Studies on Cavitation Occurring on the Runner Blade of a Darrieus-Type Water Turbine*

Yasuo TAKAMATSU**, Akinori FURUKAWA**,
Kusuo ŌKUMA **, Kazuki TAKENOUCI***,
Toshihiko SASAKI**** and Guo-hua ZHAO*****

Cavitation tests were carried out on a Darrieus-type cross-flow water turbine, which could be put into practical use for small water power. In the present paper, cavitation phenomena occurring on the Darrieus runner with various blade sections are explained and the characteristics of the incident cavitation coefficient for the attack angles in relative flow around the Darrieus blades are also evaluated with theoretical considerations of the difference between the circular motion of the Darrieus blades and the linear motion of those in a uniform steady flow. As the result, a useful method is proposed for estimating the required net positive suction head (NPSH) of a Darrieus-type water turbine.

Key Words: Hydraulic Machine, Water Turbine, Cross-Flow, Darrieus Runner, Blade Performance, Cavitation

1. Introduction

Extra-low-head natural water power and water power wasted in industry have been reconsidered as energy resources for effective utilization of undeveloped resources since the oil crisis of 1973. A two-dimensional Darrieus-type water turbine has a great advantage of simple structure, so that it has been developed and tested for practical use⁽¹⁾. A Darrieus runner, being a high-speed type in principle, is recommended for operation at a circumferential speed sev-

eral times higher than an incoming flow velocity. In such high-speed operations, cavitation occurring on the runner blade, however, deteriorates the runner performance markedly. On cavitation performance of the Darrieus runner, there has been little research which is indispensable to water turbines, while much data are available for fluid dynamic performance since the Darrieus wheel was developed mainly for utilizing wind energy. Considering that the Darrieus blade shows different characteristics from blades at rest in a uniform steady flow⁽²⁾, there must also be differences in cavitation performance of both blades.

In the present paper, experimental results of cavitation phenomena occurring on the Darrieus runner are explained. Based on the considerations of the relationship between the inception of cavitation and the flow relative to the Darrieus blade, a guiding principle of cavitation limits is discussed for planning the utilization of Darrieus-type water turbines.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic view of the experimental apparatus and tested runner. Water flows from the open channel to the water pool through the test

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** Department of Mechanical Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812, Japan

*** Department of Industrial Design, Kyushu Institute of Design, 4-9-1 Shiobaru, Minami-ku, Fukuoka 815, Japan

**** Thermal Power Plant Engineering Department, Hitachi Works, Hitachi, Ltd., 3-1-1 Saiwai-cho, Hitachi 317, Japan

***** Department of Locomotive and Rolling Stock, Dalian Railway Institute, Xi Shan Chun, Shahekou District, Dalian, China

section ① (width of flow passage $S=400$ mm). Flow rate Q is measured by an orifice mounted on the delivery pipe. The amount of available head imposed on the runner H and inflow water level h_s from the water surface immediately upstream of the runner in the open channel to the midspan of the runner are adjusted by manual control of a butterfly valve ⑥. H is evaluated by subtracting the head loss between the upstream open channel and the downstream section of the runner in the state without the runner blade from the difference in the averaged total head between these sections in the operating state. Net positive suction head H_{sv} is evaluated as a margin of averaged total head at the immediate upstream section of the runner, exceeding saturated vapor head h_v at the temperature of the tested water by the formula

$$H_{sv} = P_a/\gamma + h_s - h_l - h_v \quad (1)$$

where P_a is the atmospheric pressure, γ is the specific weight of water and h_l is the head loss from the upstream open channel to the runner. In the experiments, margins to the inception of cavitation were adjusted relative to the incoming flow by changing a cross-sectionally averaged incoming velocity $\bar{V}$ or a peripheral speed U on the pitch circle of the runner, since the experimental apparatus has a channel opened to the air and the amount of H_{sv} itself is therefore not variable in a wide range. Cavitation occurring on the runner was observed through a wall of acrylic resin at the side of the test section with aid of a flashlight synchronized with the frequency of the rotation of the runner. The tested water was always supplied from the water pool downstream of the runner, and the air content and cavitation nuclei in the tested water, which affect the incipient and desinent cavitations, were not measured or controlled in the experiments. Cavitation tests were carried out several times under the same operating conditions to confirm the reliability of the measurement.

A single-bladed, two-dimensional runner with a radius of the runner pitch circle of $R=185$ mm is composed of a shaft perpendicular to the flow, a tested

Fig. 1 Schematic view of experimental apparatus and tested runner

blade ($Z=1$) ⑦, supporting arms ⑧ and runner end disks ⑨ in the test section. Time variation in generated torque in one revolution of the runner is evaluated by adding the resistance torque in the state without the blade to a torque measured in an operating state by the torque pickup ③. Time variations in forces and moment acting on a runner blade can be measured⁽¹⁾ with three strain gauges ⑩ pasted on each supporting arm. Two kinds of blades, NACA 4518 (blade A) and NACA 0018 (blade B) with straight span $B=200$ mm and chord length $l=55$ mm, are adopted for the tested section, and blade setting angle δ is taken as 0° when the camber line of the blade is tangent to the runner pitch circle at the quarter chord point, and is defined as positive when the leading edge of the blade is radially inside the position of $\delta=0^\circ$.

3. Experimental Results

Figure 2 shows the results of the performance test over wide ranges of U and $\bar{V}$ with blades A and B. In the performance test, blade A and blade B are set at $\delta=0^\circ$ and -5° , respectively, angles which afforded high blade efficiencies over a wide range of operating conditions⁽¹⁾. Since the flow relative to the Darrieus blade shows a cyclic variation in each revolution of the runner, the pressure distribution along the surface

(a) Blade A (NACA 4518, $\delta=0^\circ$)

(b) Blade B (NACA 0018, $\delta=-5^\circ$)

Fig. 2 Results of cavitation test

of the Darrieus blade varies at every rotating position of the blade. At a rotating position at which the minimum pressure on a blade takes the lowest value in a revolution, an incipience of cavitation is observed at a certain value of U or $\bar{V}$, when U or $\bar{V}$ is increased. At a higher operating point of U or $\bar{V}$, cavitation occurs in a certain region of the rotating position, and the growth and desinence are iterated in every revolution. Also shown in Fig. 2 by a dot-dash line and a double-dot-dash line are the lines on which the incipience of cavitation was observed in the upstream half and the downstream half of blade rota-

tion, respectively.

Comparing these incipient cavitation lines of both blades in the vicinity of $U/\bar{V}=4.0$ where the maximum blade efficiencies were obtained, it is seen that, for blade B, the inception occurs almost simultaneously in the upstream half and in the downstream half of blade rotation at a certain value of U or $\bar{V}$, and for blade A, the inception in the upstream half occurs at a lower value of U or $\bar{V}$ than in the downstream half or that of blade B. A fall in blade efficiency of both blades is observed at the operating point higher than the incipient cavitation line. In addition to the fact⁽³⁾ that the maximum blade efficiencies were 62% for blade B and 57% for blade A, it is concluded from the above results that the noncambered blade B is also recommended for better cavitation performance.

For the cavitation occurring in the upstream half of blade rotation, a fixed cavity was observed on the blade surface just behind the leading edge, and the growth and desinence were iterated in a revolution of the runner with a change of pressure distribution along the blade surface in a higher range of the speed ratio $U/\bar{V}$. On the other hand, in a range of $U/\bar{V} \leq 2.5$ where leading edge separation occurs, a vortexlike cavitation was observed at the center of the low-pressure region of vortices separated from the blade surface. For the cavitation occurring in the downstream half of blade rotation, the aspects of cavities of both blades were similar to those in a higher range of speed ratio in the upstream half, although flow was deformed by the existence of vortices shed from the blade and a runner shaft.

Since the lines of iso-efficiency without cavitation in Fig. 2 are nearly straight toward the origin, similarities of blade performance to the speed ratio $U/\bar{V}$ are found. This result indicates that the change of blade performance affected by the growth of cavitation can be studied by increasing $\bar{V}$ under the constant value of $U/\bar{V}$. Figure 3 shows the change of blade performance, the range of rotating position with cavitation occurrence and the time variation in torque with decreasing nondimensional NPSH, and also shows a relative flow velocity W and an attack angle α^* calculated by a theoretical method⁽³⁾ in the operating condition of $\delta = -5^\circ$ and $U/\bar{V} = 3.9$ of blade B as an example. The operating points a, b, c and d in the figure correspond to those denoted in Fig. 2.

When nondimensional NPSH is decreased, incipience of cavitation is observed at $2gH_{sv}/\bar{V}^2 \cong 60$ at the rotating position $\theta = 90^\circ$ in the upstream half of blade rotation and $\theta = 300^\circ$ in the downstream half, and the region of θ with cavitation occurrence is widened, and the torque generation in the region is deteriorated with further decrease of $2gH_{sv}/\bar{V}^2$. This

Fig. 3 Dependency of blade performance on growth of cavitation

decrease in generated torque causes blade efficiency to be lowered, although nondimensional available head $2gH/\bar{V}^2$ was almost the same as that without cavitation. In Fig. 4, Darrieus blade characteristics of lift coefficient C_l , drag coefficient C_d and center of pressure x_c obtained from the measurement of forces and moment acting on the blade with cavitation, are compared with those without cavitation. The additional letters a, b, c and d beside the plots in this figure correspond to the rotating positions shown in Fig. 3(c). Over the rotating position with cavitation occurrence where the values of characteristics are plotted by black circles in Fig. 4, behavior is different from that without cavitation, that is, decrease of C_l , increase of C_d and shift of x_c toward the trailing edge of the blade. From these characteristics, blade efficiency η_c is evaluated using Eq. (2) in ref.3, and is compared with blade efficiency η_b measured in the experiment. Good agreement of η_c and η_b is recognized in Fig. 3(a). The fact that the constant available head is independent of cavitation occurrence indicates that the increase of power loss caused by the drag of the blade makes up for the decrease of generated power due to cavitation.

4. Critical Cavitation Coefficient of Darrieus Blade

Cavitation on the Darrieus blade iterates the incipience and desinence in a revolution of the runner, as shown in Fig. 3, owing to the change of relative flow to the blade. The cavitation characteristics of the Darrieus blade were arranged from the experimental results with the cavitation coefficient σ defined by the following formula, considering that the incipient cavitation occurs when the local static pressure on the Darrieus blade falls under the vapor pressure of the fluid;

$$\sigma = \{H_{sv} - \bar{V}^2/(2g)\} / \{W^2/(2g)\}. \quad (2)$$

As the incipience of cavitation in the upstream half of

Fig. 4 Blade characteristics with cavitation

the blade rotation was observed at almost the same time as or earlier than that in the downstream half with a decrease of $2gH_{sv}/\bar{V}^2$, σ of the incipient and desinent cavitations in the upstream half of blade rotation, σ_i and σ_d , were evaluated with the relative flow at their rotational positions, respectively. In the evaluation of W and α^* , a simple method⁽²⁾ assuming $V = \bar{V}$ was employed since the value calculated by this method has sufficient accuracy in the upstream half of blade rotation in comparison with those values obtained by an iterative method⁽³⁾, which takes account of the effect of variation in circulation around the Darrieus blade on the flow field as shown in Fig. 3(c).

Figure 5 shows the characteristics of the incipient and the desinent cavitation coefficients obtained for blade B set at $\delta = -5^\circ$. The values of σ_i and σ_d show a tendency to vary roughly along a curve apart from each other and increase with α^* , while only a single value of each σ_i and σ_d was obtained from one operating condition and several values, plotted in Fig. 5, were obtained from data at different operating conditions of $U/\bar{V}$ and H_{sv} . The discrepancy between σ_i and σ_d is considered to arise from a difference in the pressure distribution on the blade surface between the upstream half and the downstream half of each rotation even at the same attack angle α^* . This is due to an unsteady flow around the blade, as conjectured from the hysteresis in blade characteristics illustrated in Fig. 4, in addition to using a simplified method for calculation of W and α^* .

The amount of H_{sv} at the incipience of cavitation on the runner is determined by the characteristics of the incident cavitation coefficient σ_i against α^* . Figure 6 shows the characteristics of σ_i against α^* for blade A, blade B and NACA 0030 ($l/R=0.300$), data for which the test results were illustrated in the previous paper⁽²⁾. The black circles in Fig. 6 indicate the results of blade B under other operating conditions of $\delta = 0^\circ$ and vary nearly along the same line with those of $\delta = -5^\circ$, which indicates that the characteristics of σ_i of a

Fig. 5 Critical cavitation coefficient of Darrieus blade

Darrieus blade against α^* are dependent only on the sectional blade profile but are independent of the setting attitude. First, comparing the results of NACA 0018 and NACA 0030 on blade thickness, a thick blade is recommended for cavitation since a thin blade has a larger σ_i at the same attack angle than does a thick blade; that is, an earlier incipience of cavitation, showing qualitatively the same tendency as in a uniform steady flow. Subsequently, seeing the results of NACA 0030, the incipient cavitation in the upstream half of the blade rotation is scarcely affected by the number of blades, since the flow field upstream of the runner is almost the same, regardless of the number of blades. Moreover, comparing the results of blades A and B from the aspect of the existence of blade camber along the runner pitch circle, a cambered section with a larger σ_i causes earlier incipience of cavitation so that a symmetrical section is preferable for cavitation.

Also shown in Fig. 6 are the variations in the minimum pressure coefficient on a blade surface against α^* obtained by various blades at rest in a steady uniform flow^{(4),(5)}. It is seen from the comparison of these with the results of the Darrieus blades that the Darrieus blade with a symmetrical section, NACA 0018, almost corresponds to that with a cambered section, NACA 4418, at rest in a uniform flow

Fig. 6 Incipient cavitation coefficient of various blade sections

Fig. 7 Example of estimation of incipient cavitation

and, on the contrary, a NACA 4518 Darrieus blade is nearly equivalent to a symmetrical section NACA 0018 blade at rest in a uniform flow. These results support the premise that the Darrieus blade has a camber closely related to flow, as discussed in the preceding paper⁽⁶⁾, and that the characteristics of the incipient cavitation coefficient for the Darrieus blade can be predicted with the data obtained from a blade in a uniform flow equivalent to the Darrieus blade⁽⁶⁾.

5. Estimation of Required Net Positive Suction Head

Variations in relative flow W and α^* are predictable⁽³⁾ for the values of incoming flow velocity $\bar{V}$ and operating speed ratio $U/\bar{V}$ for designing a runner. In the case that the characteristics of the incipient cavitation coefficients — σ_i , that is, the minimum pressure coefficients on the blade surface, in the upstream half of blade rotation are given against α^* as data beforehand, the minimum pressure coefficient along the blade surface is known for the attack angle α^* at every rotating position, and the variation in the maximum pressure drop $\sigma_i \bar{V}^2/2$ against θ can be estimated. As an example, variations in the relative flow and the maximum pressure drop against θ are calculated and illustrated in Fig. 7 for the same blade section and operating conditions as shown in Fig. 3. In the calculation, the characteristics of σ_i against α^* are approximated by a best-fit equation determined by the experimental results shown in Fig. 6. In Fig. 7, k is a nondimensional form of the maximum pressure drop on the blade surface as defined by the formula

$$k \equiv \sigma_i W^2 / U^2. \quad (3)$$

Since W and α^* vary with a phase difference to each other in one revolution of the runner, the rotating positions where σ_i or k takes a maximum value do not coincide. When the static pressure in the upstream of the runner is decreased, the incipient cavitation occurs naturally at the position with maximum value of k and it is predicted in the vicinity of $\theta = \pi/2$, which shows good agreement with the observation illustrated in Fig. 3. By the above calculation, the maximum pressure drop in each revolution of the runner (nondimensional form $[k]$) is estimated for a given blade section and operating condition, thus, the net positive suction head required to prevent cavitation on the Darrieus-type runner is predicted by the next equation.

$$[H_{sv}] = \{ \bar{V}^2 / (2g) \} \{ 1 + [k] (U/\bar{V})^2 \} \quad (4)$$

By substituting $[H_{sv}]$ into Eq. (1), the inflow water level in the water channel required to prevent cavitation on the runner is obtained as follows:

$$h_s > [h_s] = [H_{sv}] - (P_a/\gamma - h_t - h_v) \quad (5)$$

Figure 8 shows a variation in $[k]$ of various blade sections and blade setting angles against $U/\bar{V}$ evaluated by data shown in Fig. 6. Since the change of δ causes a shift of variation in α^* over one revolution of the runner, a difference in $[k]$ due to δ is found for the same characteristics of σ_i of the Darrieus blade. The NACA 0018 (blade B) set in $\delta = -5^\circ$ takes a smaller value of $[k]$ than do those of other sections and a setting attitude in the vicinity of the optimum speed ratio $U/\bar{V} = 4.0$, so that this blade with the optimum setting angle for the blade efficiency is also preferable for good cavitation performance.

6. Restriction of Available Head by Cavitation

A Darrieus-type water turbine is more applicable to lower-head water power than is that of the conventional type, in addition to reducing production and construction cost by its simple shape and structure. A guiding principle for planning the utilization of a

Fig. 8 Characteristics of incipient cavitation limit

Fig. 9 Example of installation of Darrieus-type water turbine

Fig. 10 Nondimensional available head of Darrieus-type runner (Blade B, $\delta = -5^\circ$)

Darrieus-type water turbine from the aspect of cavitation is discussed, therefore, on the merits of its simple installation to a channel, as illustrated in Fig. 9. From Eq. (5), a clear guideline is given whereby higher h_s is needed to prevent cavitation by increasing static pressure at the runner. On the other hand, since the relationship between h_s and available head H is expressed by Eq. (6) and H has characteristics approximated by Eq. (7) against operating speed ratio $U/\bar{V}$ independent of cavitation, as shown in Fig. 10, the increase of h_s brings on the increase of H and $\bar{V}^2/(2g)$:

$$h_s = H + h_1 \quad (6)$$

$$H \cong \{\bar{V}^2/(2g)\} f(U/\bar{V}) \quad (7)$$

where h_1 is the loss of head caused up- and down-stream of the runner including exit loss, and $f(U/\bar{V})$ is a function determined from data shown in Fig. 10. By substituting Eqs. (4), (6) and (7) into Eq. (5), an expression of the restriction of $\bar{V}^2/(2g)$ is derived,

$$\bar{V}^2/(2g) < \frac{h_2}{1 + [k](U/\bar{V})^2 - f(U/\bar{V})} \quad (8)$$

where $h_2 = P_a/\gamma - h_t + h_v + h_1$. By substituting Eq. (7) into Eq. (8), the maximum available head consumed by the Darrieus-type runner without cavitation $[H]$ is expressed by the equation,

$$H < [H] = \frac{h_2 f(U/\bar{V})}{1 + [k](U/\bar{V})^2 - f(U/\bar{V})} \quad (9)$$

In Fig. 11, maximum available head $[H]$ predicted by Eq. (9) against speed ratio is compared with the experimental results, where predicted results are shown by solid lines and experimental results with and without cavitation are plotted by black and white circles, respectively. Good agreement of the predicted results with the boundary between the experimental ones with and without cavitation makes it possible to utilize Eq. (9) in predicting the cavitation limits of H of the Darrieus-type runner. The results in Fig. 11 also show that H consumed effectively by the Darrieus-type runner is restricted to an extremely low value, and suggest that the Darrieus-type water turbine

(a) Blade A ($\delta = 0^\circ$) (b) Blade B ($\delta = -5^\circ$)

Fig. 11 Estimated results of maximum available head restricted by cavitation

essentially should be operated only in an extra-low-head condition.

7. Conclusions

Cavitation tests were carried out on a Darrieus-type cross-flow water turbine to study cavitation phenomena occurring on the Darrieus blade in a circular motion in a uniform flow. The relationships between incipient cavitation and relative flow to the blade were examined based on the experimental data. The results are summarized as follows:

(1) The incipience of cavitation occurs at the rotating position of maximum pressure drop on the blade in one revolution of the runner. With a decrease in NPSH, the region with cavitation is widened and the incipient and desinent cavitations are iterated in each revolution.

(2) While the amount of available head imposed on the runner with cavitation is almost the same as that without cavitation, the generated torque shows a marked decrease which deteriorates blade efficiency.

(3) Characteristics of the incipient cavitation coefficient were obtained against the attack angle, and their differences with respect to thickness and blade camber were explained.

(4) A useful method was proposed to predict cavitation limits on installation and operation, and a guiding principle was given for utilizing Darrieus-type water turbines.

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