Development of a twin-flapping-foils unit to generate hydroelectric power from a water current

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Abstract. Most of the conventional hydraulic turbines have been used for those sites having the static head larger than around 1 m. To extensively utilize not only large hydro-power but small one, which is one of renewable energy resources, development of an energy conversion system being operable under an extremely low head stream is crucial. A twin-flapping-foils unit which works based on the lift acting on the flapping foils in a stream is proposed. The foils oscillate in the transverse direction of the flow due to the lift. The pitching motion of the foils is caused by their own transverse movement through the mechanism consisting of crankshafts and con-rods. In the unit, each foil is supported vertically with a shaft in a manner of a cantilever so that no other parts need to be submerged in a water current. An experimental model with symmetric foils of 100 mm chord and 300 mm span was designed to generate average power output of 10 W at a flow velocity of 1 m/s. Through the tests carried out in the circulating water channel, the performance of the unit was verified to satisfy the design specifications. Further, the demonstration tests by using an irrigation stream performed for over a half year clarified the performance equivalent to that in the in-door water channel and the durability to a certain extent, and showed the applicability to the practical use of lighting a LED street lamp during night even at this scale model.

1. Introduction
Various forms of renewable energy utilization are being developed as alternatives to power generation from petroleum fuels. In Japan, there are many small and medium-size streams and irrigation channels that represent a potential source of renewable energy [1]. These streams hold promise as micro-hydropower for distributed generation, much like solar and wind energy sources.

Waterwheels and some kinds of hydraulic turbines are conventionally used for micro-hydropower generators. They can be applied to sites with static heads of above around 1 m [2]. In general some measures, which increase the initial costs of hydropower, need to be taken in order to gain appropriate heads. This is one of the reasons that the micro-hydropower has not been spread.

In recent years, advances have been proposed for extracting the flow energy of river stream, oceanic and tidal current by using the flapping foils [3]-[6] et al. These methods are operable under an extremely low head stream without employing some measures to increase heads.

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In this paper, to extensively utilize not only large hydro-power but small one, a twin-flapping-foils unit is proposed. This unit works based on the lift acting on the flapping foils in a stream. The foils oscillate in the transverse direction of the flow due to the lift. The pitching motion of the foils to provide a certain incident angle against the flow is caused by their own transverse movement through the mechanism consisting of crankshafts and con-rods. In the unit, each foil moving in anti-phase mode of oscillation to improve the power generation efficiency [7] is supported vertically with a shaft in a manner of a cantilever so that no other parts need to be submerged in water current. As an experimental model, a symmetric foil having 100 mm chord length and 300 mm span was designed to generate average power output of 10 W at a flow velocity of 1 m/s. Through the tests carried out in the circulating water channel, the performance of the present unit was verified to satisfy the design specifications. Further, the demonstration tests by using an irrigation stream performed for around a half year clarified the performance equivalent to that in the in-door water channel and the durability to a certain extent and showed the applicability to the practical use of lighting a LED street lamp during night.

2. Method of Analysis

In the flapping foil generator, the equation for power extracted from the stream is as follows:

\[ W = \frac{dh}{dt} L + \frac{d\alpha}{dt} M \]  \hspace{1cm} (1)

where \( W \) is the power, \( t \) is time, \( h \) is the transverse displacement of the wing, \( \alpha \) is the angle of the pitching oscillation, \( L \) is the lift and \( M \) is the moment.

From the two-dimensional oscillating wing theory based on the potential flow, the lift and the moment are as follows [8]:

\[ L = \pi \rho b^2 \left[ \frac{d^3 h}{dt^3} + U \frac{d\alpha}{dt} - a \frac{d^2 \alpha}{dt^2} \right] + 2\pi \rho UbC(k) \left[ \frac{dh}{dt} + U\alpha + \left( \frac{b}{2} - a \right) \frac{d\alpha}{dt} \right] \]  \hspace{1cm} (2)

\[ M = \pi \rho b^2 \left[ ba \frac{d^3 h}{dt^3} - U \left( \frac{b}{2} - a \right) \frac{d\alpha}{dt} - \frac{b^2}{8} + a^2 \right] \frac{d^2 \alpha}{dt^2} \]

\[ + 2\pi \rho Ub \left( \frac{b}{2} + a \right) C(k) \left[ \frac{dh}{dt} + U\alpha + \left( \frac{b}{2} - a \right) \frac{d\alpha}{dt} \right] \]  \hspace{1cm} (3)

where \( \rho \) is the air density, \( b \) is the semichord, \( U \) is the free-stream velocity, \( a \) is the pitch axis position, \( k \) is reduced frequency and \( C(k) \) is Theodorsen function.

The average power generation extracted from the stream is calculated by integrating over one cycle the instantaneous power.

The power generation efficiency \( \eta \) is defined by

\[ \eta = W_m / \left( \frac{1}{2} \rho S U^3 \right) \]  \hspace{1cm} (4)

where \( W_m \) is the average power generation, \( S \) is the maximum sweep area of the wing across the stream. The denominator of equation (4) indicates the power in the flow passing through the area \( S \).

3. Experimental model

Figure 1 shows the experimental model. Each of the twin foils is vertically mounted in the manner of a cantilever with a support shaft at its half-chord to be able to pitch and is only the component immersed in water. Also, each support shaft is suspended as a pendulum which swings freely in the transverse direction of the flow.

The transverse reciprocating movement of the foil is converted into the rotary shaft motion through a crank rod mechanism. This rotary motion for driving an electric generator with a set-up gear, in turn, transformed into the reciprocating pitch motion of the foil through a crank rod mechanism attached to
another end of the rotary shaft. The phase angle between the transverse and pitch motion is controlled with the angle of the cranks on both ends.

The foils have a symmetrical NACA 0015 airfoil and a rectangular planform of 100mm chord length and 300mm span with endplates of 60mm width both ends.

The specifications of the experimental model for the amplitude of pitch motion $\alpha_0=50$ deg at the flow velocity $U=1$ m/s are shown in Table 1. Both the average generating power $W_m$ and the efficiency $\eta$ shown in Table 1 are reflected the 3D effect of the foil obtained in the previous study [9]. The generator used is shown in Table 2.

**Table 1. Specification of experimental model**

| Parameter | Value |
|-----------|-------|
| $b$ (m)   | 0.05  |
| $l$ (m)   | 0.30  |
| $U$(m/s)  | 1.0   |
| $\alpha_0$ (deg) | 50.0 |
| $W_m$ (W) | 10.0  |
| $\eta$    | 0.19  |

**Table 2. Specification of generator**

| Parameter       | Value      |
|-----------------|------------|
| Type            | AC Three-phase |
| Output (W)      | 35.0       |
| Number of poles | 24         |
| Diameter (m)    | 0.126      |
| Weight (kg)     | 1.6        |
4. Experiments

4.1. Indoor tests
The indoor tests were performed using the high-speed circulating water channel at the Ito campus of Kyushu University. The water channel is a vertical circulating type with a measurement part having a channel width of 2000mm, a water depth of 1000mm, a length of 4000mm, and a flow velocity adjustable in the range of 0.3m/s - 3.3m/s. Figure 2 and 3 show view of the circulating water channel and the installed experimental model respectively.

![Figure 2. Circulating water channel](image)

![Figure 3. Experimental model Installed](image)

4.2. Field tests
The field tests were carried out at Oishi Nagano irrigation stream in Ukiha city Fukuoka prefecture. Figure 4 and 5 show view of the irrigation stream and the experimental model installed, respectively. The flow conditions are listed in table 3.

![Figure 4. Irrigation stream](image)

![Figure 5. Experimental model installed](image)

| Table 3. Condition of irrigation stream |
|----------------------------------------|
| Width (m)                              | 1.2 |
| Depth (m)                              | 0.65|
| Flow velocity (m/s)                    | 1.0 ~ 1.2 |
4.3. Experimental results and discussion

Figure 6 shows the time histories of the power output and the lift acting on a foil at the flow velocity of 1m/s. The power output indicates the power of driving the generator, i.e. the mechanical output, which is obtained in the experiments by multiplying the driving torque and the revolution speed measured by the torque meter. The measured values are compared with the theoretical ones based on the two-dimensional potential flow theory of equations (1) and (2). Although the measured values show qualitatively good agreement with the theoretical ones in both the power and the lift, the measured values quantitatively correspond to around 60% of the theoretical ones. This ratio almost corresponds to the 3D effect of the foil obtained in the previous study [9]. The average power output versus revolution speed on the indoor circulation channel tests is shown in figure 7. At each flow velocity, the power output varies with the revolution speed and has an optimum speed at which the power is maximized. Figure 8 shows the power versus flow velocity. The power of 9.6W was obtained with the optimum revolution speed at the design flow velocity of 1m/s. This power shows good agreement with the design value.

![Figure 6. Time history of power and lift at U=1m/s](image)

![Figure 7. Variation of average power with revolution speed](image)

![Figure 8. Variation of average power with flow velocity](image)
Figures 9 and 10 show the average efficiency versus revolution speed and that versus flow velocity, respectively. The efficiency also varies with the revolution speed and the maximum value of 0.18 was obtained at the design flow velocity showing good agreement with the design specification.

The demonstration tests were carried out from September 2013 to May 2014, lighting a LED street lamp during night by the electricity charged in a battery to show the applicability to the practical use. In the tests, the performance equivalent to that in the in-door water channel was clarified. Figure 11 shows the lamp being lit during night. Concerning the battery charging system, a few slight troubles occurred through the period of the tests, however, the durability to a certain extent also clarified.

5. Conclusions
The performance and durability of a 10W hydroelectric generator utilizing twin flapping foils was investigated experimentally both on the indoor and on the field, with the aim to demonstrate the applicability to an extremely low head stream. The findings were essentially as follows.
1. The proposed unit was verified to be able to extract the energy from an extremely low head stream.

2. The average power output of the unit was verified to satisfy the design specification.

3. In the real irrigation stream, the performance equivalent to that in the in-door test and the durability to some extent were clarified.

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