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Investigation of dual varying area flapping actuator of a robotic fish with energy recovery

I. Tipans, J. Viba, M. Irbe and S.K. Vutukuru*

Riga Technical University, Faculty of Mechanical Engineering, Transport and Aeronautics, Department of Theoretical Mechanics and Strength of Materials, Kipsala street 6B, LV-1048 Riga, Latvia
*Correspondence: vshravankoundinya1989@gmail.com

Abstract. Autonomous under-water vehicles (AUV) performing a commanded task require to utilize on-board energy sources. At the time when on-board power source runs low during operation, the vehicle (AUV) is forced to abort the mission and to return to a charging station. The present work proposes the technique of an energy recovery from surrounding medium. This effect is studied for dual action actuator movement that obtains energy from fluid. It is realized that a flapping or vibrating actuator can be used for energy extraction phenomenon apart from the non-traditional propulsive technique. In the present work a simple dual flapping actuator that can switch between simple flat plate and perforated plate at extreme end positions (angles) by using an efficient mechatronic mechanism that would help in overcoming viscous forces of the operating medium is extensively studied. The main objective of the present article is to develop a new approach for energy gain and recharge power pack of on-board sources from the surrounding medium and to create a robotic fish that would work autonomously by using unconventional drive along with the possibility of energy restoration by using dual varying area type vibrating actuator. At the time of recharge, the robotic fish would project its tail (actuator) out of water and use surrounding medium (air) to scavenge the energy. All the equations describing the process are formed according to classical laws of mechanics. The mechatronic system is explained and the results obtained are discussed in detail for air as the operating fluid to scavenge energy.

Key words: energy extraction, flapping tail, robotic fish.

INTRODUCTION

Highly growing wakefulness for carbon-free environment and also a climate friendly energy requirement led to the development of a new concept of renewable energy. Such energy sources are available in abundance (like ocean, air currents).and are very attractive as these sources are mostly readily accessible in nature. Ever since the technique of harmonically oscillating wing of a windmill was used for the process of energy extraction (Mckinney & DeLaurier, 2012), further research in this field was explored by many eminent researchers. Research work in this direction includes entirely passive motion approach (Peng & Zhu, 2009), motion in a definite order approach for wings that are arranged in tandem in the path of oncoming flow for sinusoidal and non–sinusoidal motion (Ashraf et al., 2011) and studies of power extraction through modified motion oscillating foil (Xie et al., 2014).Considering the shape driven effects, chord-like flexibility and related outcome for power extraction (Jeanmonod & Olivier, 2017) and combined foil effects on energy extraction (Boudis et al., 2018) were performed. It is important to note that as a result of experiments it is demonstrated that flapping foils when subjected to unsteady and turbulent flow are set into self-unsteady motion, and when effectively controlled, maximum energy extraction can be achieved which is similar to high aspect ratio windmills. Relevant performance parameters were analysed (Simpson et al., 2008). Experiments were followed by numerical investigation pertaining to energy extraction performance for a flapping–foil power generator. Experiments were validated and it was concluded that increased pitching amplitude is good for achieving good power output (Lu et al., 2015). Interesting unmanned vehicle using flapping – hydrofoil for the purpose of energy generation in ocean is designed (Sun et al., 2016). Power generation and basic mechanism for the flapping wing along with three different types of flapping power generators are discussed. Most important is the third type which is determined by fully driven motion – the plunge and pitch motion are through fluid and body interactions, and oscillation motion has a controlled mechanism. Power output is measured by connecting viscous damper for the plunge motion (Ashraf et al., 2019). Flapping wing concept to produce power from tidal current is developed by BioSTREAM company in 2019. Initially in the flow, the pitch angle is adjusted and the resulting plunge motion of the fin is forced to drive a gear box where in the flapping motion is then turned into a rotating motion that drives conventional dynamo. Further, a good review of oscillating foil energy converters is available (Xiao & Zhu, 2014).

In the present work, by paying particular attention to aquatic world a new concept of energy extraction, similar to the propulsive technique (Viba et al., 2011) is studied. In addition, the concept of fluid-body interactions phenomenon according to Tipans et al. (2019b) is used in the present article. The dual tail fin model is shown in the Fig.1 and also Dual flapping tail actuator in diving motion from left to right inside water can be seen from Fig. 2. The advantage of flapping / harmonically oscillating flat plates is based on the fact that they are easy to manufacture, maintain and perform effectively even in shallow waters. Flat plates are advantageous in a way that they form early leading-edge vortices (LEV).

MATERIALS AND METHODS

Dual actuator actions for diving and charging positions

As shown in Fig.1, during the diving motion of the robot the tail form is changed from single tail to dual tail with ability to rotate about the axis O (Fig. 3), and the same process continuously repeats thereby achieving the diving force, and that diving force is maintained unceasing (Viba et al., 2010; Viba et al., 2011). The tail fin here consists of two perforated flat plates whose actions are synchronous. The tail fins (perforated plate) under locked position form the single tail and this specific condition is called 'locked in' because there is no relative movement of the two perforated plates (tail fin) and the perforations fit in exactly there by forming a complete flat plate, this single tail fin under extreme angles of propulsive strokes change into perforated plate due to relative movement of the plates in that position. The geometry of the two perforated plates is as mentioned (Tipans et al., 2019a). However, the present article only focuses on the novel concept of scavenging energy from surrounding medium and does not refer to robotic fish docking position or to the method by which the fish is held stationary in the running waters. As already stated, keeping in view the additional advantage of the flat plate structure the same technique of controlled flapping motion is investigated and the present work offers a novel solution for energy recovery from the surrounding medium and at the same time ensuring that the model is practically realizable. It is also anticipated that this switching of flat plate to a perforated (varying area) helps to overcome the viscous nature of the fluid medium and to improve the propulsive stroke performance.

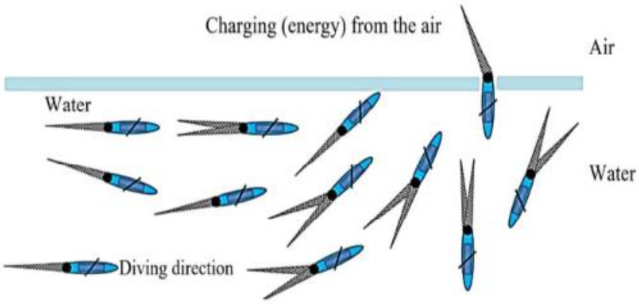

Figure 1. Dual tail and single tail fin flapping actuator in diving motion inside water along with the technique of charging from air.

At the time of charging, the single tail fin (locked-in condition) of the fish is extended out of water, and the surrounding medium (air) is used for charging (Fig. 3). The air-flow is assumed to be laminar and is from right to left. The single tail fin at the extreme angles initiates plates relative motion (perforated plates of tail fin) and by the action of wind is set into flapping (curvilinear oscillations) which is required for the energy scavenging Fig. 14. Thereby though dual plates exists as the tail fin for the robotic fish, this article refer more to single tail fin as this particular action of robot is very crucial for the purpose of energy scavenging from the local medium.

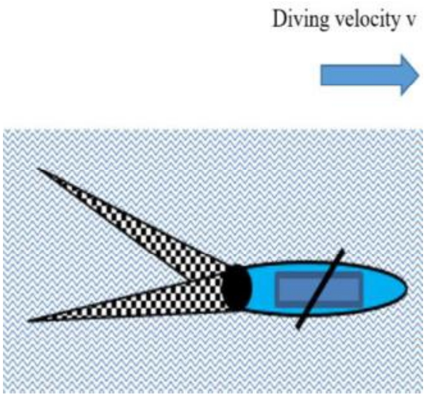

Figure 2. Dual flapping tail actuator in diving motion inside water.

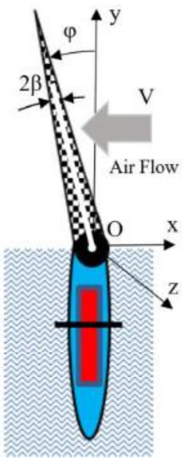

Figure 3. Flapping actuator in charging position in air.

The robotic fish prototype with related mechatronic system is shown in the Fig. 15–16. All the calculations performed considering the existing successful robotic fish prototype model. The components and material are so chosen to keep the weight of the robotic fish as low as possible and to be impervious to water. The mechanism of flapping tail fin is tested in wind tunnel, the non-stop flapping of the fin is expected to ensure promising results.

Mathematical model of the one tail robot horizontal motion in fluid

We consider the motion of a simplified, one-tail actuator for horizontally diving robot (Fig. 3). Assuming a simple linear motion for the robotic fish in water with a mechatronic system, it is possible to come up with a triangular tail with flapping/curvilinear oscillations about the axis O for a given time function. The hull and the tail is described as a mechanical system of one degree of freedom (1 DOF) defined by the coordinate x. In order to avoid additional movement from the tail rotation leading to instability, it is considered that the rotation axis O coincides with the centre of mass of the tail fin for the robotic fish. Thereby, the differential equation for the robot motion will be (1):

$$(m0 + m)\ddot{x} = -N1x - N2x - b\dot{x}^2 sign(\dot{x}), \tag{1}$$

where $m0$ is a mass of the hull; m is a mass of the tail; $\ddot{x}$, $\dot{x}$ are correspondingly the acceleration and velocity of the hull; $N1x$ is a fluid interaction component in a pressing zone; $N2x$ is a fluid interaction component with the tail in suction zone; $b\dot{x}^2$ is non-linear interaction of the hull with fluid in rectilinear motion, depending of motion velocity v = $\dot{x}$ directions; b is constant.

To determine the vector components N1x and N2x, the interactions on two infinitely small tail areas in the pressure and suction zones are considered, as shown in Fig. 4. The direction of the angular velocity of the tail rotation as well as the direction of relative motion of the housing must also be taken into account. Since the rotational velocity component of a given area depends on the distances to the axis of rotation, that is expressed by (1) as an integral-differential equation which can be solved approximately by using numerical methods.

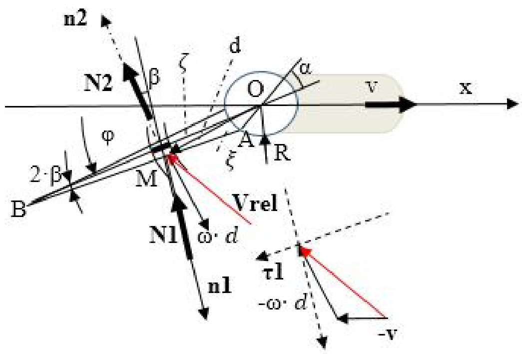

Figure 4. Model for tail - fluid interaction calculations.

Before integration, we write analytical link equations (2), (3) at pressing (upstream zone) for triangles OAB and OMB Fig. 4:

$$\xi = \frac{Rsin(\gamma)}{\sin(\alpha + \beta - \gamma)}; \tag{2}$$

$$d = \frac{R\ sin(\alpha + \beta)}{\sin(\alpha + \beta - \gamma)}, \tag{3}$$

were ξ, d and R are shown in Fig. 4, but angle γ is ∢ MOB.

According to engineering calculation method described by (Tipans et al., 2019a) to determine forces N1x and N2x, we first find forces in normal direction N1, N2 (Fig. 4). They depend on relative velocity projection squares as given by (4), (5):

$$|N1| = B.\rho\left|\int_0^{\beta}(v.sin(\varphi-\beta)+\omega.\xi)^2 d\xi\right|; \tag{4}$$

$$|N2| = B.\rho.C\left|\int_R^{R2}(v.sin(\varphi)+\omega.\zeta)^2 d\zeta\right|, \tag{5}$$

where ξ is a distance from side AMB and $d\xi$ is a differential of ξ, both calculated by (3); ζ is a radial distance along OB (Fig. 3); C is a constant, approximately equal to 0.5 (Tipans et al., 2019).

For the approximate solution of equation (1), the following force equation *N1x* and *N2x* can be taken as (6) & (7):

$$F1x = |N1|.sign\left(v.sin(\varphi-\beta)+\omega.\frac{R+R2}{2}\right).sin(\varphi-\beta); \tag{6}$$

$$F2x = |N2|.sign\left(v.sin(\varphi)+\omega.\frac{R+R2}{2}\right).sin(\varphi) \tag{7}$$

An example of numerical modeling is given below with parameters: R = 0.05 m; R2 = 0.25 m. For the tail fin rotation angle and angular velocity is given by (8), (9) and corresponding graphical results shown in Fig. 5 & Fig. 6 below respectively:

$$\varphi = a[\sin(pt) + 2(\lambda_3)\sin(3pt+\varepsilon_3)]; \tag{8}$$

$$\omega = a[p\cos(pt) + 6p(\lambda_3)\cos(3pt+\varepsilon_3)], \tag{9}$$

where ε_3 = -1.571, λ_3 = ±0.1, p = 5 and a = 0.5.

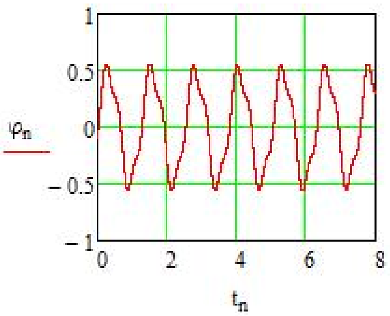

Figure 5. Tail rotation angle for varying time.

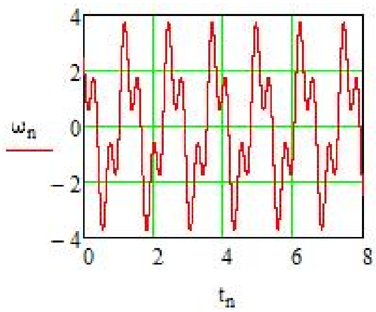

Figure 6. Angular velocity for varying time for the tail fin, $\lambda_3 = -0.1$.

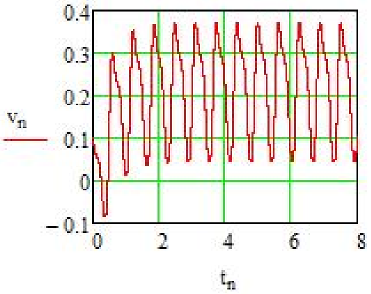

Figure 7. Hull velocity ahead. $\lambda_3 = -0.1$.

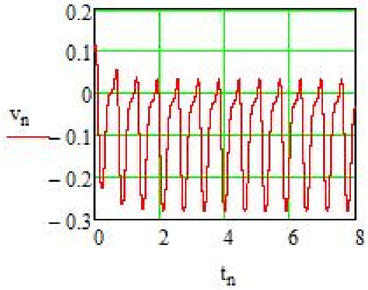

Figure 8. Hull velocity in reverse motion. $\lambda_3 = +0.1$.

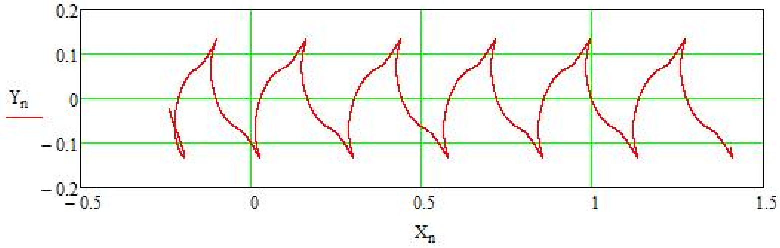

Figure 9. Absolute trajectory of tail edge point B, moving forward in plane (X, Y), $\lambda_3 = -0.1$.

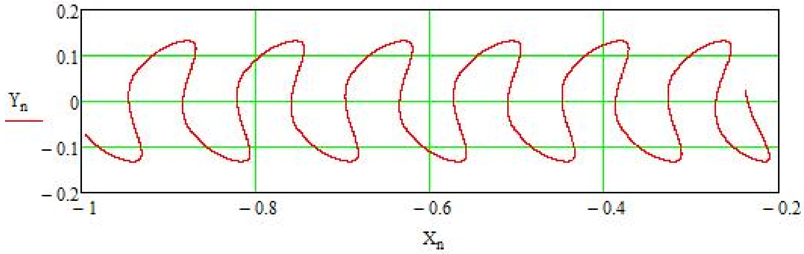

Figure 10. Absolute trajectory of tail edge point B, moving backward in plane (X, Y), $\lambda_3 = +0.1$.

The following conclusions can be drawn from the results of numerical modelling:

1. Periodic modes start very quickly because the frontal force of the interaction is proportional to the density of the operating medium.

2. By changing the polyharmonic rotation phases, it is possible to move in both directions in the flow (forward and backward).

3. Acquired analytical - numerical relationships can be used in the synthesis of mechatronic engine.

Mathematical model for the robot power pack charging with single flapping fin actuator

In the charging position, the position of robotic fish is static and is not influenced by water currents. The fin (tail), as an actuator, interacts with the flow of air by rotating about a fixed axis *Oz* according to the following differential equation (Fig. 3):

$$J_z\ddot{\varphi} = Mwin_z - Mel_z(\varphi) - Mgen_z(\dot{\varphi}), \tag{10}$$

where J_z is a tail mass moment inertia about rotation axis z; $\ddot{\varphi}$ – angular acceleration;, $\varphi, \dot{\varphi}$are correspondingly the angle and angular velocity;$Mwin_z$ is an air flow interaction moment; $Mel_z(\varphi)$ is a moment from linear or non-linear elastic spring; $Mgen_z(\dot{\varphi})$ is a linear or non-linear moment from energy generator.

The moment $Mwin_z$ is determined separately for the pressure and suction zones, similarly to the previous procedure (2)–(7). If the flow-induced pressure and suction zones for the triangular tail do not change direction, the integral-differential equation is simplified. As an example, for a theoretically infinite thin sharp plate β=0) we obtain (11) – (12):

$$Mwin_z = (1 + C) \cdot B(\omega) \cdot \rho_a \left[\int_{R1}^{R2} (V \cdot \cos(\varphi) - \zeta \cdot \omega)^2 \cdot \zeta \cdot d\zeta \right]; \tag{11}$$

or

$$Mwin_z = (1 + C) \cdot B(\omega) \cdot \rho_a \cdot \left[\frac{(R2^4 - R1^4}{4}\omega^2 + 2\frac{R1^3 - R1^3}{3}\omega V cos(\varphi) + \frac{(R2 - R1)Vcos(\varphi)^2}{2} \right], \tag{12}$$

where V is a flow velocity; $R1$, $R2$ are the radial distances of interaction zone; C is a parameter, explained before; $B(\omega)$ is a perforated plate area exchange expressed as ω function; ρ_a is an air density.

Eqs (10) and (12) are used for calculating the robot's energy charge. It should be noted that with the help of a mechatronic device, the interaction area of the perforated tail can be changed in the system and that the power charging system can change the generator parameters as well as its optimum control rules.

Modelling results are given below as an example of a relatively small plate. A case with a linear spring and a linear generator characterization in the following form is considered:

$$Mel_z = c \cdot \varphi; \; Mgen_z(\dot{x}) = b \cdot \dot{\varphi}, \tag{13}$$

where c, b are the constants.

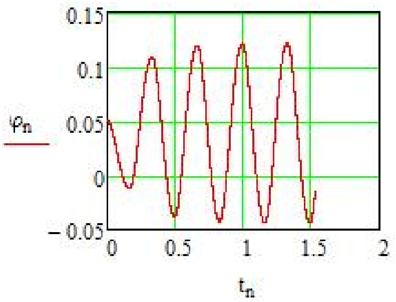

Figure 11. Angle of the perforated plate varying with time.

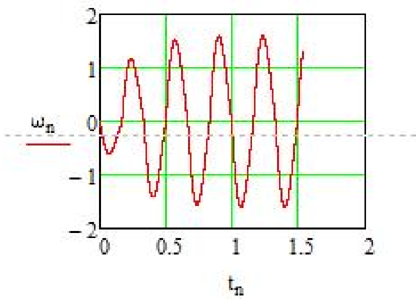

Figure 12. Angular velocity of the perforated plate varying with time.

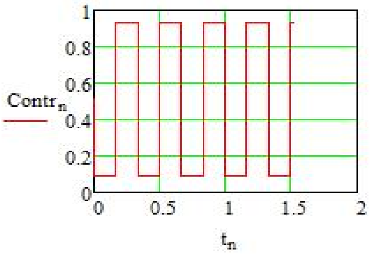

Figure 13. Area control action for the perforated plate.

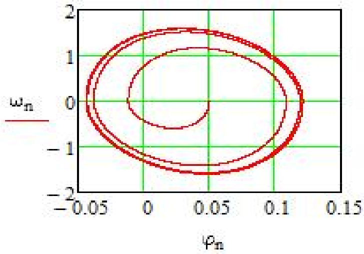

Figure 14. Motion in phase plane.

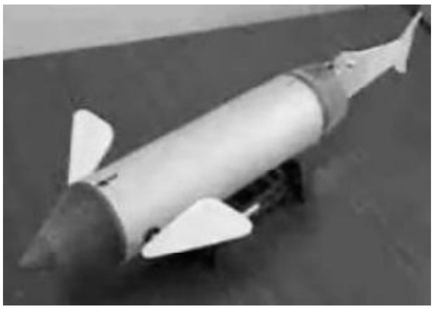

Figure 15. Existing Robotic fish prototype. Tail fin without perforated plates.

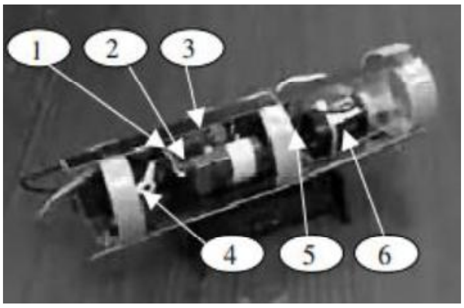

Figure 16. Mechatronic system of fish: 1 – Micro controller; 2 – power supply; 3 – signal detector from radio; 4 – attachment for pectoral fins for levelled motion; 5 – direction controller; 6 – velocity control.

Figure 17. Robotic fish in action.

The following additional conclusions can be drawn from the results of numerical modelling:

– opening and closing of flat plate perforations can reduce or increase the interaction area;

– it changes forces of interaction, and oscillations are induced in a flexible system; the oscillation is very stable as the periodic cycle is achieved in three to five strokes.

RESULTS AND DISCUSSION

In this study, the application of dual mechatronic actuator is considered. First, the dual-action actuator in the robot's fish dive motion allows the robot to move back and forth by changing the tail drive phase. Similarly, in future studies, the dual actuator can provide not only rectilinear motion but also steering and floatation. Accordingly, in the mechatronic control of the energy charge mode, the tail interaction area can be changed by opening or closing the perforations. The study shows how in engineering calculations it is possible to obtain relatively simplified differential equations for object rotation and planar motion in fluid. The speed of the hull in forward motion is more as compared to the hull speed in reverse motion as it can be seen from the obtained calculations Fig. 7–8.

Though the calculations involved are for the small, flat perforated plates the same can be extended to plates of any size and geometry. Computer modelling is used instead of practical test for validating the results. The results obtained, discussed in this article ensure that the concept is practically realizable.

CONCLUSIONS

The dual action actuator ensures the long-term functioning of the underwater robot fish. For this purpose, it shall be possible to switch the mechatronic control system from the movement of the hull dive cycle to the movement of the power refill cycle in the air stream. Energy replenishment is also possible underwater. In this case, the underwater stream should be used. The engineering calculation method proposed in the study allows to analyse the interaction between the motion of different objects and fluids. The method makes it possible to model the complex motion of an object in a fluid, as described by integral differential equations.

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