A Drift Force On Submerged Body In AUV Design

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***Abstract*--Autonomous Underwater Vehicles (AUVs) are robots able to perform tasks without human intervention (remote operators). Research and development of this class of vehicles are growing, due to the excellent characteristics of the AUVs to operate in different situations. Therefore, this study aims to analyze the drift force over different geometric configurations of an AUV hull, in order to reduce the drag force on the body. It is important to design an AUV with minimizing the drag forces acting on the hull to make AUV cruising smoothly. We also simulate the drift force for our X4-AUV ellipsoidal shape to compare the results with other hull shape.**

***Index Terms*--AUV, Drift force, Ellipsoid, Slenderness ratio.**

I. Introduction

Underwater vehicles are being used in an ever increasing number of applications ranging from scientific research to commercial and leisure activities. Most of them tend to be used for a specific application, consequently, there is a wide variety of underwater vehicles in operation. These vehicles can be categorized into several different groups according to their particular characteristics. One of these characteristics is the method of control and the groups used in this category are defined as illustrated in Fig. 1.

This work focuses on Unmanned Underwater Vehicles UUVs) and more specifically AUVs. AUVs have onboard control systems that use the information recorded by sensors to determine the demands to be sent to the vehicle actuators to complete the defined missions. The reliance on these components dictates a need for a robust design. A constraint on the use of an AUV is the limited energy supply that can be carried onboard. Most AUVs use batteries of various types to provide both propulsion and power. Therefore the total energy available is limited by the available volume (or weight) for batteries and the energy density of the chosen batteries.

These two characteristics of AUVs heavily influence the design choices during the development of an AUV. The autonomous nature of the vehicle means that key design factors include reliability, robustness and controllability. The limited energy available means that the energy cost associated with the various choices is a key factor in the design evaluation process. The combination of these factors shows that the design cycle for an AUV is highly iterative.

In contrast, ROVs are operated with a connection to a surface station, either on land or on a surface vessel. This connection is used to provide a communication link between the vehicle and a human operator, allowing human control, rapid data transfer and much larger power supply. On most ROVs the control system is dependent on partly human, partly automation; some elements of the control systems are undertaken using automatic control (for example depth control) allowing the human operator to concentrate on the intricacies of the particular task. The larger power supply allows the designer (and operator) to design the vehicle with less consideration for the energy required and this freedom also allows redundancy to be built into the design, for example in thruster configurations, which is not found on energy limited AUVs [1].

The required range of a vehicle can significantly influence the characteristics of an AUV during the design of the vehicle. For example, the design of a short range AUV requires less emphasis on propulsive efficiency in energy use. This freedom allows the short range AUV designer to include more energy consuming devices and to be optimized for the mission requirements. On the other hand, the key to successful long range AUV design is a compromise between functionality limitations and mission range requirements and hence greater emphasis on hydrodynamic efficiency. The AUVs were first built in the 1970s, put into commercial use in the 1990s, and today are mostly used for scientific, commercial, and military mapping and survey tasks [2].

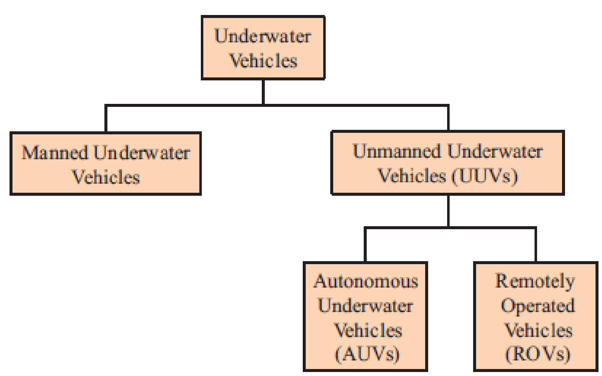


Fig. 1. Types of underwater vehicles

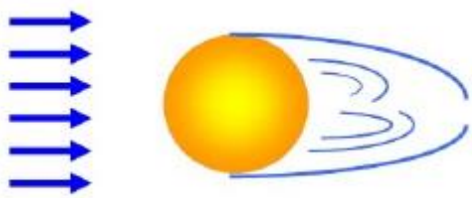
II. General design of an AUV

There are several aspects in AUV electrical and mechanical design need to be looked at closely so that the design will be successful. In order to design any AUV, it is essential or compulsory to have strong background knowledge, fundamental concepts and theory about the processes and physical laws governing the underwater vehicle in its environment. Therefore, the major design aspects that need to be considered [3] are identifying hull design, propulsion, submerging and electric power.

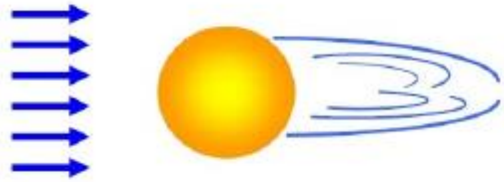
A. Hull Design: Shape and Drag

The most basic characteristic about an AUV is its size and shape. The basic shape of the AUV is the very first step in its design and everything else must work around it. The shape of the AUV determines its application, efficiency and range. There have been a wide variety of AUVs in size and shape, ranging from [4]:

- Conventional torpedo proportions, large and small.
- Laminar flow, bulbous hull to reduce drag.
- Streamlined rectangular style.
- Multi hull vehicles, splitting the energy, propulsion and mission management from the sensor payload into separate hulls.



(a) Laminar boundary layer



(b) Turbulent boundary layer

Fig. 2. Laminar and turbulent boundary layer separation

The laminar flow body achieves low drag by maintaining laminar flow over most of its length by virtue of its bulbous shape. From a simple perspective of drag reduction, a form that promotes laminar flow within the boundary layer is the best choice. In laminar flow, fluid particles move in layers and skin friction drag is much lower than that in a turbulent flow where fluid particles more erratically resulting in higher shear stresses between layers (see Fig. 2). For determining whether a flow will be laminar or turbulent, a Reynolds Number (the ratio of inertial forces to viscous forces) is used. Laminar flow occurs at low Reynolds numbers, and is characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by random eddies, vortices and other flow fluctuations. To sustain laminar flow, a hull can be designed such that the diameter increases gradually from the nose to create a favorable pressure gradient over the forward 60 – 70% of the hull. In this area, the surface must be smooth and as hydrodynamically clean as possible. Forward-mounted hydroplanes cannot be allowed because they disturb the laminar flow. Consequently all hydroplanes are to be fitted on the-boom. Acoustic payload, communication and navigation transducers must be located as far aft as possible so that the resulting openings or protuberances do not disturb the laminar flow. Figure 3 shows a typical shape of such a hull. The main disadvantage of this unique shape of the laminar flow body is that it does not readily permit lengthening or shortening of the vehicle, thus limiting the possibility of modular expansion [5].

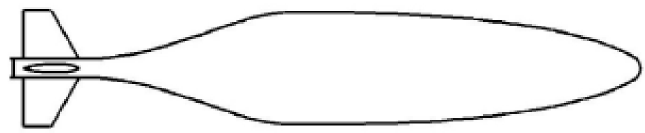


Fig. 3. Outline of laminar flow body

There have been a wide variety of AUVs in size and shape such as spherical hull shape, torpedo and non-torpedo shape, streamlined shape etc. as shown in Fig. 2 – 8 [1], [6], [7]. Most AUVs used in science and industry today can be classified into a torpedo shaped design and a non-torpedo shaped design independent of other characteristics. Figures 6 and 7 show some of the state of the art AUVs in the science community today. This classification is important because it governs a lot of the characteristics of the AUV. A typical torpedo shaped or single hull AUV has less drag and can travel much faster than its non-torpedo shaped counterpart.

A torpedo shaped AUV usually uses an aft thruster and fins to control its motion; thus these designs need some translational speed to keep full control of the vehicle. This class of AUVs in general has a much longer range and can work well in areas with moderate currents. They are appropriate for low resolution scalar surveys in larger areas, but are not suited for optical surveys or high resolution bathymetric surveys of a smaller area. These AUVs have 6-DOFs, namely *x*-, *y*-, *z*-translation, roll, pitch and heading, but these cannot be controlled independently, making the autonomous control of these AUVs relatively harder.

The non-torpedo shaped AUVs are typically designed to be completely controllable at much lower speeds. The multiple hull design makes these kinds of AUVs passively stable in pitch and roll, which means the other DOFs can be independently controlled using multiple thrusters. A larger form factor for these vehicles means a higher drag, which makes their use difficult in areas with significant currents. The lower speeds and high maneuverability of this class of AUVs means higher navigational accuracy to follow very close tracklines. They are well suited for high resolution photographic surveys, multibeam mapping and sidescan surveys. The difference in the two classes of AUVs is analogous to that of the airplane and helicopter. They have their own advantages and cater to different applications. The science community will always have these two kinds of AUVs co-exist to meet the complete set of requirements.

AUVs have tended to be designed around length to-diameter (L/D) ratios of five to eight, mimicking in some respects naval torpedoes and aircraft drop tanks to provide the maximum volume for minimum drag. But AUVs have the additional design constraint to reduce the risk of collision with the mother ship during launch and recovery and will have a larger footprint on the ship's deck. However, the drag coefficient (CD) values for the National Advisory Committee for Aeronautics' (NACA) aerofoil solid of revolution versus *L/D* ratios of two to 10 show a surprisingly constant *CD* down to a *L/D* value as low as three (excludes control surfaces) [1]. Similar results are seen in early wind tunnel work performed on airship models. Thus, short, fat AUVs do not have a significantly higher *CD* than slender ones and are inherently easier to handle and store on board a ship, although short vehicles may have stability issues that need to be considered. A more important drag consideration is the variation in drag between the idealized shape and the practical vehicle.

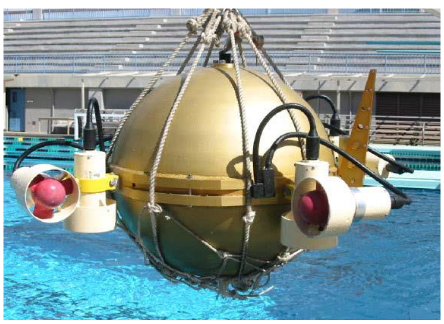


Fig. 4.ODIN spherical hull shape [7]

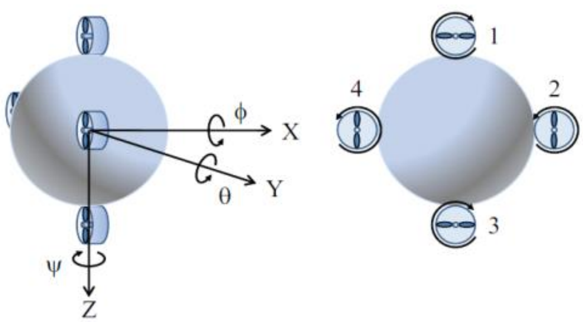


Fig. 5.X4-AUV with spherical hull shape [1]

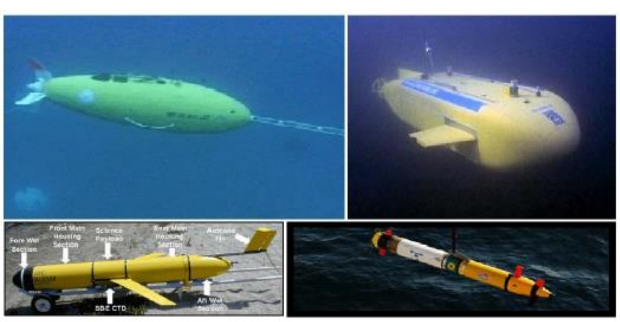


Fig. 6.Torpedo shaped AUV [1]

Fig. 7. Non-torpedo shaped AUV [1]

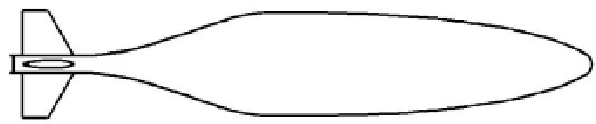


Fig. 8.Caption AUV with laminar flow body [1]

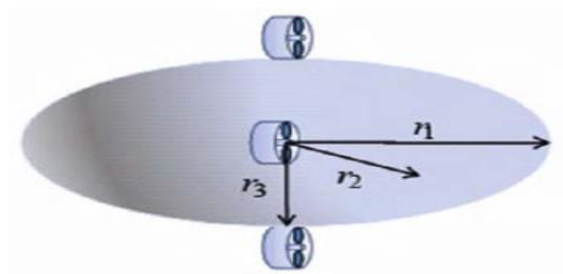


Fig. 9.X4-AUV with an ellipsoidal body that mostly closes to a streamlined shape [1]

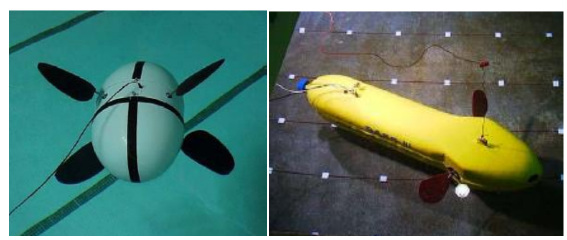


Fig. 10.Biomimetic robots Bass3 (left) and Pilot Fish (right) [1]

B. *Submerging*

In the case of a submersible vehicle, since the volume of the vehicle remains constant, in order to dive deeper, it must increase the downward force acting upon it to counteract the buoyant force. This can be accomplish either by increasing its mass via the use of ballast tanks or by using external thrusters. Ballasting is the more common approach for submerging. This method is mostly mechanical in nature and involves employing pumps and compressed air to take in and remove water. The alternative is to use thrusters that point downwards. This is a much simpler system, but is quite inefficient in terms of power consumption and not really suited at great depths. To reduce the size of ballast tanks or the force required by thrusters for the process of submerging, AUVs are usually designed so as to have residual buoyancy. That is, the weight of the vehicle is made to be more or less equal to the buoyant force.

C. *Submerging*

Some sort of propulsion is required on all AUVs and is usually one of the main sources of power consumption. Most AUVs use motors for propulsion due to the scarcity and cost of alternative systems. The location of the motors affects which DOFs can be controlled. The positioning of the motors can also affect noise interference with onboard electronic components, as well as propeller-to-hull and propeller-to-propeller interactions. Propeller to-hull and propeller-to-propeller interactions can have unwanted effects in the dynamics of an AUV. When travelling at a constant speed, the thrust produced by the motors is equal to the friction or drag of the vehicle. Power consumption for the propulsion system increases dramatically as the speed of the vehicle increases. This is because the thrust power is equal to the product of the thrust and the speed, meaning thrust power is a function of speed cubed. Therefore, because of an AUV's limited energy supply, it must travel at a speed that does not draw too much power, but at the same time does not take too long to complete its mission.

D. Submerging

Electric power is commonly provided via sealed batteries. The ideal arrangement of batteries is to have them connected in parallel with diodes between each one to allow even discharge and to prevent current flow between batteries. Fuses or other protective devices should also be used to prevent excessive current flow in case of short circuits occurring or components malfunctioning. The restrictive nature of power on AUVs influences the types of components and equipment that can be utilized. Components and equipment should be chosen so as to draw as little power as possible in order to allow the batteries to provide more than enough time for the vehicle to complete its mission.

III. Drift Force on Submerged Sphere

Spherical coordinates are used in the formulation of the drift forces of the sphere. The potential function is obtained in the spherical coordinates which is then differentiated to the generate velocity components. The velocity squared term is further simplified and an integrand is obtained in terms of hyperbolic and trigonometric functions of ka, θ and μ. The graphs for the dimension less force are developed for different values of ka which can be used to calculate the second order drift forces for a rigid sphere [8]. Based on the derived drift force formula for a sphere [8], we simulate the ODIN model where it was the first version of AUV that developed by using a sphere shape to get the drift force for this AUV by referring to the parameters in Table 1.

The squared velocity results in the sphere submerged in water with different water depths have been calculated keeping the ratio of depth of submergence to the radius as constant parameter. The results showed (Fig. 11) that as the water depth increases the mean drift force decreases. Also, drift force peaks for intermediate values of ka showing an almost similar trend as shown by hemisphere. The higher values of ka the force almost approaches to zero. Also, it is seen that as the sphere comes closer to the surface the drift force increases as can be seen from the plot.

TABLE I
ODIN Parameters[4].

Parameter	Value & Description
r	0.3 m radius of the vehicle
m	125 kg mass of the vehicle
g	$9.8\,\frac{m}{s^2}$ acceleration of gravity
lx	$\frac{2}{5}mr^2 kgm^2$ moment of inertia for a sphere
zg	0.05 m vertical location of the CG
ρ	$1000\,\frac{kg}{m^3}$density of water
Kp	$0kgm^2$ hydrodynamic added moment of inertia

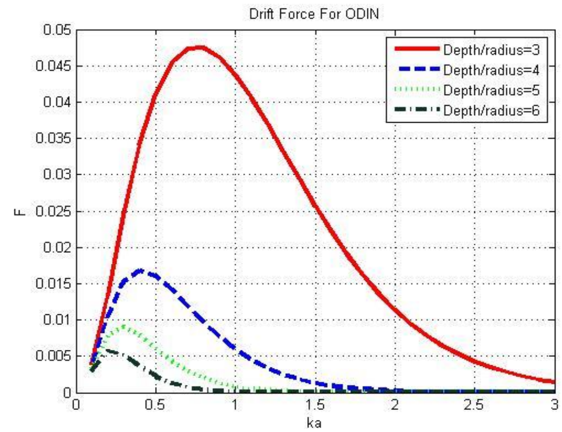


Fig. 11. Drift force for ODIN

IV. Drift Force on Submerged Ellipsoid

Ellipsoid shape has three major axes to be considered as shown in Fig. 12. Nowadays, most of the AUV body design is based on torpedo or ellipsoidal shape.

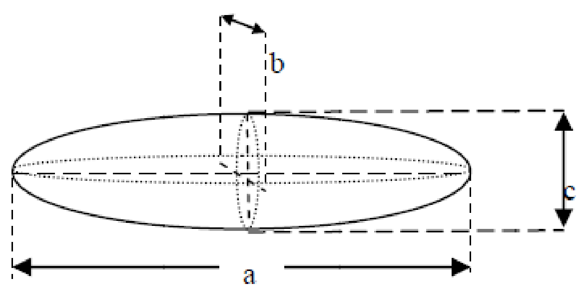


Fig. 12. Ellipsoid geometry [3]

In order to prove and demonstrate the theory for the ellipsoid, an ellipsoid AUV model and its parameters as shown by Wang et al [8], will be implemented to the derived drift force formula for ellipsoid proposed by A. Gupta [9]. The formula implementations were derived based from the Wang et al AUV [9], length in the horizontal plane and longitudinal plane. The dimension value also considered where finally the ratio of value *a*, *b*, and *c* obtained. This ratio value can be applied to any types of ellipsoid body for obtaining the drift force. Based on Fig. 13:

- Horizontal plane: 1458.54 $cm^{2\cdot}$ $(\pi ab/4)$ used to obtain the minor axial length.
- Longitudinal plane: 9040 cm^2. $(\pi ac/4)$ used for the vertical minor axial length.
- The maximum dimension=200, so assuming a = 200 and by equating the areas, value of b = 92. 7 cm and c = 57. 56 cm
- Ratio of a: b: c = 1: 0.4635:0.2878. The maximum value of a: b: c = 1: 0.5:0.3.

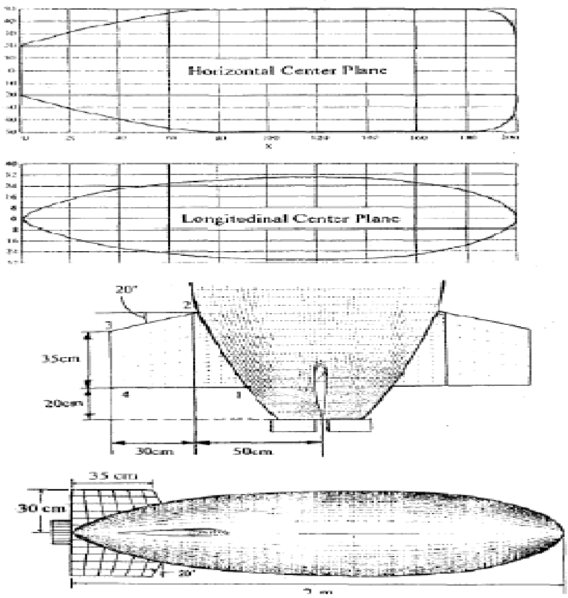


Fig. 13. AUV model as shown by Wang et al [8]

Based on the slenderness ratio given in [8], we simulate the model in [9], to calculate the drift force for our ellipsoidal X4-AUV as shown in Fig. 14.

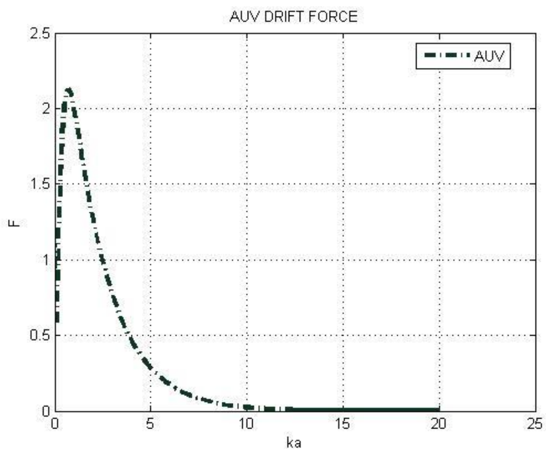


Fig. 14.X4-AUV ellipsoid version drift force (a:b:c = 0.99:0.19:0.199) using Wang Model.

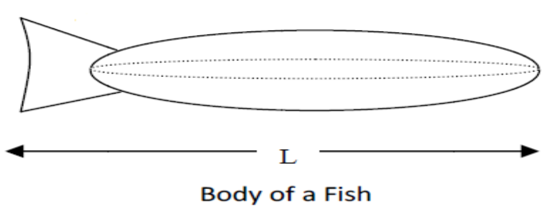


Fig. 15.Length of fish [8]

Then, to illustrate a real life example, an example of a fish's body (streamlined shape) is considered which is approximated as an ellipsoid. The drift forces acting over body of different fishes have been shown in the graph (Fig. 16), which proves that slender body of a fish face very less load as compared to other structures. The fish's body has been assumed as an ellipsoid with the major axes a = 0. 93L, b = 0. 195L and c = 0.112L, where L is the overall length of the fish. This is a reasonable assumption for the dimension for dorsal = a, lateral = b, and head aspect = c, but less accurate with tail aspect of fish [9].

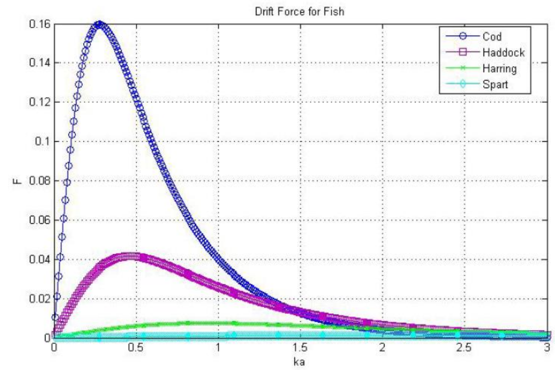


Fig. 16.Drift force for fish [9]

The different fishes are considered for analyses with their respective overall lengths are given in Table 2 [8]. It can be concluded from the graph that the longest fish is having a maximum force which is expected as the longest fish will have the maximum surface area for the same ratio of the axes. The drift force on ellipsoidal X4-AUV using the slenderness ratio for ellipsoid based on fish characteristic is shown in Fig. 15.

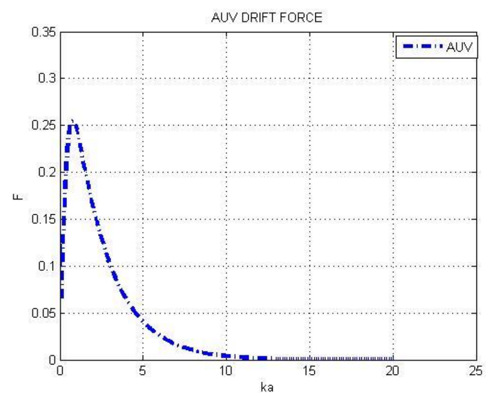


Fig. 17.X4-AUV ellipsoid version using fish behavior drift force (a=0.93L, b=0.1995L, and c=0.112L).

TABLE II
Geometrical Approximation of Different Fishes [9].

Fish	Length
Cod	120 cm
Haddock	60 cm
Herring	30 cm
Sprat	15 cm

V. DISCUSSION

An AUV with spherical hull shape design facing with the drag forces against a stream are relatively higher than other AUVs. It is proven that AUV with ellipsoidal body that mostly closes to a streamlined shape can reduce the drag force on the body. In order to provide the minimum drag to the maximum volume AUV, the AUV were tended to be designed with the guide of slenderness ratio where the value of length divided by the diameter. The best ratio for the AUV body development were in the range of 5 to 8, mimicking in some respects naval torpedoes and aircraft drop tanks to provide the maximum volume for minimum drag. In the ellipsoid approach, the best slenderness ratio that needs to be followed is 5 where this will improve the performances and the efficiency to the fullest [4]. Long and slender shapes are therefore better for frontal drag. The comparison of the slenderness ratio between models which discussed in this paper is shown in Table 3.

From Fig. 14 and Fig. 17, we can see that the simulation on X4-AUV with an ellipsoidal shape which follow slenderness mimic to the fish give the lower drag force compared to the slenderness ratio proposed by the Wang where the calculation for the drift force based on the equivalent area method.

TABLE III
Slenderness Ratio of AUV Models.

Model	Slenderness ratio (l/d)
ODIN (Sphere)	30cm/30cm=1
Wang et al AUV (Ellipse)	200cm/92.7cm=2. 2 (major) 200cm/57.56cm=3. 5 (minor)
X4-AUV (Ellipsoid)	100cm/20cm=5

VI. CONCLUSION

Minimum drag is one of the important parameters of the AUV with respect to the shape and size. From this study, the streamlined shape of the AUV hull can reduce the drag force on the body. Therefore, it is important to know the best value for the slenderness ratio to enable the shape and size of the ellipsoid mimic to the biological fish which can give the minimum drag force.

VII. FUTURE WORKS

Based on this study, we will design and develop an X4-AUV with an ellipsoidal shape by choosing the appropriate slenderness ratio to get the streamlined body that close to the slenderness ratio of biomimetic ellipsoid (fish).

VIII. ACKNOWLEDGEMENT

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