Multi-Body Dynamics Modelling on a Self-Propelled Pufferfish with its Application in AUV

Ruoxin Li, Qing Xiao, University of Strathclyde, Glasgow/UK, qing.xiao@strath.ac.uk
Lijun Li, Hao Liu, SJTU-CU ICRC, Shanghai/China

Abstract

We developed a Computational Fluid Dynamics (CFD) based tool coupled with a Multi-Body Dynamics (MBD) technique to investigate a self-propelled pufferfish motion within a still water environment. The 3D pufferfish model consists of body, caudal, dorsal and anal fins. The locomotion of fish is entirely determined by the computation and fully induced by the oscillation motion of fish fins. The influence of the phase angle difference on the fish swimming behaviour is examined by varying the angle difference between the caudal, dorsal, and anal fins. The swimming displacement, hydrodynamic force and the wake pattern are analysed.

1. Introduction

Along with the exploitation of sea resources, Autonomous Underwater Vehicles (AUV) have become an important tool as they are suitable for long-term, regular or risky tasks, such as the exploration of deep sea oil, the inspection of fatigue problems of offshore platforms and so on. Living in the ocean for thousands of years, fish has the best propulsion and manoeuvring ability to adapt to the aquatic environment. Studies into the locomotion of fish swimming and manoeuvring have provided vital insights for the AUV design. Comparing with the traditional AUVs, the fish-like robots have their advantages of effective propulsion, stable and flexible features.

According to the study of *Sfakiotakis et al. (1999)*, there are two types of propulsion mechanisms, i.e. the Body and/or Caudal Fin (BCF) and the Median and/or Paired Fins (MPF). Generally, previous studies about the locomotion of fish swimming can be divided into two groups based on the aforementioned two mechanisms: (a) investigation on the fish body motion by prescribing the motions of fish while omitting the influence of fins except the caudal fin; (b) researches on the effect from an isolated fins, such as pectoral, dorsal and anal fins, on propulsion efficiency. Within the former group, typical studies of numerical simulations about anguilliform and carangiform swimming have been carried out by *Kern and Koumoutsakos (2009)*, *Borazjani and Sotiropoulos (2008, 2009, 2010)*. Most researches within the latter group used experimental measurements. Foil-like fins, standing for pectoral fins, were investigated by *Lauder and Madden (2007)* to analyse the kinematics and hydrodynamics of the fins. Other work was also reflected in the paper of *Barbera et al. (2011)* and *Beal et al. (2007)*. Recently, studies with a combined motion of pectoral fins and fish body are considered by researchers, such as *Xu and Wan (2012)*. Nevertheless, the influence of dorsal and anal fins on swimming behaviour is usually ignored because of the complexity of the problem.

One typical example of fish species adopting the MPF swimming is pufferfish. Biologically, it appears an extraordinary performance on manoeuvrability although it swims slowly. *Itai and Tamar (2003)* found that the shape of the pufferfish body can deform passively to accommodate the higher swimming speed. Meanwhile, the flapping motion of dorsal and anal fins was in phase with each other and had a phase difference of 180°with the pectoral fin.

In the present work, numerical simulations are carried out to investigate the pufferfish model, which is based on a live fish experimental testing conducted at SJTU as shown in Fig. 1. The dorsal, anal and caudal fins are taken into account while all the fins are considered to be rigid. Phase angle difference is tested to examine its influence on the swimming performance. To achieve this goal, the modelling system is constructed by a series of interconnected bodies. An in-house code based on the theory of Multi-Body Dynamics combined with a Computational Fluid Dynamics tool is used.

Fig. 1: A photo of pufferfish experiment done at SJTU

2. Problem description

2.1. Multi-Body fish model and kinematic equations

The 3D pufferfish model, shown in Fig. 2, is extracted from a live fish experimental data, which was tested in Shanghai Jiao Tong University (SJTU), China. The fish model consists of four parts: the main fish body, dorsal, caudal and anal fins. The total length is about 0.12 m. The shape of each cross-section of body is approximately elliptical. The largest major- and minor-axis of fish body are about 0.04 and 0.03 m, respectively.

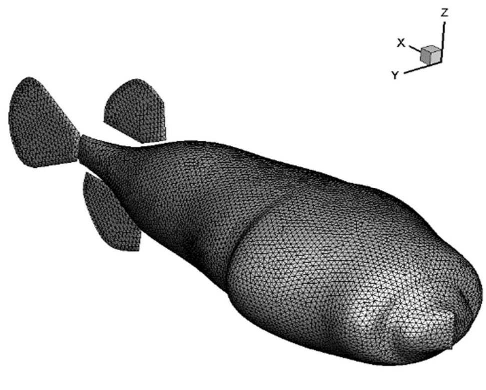


Fig. 2: 3D pufferfish model

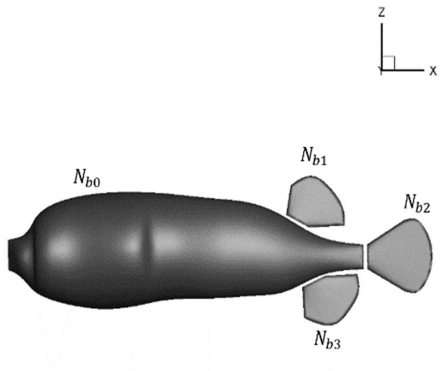


Fig. 3: Numbering for each part of the fish model

Four parts are numbered from N_{b0} to N_{b3} as shown in Fig. 3. Each fin is connected to the main body with a virtual hinge joint. The fins in the present work are considered rigid. The density of whole body is the same as the environment (water). To carry out the numerical modelling, the surface of the fish model is meshed with unstructured grid while tetrahedral cells are used for the rest of fluid field, and the total number of grid cells is about one million. In order to ensure the accuracy of numerical simulation, the computational domain should be large enough, where the length (X direction) of the domain is 12 times of the body length (BL), while its width (Y direction) and height (Z direction) are 10BL.

Unlike most existing researches, where the fish swimming speed and path are prescribed, here, only the rotational motions of the fins are given as a function of:

$$\gamma = A\sin(\omega t + \varphi)$$

where *A* is the amplitude, ω is the frequency which is identical for all the motions, and φ is the phase angle. The amplitude and frequency of each fin are obtained from the experimental testing and summarised in Table I. In the present study, the undulation of caudal peduncle is omitted implying that there is no deformation along the main body of the fish.

Table I: Motion parameters for the fish model

	Dorsal fin (d)	Caudal fin (c)	Anal fin (a)
Amplitude (rad)	0.94	0.45	0.94
Frequency (rad/s)	21.4		
Phase angle (rad)	0	$\frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}, \pi$	0

2.2. Numerical simulation

The commercial software ANSYS Fluent 15.0 is used for solving the fluid field based on a finite volume method. The governing equations are the three dimensional incompressible continuity and momentum equations:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2 \boldsymbol{u}$$

$$\nabla \cdot \boldsymbol{u} = 0$$

A first order implicit time matching scheme is used for the transient term. Second-order upwind scheme is employed for diffusion term discretization. Pressure-Velocity coupling can be achieved by the Fractional Step scheme. The in-house code of Multi-body dynamics algorithm is written in the User Defined Function (UDF) and compiled into Fluent. In order to maintain the mesh quality during the simulation, smoothing and re-meshing mesh functions are employed with Diffusion and Local Cell settings in ANSYS Fluent.

2.3. Solution algorithm

We follow the following four stages in one time marching step during the simulation. At the beginning, the velocity of the fish and fins are estimated with our in-house code using Multi-Body Dynamics Theory. The main body (N_{b0}) is set as the reference body, and its initial information such as the location and velocity are given. Fins are connected to the main body via virtual hinges. Apart from the global coordinating system, each body N_{bn} has its own local reference frame F_n. The velocity of body *j* is a (6 ×1) matrix:

$$\eta_j = \left(V_j^T, \Omega_j^T\right)^T$$

and can be transformed to the local reference frame of Body *i* by following the adjoint map operator which can be expressed as:

$$Ad_{{}^j g_i} = \begin{pmatrix} {}^jR_i & {}^jR_i\, {}^i\hat{P}_j^T \\ 0 & {}^jR_i \end{pmatrix}$$

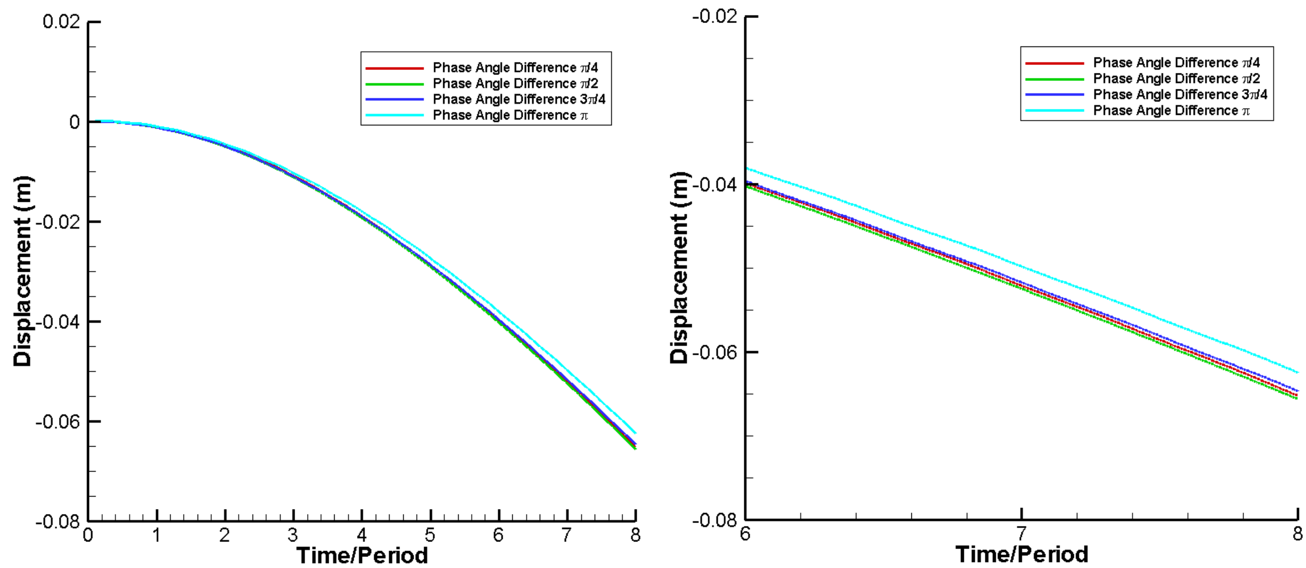
where ${}^jR_i$ and ${}^iP_j$ are the orientation matrix and the position vector of F_j with respect to F_i. Based on the reference body and the relative relations, the position and velocity of other bodies can be calculated. The information of velocity is then transferred to CFD software. Using Dynamic Mesh tool, the body position is updated. At the third step, the fluid field around fish is solved by CFD, so that the force and moment of the fish body and fins are obtained. Finally, this information is passed back to the UDF and the in-house code will calculate updated velocities.

3. Results and discussions

According to the experiment, the phase angles between dorsal and anal fins are almost identical. Therefore, only phase angle difference between caudal and dorsal fins is tested in the present work with their specific values of $\frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}, \pi$. The fish body displacement in the X direction, hydrodynamic force imposed on the fish and the relevant fluid field will be presented in the following parts.

3.1. Displacement

Fig. 4 (a) shows the fish body displacement in the X direction during the first 8 periods for the four cases associated with different phase angle difference. The displacement is shown as negative as the fish model swims towards the negative direction of the X axis.



(a) Displacement for 8 periods (b) Displacement in 7th and 8th period

Fig. 4 Comparison of the fish body displacement in the X direction

There is no significant discrepancy among $\frac{\pi}{4}, \frac{\pi}{2}$ and $\frac{3\pi}{4}$. As can be seen from Fig. 4 (b), where an zoom-in plot is presented, the displacement for the case with a phase angle difference of π between caudal and dorsal fins is slight smaller from the others, meaning the pufferfish model swims the most slowly when the caudal fin is out of phase with the other two fins.

3.2. Hydrodynamic forces

The resultant hydrodynamic forces along X direction within 6th to 8th period are compared in Fig. 5 for various cases. For all cases, two peaks are observed in one oscillating period. The resultant force for a phase angle difference of π/2 is dramatically different from the other three cases. Although the motions of the fins are prescribed by notable phase angles difference, no obvious phase lag is noted for the resultant force.

Fig. 6 shows the force on the fish body and fins from 6th to 8th period. Both dorsal and anal fins produce thrust and the force on the dorsal fin is slightly larger than the anal fin. This is because the area of former is a little larger than that of the latter. Biologically, the caudal fin plays the most important role during the self-propulsion swimming process, thus the force generated by the caudal fin contributes most to the resultant force as indicated by Fig.6.

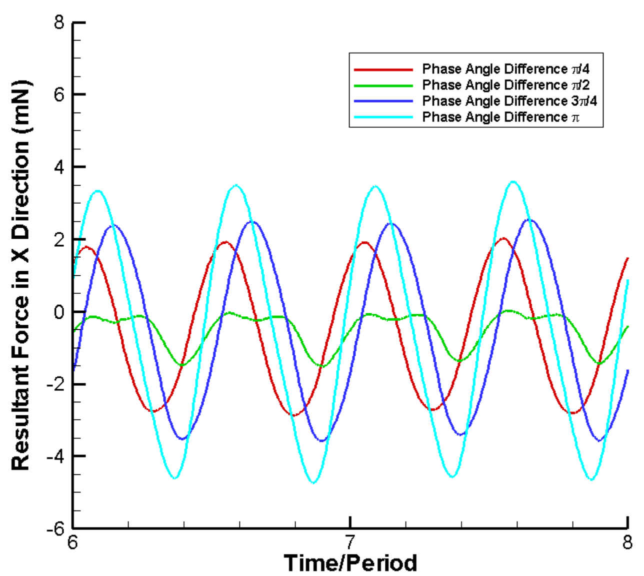


Fig. 5: Comparison of resultant force for cases with various phase angle difference

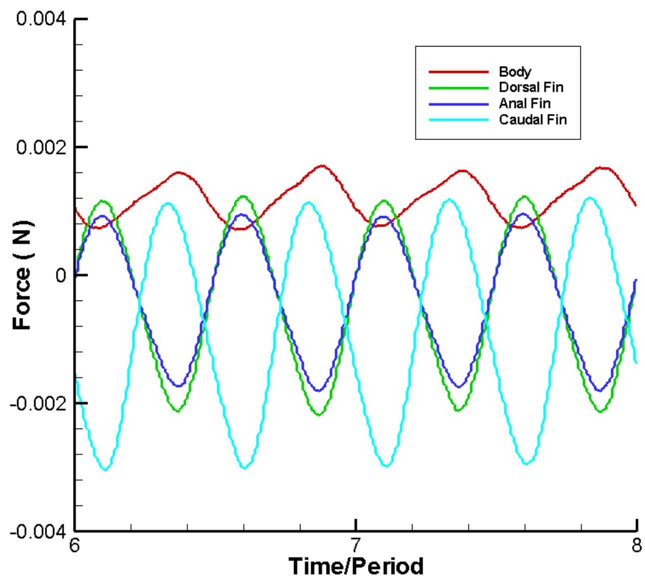
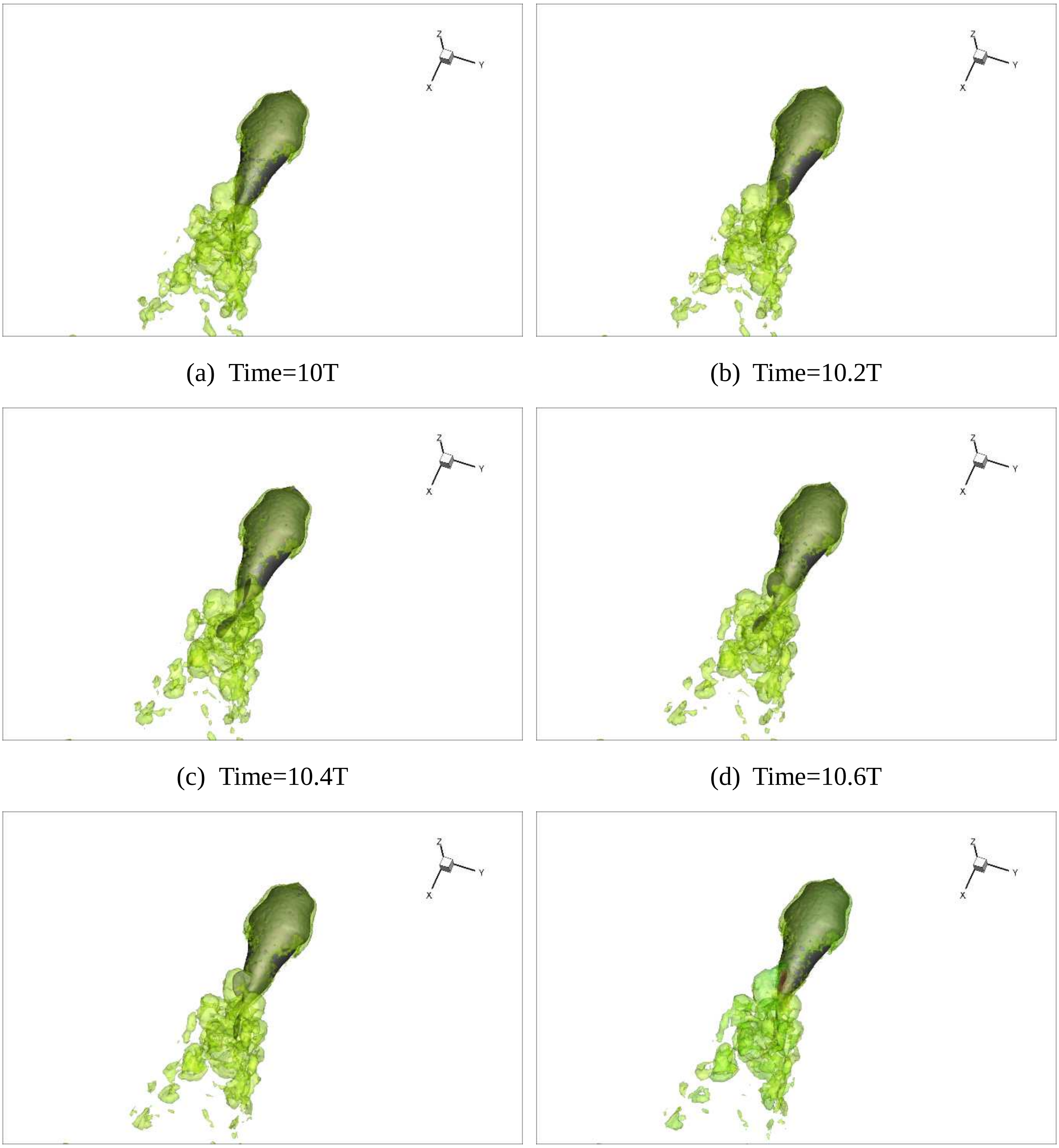


Fig. 6: Comparison of force on fish body and fins with a phase angle difference of π/2

3.3. Wake pattern

Fig. 7 shows the snapshots of flapping motion and development of wake pattern of the fish and fins within 10th period for phase angle difference of π/2. The iso-surface is generated when the vorticity magnitude is 10. As all three fins generate vortices as well as the fish body, the vorticity field is rather complex as can be seen from the figures. The detailed examinations are performed in the on-going research.



(a) Time=10T (b) Time=10.2T

(c) Time=10.4T (d) Time=10.6T

(e) Time=10.8T (f) Time=11T

Fig. 7: Iso-surface of fluid field vorticity coloured by pressure

4. Conclusions

With a use of numerical modelling method, we investigated the influence of phase angle difference on a self-propelled pufferfish model. For the first time, a Multi-Body Dynamics theory is combined with a CFD method in order to solve the free swimming fish problem propelled by flapping fins motions. Our simulation results shown that for the displacement of the pufferfish, there is no significant difference. In terms of the resultant force, the result from the case with a phase angle difference of $\pi/2$ differs from the others dramatically. By investigating the resultant forces around fish body and fins, it is noted that the caudal fin plays a major part for propulsion force generation. The overall thrust they generated is quite small which is possibly related to the fact that all the fins are modelled as rigid which are actually flexible in reality. The study on flexible fins driven self-propelled fish will be presented in a separated paper in the near future. With its application in bio-inspired AUV design, the present study indicated that, in addition to caudal fin which is always used in the past, the contribution of dorsal and anal fin may also need to be considered for the system thrust generation.

Acknowledgment

Results were obtained using the EPSRC funded ARCHIE-WeSt High Performance Computer (www.archie-west.ac.uk). EPSRC grant no. EP/K000586/1.

References

BARBERA, G.; PI, L.; DENG, X. (2011), *Attitude control for a pectoral fin actuated bio-inspired robotic fish*, Int. Conf. Robotics and Automation (ICRA), pp.526-531

BEAL, D.N.; BANDYOPADHYAY, P.R. (2007), *A harmonic model of hydrodynamic forces produced by a flapping fin*, Experiments in Fluids 43(5), pp.675-682

BORAZJANI, I.; SOTIROPOULOS, F. (2008), *Numerical investigation of the hydrodynamics of carangiform swimming in the transitional and inertial flow regimes*, J. Experimental Biology 211(10), pp.1541-1558

BORAZJANI, I.; SOTIROPOULOS, F. (2009), *Numerical investigation of the hydrodynamics of anguilliform swimming in the transitional and inertial flow regimes*, J. Experimental Biology 212(4), pp.576-592

BORAZJANI, I.; SOTIROPOULOS, F. (2010), *On the role of form and kinematics on the hydrodynamics of self-propelled body/caudal fin swimming*, J. Experimental Biology 213(1), pp.89-107

GORDON, M.S., PLAUT, I.; KIM, D. (1996), *How puffers (Teleostei: Tetraodontidae) swim*, J. Fish Biology 49(2), pp.319-328

KERN, S.; KOUMOUTSAKOS, P. (2006), *Simulations of optimized anguilliform swimming*, J. Experimental Biology 209(24), pp.4841-4857.

LAUDER, G. V.; MADDEN, P. G. (2007), *Fish locomotion: kinematics and hydrodynamics of flexible foil-like fins*, Experiments in Fluids 43(5), pp.641-653

SFAKIOTAKIS, M.; LANE, D. M.; DAVIES, J.B.C. (1999), *Review of fish swimming modes for aquatic locomotion*, IEEE J. Oceanic Engineering, 24(2), pp.237-252

XU, Y.G.; WAN, D.C. (2012), *Numerical simulation of fish swimming with rigid pectoral fins*, J. Hydrodynamics, Ser. B, 24(2), pp.263-272