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Comparison of Swimming Performance between Two Dimensional Carangiform and Anguilliform Locomotor

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Abstract – *The flapping hydrodynamics of fishlike structure entices the spotlight of researchers nowadays due to its remarkable strength in producing high efficiency propulsion by the coordinated manipulation of vortex shedding. The research field shows a substantial room for improvement and in the current study, the flapping hydrodynamics between carangiform mode and anguilliform mode of swimming was investigated. Using ANSYS CFX software, simulation was carried out to study the effect of the inlet flow velocity to the wake and swimming performances of both swimming modes. The ratio of flapping velocity and cruising velocity (Strouhal number) stands out to be a prominent parameter that would determine the propulsive efficiency. Carangiform and anguilliform swimmer reach their optimal Strouhal number at 0.290 and 0.305 respectively, while peaking their propulsive efficiency at 0.86 and 0.71 accordingly. Hence, carangiform swimmer outperforms anguilliform swimmer due to its lesser body undulation. The upper and lower critical Strouhal number exist as well when the inlet flow keep increasing.*

Keywords: Flapping Hydrodynamics, Carangiform Swimmer, Anguilliform Swimmer, CFX Simulation

1.0 INTRODUCTION

Flapping hydrodynamics is the study on liquid motion due to the manipulation of flapping mechanism. Using flapping mechanism, fish would able to coordinate the rhythmic unsteady body and tail motion to minimize the energy required for steady swimming [1], and to circumvent the high drag water environment as a high speed swimmer [2]. The consequent research query is the identification of fish's optimal swimming performance. Most of the researches have corroborated that, most of the cetaceans would swim within a narrow range of Strouhal number, *St*, with the range of $0.2<St<0.4$, peaking at about $0.25<St<0.35$ [3-5].

The locomotion style of fishes gives considerable impact to the swimming performance. The fish locomotion can basically divided as body and caudal fin (BCF) locomotion and median and paired fin (MPF), and too cater the research purpose of the paper, introduction of BCF locomotion will be underlined in this section. BCF locomotion can be generally spanning from undulatory to oscillatory motions. Undulatory motions involve the passage of a wave along the propulsive structure, while in oscillatory motions the propulsive structure swivels on its base without exhibiting a wave formation. In other words, BCF swimmers can be classified according to the extent of body undulation such as anguilliform, subcarangiform, carangiform, thunniform and ostraciiform swimmers, as shown in Figure 1.

For the more detailed locomotion difference, the carangiform swimmers bend through about half of a wave, which only reaches a substantial amplitude in the posterior part third of their bodies, meanwhile anguilliform swimmers undulate with about one complete wave on their bodies, with substantial undulation amplitude even close to head [6].

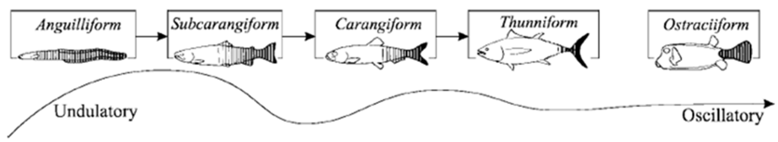

Figure 1: The classification of BCF swimmers, with the spectrum of propulsion ranging from undulatory to oscillatory locomotion (Taken from [7]).

Generally carangiform mode will be more efficient since the thrust is produced only at the trailing edge of the tail since any relatively larger portion of body undulation is wasted energy and to swim efficiently the structure shall undulate their body parts within the smallest degree as possible [8]. For the eels, its body and tail is lack of apparent flow separation and upon their undulating movement, a single, large vortex ring wrapping around their body in the centre, producing thrust almost exclusively along the body, but not at the tail tip, which seems to give rise to formation of drag [9]. Since these previous researches only report their justification based on some physical reasoning, the investigation using mathematical modelling and simulation will be carried out to investigate the swimming mechanics of the carangiform and anguilliform swimmer. The highlighted question is the unknown comparative swimming performances between two contrasting swimmers, the carangiform and anguilliform swimmer, when both of them are subjected to different water flow conditions. The relationship between the undulating structure and the surrounding flow would be one-way fluid structure interaction, and it is studied in two-dimensional form.

2.0 METHODOLOGY

The modelling was completed using the ANSYS CFX 14.0 commercial software, while the Design Modeller software was applied to generate the geometry of slender body. To resemble the chord-wise section of the caudal fin, NACA 0016 was applied [10], and the yielded equation is illustrated as Equation (1).

$$y = 0.8(0.297x^{0.5} - 0.126x - 0.354x^2 + 0.284x^3 - 0.102x^4) \quad (1)$$

2.1 Movement Equations

Albeit complex swimming locomotion in nature, only two modes of swimming pattern need to be considered, the carangiform and anguilliform swimming modes. In such case, mathematical models can provide simplified representation of the flow-body interaction that can be studied more extensively. The motion for a straight line carangiform swimming mode could be fully described by specifying the motion of its backbone with several key kinematic parameters, and can be characterized by a traveling backbone wave of smoothly varying amplitude and undulating frequency. The general equation of the backbone waveform, z(x) [11] can be written as Equation (2).

$$z(x)=a(x)sin\left(\frac{2\pi}{\lambda}x-2\pi ft\right) \tag{2}$$

The wavelength, λ is set as a constant variable with the value of 1.67m meanwhile the frequency of the undulating backbone is fixed at 2.07Hz [12]. z(x) is the displacement of centerline, λ is the wave length and f is the undulating frequency. The wave amplitude $a(x)$ is defined by a form of quadratic polynomial [13] as shown as Equation (3).

$$a(x) = C_0 + C_1x + C_2x^2 \tag{3}$$

in which C_0, C_1 and C_2 are coefficients which will determine the geometry of the wave amplitude along the slender body in which $C_0 = 0$, C_1=0.00232 and C_2=-0.163. In the meanwhile, the backbone amplitude equation for anguilliform swimmer can be defined as a cosine wave form as suggested in Equation (4).

$$a(x) = 0.095\ cos\ (2.5x) \tag{4}$$

2.2 Governing Equations

The Reynolds Averaged Navier-Stokes (RANS) equations were applied in this study. There are quite a number of RANS models existed, and among the models, according to the study done by Ugur et al. [14], the SST model displayed a better overall predictive capabilities among them in terms of velocity, vorticity and shear stress. Since it is able to capture the thickness of the shear layer more accurately, it will be a robust model among the variation among RANS equations to model the effect of turbulence flow of the near wake of body. The governing equations include the RANS continuity equation and momentum equation is shown in Equation (5) and (6).

$$\frac{\partial \overline{u_i}}{\partial x_i}=0 \tag{5}$$

$$\rho\left(\frac{\partial \overline{u_i}}{\partial t}+\overline{u_k}\frac{\partial \overline{u_i}}{\partial u_k}\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}\left(C\frac{\partial \overline{u_i}}{\partial x_j}\right)+\frac{\partial R_{ij}}{\partial x} \tag{6}$$

To close the above equations, WKO is one of the methods. However the model has two problems: the spurious sensitivity to free stream condition and not reliable in flows with detached shear layer. As a result SST model is developed from the WKO by introducing a limiter to the formulation of eddy viscosity in order to improve predictions in adverse pressure gradient boundary layers and to solve the problem of free stream sensitivity. The model is further developed into some functions and they have been coded in the ANSYS CFX software.

2.3 Definition of Parameters

Strouhal number, St can be physically interpreted as the ratio between flapping velocity of the trailing edge and the flow velocity altered due to the flapping trailing edge. Mathematical, St can be formulated as Equation (7) [15].

$$St=\frac{fA}{U_A} \tag{7}$$

where A is the mean lateral excursion of caudal fin at trailing edge, while U_A is the average fluid flow velocity behind the trailing edge, or in other words, the swimming velocity of the flapping structure.

The next instrumental parameter of interest to be put forward is the propulsive efficiency, η, which is applicable when the simulated structure starts to flap. The propulsive efficiency, which also can be termed as Froude efficiency, is the ratio of thrust power output to the total power input produced from the propulsor [16]. The mathematical expression of the propulsive efficiency can be written as simple as Equation (8) [15].

$$\eta = \frac{P_{out}}{P_{total}} \tag{8}$$

where P_{out} is the power output, P_{total} is the total power required. Then the P_{total} is the summation of work done by inertia forces (power input, P_{in}) and work done by hydrodynamic forces on body surface (power input, P_{out}). Since the current study only involve two-dimensional movement, some researchers such as Le et al. [17] and Benkherouf et al. [18] applied the equation of power input in a more reduced and simpler form, expressed in Equation (9).

$$P_{in} = \int_o^T F_y(t)\frac{\partial h}{\partial t}dt = \overline{F_y V} \tag{9}$$

where $\frac{\partial h}{\partial t}$ is the traveling velocity of the flapping motion and F_y is the force imposed by the body to the surrounding fluid in y-direction. Only F_y is considered, while F_x and F_z are omitted from computation because the structure only will flap in y-direction. The equation will be as simple as the product of average y-direction force and average y-direction velocity caused by the flapping structure. Similarly the power output can also be reduced into a simpler form that could fit the condition of current study.

$$P_{out} = \int_o^T F_x(t)U_x(t)dt = \overline{F_x U} \tag{10}$$

where $\overline{F}_x$ denotes the average value of thrust while $\overline{U}$ is average swimming speed of the flapping structure. Therefore the propulsive efficiency of the flapping structure can be calculated from Equation (11).

$$\eta = \frac{\overline{F_x U}}{\overline{F_x U} + \overline{F_y V}} \tag{11}$$

3.0 RESULTS AND DISCUSSION

Throughout the current study, the manipulated parameter is the inlet flow velocity. The flapping frequency and amplitude are fixed. The swimming performance of carangiform swimmer can be accessed through several parameters including the cruising speed, Strouhal number, the thrust force, swimming efficiency.

For a better demonstration, relationship between cruising speed and inlet velocity for both swimmers is combined in a single graph, Figure 2. From the figure, carangiform swimmer is able to cruise at a relatively higher speed compared with anguilliform swimmer at all the

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condition of inlet velocity flow. By taking all the computed coordinates for both of the carangiform and anguilliform swimmer, the relationship between cruising speed and inlet velocity can be outlined respectively in the form of sixth order polynomial equation:

$$u = -0.003U^6 + 0.07U^5 - 0.53U^4 + 1.95U^3 - 3.45U^2 + 1.98U + 1.14 \quad (12)$$

$$u = -0.001U^6 + 0.04U^5 - 0.27U^4 + 1.03U^3 - 1.70U^2 + 0.75U + 0.806 \quad (13)$$

where Equation (12) and (13) is valid for the range $0.0 < U < 6.0$ m/s for carangiform swimmer with $R^2 = 0.993$ and for anguilliform swimmer with $R^2 = 0.990$, respectively. From Equation (12) and (13), it can be deducted that carangiform swimmer also possesses higher maximum cruising speed compared with anguilliform swimmer since carangiform swimmer recorded a maximum swimming speed of 1.53 m/s while anguilliform swimmer can swim at a highest speed of 0.93 m/s.

Nonetheless the cruising speed only represents the resulting inertia component at the wake of the flapping structure. Flapping structures would produce unsteadiness too behind the trailing edge, and to take this into consideration, Strouhal number is the next important parameter to be applied for further analysis. The flow unsteadiness and cruising momentum are both produced by the flapping structure; and the change of force experienced by the structure must be taken into consideration. The relationship between the flapping efficiency of the structure and the ratio of these two parameters (Strouhal number) is the key interest in current study. By taking F_x and F_y into current computation, the relationship between the Strouhal number and propulsive efficiency can be illustrated in Figure 3.

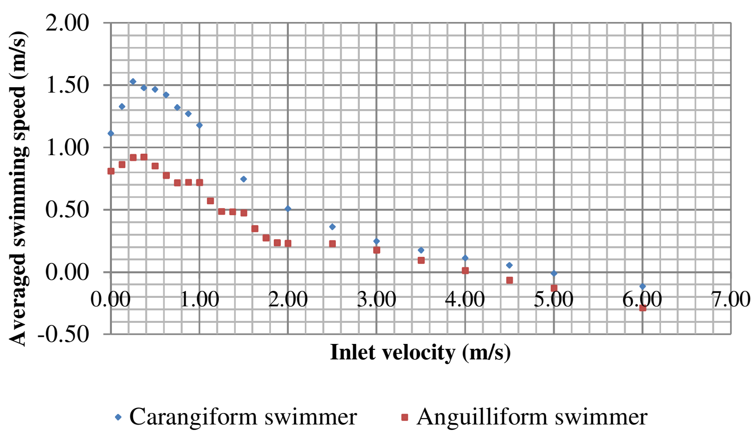

Figure 2: Comparison of relationship between averaged swimming speed and inlet velocity for anguilliform and carangiform swimmer.

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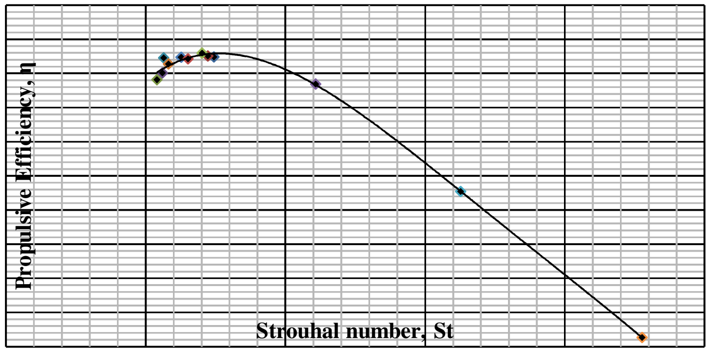

Figure 3: Relationship between Strouhal number and propulsive efficiency for carangiform swimmer.

From the scattered data, a polynomial equation can be formulated and the third order polynomial equation is the best-fitted equation compared with the second and third order, with R^2 equals 0.997. The best fitted equation to describe the relationship will be:

$$\eta = -5.82St^4+16.9St^3-18.28St^2+7.1St-0.035 \quad (14)$$

The above equation is valid when 0.24<*St*<0.91. By differentiating the above equation and considering the case where $d\eta/dSt$ equals to zero, the value of Strouhal number when the efficiency culminates will be 0.305, which falls within the range of general optimal Strouhal number of 0.2<*St*<0.4. Although the oscillating structure loses its thrust while drag develops when *St* goes beyond 1.0, the structure still keeps swimming steadily ($u > 0$) due to its vorticity manipulation which recaptured the energy imbued in the oncoming vortex at its wake. This continues until the inlet velocity poses the mighty inertia force to override the endeavour of vorticity manipulation; and subsequently this will push back the flapping structure. At this stage, *St* will be in negative value. The calculation of propulsive efficiency is meaningless when *St*>1 and *St*<0 because beyond that range, the thrust produced by the structure (imparted from the force of fluid and vortex) has been transformed into drag imposed onto the structure. The graph of the relationship between horizontal force, F_x (thrust or drag) and Strouhal number is plotted in Figure 4 for better demonstration.

There are two important findings which can be deducted from this study: the upper and lower critical Strouhal number. The upper critical Strouhal number ($St_{upper,crit} = 1$) can be therefore defined as the Strouhal number when the flapping structure starts to lose thrust while the lower critical Strouhal number ($St_{lower,crit} = 0$) is the Strouhal number when the flapping structure loses both its thrust and ability to propel using vorticity.

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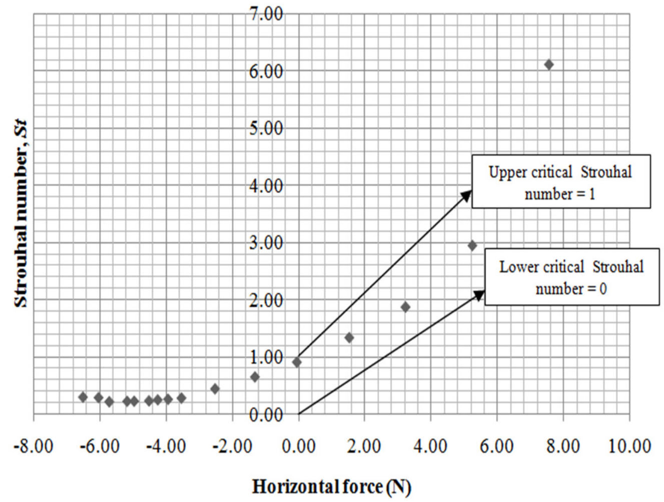

Figure 4: Relationship between horizontal force and Strouhal number for Carangiform swimmer.

The relationship between Strouhal number and propulsive efficiency for anguilliform swimmer is plotted in Figure 5 for further analysis. From Figure 5, an increase in propulsive efficiency can be seen when the Strouhal number raises from 0.21 to 0.30, followed by a decline from 0.30 to 0.86. To compute the optimal Strouhal number, an equation that relates Strouhal number and propulsive efficiency is required to be determined. This equation can be presented in a form of third order polynomial as written as follows.

$$\eta = -22.12St^4+55.88St^3-49.355St^2+16.96St-1.261 \qquad (15)$$

where R^2 = 0.968 and it is valid for the range $0.21<St<0.86$. Similar with the method to find the optimal Strouhal number as explained in previous section, when $d\eta/dSt = 0$, then $St = 0.29$, and thus making this the optimal Strouhal number for anguilliform swimmer. From Figure 6, anguilliform swimmer will start to lost its structural thrust at $St = 0.75$, making this value as the higher critical Strouhal number, $St_{upper,crit} = 0.75$, as shown in Figure 6. While at $St = 0$, the flapping structure is losing both its structural thrust and ability to manipulate vorticity for swimming forward, and thus this could be defined as its lower critical Strouhal number, $St_{lower,crit} = 0$.

By substituting the corresponding optimal Strouhal number, the maximum propulsive efficiency is 0.86 for carangiform swimmer and 0.71 for anguilliform swimmer. Accordingly the maximum propulsive efficiency of carangiform swimmer is also higher than the anguilliform swimmer. Besides that the general propulsive efficiency for carangiform swimmer is also higher than anguilliform swimmer. This finding has corroborated the hypothesis suggested by Lighthill [19] that carangiform swimmer is able to thrust more efficiently than anguilliform swimmer. This can be subjected to the reason that anguilliform swimmer needs to move his body more extensively compared with carangiform swimmer, and such undulation will entail increment in the generation hydrodynamic force, which is the wasted energy in propulsion [20].

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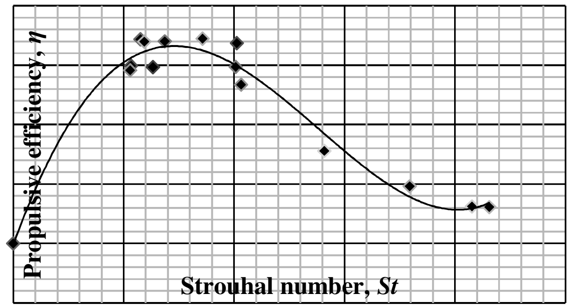

Figure 5: Relationship between Strouhal number and propulsive efficiency for anguilliform swimmer.

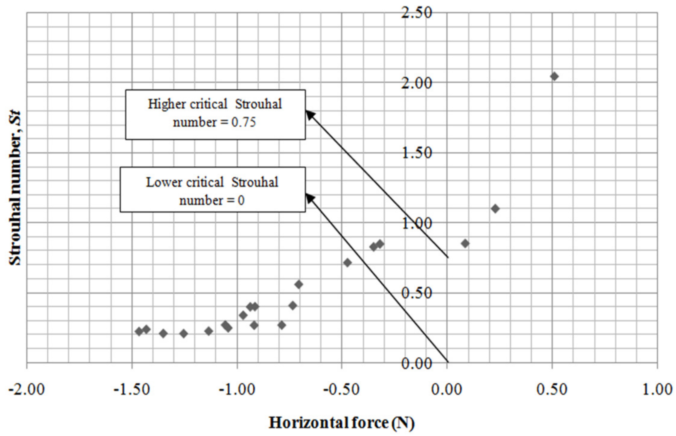

Figure 6: Relationship between horizontal force and Strouhal number for anguilliform swimmer.

These corresponding optimal Strouhal number is also falling within the range of Strouhal number where the aquatic animals in nature is used to be. The comparison is shown in the Figure 7 and it can be deduced that most of the natural animals swim at its optimal propulsive efficiency or minimal swimming cost.

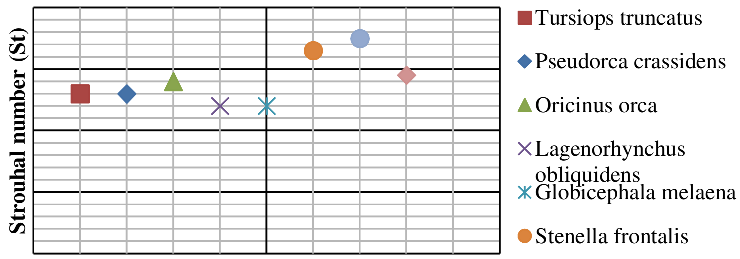

Figure 7: The computed optimal Strouhal number and mean Strouhal number of some carangiform aquatic animals taken from Rohr and Fish [2].

4.0 CONCLUSION

From all the results and discussion presented in previous chapter, several important conclusions can be drawn regarding the study of flapping hydrodynamics of fishlike structure. The cruising speed of carangiform swimmer will increase when the inlet velocity increases from 0 *m/s* to 0.25 *m/s*, and beyond that the cruising speed keeps dropping. The optimal Strouhal number for carangiform swimmer is 0.305 with optimal propulsive efficiency of 0.86. The cruising speed of anguilliform swimmer will increase when the inlet velocity increases from 0 *m/s* to 0.375 *m/s*, and beyond that the cruising speed keeps dropping. The optimal Strouhal number for anguilliform swimmer is 0.29 with optimal propulsive efficiency of 0.71.

Carangiform swimmer outperforms anguilliform swimmer as it has a higher cruising speed and optimal propulsive efficiency. By the way, there is a finding that upper and lower Strouhal number exists with an increasing inlet velocity. Upper Strouhal number is the value of Strouhal number when the flapping structure starts to lose thrust while the lower critical Strouhal number is the value of Strouhal number when the flapping structure loses both its thrust and ability to propel using vorticity manipulation. These characteristic shall be taken into account during the design of unmanned underwater vehicle by avoiding the critical Strouhal numbers.

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