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Experimental Study on a Three-Wing Configuration of Flapping Wing Hydroelectric Power Generator

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ABSTRACT

A hydroelectric power generator, which is able to extract the water flow energy from the hydroelastic response of an elastically supported rectangular wing, is experimentally investigated. In the previous paper, the generating power rate and the efficiency were examined through the experiments with a single wing apparatus, and the feasibility of the flapping wing hydroelectric power generator was verified. In this paper, the influence of the neighboring wings is examined by using three single-wing experimental apparatuses, with the intention of achieving a practical cascade wing generator. Tests revealed that the cascade moving antiphase with the neighboring wings at narrower intervals has a higher rate of electric power generation.

1. INTRODUCTION

Various forms of natural 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 electric power estimated at several million kilowatts (JAWERP 2005). These streams hold promise as micro-hydropower for distributed generation, much like solar and wind energy sources.

Waterwheels and some kinds of turbines are traditionally used for micro-hydroelectric generators. They can be applied to sites with heads of above 1-2m, i.e. with flow-velocities of 4-6m/s (NEDO 2003). In general some measures, which increase the initial costs of hydropower, need to be taken in order to gain appropriate heads.

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This is one of the reasons that the micro-hydropower hasn't been spread.

Recent proposals and modifications for increasing their efficiency under lower-flow velocities have included such variations as the Darrieus waterwheel and the spiral turbine blade (Shiono 2003, Okuma 2007) which can be applied to sites with lower heads.

Advances have also been proposed for wind power generation. One of these proposed methods utilizes the flutter phenomenon, which causes destructive vibrations in aircraft wings and bridges but which has long been studied as a possible means of generating power (Dancan 1948, McKinny 1981).

Recently, Isogai et al. proposed a new concept of power generation utilizing a flapping wing, which has an efficiency comparable with a wing mill (Isogai 2003, Shimizu 2008). In their system, the wing is supported elastically in the heaving direction, while the pitching oscillation of the whole wing is excited by an electric motor with a prescribed frequency and amplitude. The system extracts the wind energy from the sway oscillation of the wing induced by forced pitching oscillation. In a previous paper, the authors verified the feasibility of this type of system for a hydroelectric power generator at sites with flow-velocities of around 1m/s, i.e. with heads of around 0.1m, by using a single wing apparatus (Abiru 2011).

In this study, the investigation is directed toward the practical utilization of the system in a cascade style in which neighboring wings are arranged continuously perpendicular to the flow direction in order to use effectively the full width of the water flow.

In a cascade-wing design, in-phase moving of the wings decreases the per-wing lift forces as a result of the interference between the upper and the lower surface pressures of wings facing each other. Consequently, it is predicted that the per-wing electric power generation rate and efficiency will both decrease. On the other hand, antiphase movement increases the per-wing lift forces as a result of the emphasis between wings facing each other, and consequently, increases both in the per-wing electric power generation rate and in efficiency are predicted.

In this paper, the effects of neighboring wings in a cascade generator are experimentally investigated by using three single wing experimental apparatuses.

2. METHOD OF ANALYSIS

In a flapping wing generator, the governing equation of motion can be derived as follows (Isogai 2003):

$$M_s \frac{d^2 H}{dt^2} + \omega_s{}^2 M_s (1+ig) H = L + M_p \left(X_{cg} - A\right) \frac{d^2 \alpha}{dt^2} \tag{1}$$

where t is time, H is the sway displacement of the wing, α is the displacement of the forced pitching oscillation, M_s is the total mass relating to the sway oscillation including the masses of the wing, the electric motor, and the equivalent mass added by the mechanical snubber, ω_s is the natural circular frequency of the sway oscillation, g is the structural damping coefficient equivalent to the electric power generation and the original damping of the structure, X_{cg} is the position of the center of mass of the wing, A is the pitch axis position, M_p is the wing mass, and L is the lift. To eliminate unfavorable

effects on power generation (Shimizu 2008), the wing is designed so that the pitch axis position coincides with the center of mass of the wing. With this assumption, the second term of the right-hand side of Eq. (1) can be removed. Two-dimensional unsteady hydrodynamic forces based on the potential flow theory (Theodorsen 1935) are employed to solve Eq. (1). After the following design parameters, namely, the semichord length b, the wingspan l, the flow velocity U, and the amplitude of forced pitching oscillation α_0 are provided, it can be easily identified from the dimensionless form of Eq. (1) that the hydroelastic response of the system is governed by the following five nondimensional parameters: reduced frequency k (= $b\omega/U$, ω : circular frequency of the forced pitching oscillation), g, ω_s/ω, mass ratio μ (= $M_s/\pi\rho b^2 l$), and a (= A/b). With the assumption of a simple harmonic motion of the wing, the analytical solution of Eq. (1) can be obtained from the five nondimensional parameters. Then, the mean power generation extracted from the stream is estimated by integrating over one cycle the instantaneous dissipation power through the artificial structural damping equivalent to the electric power generation.

The power generation efficiency η_p is defined (McKinney 1981) by

$$\eta_p = W \Big/ \left[\frac{16}{27} \left(\frac{1}{2} \rho S U^3 \right) \right] \tag{2}$$

where W is the mean power generation rate, S is the maximum sweep area of the wing across the stream, and the coefficient 16/27 is referred as the Betz coefficient (Johnson 1985). The denominator of Eq. (2) indicates the theoretical limit for the extractable power generation rate from the stream.

The following experiments are carried out in a confined water channel, while the Betz coefficient is for free flow conditions. Eq. (2) is applied, however, in the reason that the channel has an enough flow sectional area with the width of 15-20 times the sweep stroke of the wing and with the depth of over 3 times the wing span.

3. EXPERIMENTAL MODEL

Fig. 1 shows a schematic view of the single-wing experimental apparatus. The cascade-wing apparatus consists of three single-wing apparatuses. The wing is supported vertically in the manner of a cantilever and is the only component immersed in water. Both the wing and the electric motor to excite the pitching oscillation of the wing are supported by leaf springs that are design to work both as a linear guide for the sway oscillation and as elastic elements. The wing mass in the sway direction necessary to achieve a hydroelastic response is obtained by using a mechanical snubber mechanism. An appropriate load equivalent to generate electricity is provided by

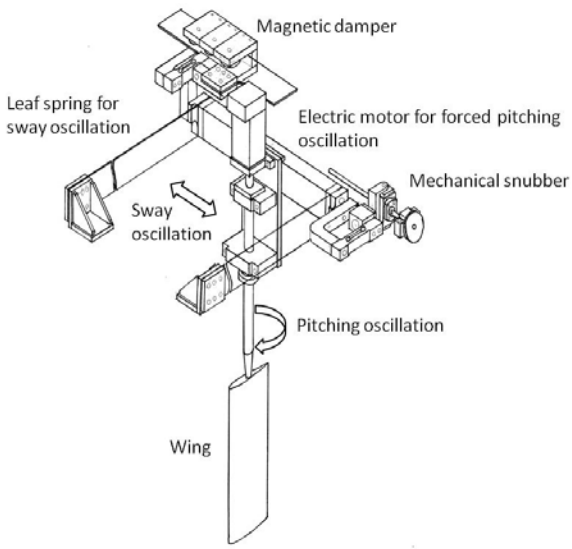


Fig. 1. Schematic view of single-wing apparatus

magnetic dampers. The rectangular wing has a symmetrical NACA 0015 airfoil section with a semichord length of 50 mm and a wingspan of 300 mm. Five nondimensional parameters (k, g, ω_s/ω, μ, and a) are determined to give a power generation efficiency as high as possible at a flow velocity of 1 m/s within the practical constraints of manufacturing an experimental apparatus. The specifications of the experimental apparatus for the amplitude of pitching oscillation α_0 = 50 deg at the flow velocity U =1 m/s are shown in Table 1. Fig. 2 shows the view of the fabricated single-wing experimental apparatus.

Fig. 3 shows the mechanism of the mechanical snubber. The linear motion caused by the sway oscillation of the wing is transformed into the rotary motion of the disk through the ball screw. The inertia force in the direction of the sway oscillation F_m is given (Ohmata 1985) by

$$F_m = 2M\left(\frac{\pi R}{l_d}\right)^2 \ddot{H} \tag{3}$$

where M is the mass of the rotation disk, R is the radius of the disk and l_d is the lead of the ball screw. Eq. (3) shows that the force F_m is equivalent to an inertia force generated by a mass equal to the disk mass times $2(\pi R/l_d)^2$. In the experimental model, the value of the ratio (R/l_d) was 2.03 and an equivalent mass of 16.3 kg was obtained from a disk with a mass of 200 g. The mechanical snubber device is shown in Fig. 4.

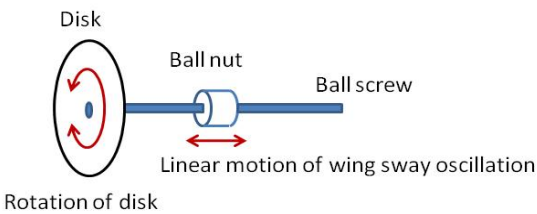


Fig. 3. Mechanism of mechanical snubber

Table 1. Specifications of single-wing apparatus

b [m]	0.05	g	0.70
l [m]	0.30	ω_s/ω	0.95
U [m/s]	1.00	μ	10.00
α_0 [deg]	50.00	a	0.00
ω [rad/s]	6.00	W [W]	6.30
k	0.30	η_p	0.46

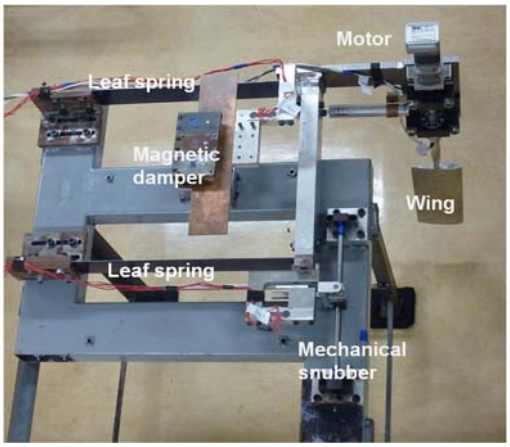


Fig. 2. Fabricated single-wing apparatus

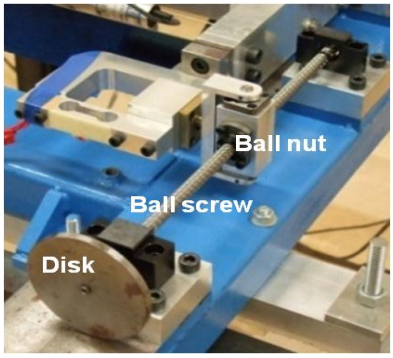


Fig. 4. Mechanical snubber

A magnetic damper is used to provide an appropriate load to generate electricity. The device consists of three pairs of opposing neodymium magnets having narrow

gaps and a sliding copper plate inserted into the gaps between the magnets without contact being made. The damping coefficient is adjustable by shifting the position of the center pair of magnets. In the following water channel experiments, the damping coefficient was adjusted to a value at which the highest electric generating efficiency was obtained in the previous paper (Abiru 2011). The specifications of the magnetic damper are shown in Table 2. Fig. 5 shows a view of the magnetic damper.

Table 2. Specifications of magnetic damper

Magnet	Material	Nd-Fe-B
	Size	ϕ 30 mm× 15 mm
	Number	6
Copper plate	Material	C1100P
	Thickness	2 mm
Clearance		1 mm
Damping coefficient		38.0 ~ 89.0 Ns/m
Equivalent structural damping		0.3 ~ 0.7

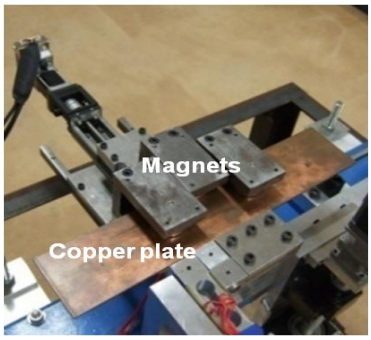


Fig. 5. Magnetic damper

Mean power generation is estimated by integrating over one cycle the instantaneous dissipation power of the magnetic damper obtained from the force generated by the magnets and the velocity of the sliding copper plate.

The experiments were performed using the high-speed circulating water channel at the Ito Campus of Kyushu University. Fig. 6 shows view of the circulating water channel. The water channel is a vertical circulating type with a measurement part having a channel width of 2000 mm, a water depth of 1000 mm, a length of 4000 mm, and a flow velocity adjustable in the range of 0.3–3.3 m/s.

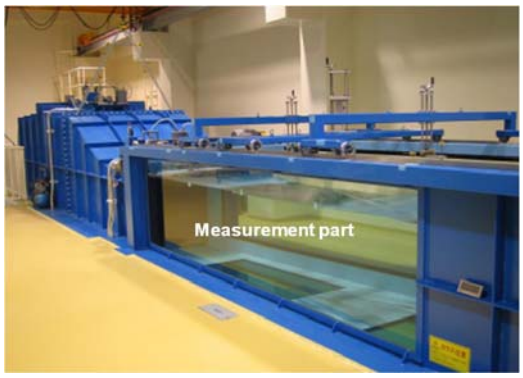


Fig. 6. Circulating water channel

4. EXPERIMENTAL RESULTS AND DISCUSSION

The cascade-wing generator apparatus consists of three single-wing apparatuses installed in the water channel, with neighboring wing's pitching oscillation in either the in-phase or the antiphase mode. In both modes, the "wing gap" (the initial perpendicular distance between the two wings) was taken as the variable parameter, and the electricity power and efficiency were measured. Fig. 7 shows the three single-wing apparatuses as installed, and Fig. 8 shows them under in-phase (Fig. 8(a)) and antiphase (Fig. 8(b)) oscillation with a flow velocity of 1 m/s.

The forced pitching oscillation of the wing by the electric motor induced sway oscillations, resulting in oscillation with a phase difference of approximately 90 deg between the pitch and sway in both the in-phase and antiphase modes.

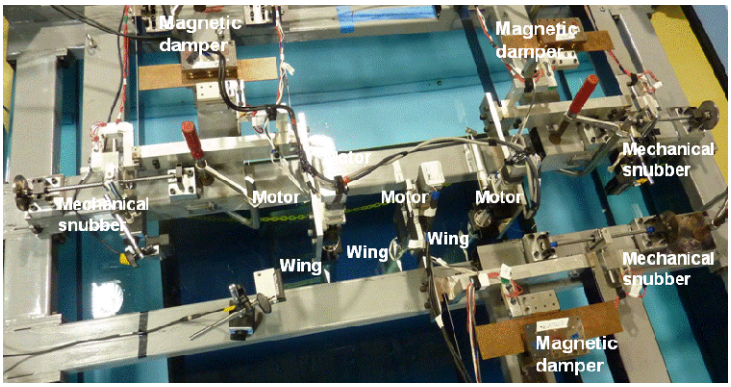
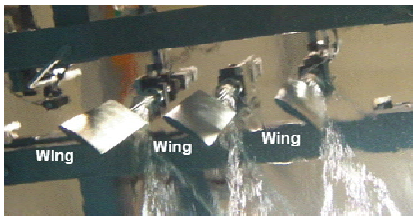


Fig. 7. Arrangement of three single-wing apparatuses



(a) In-phase mode

(b) Antiphase mode

Fig. 8. Induced sway oscillations by forced pitching oscillations

Figures 9 and 10 show the variation of power and efficiency, with respect to the wing gap at several pitching oscillation amplitudes in the apparatus B (used as the middle wing), respectively. At each pitching amplitude, the power generation increases with increasing flow velocity. With an amplitude of α_0=50deg and at the design flow velocity of 1 m/s, the power generation of around 3W and the efficiency of around 0.3 were obtained, which are corresponding to the values in the previous paper (Abiru 2011).

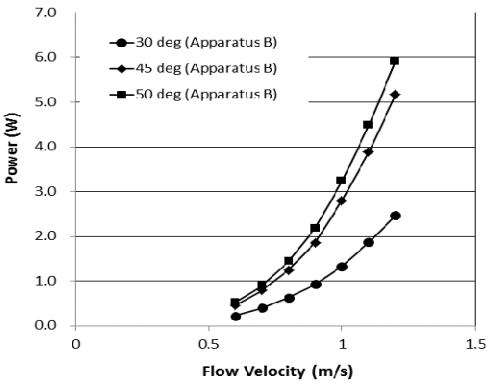


Fig. 9. Power versus flow velocity

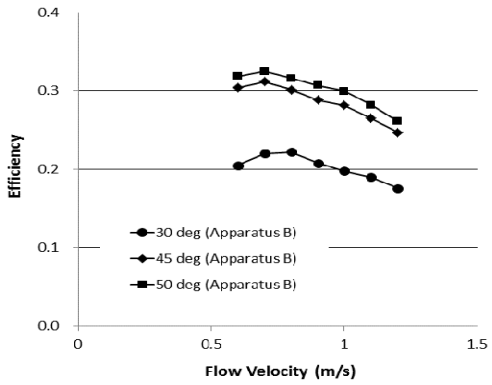


Fig. 10. Efficiency versus flow velocity

Figures 11 and 12 show the comparison between the three apparatuses on the powers and the efficiencies. No considerable difference between the three apparatuses is observed, therefore, concerning the two outer apparatuses the average values of them are used in the following discussions.

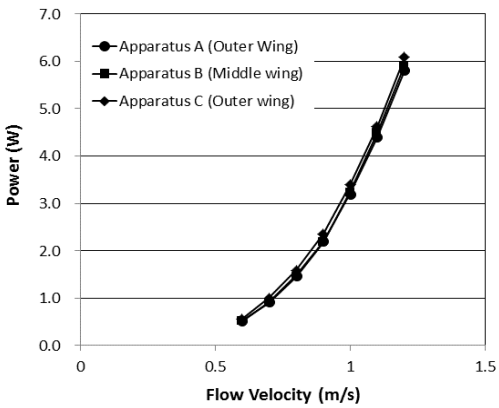


Fig. 11. Comparison of powers between three apparatuses

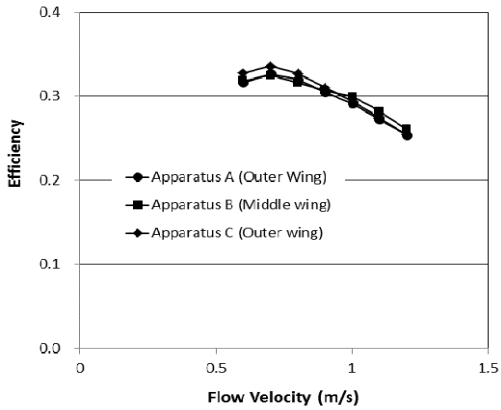


Fig. 12. Comparison of efficiencies between three apparatuses

Figures 13 and 14 show the comparison of the per-wing power and efficiency between the middle and outer wings in the three-wing configuration with respect to wing gap expressed as ratios to those obtained with a wing gap of 500 mm, at which the wing gap influence is negligible, in both the in-phase and antiphase operations with a pitching amplitude α_0 of 50 deg at a flow velocity of 1 m/s.

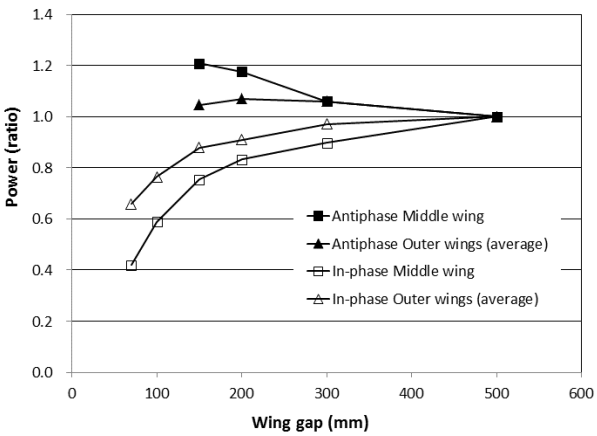


Fig. 13. Comparison of powers between middle and outer wings in cascade

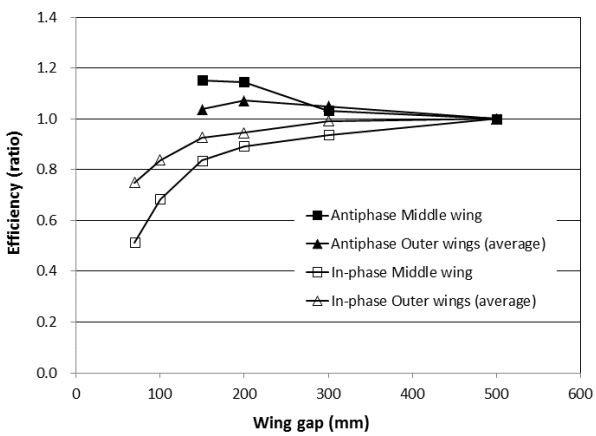


Fig. 14. Comparison of efficiencies between middle and outer wings in cascade

In the antiphase oscillation, the power and efficiency per wing both increase with the decrease in wing gap. The trend is the opposite of that observed for in-phase operation. These trends are enhanced in the middle wing which is influenced from both outer wings.

Figures 15 and 16 also show the influence of wing gap on the per-wing power and efficiency on the middle wing with the pitching amplitude taken as the parameter. In the in-phase mode, the pitching amplitude has no observable effect on the power or efficiency. In the antiphase mode, the pitching amplitude also has little or no observable effect, down to a wing gap of around 200 mm, but the effect became considerable with

a wing gap of 150 mm, for which the generation power and efficiency generally increased at a pitching amplitude of 30 deg, and were almost saturated at pitching amplitudes of 50 deg. This behavior may be attributed to the occurrence of flow occlusion due to the close interwing proximity for pitching amplitudes of 45 and 50 deg, but not for 30 deg. The influence of the wing gap was found to be somewhat larger on the power than on the efficiency. In the in-phase mode, the per-wing power and efficiency were reduced to 42 and 51%, respectively, with a wing gap of 70 mm. In the antiphase mode, they increased by about 21-48% and 15–28% with a wing gap of 150 mm, respectively.

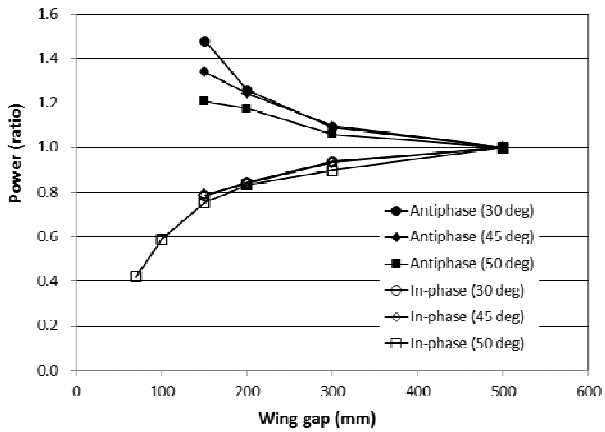


Fig. 15. Power of middle wing versus wing gap

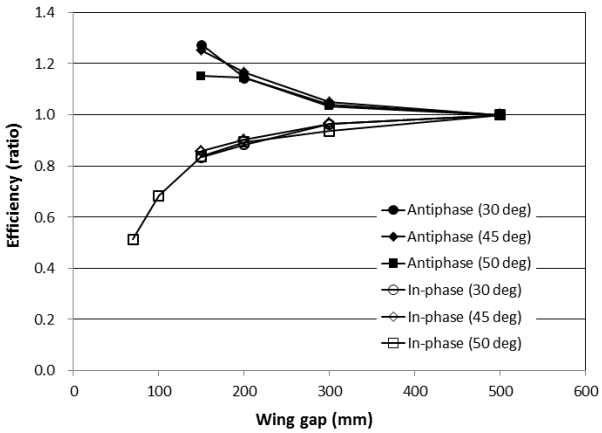


Fig. 16. Efficiency of middle wing versus wing gap

Fig. 17 shows the estimated change in the generation rate per meter of flow width with wing gap at flow velocities of 1.0 m/s for a cascade-wing generator in which the every wing is arranged continuously with a specific gap and has neighbors in both sides.

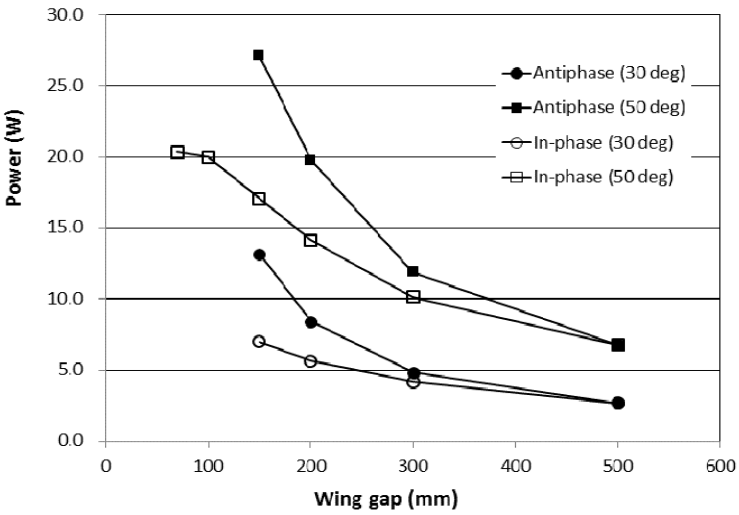


Fig. 17. Power per unit channel width versus wing gap

In both the in-phase and antiphase modes, the generation rate generally increases with a decrease in wing gap. The antiphase mode resulted in the highest power of 27W per meter of flow width with a wing gap of 150 mm, which is the lower limit on the wing gap due to the tendency for collision to occur between the leading or trailing edges of the wings, which would appear to indicate that the antiphase mode together with narrow wing gaps may be better for practical applications. In the in-phase mode, due to the inferiority of per wing power and efficiency to the antiphase mode, the generation rate per meter of flow width resulted in the lower values at a narrower wing gap of 70 mm.

5. CONCLUSION

The effects of wing gap and oscillation phase were investigated experimentally for a cascade-wing model generator, with the ultimate objective of the practical development of a hydroelectric power generation system with effective utilization of wing flutter across the full width of the flow path based on the concept of a cascade-wing array perpendicular to the flow path. The findings were essentially as follows.

(1) Under in-phase oscillation of neighboring wings, the per-wing electric power and efficiency decreased with the decrease in wing gap. The per-wing power and efficiency decreased to approximately 40% of those with no neighboring-wing influence when the wing gap was 0.7 times the chord length.

(2) Under antiphase oscillation of neighboring wings, the per-wing power and efficiency increased with a decrease in wing gap. The per-wing power and efficiency both increased by about 21-48% and 15–28%, respectively, when the wing gap was 1.5 times the chord length.

(3) The generation rate per meter of flow width increased with a decrease in wing gap in both the in-phase and the antiphase operations. Under antiphase operation, the highest power generation of 27W was estimated with a wing gap 1.5 times the chord length, which is the lower limit due to the interwing collision. Under in-phase operation, in contrast, the generation rate per meter of flow width resulted in the lower values at a narrower wing gap of 0.7 times the chord length, due to the inferiority of per wing power to the antiphase operation.

(4) The results of this study, taken together, indicate that antiphase operation of a cascade wing with a narrow wing gap will provide an effective basis for practical development of a cascade flapping wing generator.

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