Counter-Rotating Type Tidal Stream Power Unit Moored by Only One Cable

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Abstract: The authors have proposed that a counter-rotating tidal stream power unit mounted rigidly on a pile, and outputs of the power unit and forces acting on the pile were investigated experimentally at a previous paper. A single propeller makes the pile undertake a reaction force orthogonal to the stream direction. On the contrary, proposed counter-rotating propellers do not require undertaking the reaction force of the pile, because the rotational torque is counter-balanced in the unit. This advantage means that the unit can be moored by only one cable. Continuously, this paper proposes such a power unit with tandem propellers, and experimentally investigates a behavior of the unit floating in a water channel. The vibrations of the power unit are induced from not only the individual but also the interacting rotations of the front and the rear propellers.

Key words: Tidal turbine, tidal stream, tandem propellers, counter rotation, generator, armature, mooring.

1. Introduction

Ocean energy resources greatly attract attention to get sustainable society with accompanying hydro, wind and solar resources, and then many kinds of the power unit have been provided for the tidal stream [1-4].

The authors have also proposed a unique tidal stream power unit at the previous paper, which is called “counter-rotating type tidal stream power unit” [5, 6]. This unit is composed of tandem propellers and a peculiar generator with double rotational armatures without a traditional stator. The output of the unit and forces acting on a pile mounting rigidly the unit were investigated experimentally [7], where the generator was replaced to an alternative mechanism with contact surfaces, as shown in Fig. 1. The contact surfaces contribute to counter-balance the rotational torque between both propellers in place of the double armatures, and the torque is adjusted by a screw. Fig. 2 shows the output of the unit, where $C_P$ is the output coefficient ($= P / (\rho \pi d_F^2 V^{3/8})$, $P$ is the output, $\rho$ is the density, $V$ is the stream velocity, $d_F$ is the diameter of the front propeller, the subscript max means the maximum value, and experimental results were represented with a dot curve), $\lambda_T$ is the relative tip speed ratio ($= (\text{the relative tip speed}) / V$), $\beta_F$ and $\beta_R$ are the optimal setting angle measured from the circumferential direction at the tip of the front and the rear blades. The output shows the convex distribution to $\lambda_T$ as well known and is maximum at about $\lambda_T = 8$.

Fig. 3 shows the force $D_T$ orthogonal to the stream direction averaged in time acting on the mono pile, where $C_{DY} = D_T / (\rho \pi d_F^2 V^{2/8})$. The tandem propellers make the rotational torque counter-balance successfully and the pile hardly undertakes the reaction force, which has also been pointed out at the item (3) in the previous paper [7].

Above advantage without the reaction force may promise that this type power unit is effective to be moored, at the seabed or constructions with only one cable while floating. The posture of the unit can be adjusted itself in response to the tidal stream direction,
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because the cable never restrain the movement of the unit, though it is necessary for the pile type unit to manually adjust the nose position.

DidEl has also proposed the tandem propellers separated horizontally and widely which quite differ from the above profile [8], and it may be difficult to keep the posture, because the flow condition metamorphoses obviously in the horizontal direction in general.

Based on the above in-house results and discussions, this paper proposes the tidal power unit moored with only one cable, and confirms experimentally the unsteady behavior of the power unit floating in a water channel.

2. Mooring Method

As mentioned above, the proposed power unit with the tandem propellers can be moored easily with only one cable due to have no reaction force. Fig. 4 shows the buoyancy \( B \), the weight \( W \) and the drag force \( D \) acting on the power unit in the tidal stream. The moment \( M_C \) induced from these forces around at the point C is written by the following equation, where \( x_1 \) and \( x_2 \) are the distances measured from the point C placed on the vector line of the drag force.

\[
M_C = Bx_1 - Wx_2 \tag{1}
\]

That is, the power unit can keep the horizontal posture regardless of the stream velocity \( V \) while having moored at the point C with \( M_C = 0 \), and the floating position/depth is adjusted itself by \( V \), as shown in Fig. 5. Figs. 4 and 5 show the unit whose weight \( W \) is heavier than the buoyancy \( B \) and it is easy to estimate the point C when \( W \) is lighter than \( B \).

Above arrangements keep the floating unit at the horizontal posture and the drag force \( D \) controls automatically the nose position in response to the stream direction.

3. Experiments

3.1 Model Tidal Stream Power Unit

The model tidal stream power unit for experiments
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Fig. 4 Forces acting on the unit in the tidal stream \((B < W)\).

Fig. 5 Mooring conditions of the unit \((B < W)\).

is shown in Fig. 6, where the upstream type at the previous paper [7] (Fig. 1) was replaced to the downstream type without any dimensional modifications.

3.2 Setup of Experiments

The model unit was submerged in the water channel (the water depth: 1.1 m, the upper and the lower widths: 2.08 m and 1.55 m) in place of the tidal stream [7], and moored with a fine cable, as shown in Fig. 7. The mooring cable was supported at the lower end of the pile covered with a streamlined cross section, and the upper end of the pile was mounted-rigidly at the bed over the stream.

The rotational speeds of the counter-rotating propellers were visualized with the high speed camera. The rotational torques, namely the loads, were estimated with the calibration curve between the rotational speed and the friction force at the contact surface which can be changed manually by adjusting the screw position as the same as the previous paper [7]. It was confirmed experimentally that the flow condition in the channel and the output of the power unit are almost the same as that presented in the previous paper [7] and Fig. 2.

The behaviors of the power unit floating in the stream, namely accelerations \((A_X, A_Y, A_Z)\) and angular

Fig. 6 Model power unit equipped with the contact surface in place of the double rotational armatures.

Fig. 7 Center of the pitching moment.
velocities ($\Omega_X$, $\Omega_Y$, $\Omega_Z$), were measured with the acceleration sensor and the gyro sensor installed in the nacelle, as shown in Fig. 6. That is, the experimental results give the unsteady motion near the nose of the power unit, where subscript $X$, $Y$ and $Z$ mean the value in the axial/shaft direction of the power unit, the value in the horizontal direction orthogonal to $X$ and the vertical direction orthogonal to $X$, in the right-handed coordinated system on the unit as shown in Fig. 8. Signals from the acceleration and the gyro sensors were accumulated in a data logger every 20 msec. The results may simulate not overall but fundamental behaviors of the power unit.

4. Vibration of the Floating Power Unit

Fig. 9 shows time-series force components $F_X$, $F_Y$, $F_Z$ near the nose of the floating power unit in the stream at $\lambda_T = 11.3$ in Fig. 2, where the force is induced from the acceleration $A$ ($F = MA$, $M$: mass of the power unit) and the unit is operated at the rotational speed, taking the comparatively large drag coefficient to increase in the precision of the measured forces which is faster than $\lambda_T$ giving the maximum output. The amplitude of the axial force $F_X$ is larger than the amplitudes of $F_Y$ and $F_Z$, owing to the fluctuating drag force induced from the rotation and the flow interaction between both propellers [7]. Besides, the amplitude of $F_Z$ is smaller than the amplitude of $F_Y$, because the hanging wire restrains the vibration of the power unit in the vertical direction. The root mean square forces of the vibrated $F_X$, $F_Y$ and $F_Z$ are about 2.8%, 0.9% and 0.3% against the drag force $D_X$ of the power unit, where $D_X$ was measured with the strain gages bounded on the pile (see Fig. 7) and is almost the same as $D_X$ of the unit mounted rigidly to the pile [7].

Fig. 10 shows the PSD (power spectrum density) of the axial force $F_X$ analyzed from Fig. 9a, which may represent the vibration of the resultant force. The
vibration has dominant frequencies induced from each rotational speed (the front propeller: \( N_F = 308 \text{ min}^{-1} = 5.1 \text{ Hz} \), the rear propeller: \( N_R = 205 \text{ min}^{-1} = 3.4 \text{ Hz} \)) and the blade passing frequency (the front propeller: \( N_F Z_F = 15.4 \text{ Hz} \), the rear propeller: \( N_R Z_R = 17.1 \text{ Hz} \)). Besides, other dominant frequencies predicted by Hanson method [7, 9] are confirmed in Fig. 10 and Table 1.

Fig. 11 shows the root mean square force \( \Delta F_{X_{rms}} \), \( \Delta F_{Y_{rms}} \) and \( \Delta F_{Z_{rms}} \) in the \( X \), \( Y \) and \( Z \) directions at the various relative tip speed ratio \( \lambda_T \), where the vibration is divided into the positive and the negative amplitudes and was averaged in time. The strength of the force corresponds to the vibration in Fig. 9. Besides, the power unit with the tandem propellers does not vibrate so as to disrupt the normal balance against the stream, that is, the unit has strength of stability, regardless of the relative tip speed ratio, but, the nose of the unit more or less rolls axisymmetrically as confirmed later. As for the single propeller, the unit vibrates in the one direction so as to disrupt the posture.

5. Dutch Roll of the Floating Power Unit

Fig. 12 shows time-series angular velocities (rotational vectors) \( \Omega_X, \Omega_Y, \Omega_Z \) in the \( X \), \( Y \), \( Z \) directions (see Fig. 8) of the floating power unit at \( \lambda_T = 11.3 \). The amplitude of the angular velocity \( \Omega_X \), namely, the rolling motion near the nose, is larger than \( \Omega_Y \) and \( \Omega_Z \), namely, the pitching and the yawing motions near the nose.

Fig. 13 shows the (power spectrum density) of \( \Omega_X \), analyzed from Fig. 12a. The angular velocity has also dominant frequencies at not only the rotational speed \( N_F, N_R \), but also the blade passing, \( N_F Z_F, N_R Z_R \).

Fig. 14 shows the root mean square angular velocities \( \Delta \Omega_{X_{rms}}, \Delta \Omega_{Y_{rms}} \) and \( \Delta \Omega_{Z_{rms}} \) in the \( X \), \( Y \) and \( Z \) directions, where the fluctuation was also divided into the positive and the negative amplitudes and was averaged in time. Not only the forces in Fig. 11 but also the angular velocities do not fluctuate in the one direction. Such an advantage is caused by the counter-rotation of the propellers and enables to moor the power unit with only a cable, which is impossible for the power unit with a single propeller.

Fig. 15 shows the time-series rolling \( \Theta_X \), the pitching \( \Theta_Y \) and the yawing angles \( \Theta_Z \) measured from
the horizontal posture facing to the stream (see Fig. 16) at $\lambda_T = 11.3$, where these angle are integrated angular velocities with a sampling time of 20 msec in Fig. 12. These fluctuate irregularly as if a dutch roll and the rolling $\Theta_X$ and the yawing $\Theta_Y$ have a similar cycle by the reason why the force $F_Y$ is larger than $F_Z$ (see Fig. 11) may mainly contribute to $\Theta_X$ and $\Theta_Y$, and then $\Theta_Y$, namely $F_Z$, may work to suppress the rolling and the yawing, because $\Theta_Y$ has the opposite phase against $\Theta_X$ and $\Theta_Z$. Besides, the flow interaction between both propellers and a gyroscopic effect may also contribute to the behavior of the floating power unit, which is not discussed in this stage because of complex phenomena.

6. Conclusions

The mooring type counter-rotating type tidal stream power unit was proposed and the behavior of the floating unit was investigated experimentally. The unit can keep the horizontal posture without rotation regardless of the stream velocity, and the nose position is adjusted itself in response to the tidal stream, while the unit is moored/supported at the moment center placed on the vector line of the drag force in the meridian plane.

The individual rotation of the tandem propellers and the flow interaction (blade passing) between both propellers bring the vibrations/fluctuations of the moored type power unit. The forces and the angular
velocities work to keep the normal balance against the stream enable to moor the power unit with only a cable. The rolling and the yawing angles of the moored type power unit have a similar cycle as if the dutch roll, and the pitching roll may contribute to suppress the dutch roll.

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