problem of determining the slip factor. The slip factors obtained by the approximate method for the two general impellers, in which the blade height decreases from the impeller entrance to impeller exit, are in good agreement with the measured ones. Therefore, it may be stated that this method will be useful to estimate the slip factor of the pumps of unknown performance. The method is especially suited for being applied to the impellers with closely spaced blades, i.e., with large blade solidity, for which the application of the method of conformal mapping is almost impossible.

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On Experimental Considerations of the Relation between Runaway Speeds and Cavitation Phenomena of Kaplan Turbine*

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Author performed a series of experiments with various Kaplan turbines to study cavitation phenomena against runaway speeds under various conditions and arrived at the following conclusions:

- (1) There are two different types of cavitation phenomena, the 1st and the 2nd types, each with its own aspect of cavitation bubbling and runaway speed.
- (2) In the case of the 1st type, there occurred the identical formation of cavitation bubbles on each of all blades of a runner, while in the 2nd type, the formation of bubbles on every other blades is identical, those on two adjacent blades are not alike.
- (3) Occurrence of the 1st type or the 2nd type of cavitation bubbles depends upon the value of cavitation co-efficient, number and angle of blades, guide-vane opening, etc., and in many cases the increase in number of blades results in the 2nd type formation of cavitation bubbles.

1. Introduction

It is a well known fact that performance of a hydraulic turbine is affected by cavitation phenomena. However, most of researches on cavitation phenomena had been performed at runner speeds in the vicinity of the normal speed. It may have been Mr. G.H. Voaden, who introduced for the first time the problems under runaway conditions.

According to his paper, runaway speed of a turbine would be boosted by cavitation, and its effect on the rate of speed rise in Francis turbine may not

be so great, but in Kaplan turbine it is indicated to be of considerable amount. Since then this matter has been considered to be one of the most important practical problems in Kaplan turbine, and from this point of view, lately it became the usual practice to perform a model test for every installation of a new Kaplan turbine. However, there are very few results those have been published.

Author has had the opportunities of testing models of various kinds of Kaplan turbines, during the course of which it was discovered that there were two different types of cavitation phenomena under the runaway state, each type having its own aspect of cavitation bubbles and runaway speeds.

It is the purpose of this paper to present the

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Fig. 1 The schematic sketch of the testing setup which is employed for the test

Fig. 2 The schematic sketch of model turbine which is used in the test

findings on the relation between cavitation and runaway speed in Kaplan turbines chiefly about these two types of cavitation developed with respect to the number of runner blades.

2. Testing Setup

Fig. 1 shows a sketch of the testing setup which is employed for the test. For the runaway test, the ball bearing was used in place of the dynamometer.

Fig. 2 shows the outline sketch of the model turbine with spiral casing, 20 guide vanes, and

elbow type draft tube. For the sake of viewing cavitation phenomena, the top portion of the draft tube surrounding the runner is made of transparent methacryl resin.

Fig. 3 shows some of the model runners with 7-and 8-blades which were used in the test.

3. Model Test

The testing setup as shown in Fig. 1 is brought into operation as follows: Set the blades of runner at desired angle $\theta(^{\circ})$. Pump water into the model turbine and expell all air out from the turbine and its feeding pipeline. Set guide vanes opening a (mm) at desired value. Then adjust the respective control valves to give a certain upper head H_u (m) and a suction head H_s (m) for running the turbine at a runaway speed. The test was carried out at $H_u = 3 \sim 4$ m with various values of H_s . Runaway speed N_R (rpm) and discharge Q_R (l/s) were measured at each setting under the stabilized state.

All numerical values obtained from the test are expressed in terms of n_R , q_R , and σ instead of N_R , Q_R and H_s , and cavitation coefficient in σ , where

$$n_R = N_R / \sqrt{H}$$

$$q_R = Q_R / \sqrt{H}$$

$$\sigma = (H_a - H_v - H_s) / H$$

$$H = \text{Effective head on turbine} = H_u + H_s$$

$$H_a = \text{Barometric pressure (m.a.q.)}$$

$$H_v = \text{Vapour pressure of water (m.a.q.)}$$

4. Cavitation Phenomena under Runaway Condition

In Kaplan turbine when it is running at a speed around its normal, cavitation usually takes place on the lower side of blades and not on the upper surface. Fig. 4 shows the typical example of fully

Fig. 3 Some of the model runners with 7-and 8-blades which were used in the test

developed cavitation bubbles at the normal speed, $\theta = 22^\circ$, $a = 15$ mm and $\sigma = 0.17$.

However, under the runaway condition, there are two different types of cavitation which can be clearly distinguished from each other by means of a strobo-scope.

Fig. 4 The typical example of fully developed cavitation bubbles

In the 1st type, cavitation bubbles are developed uniformly on all blades of a runner while in the 2nd type, different aspects of cavitation bubbles can be observed on adjacent blades but similar on every

other blades of a runner. For example, Fig. 5 illustrates these two types of cavitations on 8- and 7-blades model runners.

The 1st type on the 8-blades runner and the 1st type on the 7-blades runner are both of the same aspect.

In the 2nd type on the 8-blades runner, there are two strikingly different formations of cavitation bubbles as shown in Fig. 5, i.e. those on every other blades are similar, but two adjacent are not alike. On the blade with the odd number such as No. 1 or No. 3, the bubbles are formed around the clearance near the tip of the blade and blew up from its lower surface to the upper surface near its leading edge. On the blade with the even number such as No. 2 or No. 4, the bubbles are blew down from the upper surface to the lower surface near its trailing edge. It might be explained as such that the pressures at the passages between the blades 1-2, 3-4, 5-6, and 7-8 are comparatively high as shown by clearness

Fig. 5 Two types of cavitations on 8- and 7-blades runner

Fig. 6 The photographs of the 1st type and 2nd type of cavitation bubbles ($\theta = 12^\circ$, $a = 18$ mm)

while the pressures at the passages 2-3, 4-5, 6-7 and 8-1 are low causing high vapourization and therefore more bubbles. In the runner with 6 blades, the same 2nd type was observed as in the runner with 8 blades.

However, the 2nd type in the runner with 7 blades has the same formation of bubbles on No. 7 and No. 1 blades in series and alternately with a different formation on the rest of the blades. A close observation reveals that forming of bubbles on blades No. 7 and No. 1 are especially tense on their upper side near the leading edge, whereas least on the blades No. 6 and No. 2 immediately leading and following respectively the above two blades. For the remaining three blades No. 3, No. 4, and No. 5, the cavitation on No. 4 is somewhat smaller than the other two.

Roughly speaking, the cavitation bubbles on the runner with 7 blades also falls in the pattern of alternately different formations, but it might not be

so distinct as in runners with even number of blades.

Fig. 6 gives the views of the 1st type and 2nd type of cavitation bubbles on each blade of the 8- and 7-blades runner when $\theta=12^\circ$ and $a=18$ mm. As these photographs were taken when the runner speed was 5 000 rpm, they are not so clear to distinguish the feature as shown in the previous sketches in Fig. 5. However, from those photos showing the 2nd type, it can be seen that the formation of cavitation bubbles on each blade is not identical with the others.

The two similar photos of the 2nd type (1) and (2) were taken from the different angles under the same condition.

5. Aspect of Cavitation under Runaway Condition and its Relation with n_R - σ

Fig. 7 shows the results of n_R - σ from the experiments with the 8- and 7-blades runners at $\theta=12^\circ$ and $a=16$ and 18 mm.

In testing a runner with 8 blades, first reduce

Fig. 7 The results of n_R - σ from the experiments with the 8- and 7- blades runners ($\theta=12^\circ$, $a=16$ and 18 mm)

the value of σ from high to low. At the beginning there was a slight sign of the 1st type cavitation bubbles and as it was continued to reduce σ the bubbling grew tense while the n_R change followed the proper course as illustrated by the n_R - σ curve in Fig. 7. When the value of σ reached a certain value, however, an abrupt change in the phenomenon took place and followed a proper course of the 2nd type. To be precise, aspect of the cavitation begins to change just before the 1st course goes to another. Then the measured points n_R - σ move along the abruptly changing course as shown in Fig. 7, but they are very unstable on this steep course.

Once the aspect of cavitation and the course were switched completely into the 2nd type, they are stabilized in their proper way, vigorously forming cavitation bubbles.

Next, the increase in σ value showed just the reverse of what described before.

Whichever change of σ may be, increase or decrease, the value of σ at which abrupt change takes place, is not always the same. Fig. 7 shows several abrupt σ points irregularly distributed which would be increased by repeating the experiment.

Among the several suddenly changing courses shown in Fig. 7, Course (1) has the highest n_R value, but it is not certain whether there is no more course

at its right side having higher values of n_R .

Although at $\theta=12^\circ$, if $a=14$ or 20 mm, only one kind of abrupt σ point was obtained. In case of $a=12$ mm, only the 1st type appeared and no abrupt σ point was observed.

It could be noticed in various combinations of θ and a that there are more cases having only one or no abrupt σ point than cases with unstable and many points.

Summarizing the results of experiments with the 8 blades runner as illustrated in Fig. 7, when a is 16 and 18 mm, it seems as though Course (1) in each a is the only course that passes through the maximum n_R value.

The 8-blades runner The 7-blades runner
Fig. 8 The traces of pitting at positions corresponding to the cavitation as illustrated in Fig. 5

Fig. 9 The results of n_R , q_R - σ measured on the 6-blades runner at the various combinations of θ and a (with respect to θ)

Fig. 10 The results of n_R - σ_R measured on the 6-blades runner at various combinations of θ and α (with respect to α)

Fig. 11 The results of n_R - σ_R measured on the 5-, 6-, 7- and 8-blades runners ($\theta=12^\circ$)

The 7-blades runner gave only one abrupt σ point at this combination of θ and α , but by further repetition of the experiment there might have been more abrupt σ points found.

During the experiment when listening to the turbine closely, there was a distinctive difference in sound typical of the 1st and 2nd types. As it is marked in Fig. 7 in the 1st type when σ is large, sounds like sparking or boiling of water was heard, and when σ is small, the sirene-like metallic sound as if grinding steel plate.

The 2nd type gave the sounds similar to those usually heard at the top of a draft tube of a prototype turbine with a partial load. In this type, however, when σ is brought down to extremely small value, the sounds immediately stop to silence.

After 10 hours of the experiments with each runner, the blades were inspected and found, as shown in Fig. 8, the traces of pittings at positions corresponding to the cavitations as illustrated in Fig. 5.

The runners were made of gun metal and the

traces of pittings from cavitation appear to be the same as those found on prototype turbines.

6. n_R , q_R - σ for Various Combinations of θ and α

The results of n_R , q_R - σ measured on the 6 blades runner at the various combinations of θ and α are shown in Fig. 9. The maximum n_R value is at $\theta=9^\circ\sim 12^\circ$. The n_R - σ and q_R - σ curves are similar in shape and the n_R - q_R relation in reality can be represented in a nearly straight line.

Fig. 9 shows n_R - σ with respect to θ and Fig. 10 with respect to α .

Fig. 11 shows n_R - σ of the model runners with 5-, 6-, 7- and 8-blades when $\theta=12^\circ$.

Judging from the experiments, the greater the number of blades, the more the 2nd type cavitation can take place.

7. Conclusion

The summary of experimental results are as follows:

- (1) Kaplan runner has two types of cavitation under runaway condition the 1st type and the 2nd type.

While the cavitation bubbles of the 1st type are uniform for all blade of a runner, the 2nd type is not uniform.

- (2) The 2nd type cavitation bubbles come out regularly on every other blades when the number of blades are even while in odd number the cavitation bubbles are uniform on every other blade except certain two blades in series on which the formation of bubbles are similar and not so regular as in case of even number.
- (3) Both the 1st type and the 2nd type have their own aspects of cavitation bubbles, n_R - σ curve

and sound. On how to change from the 1st type to 2nd type, there are three kinds by various combination of θ and α .

The first instance: At fixed value of σ , the cavitation type changes abruptly from one to another.

The second instance: The changing is unstable and occurs at various σ values.

The third instance: Only the 1st type appeared throughout the experiments.

Both types of cavitation and n_R - σ curve are stable except at abrupt σ point, but at outside of the curve there is no stabilized points.

- (4) For the same value of σ , the 2nd type always has higher n_R value than that of the 1st type.

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Oil-Flow Coefficient of Pressure-Fed Journal Bearing*

By Fujio HIRANO** and Nobuhiro SHŌDAI***

Using conformal representation, the oil flow coefficient of the pressure-fed journal bearing with an axial oil groove is calculated. Though the graphical conformal mapping by Wilcock and Rosenblatt gives merely the data for particular forms of the groove, the coefficient for any value of l/L and b/L can be obtained by this analytical method where l and b are the length and width of the groove respectively, and L is the axial length of the bearing. And also the coefficient for nearly circular hole is simply calculated.

Symbols

The following symbols are used in the paper:

Q = oil flow, cm^3/s

p = oil pressure in bearing, kg/cm^2

p_1 = oil feed pressure, kg/cm^2

D = bearing diameter, cm

L = length of bearing, cm (x -direction)

l = length of oil groove, cm

b = width of oil groove, cm (y -direction)

c = diametral clearance, cm

Δr = radial clearance = $c/2$, cm

h = oil film thickness, cm

h_1 = film thickness at oil feed position, cm

e = eccentricity of journal centre, cm

n = attitude = $e/\Delta r$

φ = attitude angle

φ_1 = angle between oil feed position and load line

μ = viscosity, $\text{kg}\cdot\text{s}/\text{cm}^2$

N' = speed, rev/s

Introduction

Oil flow through a journal bearing consists of hydrodynamic flow and forced-feed flow. The latter is the component of the oil flow caused by the oil-feed pressure. It varies widely with the form of oil groove or hole. Experimental studies of the oil flow through bearings having oil grooves of various types are found in the papers of Clayton⁽¹⁾, McKee⁽²⁾, Wilcock and Rosenblatt⁽³⁾⁽⁴⁾. Wilcock and Rosenblatt estimated the oil flow coefficients for several particular oil feed grooves by means of graphical conformal mapping. More generally, using analytical method, the calculation of the coefficient is possible, and the present paper will serve to estimate of the forced-feed flow, which is necessary for the calculation of the bearing performance.

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