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Development of ProtoEusthen wheel: an amphibious robotic wheel

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This paper describes the development of "ProtoEusthen wheel" that is a new kind of amphibious robotic wheel. The wheel works as a rimless wheel on land, as a paddle wheel on the water, and as an underwater paddle wheel in the water. The mechanism of the wheel is contrived, and made. Besides, theoretical formulas of the wheel are derived, and a driving experiment of it was done for examining the formulas.

Key Words**:** Amphibious robot, Wheel mechanism, Rimless wheel, Paddle wheel

1. Introduction

A lot of amphibious robots such as "AQUA"[1], "Salamandra Robotica II"[2], and "Amphibious Whegs"[3] have been developed, but their specifications can not be said perfect in terms of transition between land and water, capability to get over large obstacles as stones, and mechanism simplicity which is shown in the number of DOF. That is why we aim to develop "ProtoEusthen", a concept of the robot that is capable of swimming, landing, and walking, and has better specification than the previous amphibious robots in those terms. This name, "ProtoEusthen" is derived from Eusthenopteron, the fish that evolved and landed on the ground. This paper's goal is to develop "ProtoEusthen wheel", the special wheel for "ProtoEusthen" as a first step for achieving "ProtoEusthen".

2. Design

The main idea of accomplishing "ProtoEusthen" is to make "ProtoEusthen wheels", and attach them to the main cylinder body of "Nanins"[4]. The concrete idea of "ProtoEusthen wheel" is a wheel which can work as a rimless wheel on land, as a paddle wheel on the water, and as an underwater paddle wheel in the water.

The basic issues for designing "ProtoEusthen wheel" must be set at first. The number of paddles (spokes) of the wheel is determined as 6 by considering the trade-off between stability and weight. Regarding the number of "ProtoEusthen wheels" which are equipped to "ProtoEusthen", 2 "ProtoEusthen wheels" & 1 caster wheel system is thought the best due to the trade-off between ability to get over obstacles and mechanism simplicity (e.g. steering). The number of motors per the wheel should be as few as possible for simplicity. Therefore, only 1 motor per 1 "ProtoEusthen wheel" is decided to be used.

2.1 Contriving the mechanism of "ProtoEusthen wheel"

The most important point for designing "ProtoEusthen wheel" is that the wheel can function as an underwater paddle wheel. To move in the water by rotating paddle-wheel-like thing, there must be always area difference between upper boards and lower boards while its rotation. For satisfying this requirement, a mechanism of Fig. 1 is contrived. This mechanism has 12 "sub-paddle boards" that are attached to 6 "main-paddle boards", namely, normal paddle boards. "Sub-paddle boards" are folded by springs at the upper side, and unfolded by strings at the Lower side, and then make the area gap. In Fig. 1, only strings of one side are illustrated for understandability. Besides, springs can not be seen actually from the view of Fig. 1, but only 1 spring is shown as a broken line in the figure for understandability, too. "String gripper" is a part which grips strings. Its edge part is rotated freely, so the strings do not twine around the part. The relative position of "String gripper" on the wheel is fixed.

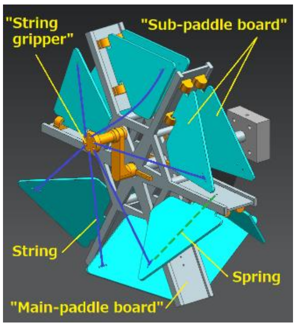

Fig. 1 The mechanism of "ProtoEusthen wheel"

2.2 Calculation of necessary rotation speed on the motor

Only critical cases of the calculation for deciding the motor's specification, especially rotation speed, are written below.

At first, minimum required rotation speed of the motor on the water is considered. "ProtoEusthen wheel" pushes aside water and gain ahead force by Newton's third law of motion as a paddle wheel. Initially, main-paddle boards' case is thought. Main-paddle board's velocity v can be roughly calculated as $r\omega$ where r denotes the radius of "ProtoEusthen wheel" and it is set as 15cm, and ω is rotation speed of "ProtoEusthen wheel". When main-paddle board's one-side area A_m is 40cm^2, volume flow of water which is pushed away by the board Q is derived as $A_m v$, namely, $A_m r\omega$. Water's density ρ is 1000kg/m^3. Therefore, the force that one main-paddle board is applied to by water F_{m1} is calculated by momentum conservation law as below.

$$F_{m1} = \rho Q v = \rho A_m r^2 \omega^2 \tag{1}$$

Next, the situation where "ProtoEusthen wheel" is rotating like Fig. 2 is considered. θ is the degree between water surface and a main-paddle board. The total ahead force that is applied to the wheel while a main-paddle board is pushing away water, namely, θ is changing from 0° to 180° F_{m1t} is,

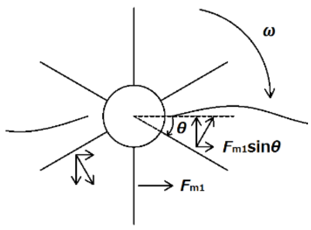

Fig. 2 Model diagram of "ProtoEusthen wheel"

$$F_{m1t} = \int_{\theta=0}^{\theta=\pi} F_{m1} \sin\theta \, d\theta = \int_0^{\pi} \rho A_m r^2 \omega^2 \sin\theta \, d\theta = 2\rho A_m r^2 \omega^2 \tag{2}$$

Hence, the total ahead force that is applied to the wheel during its one revolution F_{m1tr} is $6F_{m1t} = 12\rho A_m r^2 \omega^2$ because the wheel has 6 main-paddle boards. Thus, the force that is applied to the wheel, consequently "ProtoEusthen", by main-paddle boards per 1 second F_m is derived as below.

$$F_m = F_{m1tr} \times \frac{\omega}{2\pi} = \frac{6}{\pi} \rho A_m r^2 \omega^3 \tag{3}$$

Subsequently, sub-paddle boards' case is examined. It is almost same as main-paddle boards' case, but sub-paddle boards are assumed to push water during θ is changing from 60° to 120°. Thus, the force that is applied to "ProtoEusthen" by all 12 sub-paddle boards per 1 second F_s

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is calculated like below as well as the derivation of F_m where sub-paddle board's one-side area A_s is 74cm^2.

$$F_s = \int_{\theta=\frac{\pi}{3}}^{\theta=\frac{2\pi}{3}} \rho A_s r^2 \omega^2 \sin\theta \, d\theta \times \frac{\omega}{2\pi} = \frac{6}{\pi} \rho A_s r^2 \omega^3 \tag{4}$$

From the all above, the force that is applied to "ProtoEusthen" by main-paddle boards and sub-paddle boards F_{ms} is as below.

$$F_{ms} = 2 \times (F_m + F_s) = \frac{12}{\pi} \rho r^2 \omega^3 (A_m + A_s) \tag{5}$$

Therefore, the below equation is derived by momentum conservation law where Δt denotes elapsed time since "ProtoEusthen" starts to move, the total mass of "ProtoEusthen" m is assumed as 20kg, and V means velocity of "ProtoEusthen".

$$F_{ms} \cdot \Delta t = mV - 0 \Leftrightarrow \omega = \sqrt[3]{\frac{\pi m V}{12 \rho r^2 (A_m + A_s) \Delta t}} \tag{6}$$

If water resistance force to the robot's whole body cancels out F_{ms} 10 seconds after the robot starts to move, and minimum necessary velocity of "ProtoEusthen" is set as 0.1m/s, minimum necessary rotation speed of motor on the water is led as 5.62RPM by Eqs. 6. Note that water resistance force is simplified in the above derivation.

Secondly, minimum required rotation speed of motor underwater is considered. Main-paddle boards can not push "ProtoEusthen" forward underwater, so only sub-paddle boards are needed to be thought. In fact, sub-paddle boards work in the same way as on the water underwater, thus the force that is applied to "ProtoEusthen" underwater is $2F_s$. Hence, ω is led as well as Eqs. 6. When minimum necessary velocity of "ProtoEusthen" is 0.1m/s, minimum necessary rotation speed of motor underwater is,

$$\omega = \sqrt[3]{\frac{\pi m V}{12 \rho r^2 A_s \Delta t}} \approx 0.68\text{rad/s} \approx 6.49\text{RPM} \tag{7}$$

3. Fabrication and experiment

"ProtoEusthen wheel" which is actually made is shown in Fig. 3.

A driving experiment of "ProtoEusthen wheel" was done for measuring actual wheel's advancing velocity V at each wheel's rotation speed ω on the water and underwater. Those measured values are compared with theoretical values. Theoretical value of V on the water is led by the Eqs. 8 that is derived by solving Eqs. 6 for V. Note that only 1 wheel is used in the experiment, so F_{ms} is divided by 2. Likewise, theoretical formula of V underwater is derived by Eqs. 7 as Eqs. 9.

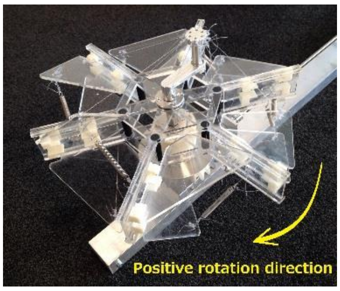

Fig. 3 Made "ProtoEusthen wheel"

$$V = \frac{6\rho r^2 (A_m + A_s) \Delta t \omega^3}{\pi m}, V = \frac{6 \rho r^2 A_s \Delta t \omega^3}{\pi m} \tag{8), (9}$$

Fig. 4 shows the test equipment. The total mass of test equipment m_t is 5.2kg, and this value is substituted for m in Eqs. 8 and 9. The measuring method is to make "ProtoEusthen wheel" rotate at objective rotation speed on the water & underwater for 1 minute. After the duration, the distance that the wheel moved forward is measured, and the wheel's advancing velocity is calculated.

The experimental result is shown in the V - ω graphs, Fig. 5 and 6. The error values between theoretical values and measured values are quite large, so the theoretical values are divided by 500 or 1000, and depicted in the graphs instead of pure values. The reason why there is no data at -40RPM in Fig. 6 is that some sub-paddle boards were broken then because the speed of springs' folding sub-paddle boards is sometimes too late at the rotation speed, and some sub-paddle boards hit the peripheral parts. To solve this problem, the springs should be changed to stronger ones, or more space around the sub-paddle boards should be made. As the error sources between theoretical values and experimental ones, 3 main factors can be thought. Initially, there are some rough assumptions while deriving the theoretical formulas, such as water resistance and water's dodging from the boards. Secondly, there are some unprecise points on the test equipment. To give an example, friction force on camera slider is not considered in the theoretical formulas. Thirdly, there can be some measurement errors, for instance time and length.

Fig. 4 Test equipment

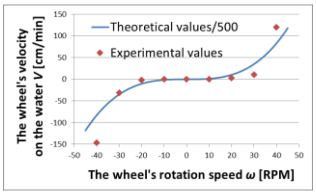

Fig. 5 V - ω graph on the water

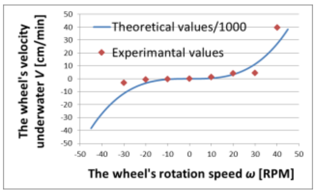

Fig. 6 V - ω graph underwater

4. Conclusion

In this research, "ProtoEusthen wheel" that is a new kind of amphibious robotic wheel is developed. The wheel's mechanism is contrived and fabricated. In addition, some theoretical formulas of the wheel are derived, and a driving experiment of the made wheel is done for examining the formulas. As a next step of this research, current "ProtoEusthen wheel" has to be improved. After that, 2 "ProtoEusthen wheels" will be made and attached to the body of "Nanins". This robot, "ProtoEusthen" should be evaluated in detail and improved.

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