

Optimization of the efficiency of a biomimetic marine propulsor using CFD

Optimización del rendimiento de un propulsor marino y biomimético utilizando CFD

M. I. Lamas Galdo¹, C. G. Rodríguez Vidal² and J. D. Rodríguez García³

ABSTRACT

The purpose of this paper is to employ a CFD (Computational Fluid Dynamics) procedure to optimize a biomimetic marine propulsor. This propulsor is based on an undulating panel which emulates the movement of a fin fish. The numerical model has been employed to analyze the hydrodynamics and improve the efficiency. Particularly, the fin shape has been studied as measure to improve the efficiency. Three fin shapes have been analyzed, rectangular, elliptic and lunate. The results have indicated that, for the same area, the lunate shape is the most efficient.

Keywords: Marine propulsion, biomimetics, CFD (Computational Fluid Dynamics).

RESUMEN

El propósito de este artículo es emplear un procedimiento de CFD (Mecánica de Fluidos Computacional) para optimizar un propulsor marino de inspiración biológica. Este propulsor está basado en un panel ondulante, que imita el movimiento de una aleta de pez, dicho modelo numérico se ha empleado para analizar la hidrodinámica y mejorar el rendimiento, de igual manera la forma de la cola ha sido estudiada como un mecanismo para generar mayores beneficios. Se han analizado tres formas de aleta: rectangular, elíptica y en media luna, los resultados han indicado que la aleta con forma de media luna es la más eficaz.

Palabras clave: propulsión marina, biomimética, CFD (Mecánica de Fluidos Computacional).

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Introduction

Biomimetics, also called biomimicry or bionics, involves the imitation of nature in man-made systems. An area of biomimetics that is recently gaining an increasing level of popularity is marine propulsion. Fish swimming is the result of millions of years of evolutionary optimization to develop very efficient movement. For this reason, several fish movements are inspiring technology for marine propulsion. In comparison with a classical rotary propeller, a bio-inspired propulsor generates less turbulence and creates an efficient jet in the direction of thrust. A propeller generates more turbulence and a jet, which rotates in the direction perpendicular to the motion, wasting a considerable amount of power.

Several mechanisms for marine propulsion that emulate the locomotion of fish have been built in recent years. Most fish swim by moving their body and/or caudal fins. This is called BCF locomotion and includes anguilliform, carangiform, thunniform and ostraciiform modes of swimming. In anguilliform mode for example, the undulation takes place along the whole body. Similar movements are observed in carangiform mode, but with the amplitude

undulations growing toward the tail. In thunniform mode, the amplitude undulations also grow toward the tail and practically take place in the posterior half of the fish. Ostraciiform locomotion is characterized by the oscillation of the caudal fin, while the body remains essentially rigid. In the available literature, there are many works about marine propulsors that imitate anguilliform (Wilbur et al., 2002; Westphal et al., 2011; Xu et al., 2012; Crespi et al., 2005; Ijspeert et al., 2005; McIsaac and Ostrowski, 2002; Lamas et al., 2010), carangiform (Kumph, 2000; Watts et al., 2007; Hirata et al., 2000; Morgansen, 2003; Heo et al., 2007), thunniform (Anderson and Chabra, 2002; Suleman and Crawford, 2008; Nakashima et al., 2006; Yu et al., 2007; Yu et al., 2009; Shen et al., 2011) and ostraciiform (Kodati et al., 2008; Hu et al., 2009; Yamamoto et al., 1995; Saimek and Li, 2001; Herr and Dennis, 2004; Guo, 2003) locomotion.

Other fish swim by moving their median and/or paired fins. This is called MPF locomotion, and includes rajiform, gymnotiform, amiiiform and labriform modes, among others. Rajiform, amiiiform and gymnotiform modes are based on the undulation of the pectoral, dorsal and anal fins respectively. Labriform swimming is based on oscillations instead of undulations. According to Sfakiotakis (1999),

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due to its lower efficiency in comparison with BCF swimming modes, MPF locomotion has inspired fewer mechanisms for marine propulsion. One can refer to mechanisms that imitate rajiform (Cai et al., 2010; Chen et al., 2011; Clarck and Smiths, 2006; Low, 2008; Zhang et al., 2008), gymnotiform (Low, 2007; Epstein et al., 2006; MacIver et al., 2004; Siahmansouri et al., 2011) and labriform (Kato, 2000; Kim et al., 2013; Gordon et al., 2000; Georgiades et al., 2009; Sitorus et al., 2009) modes of MPF locomotion.

This work is a continuation of an analysis developed by Lamas et al. (2012). In this cited paper, several fish swimming modes were studied numerically: anguilliform, carangiform, thunniform, ostraiform and gymnotiform, concluding that thunniform is the most efficient swimming mode. Given this finding, the main objective of the present study is to improve the efficiency of the thunniform movement. For the purpose, three fin shapes were analyzed: rectangular, elliptical and lunate. The effect of fin shape on propulsion efficiency has been analyzed in the literature by other authors. For example, Liu and Bosse (1999) and Yamamoto et al. (1995), concluded that a lunate flapping-foil is much more efficient than a rectangle flapping-foil. Liu et al. (2001), demonstrated that larger aspect ratios and sweepback angles promote larger cruising speeds and Li and Yin (2008), concluded that the mean thrust force on a bio-caudal fin is proportional to the product between the dimensionless second moment and the plan form area. The present paper offers a numerical perspective to delve deeper into the subject of fin shape given that a numerical model provides information that cannot be obtained experimentally. Furthermore, a numerical computation of efficiency is much faster and less expensive than an experimental setup. The model developed in this work provides a useful tool to evaluate different configurations.

Problem definition

The working principle of the biomimetic propulsor developed in the present paper is shown in Fig. 1. It consists of an undulating panel, which produces a wake in the opposite direction of movement. The pressure field in the region of the wake produces thrust.

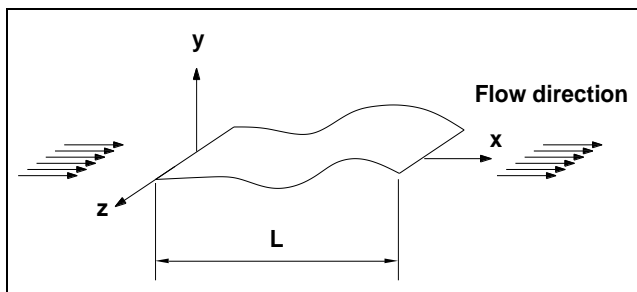


Figure 1. Geometry of the problem.

The thunniform swimming mode was modeled using the following equation for the undulation of the fin:

$$y = A(x) \sin \left[2\pi \left(\frac{x}{\lambda} - \frac{t}{T} \right) \right] \quad (1)$$

where λ represents the wavelength, T the period and $A(x)$ the amplitude, given by:

$$A(x) = A_{max} \frac{x}{L} \quad (2)$$

Numerical procedure

Governing equations

The governing equations are those of conservation of mass and momentum, Eqs. 3 and 4 respectively. The problem was modeled as turbulent due to the high Reynolds numbers. The $k-\epsilon$ turbulence model was employed because this is robust, economical and reasonably accurate for a wide range of cases (Versteeg and Malalasekera, 2006).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (3)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial}{\partial x_j} (-\overline{\rho u_i u_j}) \quad (4)$$

In order to save computational time, the problem was solved using a domain, which moves with the fin (if the problem is solved in a fixed coordinate system, a very large domain would be necessary to encompass the advancing position of the fin).

Boundary conditions and initial conditions

The boundary conditions are indicated in Fig. 2. The domain presents an inlet and an outlet. The undulating fin was modeled as a no-slip wall and the top and bottom surfaces were assumed as slip walls, corresponding to an infinite medium. In virtue of the symmetry, only half of the domain was simulated.

As an initial condition, the velocity was set to the cruising velocity obtained in a previous paper, Lamas et al., (2012).

Calculation of the efficiency

The total power required for the propulsive motion of the fin consists of two components; one is the swimming power required to produce the vertical oscillations of the fin and the other is the useful power required to thrust. The efficiency was computed as the ratio between the useful power and the total power.

The swimming power was computed as:

$$P_s = \int p \frac{dy_{wall}}{dt} dS \quad (5)$$

where p is the pressure of the surface of the plate and dy_{wall}/dt refers to the y -component of the velocity at the surface of the fish.

The useful power was computed as the time-average thrust multiplied by the free-stream velocity:

$$P_U = -F_{px} U_\infty \quad (6)$$

where the minus sign indicates that the velocity of swimming is reverse to that of the stream.

Computational mesh

The 3D CAD was designed using SolidEdge ST and then exported to Gambit 2.4. Figure 2 shows the computational mesh used for the rectangular configuration. In this figure, the front surface and the internal mesh were omitted for clarity. This mesh has 600000 tetrahedral elements, and was refined on the fin surface and the wake region. The meshes employed to simulate the elliptical and lunate fins are similar to that shown in Fig. 2.

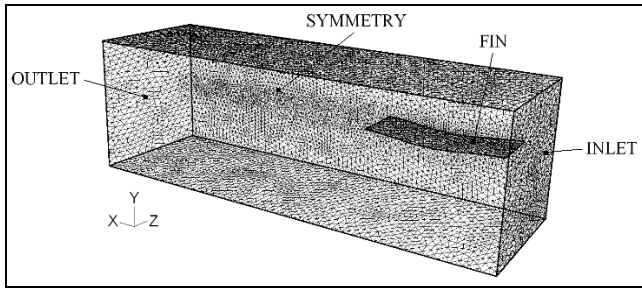


Figure 2. Computational mesh.

Numerical aspects

Ansys Fluent 6.3 software was employed for the computations. The PISO algorithm was chosen for the pressure-velocity coupling. A second order interpolation was used for the discretization of the convective terms and an implicit scheme for the temporal treatment, with a constant time step of 0.001 s. Both time step and size mesh were checked in order to obtain independence of these parameters in the results.

In order to reach a steady state, 20 periods of time were computed. The results presented herein correspond to the 20th time period.

Validation of the model

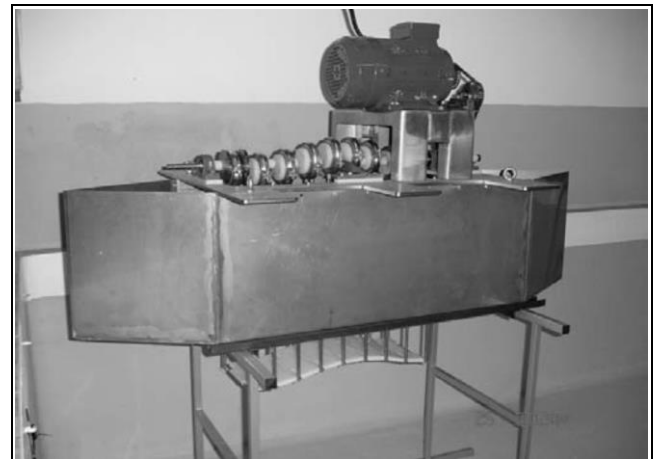
The numerical model has been validated elsewhere, Lamas et al. (2012). In this previous work, the results obtained numerically were compared with experimental measurements performed in the mechanism shown in Fig. 3 (a). Fig. 3 (b) indicates the mechanism installed in a catamaran 2.16 m long.

The experimental results were based on tying the ship to a fixed point by means of a rope, as can be seen in Fig. 3 (b). The thrust was measured at different oscillation frequencies of the fin. A variable-frequency drive control was used to control the oscillation frequency of the electrical motor. Numerically, these setups were simulated using a zero free-stream velocity. Numerical and experimental results of the thrust are compared in Fig. 4. These were obtained at different frequencies of oscillation from 6 to 15 Hz. As can be seen, a satisfactory concordance between numerical and experimental results has been found.

Results and discussion

The three caudal fin shapes analyzed in the present work are shown in Fig. 5. All have an area of 0.104 m². Concerning the lengths, these are 0.520 m for the rectangular, 0.538 for the elliptical and 0.541 for lunate fin shape. These small differences in length makes the difference in the Reynolds number negligible and thus, the different effect of turbulence intensity on drag.

The results of the efficiency against the frequency of oscillation are presented in Fig. 6 for all three fin shapes. As can be seen, the efficiency increases with the frequency of oscillation and then decreases. Additionally, the efficiency is higher for the lunate shape and lower for the elliptical shape. The reason for these results is the configuration of the wake behind the fin. This wake is an array of von Karman vortices which generate thrust. Several authors relate these vortices with drag-reduction properties, including Gopalkrishnan et al. (1994), Barrett (1996), Anderson (1996) and Streitlien et al. (1996). For this reason, the adequate configuration of the wake has a crucial repercussion on the efficiency. This wake is indicated in Fig. 7, which represents the pressure field around the lunate fin shape running at 10 Hz. The instants $0.25t/T$, $0.5t/T$



(a)



(b)

Figure 3. Experimental prototype. (a) Mechanism of the fin; (b) Fin and ship floating in water.

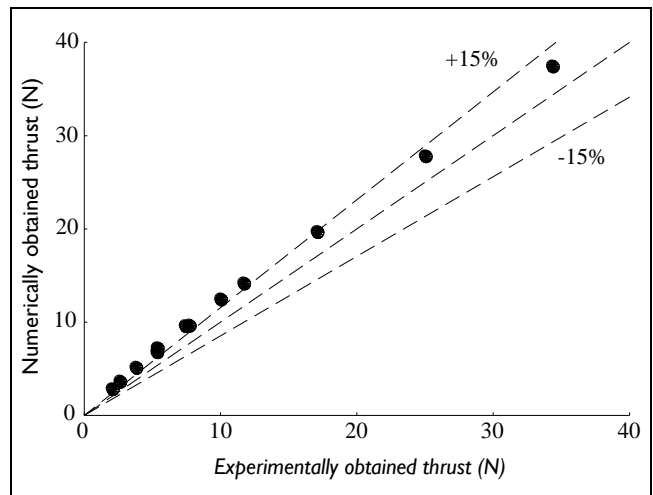


Figure 4. Thrust numerically and experimentally obtained at frequencies of oscillation between 6 and 15 Hz.

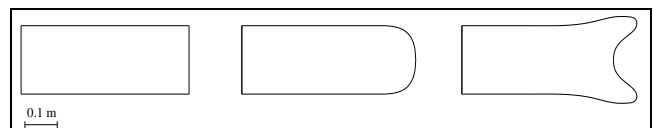


Figure 5. Rectangular, elliptical and lunate fin shapes analyzed.

and $0.75t/T$, where T is the period, are represented. As can be seen, a reverse Karman vortex street is generated behind the fin, i.e., a staggered array of vortex with the signs of vorticity reversed.

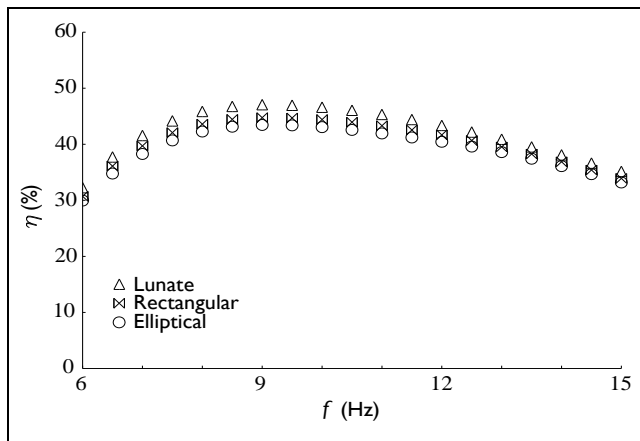


Figure 6. Efficiency of the fins against frequency of oscillation.

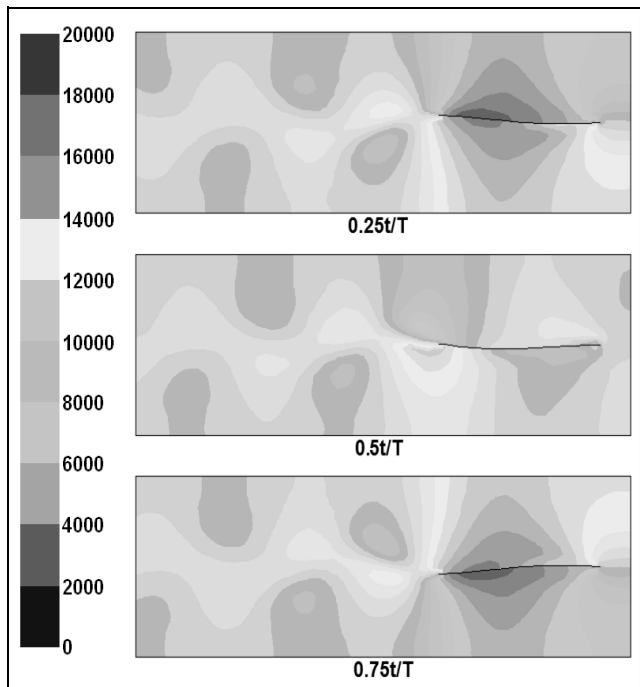


Figure 7. Pressure field (Pa) at $f = 10$ Hz; lunate fin shape.

Conclusions

This work has presented a biologically-inspired marine propulsor based on an undulating fin that imitates a thunniform movement. Three fin shapes were studied in order to improve the efficiency and the results have shown that the lunate shape is the most efficient.

In future works, it is important to determine more modifications in order to improve the efficiency, for instance other dimensions such as length and width. Other possible modifications to improve efficiency could include a nozzle around the fin in order to avoid lateral losses.

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