Counter rotating type hydroelectric unit suitable for tidal power station

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Abstract. The counter rotating type hydroelectric unit, which is composed of the axial flow type tandem runners and the peculiar generator with double rotational armatures,was proposed to utilize effectively the tidal power. In the unit, the front and the rear runners counter drive the inner and the outer armatures of the generator, respectively. Besides, the flow direction at the rear runner outlet must coincide with the flow direction at the front runner inlet, because the angular momentum through the rear runner must coincides with that through the front runner. That is, the flow runs in the axial direction at the rear runner outlet while the axial inflow at the front runner inlet. Such operations are suitable for working at the seashore with rising and falling tidal flows, and the unit may be able to take place of the traditional bulb type turbines. The tandem runners were operated at the on-cam conditions, in keeping the induced frequency constant. The output and the hydraulic efficiency are affected by the adjustment of the front and the blade setting angles. The both optimum angles giving the maximum output and/or efficiency were presented at the various discharges/heads. To promote more the tidal power generation by this type unit, the runners were also modified so as to be suitable for both rising and falling flows. The hydraulic performances are acceptable while the output is determined mainly by the trailing edge profiles of the runner blades.

1. Introduction

To cope with the warming global environments, the hydropower should occupy the attractive attention of the electric power generation systems as clean and sustainable energy source with highest density, in cooperation with the wind and the solar powers. That is, we should make effort to utilize effectively the large/small/mini/micro hydropower not only on the land but also on the ocean, without nature disruptions. For contributing fruitfully to such demands, it is required to prepare more several types of the hydroelectric unit suitable for the individual hydro-circumstances.

The propeller type, Darrieus type and the cross-flow type hydraulic turbines have been prepared for the small hydropower on the land and/or the ocean (e.g. http://www [1], Furukawa et al. [2], Fukutomi and Nakase [3]). The unique turbine with the counter-rotating runners has been proposed (Nielsen et al. [4]), and the author also invented the counter-rotating type hydroelectric unit, which is composed of the tandem runners and the peculiar generator with the double rotational armatures (Kanemoto et al. [5]). In this unit, the front and the rear runners counter-drive the inner and the outer armatures of the peculiar generator, respectively, while the rotational torque is counter-balanced successfully in the runners/armatures. The unit has promising advantages that not only the output voltage is sufficiently high without supplementary equipments such as a gearbox, but also the rotational moment hardly acts on the mounting bed owing to the momentum balance. That is, it is not necessary to set rigidly the unit on the mounting bed anchored to the ground. The fundamental performances and the flow conditions around the runners have been investigated and the design data for the runners have been presented (Tanaka et al. [6]).

This type hydroelectric unit can be supplied to not only the hydropower on the land but also the tidal power

on the ocean, in place of the traditional bulb type turbines. In this paper, this unit is operated at the on-cam condition in response to the gradual change of the tidal head at the power station. At the tidal power station with the traditional type hydroelectric unit, a pair of the units, whose inlet and outlet are replaced each other, must be set uselessly in general, to get the fruitful output from not only the rising but also the falling tides at the station with the dam/weir/sluice. Then, the runner blades are modified so as to work effectively at the bidirectional flows, and the hydraulic performances are also investigated experimentally and numerically.

2. Counter-Rotating Type Hydroelectric Unit

2.1 Model Unit

The model counter-rotating type hydroelectric unit is shown in Fig. 1 and the velocity triangles around the axial flow type runner blade are shown in Fig. 2. The axial flow at the inlet section gives the rotational torque to the front runner, and swirls at the outlet section. 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 the outer armatures of the generator, respectively.

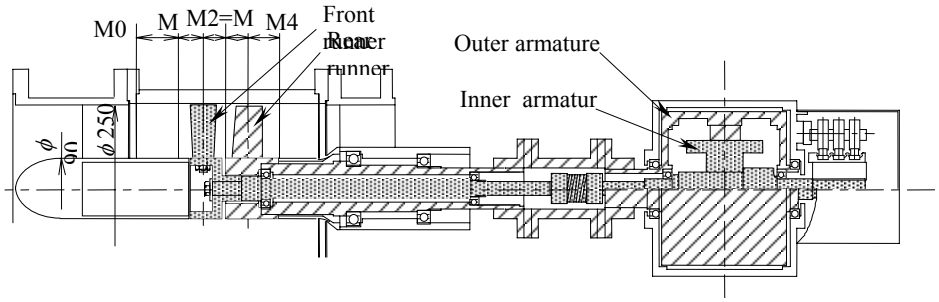


Fig. 1 Model counter-rotating type hydroelectric unit

2.2 Synchronous Generator

Taking account of supplying the output not only to the grid but also to the isolated power systems, the model counter-rotating armature type synchronous generator with the inner and the outer rotational armatures (3-phases, 4-poles, permanent magnet, AC generator with the double rotational armatures) shown in Fig. 3, was prepared. The rated output P is 1 kW at the relative rotational speed N_T = 1500 min^{-1}, while the induced frequency is f =50 Hz and the induced voltage is E = 100V. The characteristics were investigated experiment-ally, where the armatures were driven by two motors, respectively, in place of the proposed tandem runners.

Figure 4 shows the relation of the rotational torque between the inner armature T_F* and the outer armature T_R*, in keeping the rotational speed of the inner armature constant at N_F = 750 min^{-1}, while the rotational speed of the outer armature N_R was changed variously by the external loads. These values T_F*, T_R* do not have the mechanical torques of the bearings and the slip ring to know the fundamental characteristics, and T_R* is given by the absolute value though T_R* is in the opposite direction to T_F*. It is obviously confirmed that T_R* coincides strictly with T_F* irrespective of the relative rotational speed N_T (= N_F - N_R) and the output/load, because the rotational torques should be counter-balanced dynamically between the inner and the outer armatures.

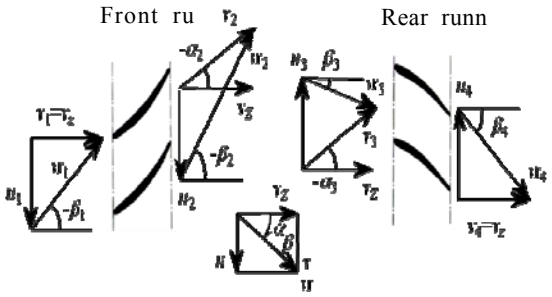


Fig. 2 Velocity triangles through the counter-

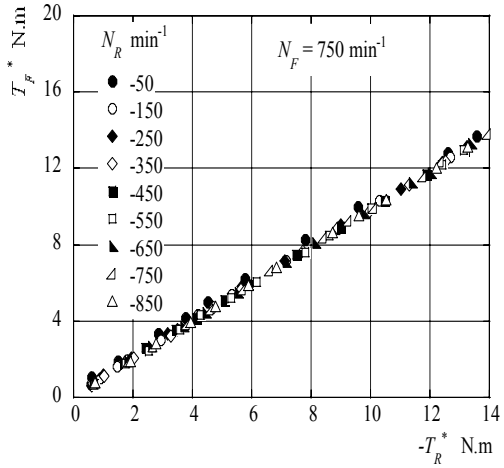


Fig. 4 Rotational torque between the inner and

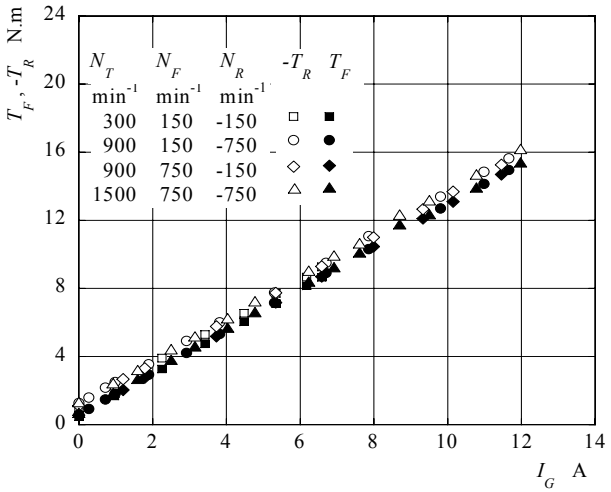


Fig. 5 Rotational torques against the induced electric current

Figure 5 shows the rotational torques T_F and T_R (absolute value) against the induced electric current I_G, at the various relative speeds N_T, where these torques include the mechanical torques to know the characteristics in the practical use. The torques T_F, T_R are in proportion to the induced electric current I_G, but the torque T_R of the outer armature is slightly larger than T_F of the inner armature due to the mechanical torque of the larger bearings and slip ring.

The output P and the induced voltage E against the induced electric current I_G are determined by the relative rotational speed N_T (= N_F-N_R), as shown in Fig. 6. The output increases with the increase of the voltage E at the same I_G and increases with the increase of I_G at the same N_T, while E is proportional to N_T.

2.3 Doubly Fed Induction Generator

The doubly fed induction generator is boarded on the power unit with large capacity for making the output supply to the grid system (Muller et al. [7]). It is not necessary to control mechanically the runner speeds for guaranteeing precisely the induce frequency for the grid system. The frequency f_1 induced from the outer armature (the primary feed) can be easily kept constant by modulating the frequency f_2 of the inverter connected to the inner armature (the secondary feed) in response to the relative runner speed. The output P_1 and the voltage E_1 induced from the outer armature can also be kept constant, by modulating the input P_2 and the voltage E_2

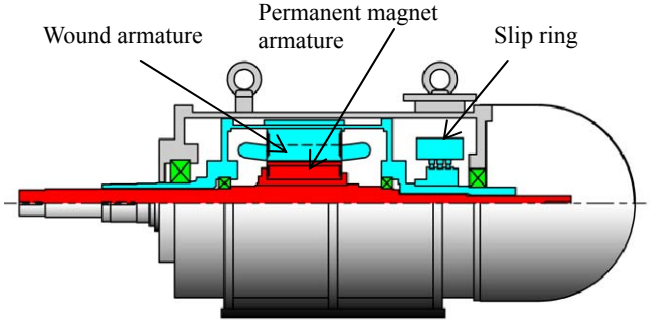


Fig. 3 Model double rotational type synchronous generator

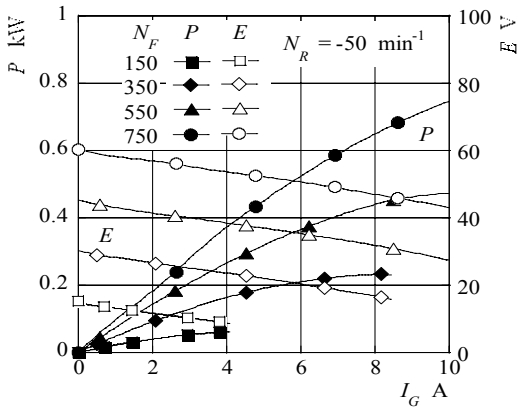


Fig. 6 Output and the induced voltage against the induced electric current

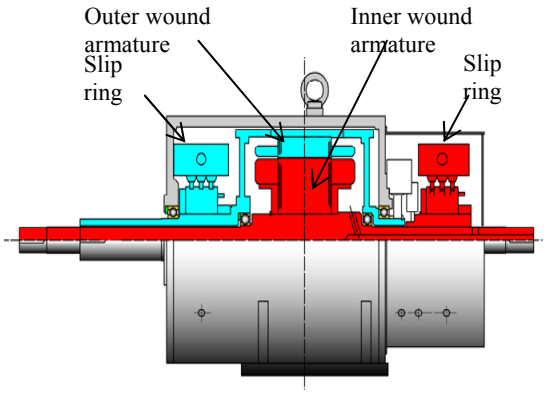


Fig. 7 Model double rotational type doubly fed induction generator

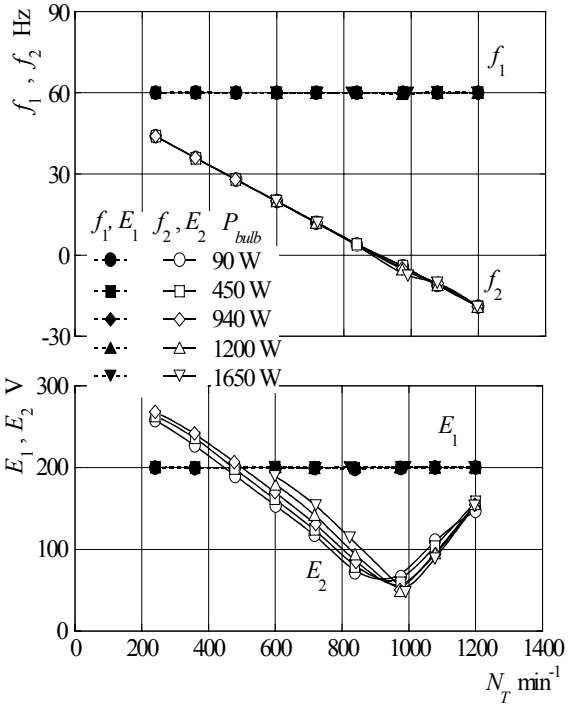


Fig. 8 Frequencies and voltages against the relative rotational speed

of the inverter connected to the inner armature.

Figure 7 shows the trial model of the counter-rotating armature type doubly fed induction generator. The rated output is P = 1.2 kW and the voltage is E_1 = 200 V at N_T = 900 min^{-1}, where the number of the poles is 8. The characteristics were investigated as follows. The motor shaft was connected to the shaft of the inner armature while the shaft of the outer armature was kept stationary, because the electric characteristics depend only on the relative rotational speed between both armatures. The rotational speed of the motor, namely the rotational speed of the inner armature, which is the relative rotational speed, was controlled by the inverter. Another inverter controlled the frequency f_2 and the voltage E_2 which are supplied to the secondary feed (the inner armature) of the generator. The output was measured by the power meter and was consumed through the electric bulbs (the lamps, P_{bulb}), while the frequency and the voltage induced from the outer armature (the primary feed) were kept constant at f_1 = 60Hz and E_1 = 200 V.

Figure 8 shows the frequency f_2 and the voltage E_2 of the inner armature for keeping f_1 and E_1 of the outer armature constant, where N_T is the relative rotational speed (= N_F-N_R, N_F and N_R are rotational speed of the inner and the outer armatures, and give the positive value in the N_F direction) as the same as the nomenclatures described above. The frequency f_2 is in inverse proportion to the relative rotational speed N_T irrespective of the external load P_{bulb}, though the revolving direction of the magnetic field must be changed, which means that f_2 is negative, at N_T faster than the synchronous speed 900min^{-1}. The voltage E_2 depends not only on N_T but also on P_{bulb}, namely the output P_1. The input P_2 comes to be negative at N_T faster than 900 min^{-1}, as shown in Fig. 9. That is, P_2 changes fortunately from the input to the output, then the net output from the generator is $P = P_1 - P_2$.

2.4 Experimental Setup

The model hydroelectric unit shown in Fig. 1 was connected to the penstock and the discharge pipes in the test loop. The turbine head H and the discharge Q were given by the booster pumping system stood at the upstream, where Q was measured with the orifice and H was derived from the pressure on the casing walls at sections M1 and M4 in accordance with the standards/codes (IEC et al. [8]). Figure 10 proves the operation of the model unit with the above synchronous generator (Kanemoto et al [5]), where, N_{G11F} (= $N_F D/H^{1/2}$: m, min^{-1}, D: the runner diameter = 245 mm) and N_{G11R} (= $N_R D/H_G^{1/2}$: m, min^{-1}) are the unit rotational speed of the inner/front and the outer/rear armatures/runners, P_{G11} [= $P_G/(D^2H^{1/2})$: m, kW] is the unit electric output, M_{G11} [= $M_G/(D^3H)$: m, kN-m] is the unit rotational torque, and the runner blades were tentatively designed so as to get the axial flows at the inlet and the outlet of the tandem runners with N_F = -N_R. The rotational speeds N_{G11F} and N_{G11R} are adjusted themselves in response to the external bulb load, as the rotational torque M_{G11} of the inner armature coincides with that of the outer armature. The rotational speed N_{G11R} is in nearly proportion to N_{G11F}, and M_{G11} increases with the decrease of N_{G11F}. Such operations cause the increase of the

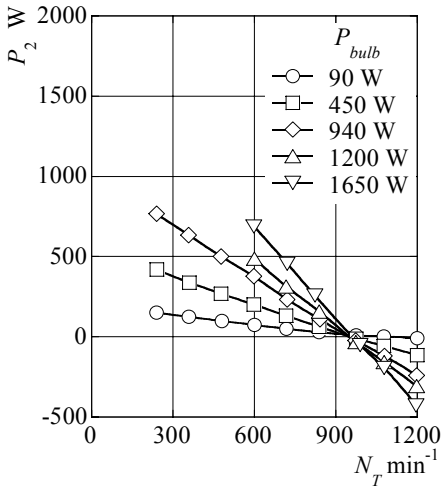


Fig. 9 Input against the relative rotational speed

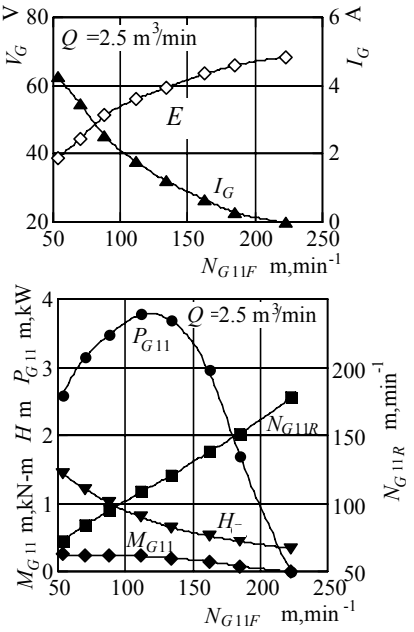


Fig. 10 Operation of the model unit

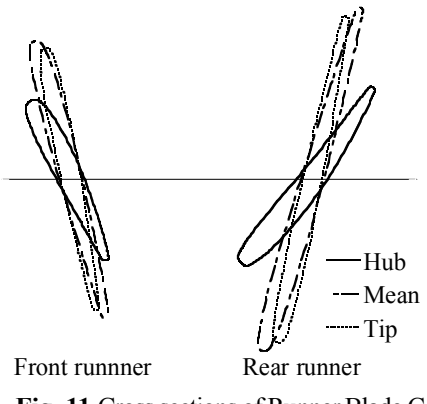


Fig. 11 Cross sections of Runner Blade C

turbine head H with the increase of the angular momentum change through the runners, namely M_{G11}, at the constant discharge. The induced electric current I_G goes down and the induced voltage E goes up with the increase of the rotational speed, and the runaway speed is about N_{G11F} =225 m, min^{-1}. The product $3^{1/2}I_GE$ gives the electric output and P_{G11} is maximum with the induced frequency 27 Hz at N_{G11F} = N_{G11R} = 120 m, min^{-1}.

In the followings, the front and the 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 speeds were 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. On-Cam Operation

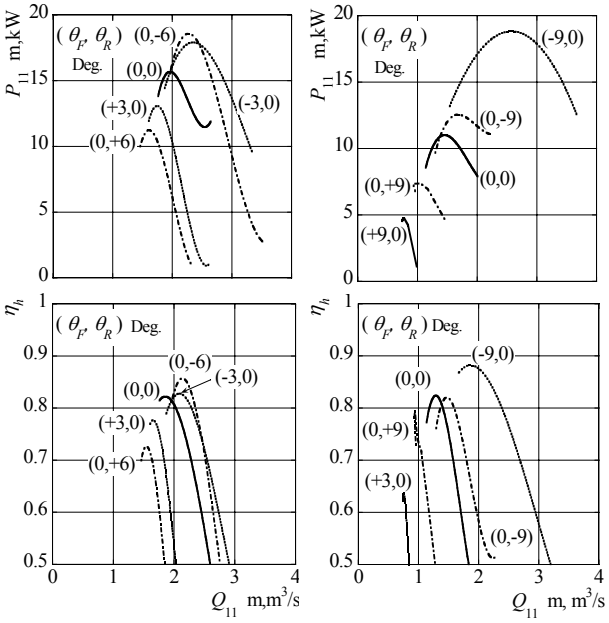
3.1 Preparation of Counter-Rotating Type Runners

To operate the counter-rotating type hydroelectric unit at the on-cam condition, the following runners were prepared. The diameter D is 245 mm, with the hub diameter of 90 mm and the casing diameter 250 mm. Figure 11 shows the runner blade sections, called here Runner Blade C, designed so as to take the flow conditions described in 2.1 and 2.4 at the normal operation. The camber lines of the front and rear blades are single arcs, and the thickness of both blades are referred to the NACA 0009 hydrofoils. In this paper, two types of runners were prepared using Runner Blade C, where Runner C23 is composed of two front blades and three rear blades and Runner C53 is composed of five front blades and three rear blades. Runner C23 may be suitable for the lower tidal head, namely the lower range of the tide, and Runner C53 may be suitable for the higher head, namely the higher range of the tide.

The model unit was operated at the relative rotational speed n_T = 900 min^{-1} which corresponds to the frequency 60 Hz induced from the counter-rotating armature type generator with 8 poles. The setting angle of the blade was defined by the central angle around the twist center measured from the dimensions given in Fig. 11. These are shown by θ_F for the front and θ_R for the rear blades, where the angle is positive when the blade leans to the tangential direction (in the clockwise for the front blade, in the counter-clockwise for the rear blade in Fig. 11).

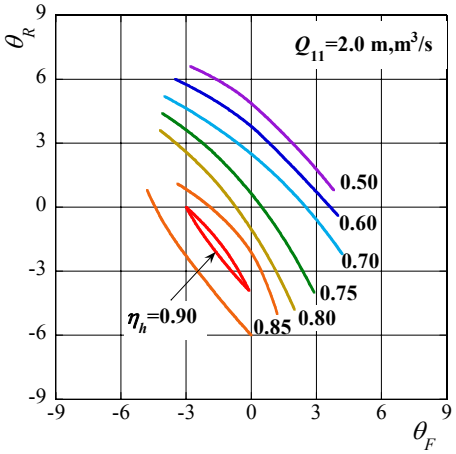
3.2 Output and Hydraulic Efficiency

The variable discharge performances are shown in Fig. 12, where Q_{11} is the unit discharge [=$Q/(D^2H^{1/2})$: m, m^3/s], P_{11} is the unit output [=$P/(D^3H^{3/2})$: m, kW, P: the shaft output defined by the standards/codes (IEC et al. [8])], and η_h is the hydraulic efficiency [=$P/\rho gQH$]. The performances satisfy the similarity law for the traditional hydraulic turbines, and the experimental results are represented with the curves. The unit output P_{11} and the hydraulic efficiency η_h have the same features against the unit discharge Q_{11}, regardless of the blade setting angle and the number of the blade.

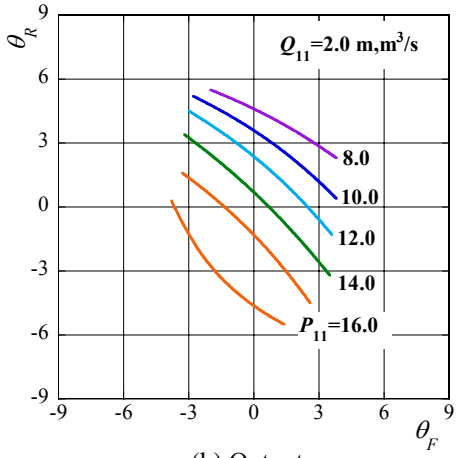


(a) Runner (b) Runner

Fig. 12 Outputs and efficiencies of Runners



(a) Hydraulic efficiency



(b) Output

Fig. 14 Optimum blade setting angles at Q_{11}=2 m,m^3/s of Runner C23

The performances at the normal setting angle (θ_F = θ_R =0), however, suggest that Runner C23 is suitable for the higher discharge, namely the lower head, and Runner C53 is suitable for the lower discharge, namely the higher head, as expected at the design. The maximum output or the maximum efficiency is got at larger unit discharge with the decrease of not only the number of the blade but also the blade setting angle.

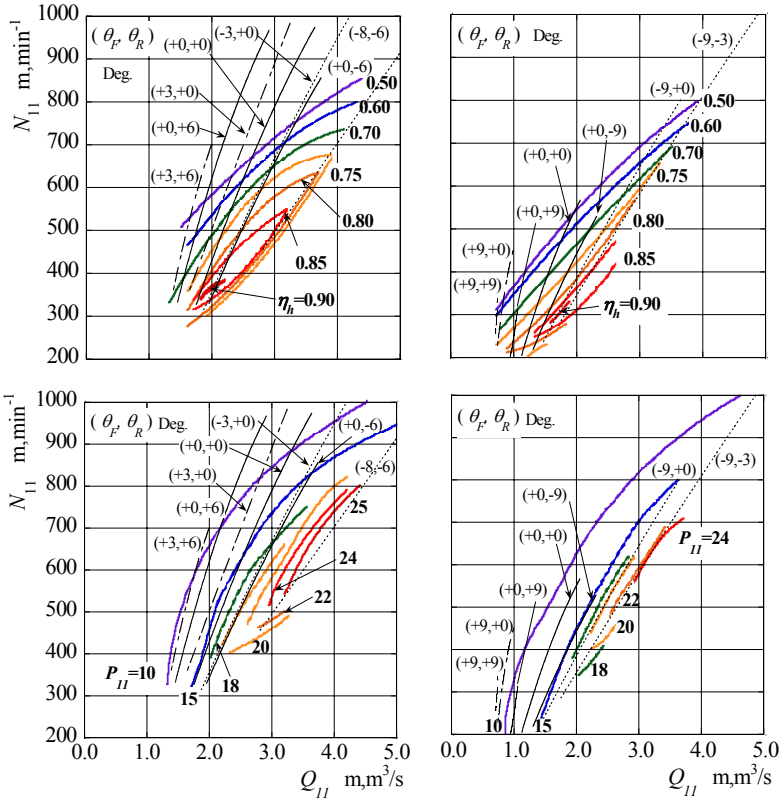
3.3 On-Cam Hill Chart

The relation between the unit relative rotational speed N_{11} [=$n_T D/H^{1/2}$: m, min^{-1}] and the unit discharge Q_{11} for each blade setting angle (θ_F, θ_R) are shown by the thin lines in Fig. 13, where these are derived from Fig. 12 and the hydraulic efficiency η_h and the unit output P_{11} on the each thin line were connected at the same value, and shown by the thick lines. That is, Fig. 13 gives the on-cam hill chart for the hydraulic efficiency η_h and the unit output P_{11}. This figure gives the optimum blade setting angle to operate the hydroelectric unit at the specified performances (Ida et al. [9]). To get the higher efficiency or output, the blades must be turned to the axial direction, as recognized in Fig. 14. At such blade adjustments, for instance, the maximum efficiency is at the lower discharge Q_{11} and at the lower rotational speed N_{11}.

4. Operation at Bidirectional Flows

4.1 Modification of Blade Profiles

As mentioned above, it is necessary to set uselessly/unfortunately a pair of the traditional type hydroelectric



(a) Runner C23 (b) Runner C53

Fig. 13 On-cam hill charts

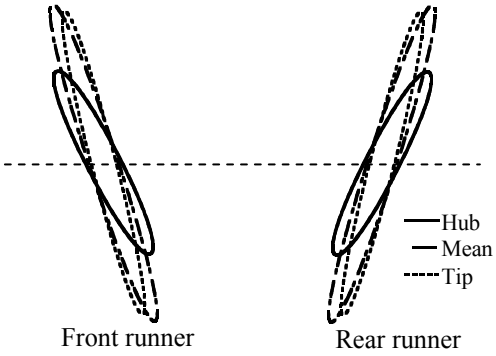


Fig. 15 Cross sections of Runner Blade D

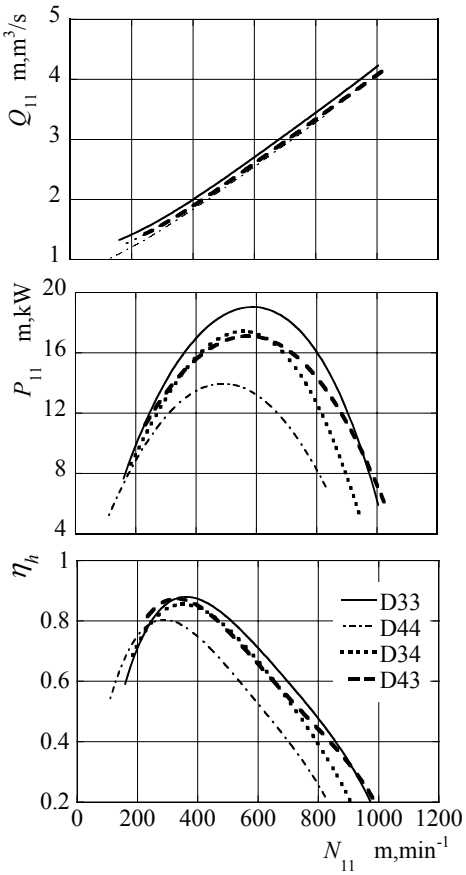


Fig. 16 Performances of Runner D

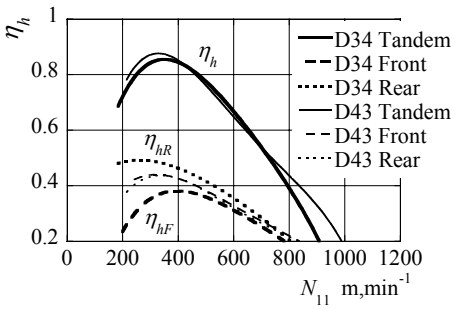


Fig. 17 Hydraulic efficiency of Runner D34 and D43

units whose nose and tail are replaced each other, for utilizing sufficiently the rising and the falling tidal energies. The counter- rotating type hydroelectric unit is, however, effective to both flow directions because the flow discharged from the rear runner is in the axial direction while the swirl-less flow attacks to the front runner as expounded above. Such flow conditions suggest that the counter-rotating runners can be supplied to both rising and falling tidal flows at the power station.

Then, the runner blades were modified so as to work effectively at the both flow directions, as shown in Fig. 15 (Runner Blade D), where the head H = 1.75 m and the discharge Q = 0.28 m3/s at the relative rotational speed N_T = 1,500 min^{-1}. 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 250 mm, as the same as the blades shown in Fig. 11.

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, 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. In the experiments, the runner speeds were not adjusted so as to keep the induced frequency constant, but the rotational torque was undoubtedly adjusted between both armatures/runners.

4.2 Turbine Performances

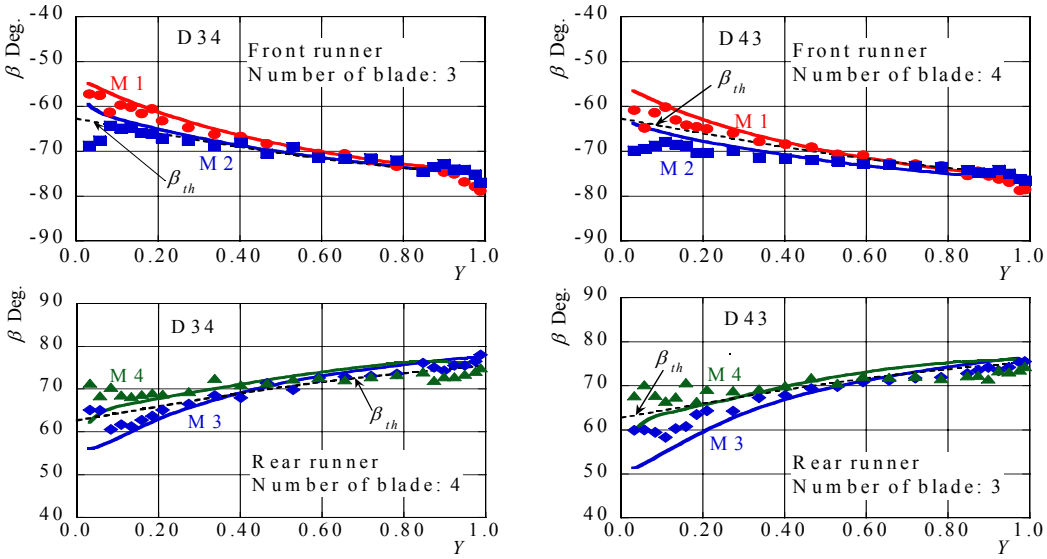
The variable head characteristics, that are the performances against the unit relative rotational speed N_{11}, are investigated experimentally and shown with the curves in Fig. 16. The performances against N_{11} have almost the same features and the maximum outputs are at N_{11} = 500-600 m, min^{-1}, regardless of the runner profiles. Judging from the relative rotational speed giving the maximum output, among the runners prepared in this paper, 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.

The maximum hydraulic efficiencies are at N_{11} = 250-350 m, min^{-1}, and the values are almost the same those at the higher Q_{11} in Fig. 12. Figure 17 shows the hydraulic efficiencies of Runners D34 and D43, where D43 means that the flow direction is changed from the direction for D34. The efficiency of the front runner η_{hF} with 4 blades (Runner D43: the thin dash line) is higher than that with 3 blades (Runner D34: the thick dash line), and the efficiency of the rear runner η_{hR} with 4 blades (Runner D34: the thick dash line) is higher than that with 3 blades (Runner D43: the thin dash line). Resultantly, the flow direction hardly affects the hydraulic efficiency η_h of the reversible/bidirectional type runners even if the front and the rear blade numbers are reasonably changed (see η_h drawn by the full lines in Fig. 17). These efficiencies are almost the same as η_h of Runner D33 (the thin full line in Fig. 16), but are obviously higher than η_h of Runner D44 (the thin dot-and-dash line in Fig. 16).

4.3 Flow Conditions around Runners

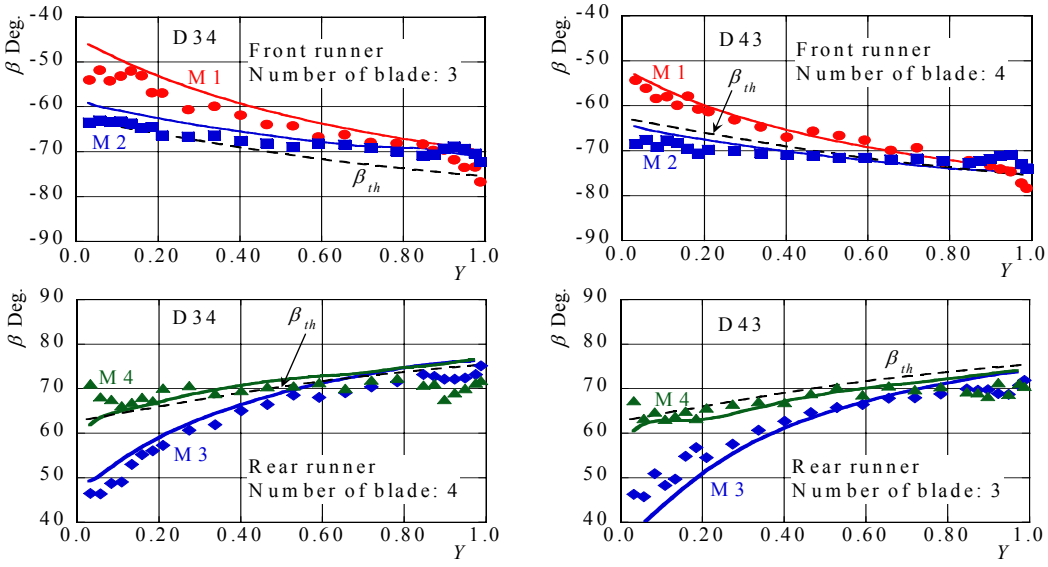
Flow conditions around the at the maximum output and the maximum hydraulic efficiency are shown in Figs.18 and 19, where β is the relative flow angle measured from the axial direction (see Fig. 2) and averaged in the tangential direction, Y is the dimensionless distance measured from the hub to the casing walls, β_{th} drawn by the thin dash line is the blade setting angle without the camber. The relative flow angles discharged from the runners are close to β_{th} at the maximum output (Fig. 18) where the runners were designed, but the flows deviate slightly from β_{th} at the maximum hydraulic efficiency (Fig.19). 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 is discharged 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 is tiny, because the flow along the suction surface of the blade does not separate in the following flow simulation even operating at the maximum efficiency with the large attack angles.

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, where the region of the simulation is shown in Fig. 20. The region from the inlet to the outlet sections was divided into the upstream (node number: 123,000), the front runner (node number: 266,000), the rear runner (node number: 352,000) and the downstream (node number: 155,000) sub-regions, and each sub-region was connected with the frozen-rotor interface. The relative flow angles are shown by the thick full lines in Figs. 18 and 19, and it is confirmed that the flow conditions are predicted well with the commercial code. The code may be useful to design the runners at the future steps.



(a) Runner D34 (b) Runner D43

Fig. 18 Relative flow angles at the maximum output



(a) Runner D34 (b) Runner D43

Fig. 19 Relative flow angles at the maximum efficiency

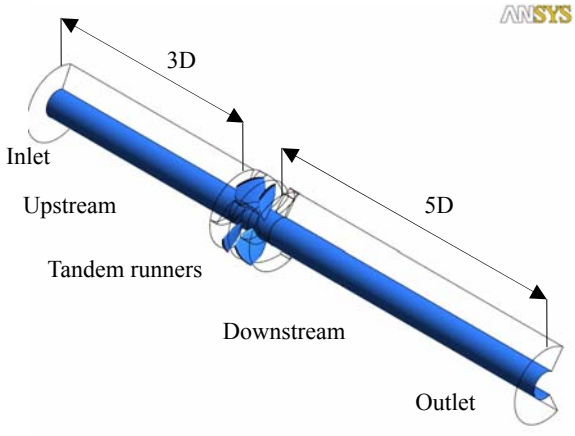


Fig. 20 Flow region in the numerical simulation

5. Concluding Remarks

The counter-rotating type hydroelectric unit was operated at the on-cam condition. The runners with small number of the blade are suitable for the higher discharge, namely the lower head. The maximum output or the maximum efficiency is got at the higher unit discharge with the decrease of the blade number. The on-cam hill chart against the unit discharge or the unit relative rotational speed was also presented. This chart gives the optimum blade setting angles to operate the unit at the specified efficiency or output. To get the higher efficiency or the higher output, the blades must be turned to the axial direction. At such blade adjustments, the maximum efficiency is at the lower discharge or at the lower rotational speed, and the maximum output is at the higher discharge or at the higher rotational speed.

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. The tandem runners in the counter-rotating type hydroelectric unit are, however, 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. Then, the runner blades were modified so as to work sufficiently at both rising and falling tidal flows, and the hydraulic perform-ances were investigated experimentally. The performances against the unit relative rotational speed have almost the same features as those of the normal runners which are designed so as to be suitable for one way flow. The unit discharge giving the maximum output is higher than one giving the maximum efficiency irrespective of the blade number, and the efficiencies are almost the same as those of the normal runners. The relative flow has the positive attack angle at the leading edge and is discharged from the trailing edge along the blade camber. That is, the momentum change always accompanies with the shock loss at the leading edge. Such flow conditions were also predicted numerically by the commercial CFD code.

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