Counter-Rotating Type Tidal Range Power Unit

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Abstract: The counter-rotating type tidal range power unit composed of the axial flow type tandem runners and the peculiar generator with double rotational armatures is proposed to utilize effectively the tidal range. In the unit, the front and the rear runners counter-drive the inner and the outer armatures of the generator, respectively. Besides, the flow runs in the axial direction at the rear runner outlet while the flow has not the swirling component at the front runner inlet, because the angular momentum change through the rear runner must coincides with that through the front runner. Such operations are suitable for bidirectional flows, namely working at the seashore with the rising and the falling tidal ranges, and the unit may be able to take place of the traditional bulb type turbines. To promote more the tidal power generation by this type unit, the runners were modified so as to be suitable for both rising and falling flows. The hydraulic performances are acceptable and take the optimum efficiency at the on-cam operation, while the trailing profiles of the runner blades determine mainly the theoretical output.

Key words: Tidal power, tidan range, bidirectional flows, counter rotation, tandem runners, double rotational armatures.

1. Introduction

To cope with the warming global environments, the ocean power with the fruitful resource more than $10^3$ TW [1] should occupy the attractive attention of the electric power generation as clean and sustainable energies with the highest density, in cooperation with the wind and the solar powers. As for the tidal range, La Rance power station in France has 240 MW at the mean difference in the tidal level of 8 m, Annapolis in Canada has 18 MW at 6.4 m, Jiangxia in China has 3.2 MW at 7.1 m [2], Lake Shiwa has 260 MW at 6 m [3] and so on. Such power stations have equipped with traditional bulb type turbines [4], in general, where it is necessary to set uselessly a pair of the turbines whose nose and tail are replaced each other for utilizing sufficiently the rising and the falling tidal energies. To reduce wasteful initial costs, the propeller type [5], Darrieus type [6] and the cross-flow type [7] hydraulic turbines, which are effective for the bidirectional flows, have been prepared for the small hydropower on the land and/or the ocean.

The authors have proposed the counter-rotating type tidal range power unit, which is composed of the tandem runners and the peculiar generator with the double rotational armatures [8-10]. In the unit, the front and rear runners counter-drive the inner and outer armatures of the peculiar generator, respectively, while the rotational torque counter-balances itself in the runners/armatures. Then, the unit has promising advantages that not only the output voltage is sufficiently higher without supplementary equipments such as a gearbox, but also the rotational torque hardly acts on the mounting bed. That is, it is not necessary to set rigidly/solidly the unit on the mounting bed anchored to the ground.

This type power unit can be provided for not only the hydropower on the land but also the tidal range power on the ocean, in place of the traditional bulb type turbines. At the tidal range power station with the traditional type hydroelectric unit, a pair of the units must be prepared uselessly as mentioned above. The
counter-rotating type power unit is, however, fortunately effective for the bidirectional flows, namely the rising and the falling flows at the tidal range power station, because the flow discharged from the rear runner is in the axial direction while the swirl-less flow attacks to the front runner as described later. The counter-rotating type runners have also been proposed by Nielsen et al. [11], but each runner drives the isolated generator.

This paper prepares the counter-rotating type runner blades to work effectively at the bidirectional flows, and discusses experimentally and numerically the hydraulic performances with accompanying the flow conditions.

2. Counter-Rotating Type Bidirectional Runners

The model counter-rotating type tidal range power unit, where the bidirectional runners are installed, is shown in Fig. 1. The runner works were explained in the previous papers [8, 10], and reconfirmed in Fig. 2 for the rising and the falling tides. At both tides, the axial flow at the inlet gives the rotational torque to the front runner, and swirls at the outlet. Its swirling flow gives again the counter-rotational torque to the rear runner, and runs into the axial direction. It means that the angular momentum change through the front runner must coincide with the angular momentum change through the rear runner, while the rotational torque is counter-balance between the inner and the outer armatures. Then, the runners successfully counter-drive the inner and outer armatures of the generator, respectively, regardless of the flow direction, namely the rising and the falling tides.

To make the runner work effective for the both flow directions, the blades were prepared as shown in Fig. 3 (Runner D in house), where the head $H = 1.75$ m and the discharge $Q = 0.28$ m$^3$/s at the relative rotational speed $N_r = 1,500$ min$^{-1}$ corresponding to 50 Hz in the counter-rotating type generator with 4 poles. The blades have the symmetrical hydrofoils without the camber. The trailing edge is also the same profiles as the leading edge, and the rear blade is the same profiles as the front blade. The diameter of the runners is 245 mm with the hub diameter of 90 mm and the casing diameter 247 mm.

To know the turbine performances and the flow conditions, four type runners called Runner D33, D34, D43 and D44 were prepared, where D gives the runner profiles in house, the numerical values give the front and rear blade numbers in order, and the runner blades were set at the hub shown in Fig. 1.

At the experiments described in the previous papers [8-10], the front and rear runner outputs were consumed with the regenerative braking circuit of the motor, respectively, in place of the peculiar generator shown in Fig. 1. The runner speed was individually adjusted so that the rotational torque of the front runner coincides with that of the rear runner, while the mechanical torque in the bearing and the pulley system was removed.

3. Turbine Performances

The performances of the model power unit, whose blades are at the original position, are shown in Figs. 3 and 4, where the experimental results satisfy the similarity
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Fig. 2  Velocity components in the bidirectional flows.

Fig. 3  Blade profiles of Runner D.

law for $H$ and are substituted with the curves to know clearly the characteristics. In Fig. 4, $N_{11}$ is the unit relative rotational speed ($= n_D H^{1/2}$: m, min$^{-1}$), $Q_{11}$ is the unit discharge ($= Q(D^2 H^{3/2})$: m, $m^3$/s), $N_{11R}$ and $N_{11F}$ are the unit rotational speed of the front and rear runners, $P_{11}$ is the unit output ($= P(D^2 H^{3/2})$: m, kW), $P$: the shaft output defined by the IEC standards/codes [12], and $\eta_h$ is the hydraulic efficiency ($= P/\rho g QH$).

The performances have almost the same features against the unit rotational speed $N_{11}$ and the maximum outputs are at $N_{11} = 500$-600 m, min$^{-1}$, regardless of the runner profiles. Judging from the relative rotational speed giving the maximum output, Runner D33 is suitable for the higher discharge $Q_{11}$ at the higher $N_{11}$, namely the lower head, and Runner D44 is suitable for the lower $Q_{11}$ at the lower $N_{11}$, namely the higher head.

Fig. 4  Variable head performances.

The maximum hydraulic efficiencies are at $N_{11} = 250$-350 m, min$^{-1}$, and the values are close to 90% as the same as $\eta_h$ of the runners designed exclusively for the one directional flow [10]. Fig. 5 shows the hydraulic efficiencies of Runners D34 and D43, where Runner D43 means that the flow direction is changed...
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Fig. 5 Hydraulic efficiencies at the rising and the falling tides.

Fig. 6 On-cam hill chart for the hydraulic efficiency.

from the direction for Runner D34. The efficiency of the front runner \( \eta_{hf} \) with 4 blades (Runner D43: the thick dash line) is higher than that with 3 blades (Runner D34: the thick full line), and the efficiency of the rear runner \( \eta_{hr} \) with 4 blades (Runner D34: the thin full line) is higher than that with 3 blades (Runner D43: the thin dash line). Resultantly, the flow direction hardly affects the hydraulic efficiency \( \eta_h \) of the tandem runners even if the front and rear blade numbers are reasonably changed (\( \eta_h \) drawn by the thickest lines in Fig. 5). These efficiencies are almost the same as \( \eta_h \) of Runner D33, but are obviously higher than \( \eta_h \) of Runner D44 (Fig. 4).

Fig. 6 gives the relation among the unit discharge \( Q_{11} \), the unit relative rotational speed \( N_{11} \) and the hydraulic efficiency \( \eta_h \) at the various adjusting angles of the blades of Runner D33, where \( \eta_h \) was connected to each adjusting angle at the same value with the smooth curve. The adjusting angles of the front and rear blade chords, \( \theta_F \) and \( \theta_R \), are measured from the original position in the anticlockwise for the left blade and the clockwise for the right blade in Fig. 3. That is, the positive adjusting angle makes the stagger angle increase, where the stagger angles at the original positions are 75.5 degrees at the blade tips for both runners. The experiments were in keeping the relative rotational speed constant at \( n_T = 900 \text{ min}^{-1} \), which corresponds to the power frequency 60 Hz induced from the counter-rotating armature type generator with 8 poles. This figure gives the on-cam hill chart for the hydraulic efficiency, where the authors can also get the chart for the output in the same manner (cutting the figure). The authors can know the optimum adjusting angle of the blade at the individual or the changed tidal circumstances, that is the vertical axis that gives the angle while keeping \( H \) constant but changing \( Q \), and the horizontal axis gives the angle while keeping \( Q \) and/or \( H \) constant but changing the rotational speed \( n_T \), namely the number of poles.

Fig. 7 shows the performances at the on-cam operation of Runner D33, while the blades have the adjusting angle optimized as the bottom. To get the reasonable performances, the blades must be turned more or less to the axial direction, namely make the stagger angle smaller than the original position. At such blade adjustments, the maximum efficiencies are at the lower discharge \( Q_{11} \) or the lower rotational speed \( N_{11} \). The maximum output is at higher \( N_{11} \) than \( N_{11} \) giving the maximum efficiency because \( Q_{11} \) increases with the increase of \( N_{11} \).

4. Flow Condition around Runners

The relative flow angles \( \beta \) are shown in Fig. 8 while operating at the maximum output (\( N_{11} = 544 \text{ m, min}^{-1} \) for Runner D34, 578 m, min\(^{-1}\) for Runner D43) and Fig. 9
while operating at the maximum hydraulic efficiency ($N_{11} = 351 \text{ m, min}^{-1}$ for Runner D34, 330 for Runner D43), where the blades are at the original position. In the figures, $\beta$ was measured clockwise from the axial direction in Fig. 2 and averaged in the tangential direction, $Y$ is the dimensionless distance measured from the hub to the casing walls, and $\beta_{th}$ drawn by the thin dash line is the blade angle. The relative flow angles discharged from the runners are close to $\beta_{th}$ at the maximum output (Fig. 8), but the flows deviate slightly from $\beta_{th}$ at the maximum hydraulic efficiency (Fig. 9).

The runner has to get the angular momentum change from the through flow, even if the blade has no camber. The relative flow has the positive attack angle at the leading edge and discharges from the trailing edge along the blade camber. That is, the momentum change always accompanies with the shock loss at the leading edge, but the loss may be small in the accelerating flow field even operating at the maximum efficiency with the large angle of attack, as assumed in Fig. 4.

To prepare the design tool for optimizing the runner profiles, the flow conditions around the runners were simulated numerically with the commercial code ANSYS CFX-11 (Fig. 10). The flow field was divided
into the upstream (node numbers: 123,000), the front runner (node numbers: 266,000), the rear runner (node numbers: 352,000) and the downstream (node numbers: 155,000), and each field was connected with the frozen-rotor interface. The relative flow angles are shown with the thick full lines in Figs. 8 and 9. It is confirmed that the flow conditions are predicted well with the commercial code useful for the runner design at the future steps.

5. Concluding Remarks

At the tidal power station with the traditional type hydroelectric unit, a pair of the units, whose nose and tail are replaced each other, must be set unfortunately/uselessly, to get the fruitful output from not only the rising but also the falling tide. On the contrary, it was confirmed that the counter-rotating type tandem runners are effective to both flow directions because the flow is discharged from the rear runner in the axial direction while the swirl-less flow attacks to the front runner. That is, the performances against the unit relative rotational speed have almost the same features and the maximum hydraulic efficiency is in close to the efficiency of the runners designed exclusively for the one directional flow. The relative flow has the positive attack angle at the leading edge and discharges from the trailing edge along the blade camber. That is, the momentum change always accompanies with the shock loss at the leading edge.

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