 2. *The effect of θ at the rolling time on the metacenter, center of gravity and center of buoyancy points.*

To calculate the time period T of a complete cycle of fluctuation of the floater, it is possible to use the equation (3).

$$T = \sqrt{\frac{K^2}{g.GM}} \times 2\pi \quad (3)$$

Based on the equation (3) K is the radius of gyration around the axis of rotation and based on the equation (4):

$$K = \sqrt{\frac{gI}{W}} \quad (4)$$

Given that the velocity of the craft under study is considered as 120 km/h, the thrust force can be obtained by Eq. (5):

$$Dr = 4\int C_f.(\frac{1}{2}\rho u_0^2)\, L.d.Z \quad (5)$$

Where: C_f is the coefficient of friction, ρ is specific weight, $u_0$is the velocity of the object and L is the length of the contact area with water.

Usually the shear and pressure forces’ distribution is created on the floating pad’s section. The thrust is not desirable such as friction force and it is usually attempted to minimize its value. For example, by reducing its amount it is possible to save fuel consumption in ships, planes, cars, submarines, and hybrid vehicles or help to increase the objects' safety exposed to fluid movement.

Therefore, the coefficient of friction C_f can be calculated by the following equation. So due to the turbulent flow based on equation (6):

$$C_f = \frac{0.0720}{\mathrm{Re}^{0.2}} \quad (6)$$

Also Reynolds number for the craft under study can be obtained by equation (7):

$$\mathrm{Re} = \frac{U.L}{V} \quad (7)$$

It should be noted that U_0 is the object's velocity up to 120 km per hour and L is the length of the floater which is considered as 4.5 m and also ν is the kinematic viscosity of water which is considered as 0.798×10^{-6} square meter per second for the sea 30°C. Equations (1) to (7) are extracted from the reference [10].

Also Table 1 shows the characteristics of the high speed craft under investigation.

Table 1. *Features of the fast craft.*

Feature	Amount	Feature	Amount	Feature	Amount
Width	200 cm	Total Weight	1500 Kg	Kind of Motor	4 cylinder / 4 steps
Length	450 cm	Pure Weight	850 Kg	Max. Power	850 HP

On the other hand, to calculate the stability of a vessel the level of buoyancy should be available. In fact, the buoyancy is the outcome of the pressure exerted on the upper and lower horizontal surfaces of the vessel or the outcome of the pressure exerted on the object in vertical direction. In calculating the center of buoyancy of the object usually the draft surface of the floating object is considered half of this amount is the line that through the axis of symmetry of the body which is considered as the center of buoyancy. Buoyancy can be calculated by equation (8).

$$F_B = \rho \times g \times \Delta \quad (8)$$

In equation (9) Δ is the weight of displaced water which is equal to the weight of the floating body. The distance between the buoyancy point and the metacenter is based on the equation (9). In this equation I is the second moment of the draft surface.

$$B_M = \frac{I}{\nabla} \quad (9)$$

In the crafts the transverse roll angle is important because it is more sensible and it is effective on the stability of the fast crafts but for the longitudinal roll angle it is negligible due to the low amount. Also changes in center of buoyancy versus the metacenter point are a function of changes in center of buoyancy and metacenter point at the same time.

But to analyze the effect of the vessel speed and its dimensions on dynamic balance it is necessary to analyze the lift, drag, and momentum coefficients are calculated and evaluated. For this purpose the Lift coefficient effective on fluid flow on rudder blade can be calculated by Equation (10).

$$C_l = \frac{L}{\frac{1}{2}.\rho.\mathrm{A_r}.\mathrm{U}^2} \quad (10)$$

Where: C_l is lift coefficient, ρ is the density of sea water, A_r is the floater's surface, U is the floater's velocity and L is its length.

But in addition to the lift coefficient, another factor that is effective in the design of the rudder is drag coefficient calculated by the Equation (11).

$$C_d = \frac{D}{\frac{1}{2}.\rho.\mathrm{A_r}.\mathrm{U}^2} \quad (11)$$

Where: C_d is the coefficient of drag and C_Q is the coefficient of momentum. The momentum coefficient can be obtained by Equation (12).

$$C_Q = \frac{QR}{\frac{1}{2}.\rho.\mathrm{A_r}.\mathrm{U}^2.C_m} \quad (12)$$

Where: C_m is the coefficient of momentum calculated by Equation (13).

$$C_m = \frac{\mathrm{A_r}}{b} \quad (13)$$

In the mentioned equations ρ is the density, U is the floater's velocity, A_r is the floater's surface, C_l is lift coefficient and C_d the coefficient of drag.

2.2. Analysis

As discussed in Equations (1) and (2) and the calculation of metacentric, center of gravity and center of buoyancy points, the metacenter point should be above the center of gravity for the transverse stability of the vessels; on the other hand based on the conducted equations and Fig. (3) it is observed that the metacentric center is above the center of gravity which leads to the stability in water such as moving right or left and prevent rolling and sudden deviation. Given that the military craft under study has four crews and carries military equipment such as machine guns and rocket launchers, the planned metacentric point in Figure (3) (GM) is about 100 cm above the center of gravity and the center of buoyancy is 20 cm lower than the center of gravity which indicates the proper conditions for roll angle and transverse stability.

In Figure (3) G is the gravity of the floating object, B is the center of buoyancy and M is the metacentric center.

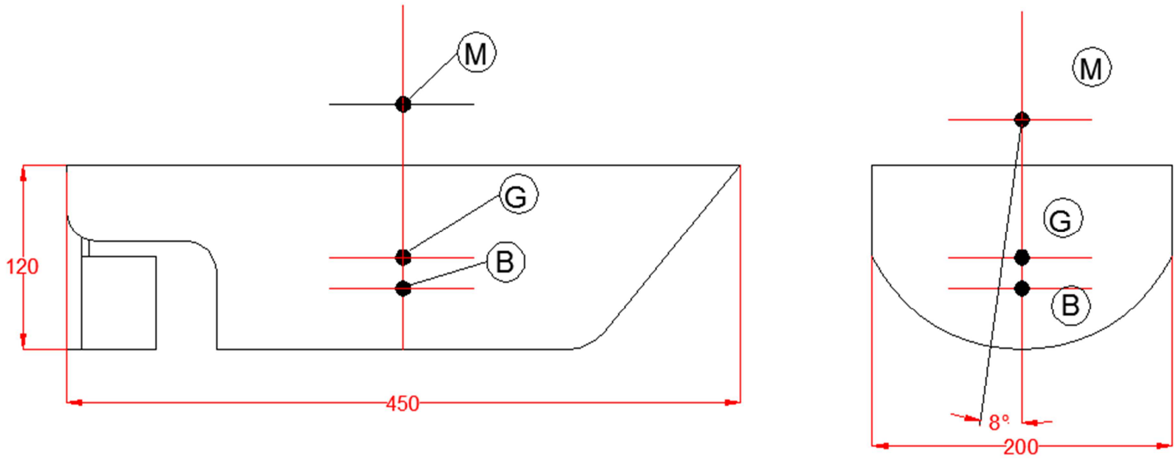

Fig. 3. *Metacenter, center of gravity and center of buoyancy points.*

As mentioned in Figure (3) the side and front view of the fast craft present the important centers of stability. On the right side the object may roll right or left due to severe wind. Therefore the roll point should be considered at the metacenter point.

After the floater's rolling the underwater section is changed or the form of the displaced water is changed such that the center of buoyancy is changed under the roll angle. Given that no object on the floater is displaced, the center of gravity remains unchanged at the point G. Also the weight, buoyancy and balance are unchanged. Another point is that normally the metacentric point should be between 0.5 and 3 meters so that it has good stability at the time of rolling and it does not exceed this value so that the steering of the vessel is not in trouble. In the high speed craft under study the metacenter is 100 cm above the center of gravity which is very desirable.

On the other hand, the propeller is affected by flow velocity around the hull that this velocity distribution is different than the steady state of the still water. This difference is due to the formation of boundary layer adjacent to the floating body and the creation of rotational speed caused by the waves. The effect of velocity distribution is usually displayed by Wake coefficient that is obtained based on the equation (14).

$$W = \frac{V - V_A}{V} \qquad (14)$$

Where: V_A is the water flow velocity in the propeller (when there is no propeller) and V is the forward velocity of the object under investigation. W is Wake coefficient which is usually between 0.05 and 0.5 [11].

For a closer look at hydrodynamic flows around the fast crafts dual situations are considered. That is, once it is assumed that:

a) The fast craft is moving along and the purpose is to know the situations around the floater by the turbulent flows.
b) If the vessel is chased by the enemy and the speed of both crafts are the same, what will happen for their body and how is the form of hydrodynamic flows?

In both assumptions first the problem inputs are considered based on Table 1.

Then given that the flow is affected by the velocity and sea water, the flow is considered turbulent. Accordingly the relations FLUENT software (FLUENT 16.00 & Gambit 2.4.6) is used to simulate and analyze the problem.

The results based on the table (2) and (3) are analyzed in the form of diagrams (5) to (9).

Table 2. *The results of double moving objects (being chased).*

parameter	amount
C_d	2.48×10^{5}
C_L	8.39×10^{5}
Continuity	4.54×10^{-4}
X-Velocity	3.55×10^{-4}
Y-Velocity	3.98×10^{-4}

Table 3. *The results of single fast craft's movement.*

parameter	amount
C_d	8.96×10^{5}
C_L	1.46×10^{6}
C_m	7.93×10^{6}
Continuity	7.86×10^{-4}
X-Velocity	5.85×10^{-4}
Y-Velocity	7.042×10^{-4}

Figures (4), (5) and (6) present the coefficient of drag, lift and momentum around the fast craft when it moves at a velocity of about 12 km/h.

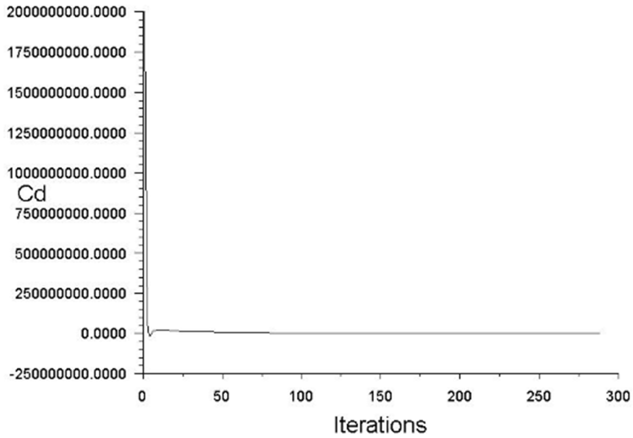

Fig. 4. *Drag coefficient influenced by fast craft's movement.*

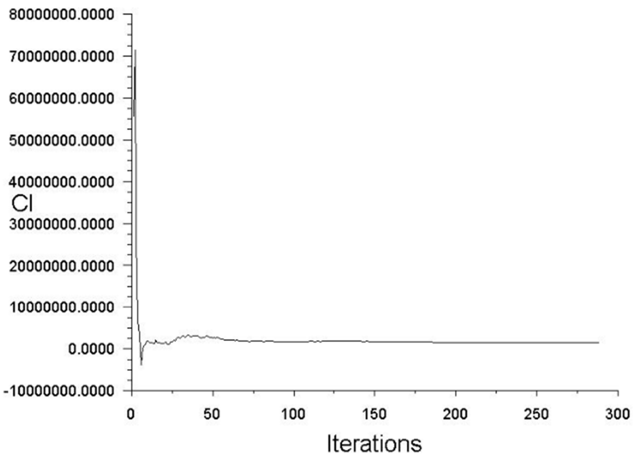

Fig. 5. *Fast craft's lift coefficient.*

The single fast craft's coefficient of momentum at a velocity of about 12 km/h is based on Figure (6).

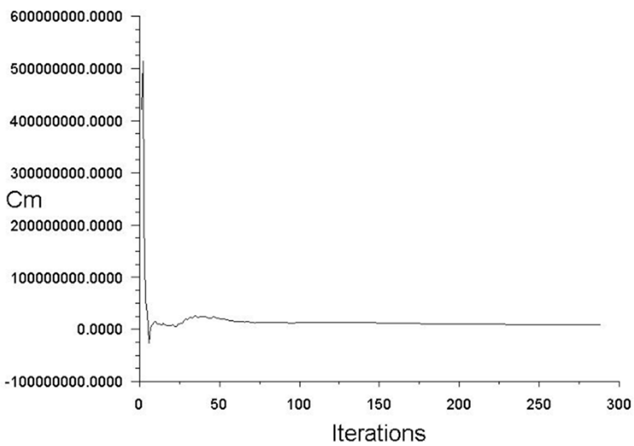

Fig. 6. *Fast craft's momentum coefficient.*

Also the static pressure lines' contour created in the fast craft's movement is obtained as Figure (7). The Figure indicates that there is no critical pressure in the front curvature of the floater and even its lateral surfaces.

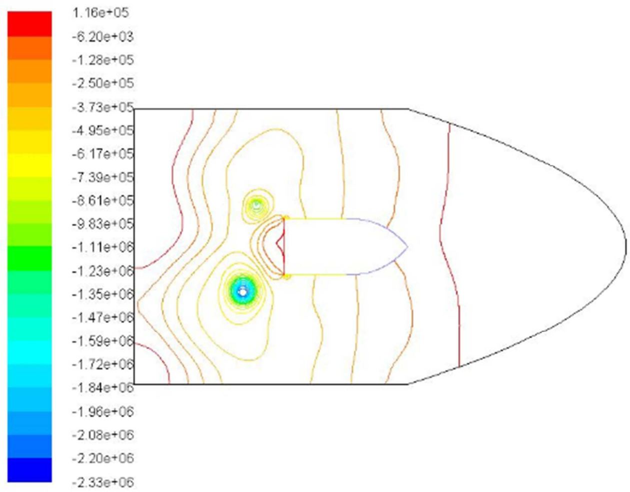

Fig. 7. *Static pressure contour created on the vessel's body.*

As it can be observed in Figure 8, the effect of velocity vector on the front side of the floating object are desirable and normal in the side parts but they are critical in the rear side of the craft which will be followed by negative impact in creating drag and reducing thrust. Therefore it is better to create a curvature proportional to the fluid flow on the rear corners of the craft to minimize drag. In any case, according to the high velocity of the moving object comfort of the crew and good steering are considered as the advantages of this craft.

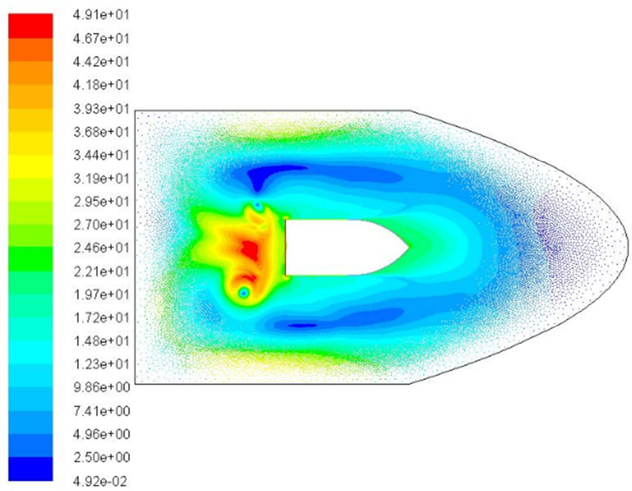

Fig. 8. *The velocity vector of the moving object (m/s).*

But in the charts shown in Figures (9) to (12) a condition of the crafts is simulated in which it is assumed that the craft is chased by the enemy and the velocity of both of them is identical. Figures (9) and (10) represent the drag and lift coefficients created on both floaters.

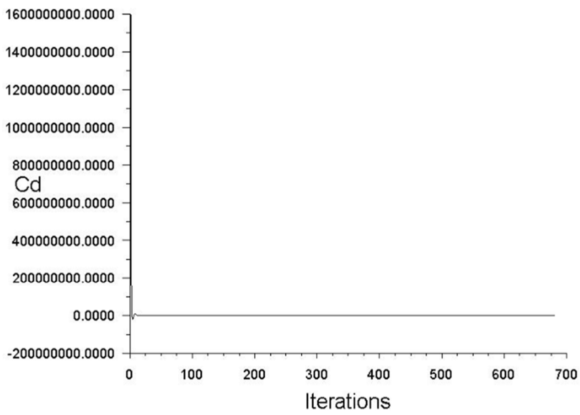

Fig. 9. Fast craft's drag coefficient.

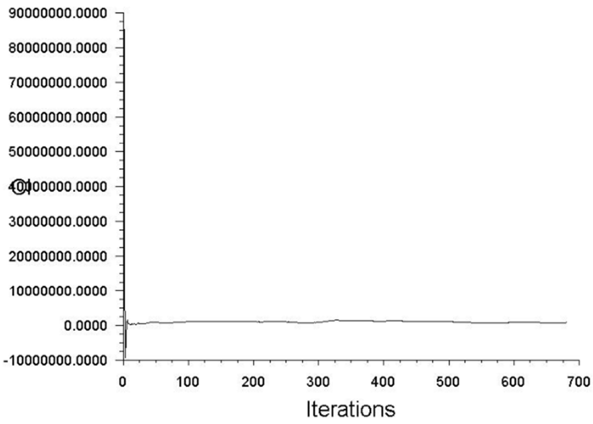

Fig. 10. Fast craft's lift coefficient.

But in Figures (11) and (12) the pressure contour and the object's velocity vector are observed. Figure (12) presents the velocity vector of the first object and has a high impact on the chaser vessel such that the front and side surfaces of the enemy's vessel are influenced by the movement of the first one. Of course it should be noted that the distance between the two objects is considered as 4m and if this distance is reduced the first craft can easily disturb the balance of the enemy and the static pressure increases significantly.

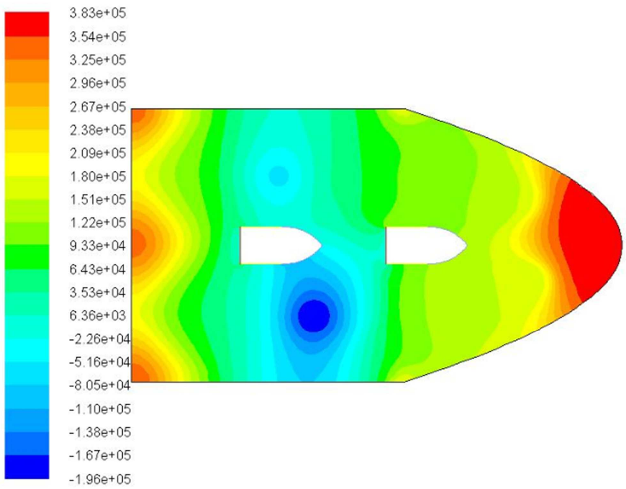

Fig. 11. Static pressure contour created on the vessels' body.

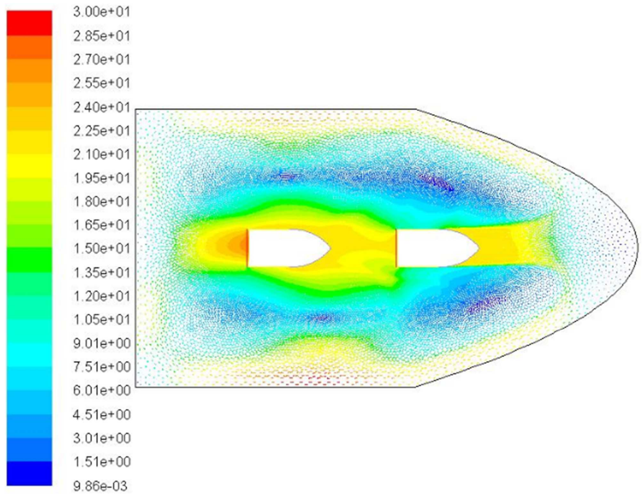

Fig. 12. The moving vessels' velocity vector's impact (m/s).

3. Conclusion

In this paper the movement dynamics of fast crafts is addressed. First the equations governing the engineering of marine vessels and design and stability specifications are investigated and then the fast craft is simulated.

In the conducted calculations first the center of gravity and buoyancy points are obtained and then the metacenter point is calculated. According to calculations, the metacenter point is 100 cm above the center of gravity which is indicative of the non-rolling of the vessel when bending to right or left and its stability. Also, to analyze the movement conditions of the vessel and the effects of waves on the hull of the vessel the drag, momentum and lift coefficients as well as the pressure lines contour and velocity vector are extracted by FLUENT as simulated diagram.

According to the simulation the drag and lift coefficients in the motion of single craft are 8.96×10^5 and 1.46×10^6 respectively and on the other hand based on the common calculations, if the lift to drag ratio is more than one, the results are desirable. Accordingly this ratio is 1.62. And in the analysis of the movement of the vessels based on the drag and lift coefficients as 2.48×10^5 and 8.39×10^5 respectively, the ratio of the two coefficients is 3.38 which indicates the accuracy of the results.

List of Symbols

Parameter	Symbol	Parameter	Symbol
Momentum	M	Radius of Gyration	K
Weight	W	Acceleration of Gravity	G
Surface Momentum	I	Coefficient of Friction	C_f
Time Period	T	Vessel's Velocity	U_0
Length of contact surface with water	L	Reynolds Number	R_e
Lift Coefficient	C_L	Floater Surface	A_r
Drag Coefficient	C_d	Rolling Angle	θ
Momentum Coefficient	C_Q	Displacement Volume	∇
Stahl Angle	A	Specific Weight	ρ
Kinematic Viscosity	N		

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