Efficiency of Swimming Microrobots using Ionic Polymer Metal Composite Actuators

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Abstract

In this paper, we present a survey of fish-like propulsion at millimeter scale in order to build high efficiency swimming microrobots. We begin with a mechanical study of the fish-like propulsion. The mechanical model we used shows that undulatory motions are more efficient than oscillatory motions. We applied these theoretical results to the design and the realization of a microrobot propelled by the beating of two fins. Fins are moved by a transducer material called I.P.M.C. (Ionic Polymer Composite Metal). The experimental results allow us to check our theoretical model of the microrobot. Lastly, we propose an improved microrobot which would have a better efficiency.

1 Introduction

Animals fascinate by their perfect adaptation to any surrounding. In the water, fish reach some performances that machines can't achieve. Some fish are able to swim very fast with low muscular power (Gray's paradox), others can change quickly their path and accelerate very fast. These performances are enviable : high efficiency, great manoeuvrability, high acceleration, noiseless motions...

In microrobotics, this way of motion is very interesting because of its good efficiency. In the case of an autonomous microrobot, the energy is limited and must not be wasted.

Several real-sized biomimetic robots have been realized to study this way of propulsion. For example, we can mention Ayers [2] and Ijspeert [1] for their works on an eel robot, Triantafyllou [9] for his pike robot and Kato [10] who studied the bass's pectoral fin effect.

Until now, microrobots which have been developed don't use fish-like motion. In fact, this motion is difficult to generate at a millimeter scale. All these microrobots are propelled by fin beating . For example, report to those of Fukuda [14] [15], Guo [13] or Mojarrad and Shahinpoors [4] [5] [6].

Our purpose is to build swimming microrobots having the best mechanical efficiency. With this aim in mind, we carried out a fluid mechanical survey of fish-like propulsion at a millimeter scale. Then, we built a prototype in order to check our theoretical model of the microrobot.

In this paper, we present a theoretical model to evaluate the thrust force, the power and the efficiency of a fish-like propeller. Then, we study several motions to find which ones are the most efficient. Secondly, we present the experimental results of the prototype. Before concluding, we propose some improvements to increase the microrobot's performances.

2 Mechanical modeling

2.1 Theory of fish undulatory motion

For a long time researchers have tried to model the fish-like propulsion, in particular for high speeds, when Gray's paradox appears. Rosen [16] was among the first to give an explanation : for high speeds, the thrust force is generated by the evolution of vortex generated by the last 2/3 of the fish's body.

For small scales, speeds of evolution are very low and this model doesn't suit very well. We chose another one proposed by Webb and Weihs [11] valid for small sizes. This one allows us to evaluate the resulting force of the motion of any fish moving very slowly.

This model must be used with the following hypothesis :

1. The fluid is incompressible and not viscous.
2. The thickness of the fish is negligible compared with its length.
3. The speeds of motions are low.
4. The mean speed U of the fish relative to the fluid is low and constant.

The principle of the model is based on the reactive force generated by the fluid on a moving thin plate. This reactive force is called the drag force. For any solid, the drag force is defined by :

$$\overrightarrow{F_n} = -\frac{1}{2} C_n \rho S \overrightarrow{V_n} \|\overrightarrow{V_n}\| \qquad (1)$$

where :

- ρ is the density of the fluid.
- S is the area of the plate.
- $\overrightarrow{V_n}$ is the speed of the solid relative to the fluid.
- C_n is the drag coefficient.

The drag coefficient depends on the Reynolds's number and on the shape of the solid. The Reynolds's number characterizes the relative speed U, the height l of the plate and the kinematics viscosity ν of the fluid. It is defined by :

$$Re = \frac{Ul}{\nu}$$

The shape of the fish (or of the fin) is defined by the functions $b_1(x)$ and $b_2(x)$. The length of the shape is L. The function $h(x,t)$ describes the fish motion in the Oxz plan according to the time t (cf. figure 1).

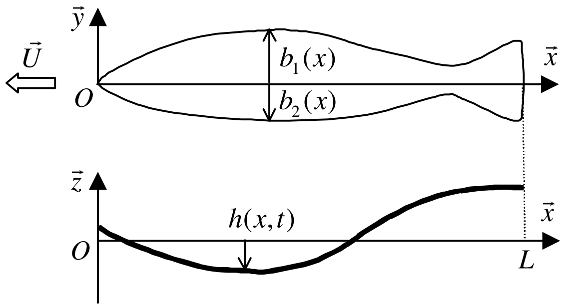

Figure 1: Shape and motion of the fish.

The total height of the fish is given by :

$$b(x) = b_1(x) - b_2(x)$$

The principle of the model consists in calculating the reactive force of the fluid for small elements of the surface, and then, in integrating on the length of the shape.

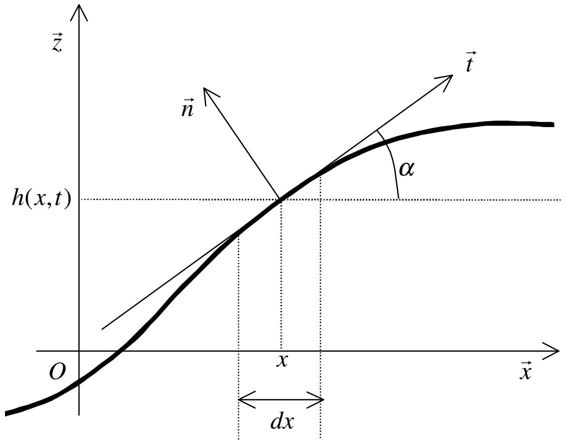

Figure 2: A small area element in the Otn reference frame.

The speed of every area element of fish in the Oxz reference frame can be written as :

$$\begin{cases} V_x &= U \\ \\ V_z &= \dfrac{\partial h}{\partial t} \end{cases} \qquad (2)$$

The speed in the Otn reference frame bound to the area element is then (cf. figure 2) :

$$\begin{cases} V_n &= -U \sin(\alpha) + \dfrac{\partial h}{\partial t} \cos(\alpha) \\ \\ V_t &= U \cos(\alpha) + \dfrac{\partial h}{\partial t} \sin(\alpha) \end{cases}$$

with :

$$\alpha(x,t) = \frac{\partial h}{\partial x}$$

and U the mean speed of the fish in the Oxz reference frame.

We suppose that the fluid has no viscosity. Therefore, the tangent force of the fluid on the plate is zero. The normal force (On axis) of the fluid on the plate (or drag force) can be written with the help of the equation (1) as :

$$\begin{cases} dF_n &= -\dfrac{1}{2}\, C_n \rho V_n |V_n| \, dS \\ dF_t &= 0 \end{cases}$$

We project these forces onto the Oxz reference frame and we get :

$$\begin{cases} dF_x = \dfrac{1}{2}\, C_n \rho b V_n |V_n| \tan\alpha \, dx \\ dF_z = -\dfrac{1}{2}\, C_n \rho b V_n |V_n| \, dx \end{cases}$$

We integrate into the length of the fish, and the forces are then :

$$\begin{cases} F_x &= \dfrac{1}{2}\, C_n \rho \displaystyle\int_0^L b V_n |V_n| \tan\alpha \, dx \\ F_z &= -\dfrac{1}{2}\, C_n \rho \displaystyle\int_0^L b V_n |V_n| \, dx \end{cases} \tag{3}$$

We call F_x the thrust force and F_z the lateral force.

2.2 Motion study

Thanks to this model, we can study the efficiency of several motions. This point is the main idea of this paper.

Using equations (2) and (3) we get the powers in each direction :

$$\begin{cases} P_x &= \dfrac{1}{2}\, C_n \rho \displaystyle\int_0^L b V_n |V_n| \tan\alpha \, U \, dx \\ P_z &= -\dfrac{1}{2}\, C_n \rho \displaystyle\int_0^L b V_n |V_n| \, \dfrac{\partial h}{\partial t} \, dx \end{cases} \tag{4}$$

P_x is called the useful power. $P_x + P_z$ is the total wasted power. The mechanical efficiency η is then :

$$\eta = \frac{P_x}{P_x + P_z} \tag{5}$$

We chose to compare two types of motion : an oscillatory motion and an undulatory motion. With this aim in mind, we used the next function :

$$h(x,t) = H \frac{g(x,t)}{\max\limits_{(x,t)} |g(x,t)|}$$

with :

$$g(x,t) = \cos(\omega t - \gamma \frac{2\pi}{L} x) - \cos \omega t$$

γ defines the type of motion : when γ tends toward zero the motion is oscillatory and when γ is equal to 1, the motion is undulatory (cf. figures 3 et 4). The max function normalizes $g(x,t)$ in order to get the same amplitude H for any value of γ.

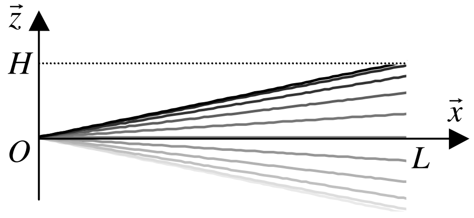

Figure 3: Half of an oscillatory motion ($\gamma \to 0$).

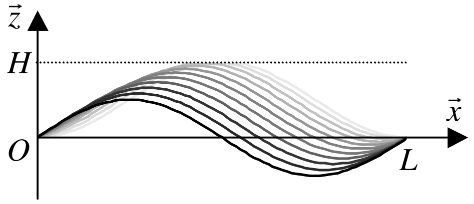

Figure 4: A quarter of an undulatory motion ($\gamma = 1$).

The figure 5 represents the efficiency η to maximum power according to the coefficient γ. It clearly shows the superiority of the undulatory swimming on the oscillatory swimming. So, microrobots should use undulatory motions rather than oscillatory motions to obtain best performances.

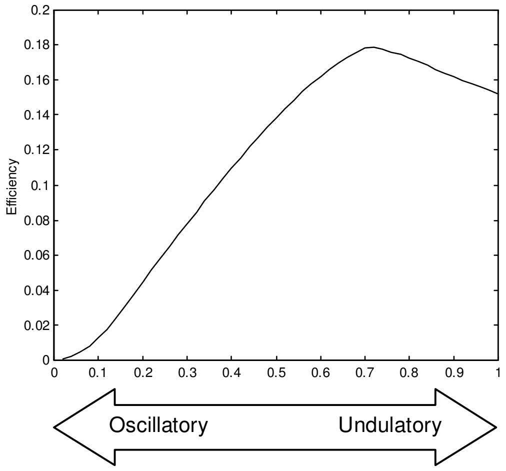

Figure 5: Efficiency of different swimming motions.

Nomenclature :

- $L = 40$ mm
- $H = 10$ mm
- $\rho = 1000$ Kg/m^3

- $b(x) = 10$ mm
- $\omega = 2\pi$ rad/s
- $R_e = 10$
- $C_n = 0.87$
- $\nu = 10^{-6}$ m^2/s

3 The microrobot

To built a small swimming robot, we had to find a compromise between the theory and the technical feasibility. So, we chose to make a first prototype very easy to build. This prototype is propelled by two beating fins. Each fin is moved by an I.P.M.C actuator.

3.1 I.P.M.C. actuators

I.P.M.C. are materials which convert the electric energy direct to mechanical energy [3] [12] [8] [7].

I.P.M.C. are made of ionic polymers and metal. In our case, we used a Nafion®-Platinum composite. The Nafion® is an ion-exchange membrane produced by the Dupont company. An I.P.M.C. actuator is made of a film of Nafion® chemically plated on its both sides with platinum. When a strip of this composite is supplied by a low voltage on its platinum electrodes, the strip bends to the positive side (cf. figure 6).

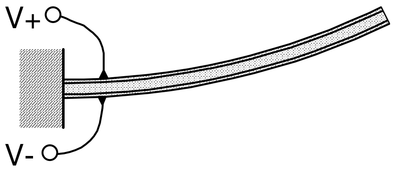

Figure 6: Bending of an I.P.M.C. actuator.

Thanks to its features, an I.P.M.C. actuator is the best material to propel a swimming microrobot : its deformations are important even for small tensions (10 % for 2 V), its consumption is low and its shape make it easy to use with fins. Moreover, it perfectly works in water. The maximum operating frequency is about 2 Hz.

The drawback of this actuator is its very complex behavior. It is non linear with great hysteresis. It doesn't exist any complete model, but some isolated features can be calculated.

To model our swimming microrobot, we needed a model of the deformed shape of an actuator. With a laser sensor, we studied the displacement of a 10×2 mm actuator supplied with a constant tension. The deformed shape of the I.P.M.C. is nearly circular for 10 mm. Then, it can be modeled for 10 mm by a bow of circle. The radius of the circle is determined by interpolation on a set of measures (cf. figure 7).

$$R = \frac{35.64 + d^2}{2d^2} \tag{6}$$

with :

$$d = -0.019037\, u^3 + 0.12011\, u^2 - 0.026596\, u$$

and u the supply tension (the wave signal frequency must be less than 2 Hz).

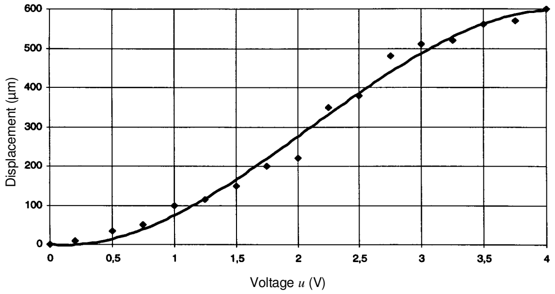

Figure 7: Interpolation of the position of a point located at 6 mm from basis.

Then, the deformed shape can be written as :

$$h(x,u) = R - \sqrt{R^2 - x^2} \tag{7}$$

This equation describes the amplitude of the motion and the shape of the actuator well enough to model the propulsion mechanism.

3.2 Propulsion mechanism

We chose to use two 12×2 mm strip of I.P.M.C. because longer actuators don't bend more. The I.P.M.C. actuators are supplied by a sinusoidal tension (2V, 1Hz). Their motions are modeled by the equation (7).

We can say that the microrobot uses more the oscillatory mode than the undulatory mode. In fact, the motion of actuators looks like the motion described by the figure 3. To increase a bit the efficiency of those propellers, we chose to use very flexible fins. The bend of the fins generates a slight undulatory motion. Fins are modeled like bending beams. We found that a fin made of a 20×10×0.01 mm polyethylene film is the most efficient.

Using the equations (7) with (4), we get the thrust force during a swimming cycle (cf. figure 8). The starting mean thrust force can reach 1.8 10^{-7} N. When the power is at the most (about 7.39 10^{-10} W), the efficiency is equal to 0.014. The efficiency is very low because the motion is near an oscillatory motion

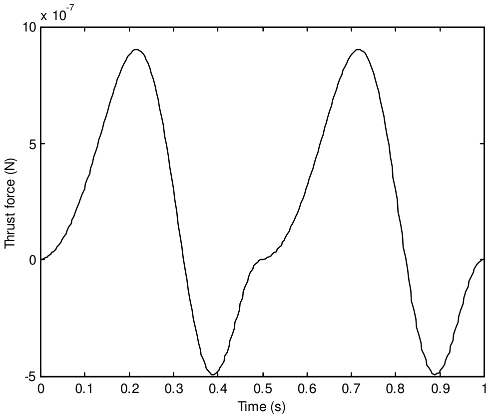

Figure 8: Thrust force during a swimming cycle.

3.3 Assembling

The microrobot floats thanks to its body made of polyethylene. The different components are put together with glue.

In order to get the mean speed of the microrobot, we evaluated the drag force of the body in water with a fluid mechanic software. Then, we drew on the same figure the graph of the thrust force and the graph of the drag force (cf. figure 9). The speed of the microrobot is the abscissa of the intersection of these graphs. We can read on the figure 9 that the theoretical speed of the microrobot is about 2.1 mm/s.

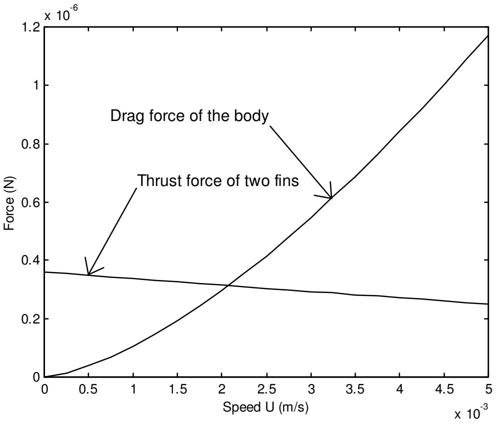

Figure 9: Evaluation of the mean speed.

4 Experimental results

The figure 10 shows the achieved microrobot. On the left, we can see the white body of the microrobot and on the right, the white fins and the black actuators.

The table 1 presents the general features of the microrobot. We notice that the real mean speed is near the theoretical mean speed. In fact, the microrobot reaches a speed about 1.8 mm/s.

Moreover, the microrobot's motion is jerky as we can imagine when we see the figure 8 (an online video on our website shows this motion very well). The thrust force generates successively an acceleration and a deceleration because its sign changes during a swimming cycle. The balance of forces is slightly positive.

Thanks to those results, we can conclude that the theoretical model of the microrobot is very near the reality.

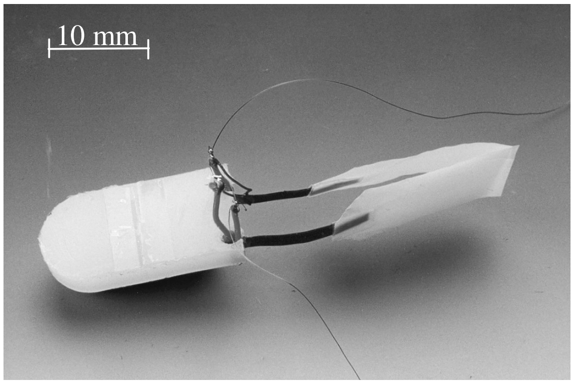

Figure 10: The microrobot.

Size	50×10×10 mm
Weight	0.69 g
Body	Polyethylene (20×10×3 mm)
Actuators	I.P.M.C. (12×2 mm)
Fins	Polyethylene (20×10×0.01 mm)
Power supply	2 V, 1 Hz (external)
Mean speed	1.8 mm/s

Table 1: General features of the microrobot.

5 Improvements

To increase the efficiency and the performances of our microrobot, the motion should be more undulatory. It could be achieved by assembling several I.P.M.C. actuators to create an eel-like waving fin (cf. figure 11).

The figure 12 presents the theoretical efficiency of a 50×10 mm eel-like waving fin according to its number of actuators. It shows that the efficiency of the fin is better with more than 3 actuators. The more actuators are, the more efficient they are. The addition of a flexible fin would also increase the efficiency.

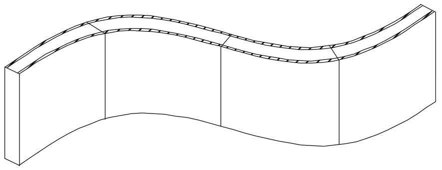

Figure 11: A waving fin made of four actuators.

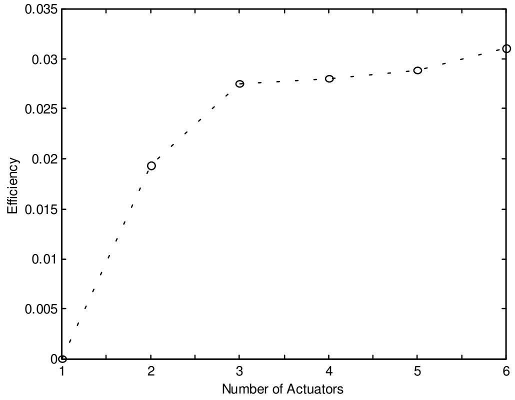

Figure 12: Efficiency of a waving fin according to the number of actuators.

6 Conclusion

For millimeter scale, the mechanical study we made shows that the fish-like undulatory motion is more efficient than the oscillatory motion.

This model allows us to design a prototype propelled by two beating fins using I.P.M.C. actuators. The experimental results agree with the theoretical forecast. Those results validate our complete theoretical model of our swimming microrobot.

At present, we are working on a new prototype using an undulatory motion in order to get a better efficiency.

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