Numerical analyses for improved hydrodynamics of deep water torpedo anchor

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ABSTRACT. The literature shows a lack on well established guidelines on the design of the torpedo anchors. This research aims to investigate the effect of various geometric parameters in the torpedo anchors’ design to optimize for higher terminal velocity. A CFD model was developed and simulations were carried out using ANSYS FLUENT commercial software. Consequently, correlations between various parameters and its resultant drag coefficient were developed. The parameters of interest included geometric changes of the original design, as well as sea water properties that reflect water depth in South China Sea. New design features are proposed and investigated in the overall parametric studies. As a result, it was found that the terminal velocity can be improved by sharper tip angle, greater aspect ratio, greater diameter ratio, and an optimum rear angle of 30°. Clear relationships between each factor and its resulted terminal velocity were developed. More importantly, the sensitivity of drag coefficient towards each of the parameters was predicted.

1. Introduction
Floating structures such as floating production storage and offloading unit (FPSO) and mobile drilling unit (MODU) must be anchored with robust mooring system. These anchorage solutions are such as the Suction Caisson Anchors, Vertical Loaded Anchors (VLA), Suction Embedded Plat Anchors (SEPLA) and Torpedo Anchors. Among them, the torpedo anchor, which was initially developed and patented by Petrobras [1], has several advantages over the others. For instance, torpedo anchors are highly economical because no external energy is required for its installation [2]. Besides, it was found that the deployment of torpedo anchors is much easier and faster as compared to similar solutions such as VLA and suction piles [3]. In essence, torpedo anchorage system has competitive edge in terms of cost reduction and simplified installation [4]. Its applications are also less affected by increasing water depth as compared to conventional anchoring concepts [5].

Typical sizes of torpedo anchors range from 10-20 meters in height and 0.325-1.2 meters in diameter. A single unit of torpedo anchor can have a dry weight of 40-100 tons. It is usually released from an installation vessel with towards the seabed till a drop height of approximately 50 meters is reached. Then, it will be released to fall vertically downward by gravitational pull. Through the free fall period, the anchor is able to achieve a very high speed, and subsequently penetrates into the seabed. However, there exists a threshold speed for torpedo anchor regardless of the drop height [6]. This point occurs when the downward acceleration is equal to zero. This particular speed limit is known as the terminal velocity. According to Raie and Tassoulas [7], higher terminal velocity will
consequently provide greater holding capacity for the platforms, by resulting in deeper penetration. This finding is in line with the results of tests conducted by Hasanloo et al. [8].

The achievable threshold speed during the free fall phase of torpedo anchor has to be pushed forward for many future applications. However, there is a lack of research conducted for improvement on the terminal velocity during the anchor drop down. Besides, there is no well-established guideline developed for the designs of torpedo anchors.

Fernandes et al. [9] conducted small scale laboratory tests by using scaled torpedo anchors according to their design ratio. It was determined that presence of rear lines could increase the drag acting against torpedo anchor while it is travelling vertically downward. Moreover, the absence of pulley can further reduce the drag, thus result in higher kinetic energy gained by the anchor. Besides, according to Hasanloo and Yu [2], there is a minimum weight required for the anchor to fall steadily at different water depth. At the same time, density of the anchor was found to have positive impact on its travelling velocity. On the other hand, aspect ratio is identified to have direct influence on the drag coefficient of cylindrical prototypes, utilized by the European Nuclear Energy Agency to study the feasibility of disposal of radioactive waste through free fall cylindrical projectiles into oceanic sediments. The relationship was categorized as followed [2].

\[
0.030 + 0.0085 \frac{L}{D} < C_d < 0.039 + 0.0109 \frac{L}{D}
\]  

(1)

Furthermore, it was concluded that the embedment depth of torpedo anchor is directly proportional to its impact velocity [10]. The dependence of impact velocity on its geometry and mass are analyzed too. On the other hand, it was shown implicitly that embedment depth of torpedo anchor is dependent on its terminal velocity [11]; the variation of tip was illustrated too, but the resulting impact on its terminal velocity was not examined. CFD procedures were proposed for 3 major phases that the torpedo anchor will encounter, namely its installation, set-up by consolidation of soil, and pull out as reported by Raie [11]. Recently, Hasanloo et al. [8] used 7 prototypes of torpedo anchors with different densities, aspect ratio, scale ratio, and fin sizes to study their influence on falling velocity during acceleration. As a result, the relationship between drag coefficient, and Reynolds number, Re was plotted.

For sea water properties, the viscosity ranged from approximately 0.0010 N.s/m² to 0.0015 N.s/m² when water depth increases from 100 meters to 2000 meters [12]. Accordingly, sea water density changes from 1024 kg/m³ to 1028 kg/m³ within the same range of ocean depth. There were field tests being conducted to test the feasibility of using torpedo anchors for FPSO. It was found that torpedo anchor is well suitable for mooring of large FPSO in deep water; in this case it is the P-50 mooring system [3]. Specifically, a total of 10 units of T-98 torpedo anchors were used in this mooring system to provide necessary holding capacity for the floating structure. The T-98 torpedo design was done purposely for this FPSO operating in water depth of 1240 meters, in the Albacora Leste Field located in the Campos Basin, Brazil. According to Brandão et al. [3] this T-98 design has a total mass of 98 metric tons, diameter of 1.07 meters, and length of 17 meters with 4 wings to ensure its directional stability.

This research aims to propose designing methods for attaining higher terminal velocity. Besides, as the coefficient of drag is the determining factor for terminal velocity, correlations between geometric changes and its resulted drag coefficient will be developed.

2. Methodology

The present research makes extensive use of FLUENT for computational fluid dynamics simulations. The working fluid is a model of sea water, and the type of fluid flow is set to be turbulent due to the high velocities involved. Several assumptions are made such as the sea water is modeled as incompressible Newtonian fluid. The changes in temperature with
increasing depth are neglected. The horizontal velocity of fluid flow is assumed to be zero in comparison to the vertical free fall velocity of the anchor. Consequently, the anchor is assumed to have perfect downward directional stability during its free fall period. The parameters of interest involve sea water density and viscosity variation, which represents the water depth in South China Sea from water surface to a depth of 2000 m as referred to Murray [12]. Besides, the effects of varied design features such as tip angle, aspect ratio, rear angle, and diameter ratio were studied comprehensively in the parametric studies. Due to the limitation of space, only the effects of tip and rear angles are discussed in this paper.

2.1. Governing Equations
The problem of interest is assumed incompressible, isothermal and furthermore, the viscosity is taken as constant throughout the fluid. These assumptions greatly simplify the Navier-Stokes equation to the form

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f}, \]

where \( \mathbf{u} \) is the velocity, \( \rho \) the density, \( p \) the hydrostatic pressure, \( \mu \) is the viscosity and \( \mathbf{f} \) the external body force. Equation (2) needs to be complemented by the mass conservation equation

\[ m = \rho u = \text{constant} \]

Taking the particle derivative of equation (3) yields

\[ \frac{Dm}{Dt} = \frac{D\rho}{Dt} u + \rho \frac{Du}{Dt} = 0 \Rightarrow \nabla \cdot \mathbf{u} = 0. \]

2.2. Model Development and Boundary Conditions
The main idea of simulation is that the anchor is set at a stationary position in the middle of the domain with fluid flowing upward through the inlet with pre-defined velocity. Effects of each factor were obtained by repeated simulations with varied values, at recurring different velocities for each set of parameters. The boundaries are designed to be far enough from the torpedo anchor, so that the analyses are not affected by its proximity. Meshing was done with pre-dominantly quadrilateral cells, with small portion of triangular cells for smooth transitions at regions of irregular geometry. The dimensions used as the datum of 2D model are shown in figure 1.

![Figure 1. Baseline model with specified dimensions.](image-url)
Besides examining the influences of varied aspect ratio and tip angle for the conventional torpedo anchor design, the effects of newly proposed design features are investigated too. Different geometries were created, while the same settings for meshing as well as its solution setup were integrated.

![Figure 2. Illustration of rear angle, β and diameter ratio, D1/D2.](image)

The examined values for the main parameters are presented in table 1.

| Parameters                      | Base model | Present study          |
|---------------------------------|------------|------------------------|
| Anchor weight (kN)              | 400        | 400                    |
| Diameter (m)                    | 0.76       | 0.5, 0.667, 1.0        |
| Length (m)                      | 12         | 10                     |
| Water density (kg/m$^3$)        | 1024       | 998.2-1027.3           |
| Viscosity (N.s m$^{-2}$)        | 0.001005   | 0.001-0.0015           |
| Tip angle, $\alpha$ (°)         | 30         | 15, 30, 45, 60         |
| Aspect ratio (L/D)              | 15.79      | 10, 15, 20             |
| Rear angle, $\beta$ (°)         | -          | 0, 15, 30, 45          |
| Diameter ratio (D1/D2)          | 1          | 1.5, 2.0, 2.5          |
| Fin                             | Finless    | Finless                |

2.3. Mesh Dependency Check
To ensure that the solution is independent of the mesh configuration, the resultant drag coefficients versus different mesh density were recorded as shown in figure 3. It is evident that the drag coefficient tends towards a constant when mesh density is increased as depicted in figure 3. The final value of drag coefficient is independent of mesh density beyond a certain limit. The coefficient of drag converges towards stable value of about 0.24 when finer mesh is utilized. Thus, based on figure 3, all the simulations henceforth are conducted with mesh density of more than 4.25 triangles per unit area and beyond.
3. Validation
Firstly, the developed CFD model was compared with the results published by Raie, [11]. In line with the full scale field test performed by Petrobras [5], the simulation was done for a T-40 torpedo anchor. It was conducted by using a torpedo anchor made of steel with overall weight of 0.4 MN, length of 12 meters and diameter of 0.76 meters. Consequently, the percentage differences between obtained drag coefficient from CFD simulations and the reported values are 5.58% and 5.73%, for inlet velocity of 80 m/s and 90 m/s respectively. Furthermore, the calculated terminal velocity only deviates 3.76% from the reported value. Both reported values and results from CFD model are tabulated in Table 2. Another validation was done by comparison with laboratory test conducted by Hasanloo et al. [8] as shown in figure 4.

Table 2. Validation of model with full scale field test.

| Reported result [11] | Present | % difference |
|----------------------|---------|--------------|
| $C_d$ at 80 m/s : 0.2016 | 0.2134 | 5.58% |
| $C_d$ at 90 m/s : 0.2007 | 0.2122 | 5.73% |
| Terminal velocity, $V_T$ : 87.2 m/s | 83.92 m/s (calculated) | 3.76% |
Figure 4. Validation of present model with laboratory test of torpedo anchor.

This validation was conducted according to the specified dimensions. However, it was scaled up 10 times as the prototypes used were 10 times smaller than actual units. The drag coefficients obtained by present model was plotted against Reynolds number. As shown in the Figure 4, the results acquired from present simulations were very close to the experimental results with an overall error below 5%.

4. Result and discussion

4.1. Effects of Tip Angle, $\alpha$

Figure 5 shows the variation of torpedo’s terminal velocity versus the tip angle. It can be observed that terminal velocity always increases as the tip angle of torpedo anchor decreases. In other words, the drag force acting upon the anchor increases as the anchor’s tip become wider. As the graphs for different viscosity almost overlaps for the same density, it shows that the viscosity of sea water is less significant to influence its aerodynamics when tip angle is manipulated.

Figure 5. Effects of tip angle on terminal velocity at varied sea water density and viscosity.

To improve the anchor’s terminal velocity significantly, a $15^\circ$ tip angle can be implemented. It is noteworthy that there is an inflexion point for all conditions, which occurs at tip angle of $30^\circ$. Beyond
this angle, the effect of tip angle on the terminal velocity is less significant, as the gradient become much smaller. Furthermore, as it can be observed from the gradient of each density, the influence of tip angle is more dominant in sea region of lower density. In other words, the significance of tip angle is greater in shallower sea region as compared to deep sea region of application, in achieving higher terminal velocity. In essence, in order to ensure higher terminal velocity, a tip angle of 30° or smaller should be utilized.

Figure 6 depicted the drag coefficient versus the Reynolds number for different tip angles varied from 15° to 60°. Tip angle of 60° has notably highest drag coefficient as compared to lower tip angles of 15°, 30°, and 45°. As tip angle varies from 15° to 45°, drag force acting on the anchor increases steadily towards constant value from 270.09 kN to 281.36 kN. Thereafter, more drastic changes in the resisting force can be observed. Furthermore, the anchor’s terminal velocity decreases as tip angle increases from 15° to 60°. Thus, a design of torpedo anchor with tip angle beyond 45° is to be avoided. Sharper anchor tip would allow the torpedo to gain higher vertical downward speed with reduced drag coefficient.

4.2. Effects of Rear Angle, β

Figure 7 shows the effects of rear angle on terminal velocity for different densities and viscosities. It is obvious that in shallower water, terminal velocity reaches its optimum values at rear angle of 30°. The decrease in terminal velocity thereafter can be due to the vortices of fluid flow at the end of torpedo anchor, when the rear part becomes too sharp. This may also be resulted due to the presence of reversed flow, as rear angle is designed to be greater than 30°. However, for deeper sea water with higher density, the terminal velocity still does increase with rear angle greater than 30°, instead of decreased beyond that point. Thus, this finding should be taken into consideration for the anchorage systems of floating platforms at different depth. The implementation of new design feature: rear angle, turned out to be capable of improving the aerodynamics of torpedo anchor. As there is an angle at the end of torpedo anchor design, the drag force is reduced as compared to the original design. Subsequently, the greater downward acceleration is allowed to achieve higher terminal velocity. Nevertheless, there is an optimum rear angle which results in lowest drag coefficient and therefore smallest drag force, that is at 30° rear angle. The re-bounce of drag acting upon the anchor might be due to reversed flow or vortices of fluid at rear end of torpedo anchor. Anyhow, the inclusion of rear angle in torpedo anchor design is beneficial.
4.3. Sensitivity Analysis

Figure 8 shows the sensitivity of drag coefficients with respect to different parameters that were investigated. It shows that aspect ratio is the most influential factor that can be used to manipulate the drag coefficient effectively. This is followed by the rear angle, water viscosity, water density, anchor’s diameter ratio, and lastly tip angle being the least dominant factor. Aside from the percentages of influence, some parameters have negative impact on the drag coefficient. The parameters that have negative correlations with drag coefficient is illustrated by darken background in figure 8 and vice versa.

![Graphs showing sensitivity analysis](image)

**Figure 7.** Effects of rear angle on terminal velocity with different viscosities at sea water density of (a) 998.2 kg/m³, (b) 1012.75 kg/m³ and (c) 1027.3 kg/m³.
5. Conclusion
Anchor will encounter higher drag force to achieve greater terminal velocity as the water depth increases. However, the effect of water depth is not significant for torpedo anchor, as its terminal velocity does not vary much with increased sea water density and viscosity. Higher terminal velocity can be achieved by implementing higher aspect ratio, lower tip angle, greater β, and greater diameter ratio into its design. It is noteworthy to recognize the optimum tip angle is 30°. In line with that, the effect of diameter ratio is not substantial, but it may be utilized as one of the cost reduction measure. Drag coefficient is the most sensitive towards changes in aspect ratio, and its influence can be as high as 47% quantitatively in comparison to any other parameters.

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