Cavitation Characteristics for Hydrofoil Section with Pressure Water Supply

Cavitation Characteristics for Hydrofoil Section with Pressure Water Supply

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The paper describes some experimental investigations of cavitation characteristics of two dimensional hydro-foil section with pressure water supply from on its surface. The same kind of experiments were made and reported already by the author. Here again the same problem will be discussed. But the location and the direction of the supplied water flow are different largely from the previous, i.e., the location is about 23% of chord length from leading edge of the foil, and the direction is 47 degrees to the chord measuring from down stream side.

Experimental results show that incipient cavitation parameter is somewhat larger when pressure water is supplied, but cavitation does not develop so fast as for none water supply. Further more, the effects of supplied water at the large angle of attack are different from the small angle.

1. Introduction

In the previous experiments[1] using a model of two dimensional hydro-foil section, the purpose to prevent or to delay cavitation was not attained, because cavitation had developed more rapidly by pressure water supply. But, on that time some prediction from on its pressure distributions of a foil was obtained that, if the position and the direction of supplied water flow were proper, cavitation might be decreased of its scale or delayed of its inception.

The same kind of experiments were done using a model of circular cylinder,[2] and obtained good results. In that experiments, the direction of supplied water flow was always perpendicular to the surface of cylinder which made right angle to the theoretical flow direction of potential flow. Experiments were made several supplied positions of water, i.e. 70°, 90°, 110°, and 130° of angle measuring from leading stagnation point of the cylinder. Good results obtained at the angles of 110° and 130°, and the best was at 130°

In experiment on this time, the position and the direction of supplied water flow are ditermined referring to the results of circular cylinder.

2. Experimental apparatus and methods

The apparatus of this experiment is the same as previous and it was shown detailed in the first report of this series papers,[3] then there isn't shown of its procedure. At the working section which has 160mm×60mm of cross sectional area, flow

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velocity varies up to 15m/sec, but the velocity through all experiments fixed at the same value, i.e., 6 m/sec, because the effects of velocity variation are unknown yet sufficiently.[4)]

The apparatus of pressure water supply is shown in Fig. 1. The pressure water

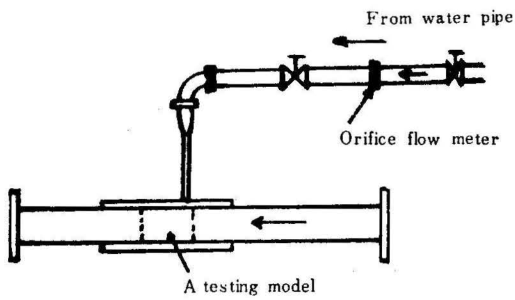

Fig. 1 Equipment of pressure water supply

is led from a water pipe directly to a testing foil. The volume of supplied water flow is measured by oriffice flow meter installed in a leading pipe of pressure water. The oriffice is a self-made and calibrated previously with water flow using the same pipe as experiments.

A testing hydro-foil is shown in Fig. 2. A pressure water leading hole (main hole) is in the foil at 15% of chord length from leading edge. Eleven small holes located at 23% of chord length at the surface of the foil are connected with the main hole. All intervals of these small holes are the same, 5 mm, and a diameter of them is

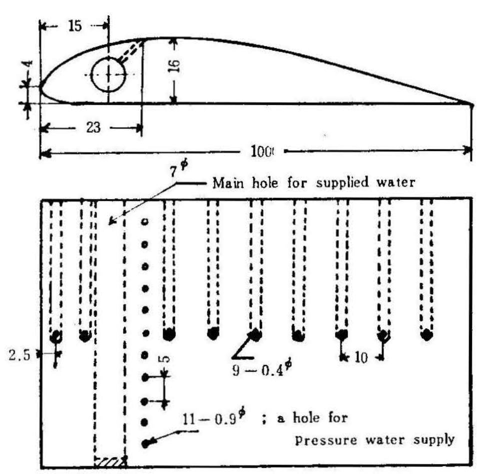

Fig. 2 Testing hydrofoil section

0.9mm. An angle between chord of the foil and axial direction of small hole is 47 degrees measuring from down stream side. Nine holes for measuring static pressure distribution along upper surface of the foil are at middle section along chord. The intervals of these pressure taps are the same fundamentally, i.e.10mm, but an interval between the first hole located at 2.5 mm from leading edge and the second hole is 7.5 mm. Furthermore, it is impossible to make the third there at 20 mm from leading edge, because of the holes for pressure water supply. Then an interval between the second and the third is 20 mm. It was certained previously that the flow shed from earch hole of those eleven for water supply is approximately equal within the range of experiments.

Lift of the foil is estimated by the method of calculation from pressure distributions along upper and lower walls of testing section.[5] Drag measurement is by the method of estimation from velocity distribution in a wake behind a foil by Jones,[6] but the results vary fairly under the same condition. Then all of the data concerning with drag are excepted from this paper.

Measured velocity of uniform flow forward of a model was corrected considering effects of model, wake and boundary layer along walls.[7] Velocity of uniform flow used here and preceeding is meant the corrected one.

Experiments are made as follows:

1. Testing hydro-foil is settled at some angle of attack in the working section, and make a flow of water in the crossed channel. Velocity is set at predetermined value, i.e. 6 m/sec. at working section.

2. Pressure distributions are measured along upper and lower walls of the channel at the worknig section and upper surface of the foil when pressure water isn't supplied.

3. The same measurments are made for existance of supplied water.

4. After these, static pressure in the working section is decreased but the velocity is maintained at the same. This is done by decreasing the pressure in a reservoir tank by vacuum pump. In this way, we can settle a flow condition at any value of cavitation parameter, although the velocity is constant. Then, the same kinds of experiments are made for these new flow conditions. If a cavitation parameter is changed by supplied water, flow condition, i.e. a static pressure is corrected until the cavitation parameter takes the same value as non-supplied water.

3. Pressure distributions

In this section, it will be shown how the pressure distributions along upper surface of the hydrofoil are affected by supplied water.

Now, relative supplied water volume is introduced as follow: Mass of fluid flow that of its momentum is changed by a hydrofoil when getting through near of it is proportional to ρVA, where ρ,V, and A are density, velocity of fluid, and sectional area of the hydrofoil respectively. By the way, effectiveness of supplied water to change a flow condition near the hydrofoil may vary with a velocity of main flow, even though the supplied water is constant. Therefore, a relative volume of supplied water is proposed as a ratio of mass of supplied water volume ρQ to the above mentioned mass ρVA, where Q is a volume of supplied water per unit time. Then, dimensionless volume μ is expressed as

$$\mu = \frac{\rho Q}{\rho VA} = \frac{Q}{VA}$$

Pressure coefficient Cp and cavitation parameter Kd are proposed as follows:

$$C_P = \frac{2(P-P_o)}{\rho V^2} \quad \text{and} \quad K_d = \frac{2(P_o-P_v)}{\rho V^2}$$

where P_o and P are static pressure in uniform flow forward of the hydrofoil and local pressure on the surface of it respectively, and P_v is saturated vapor pressure corresponding to of its water temperature.

Figs. 3∼10 show the pressure distributions on the hydrofoil. Figs. 3, 4, and 5 are

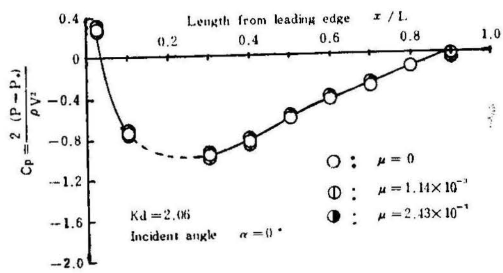

Fig. 3 Pressure distributions

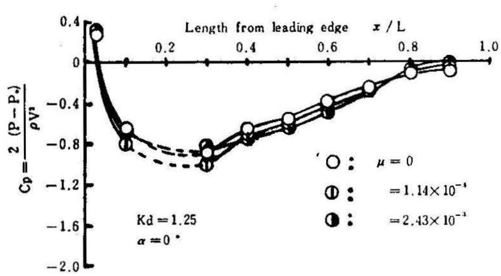

Fig. 4 Pressure distributions

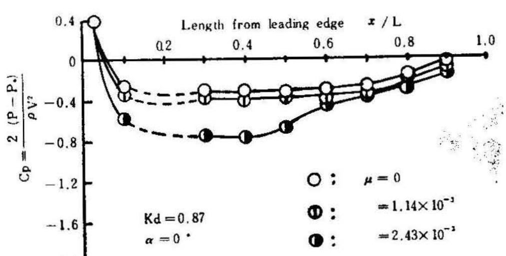

Fig. 5 Pressure distributions

for zero angle of incidence. On this angle, incipient cavitation parameter K_i is about

1.28 for none supplied water. In Fig.3, cavitation parameter K_d is 2.06, therefore this diagram shows the pressure distributions at the range of none cavitation, but for supplied water volume $\mu = 2.43 \times 10^{-3}$, there occurs already feasible cavitation. In Fig. 3, we can't recognize any variation on pressure distributions by supplied water volume. Fig.4 whose cavitation parameter is 1.25 shows in the range of cavition, but it is not so strong. The supplied water makes somewhat difference on pressure distribution in this case, especially at the region near the location of water supply. Fig. 5 whose K_d is 0.87 also shows in the cavitation range. In this case, cavitation develops nearly 90% of chord length on the hydrofoil for none supplied water and 1.14×10^{-3} of μ. Above this value of μ, a scale of cavitation somewhat decays and decreases to about 70% for 2.43×10^{-3} of μ. The difference in the pressure distributions in the diagram may indicate directly the change of cavitation scale, i.e., in the case of 2.43×10^{-3} of μ, pressure drops below fairly at the low pressure region on the hydrofoil compared with one of none supplied water.

Figs. 6 and 7 are for four degrees of incidence. In this case, incipient cavitation

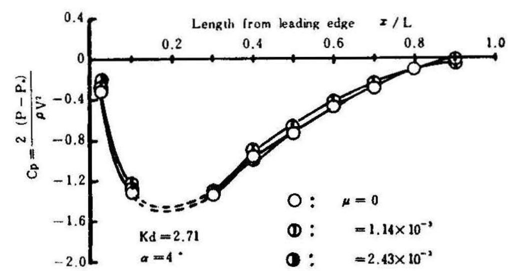

Fig. 6 Pressure distributions

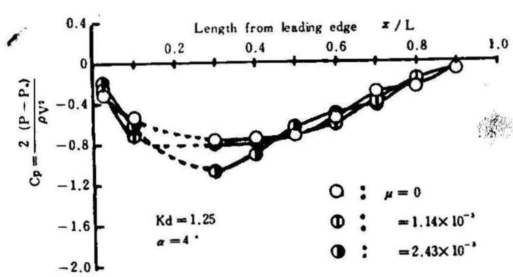

Fig. 7 Pressure distributions

parameter is about 1.64 for none supplied water. Fig. 6 whose cavitation parameter is 2.71 shows in the region of none-cavitation. An incipient cavitation parameter K_i increases gradually with supplied water volume, but when μ takes 2.43×10^{-3} which is the maximum value of μ in the experiments, the value of K_i is 2.15, therefore, all cases in Fig. 6 there isn't any cavitation. In this region, pressure distributions are almost the same for any volume of supplied water in the range of experiments.

Pressure distributions in the region of developed cavitation are shown in Fig. 7 whose cavitation parameter K_d is 1.25. The scale of cavitation is about 70% of chord length for none supplied water. In this range, cavitation decays by supplied water, and the scales of it are about 50% and 30% of chord length for 1.14×10^{-3} and 2.43×10^{-3} of μ respectively.

Figs. 8 , 9,and 10 are for 8 degrees of incident angle. An incipient parameter K_i

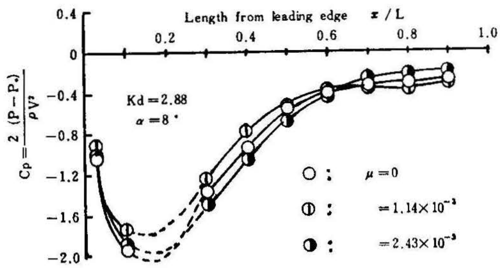

Fig. 8 Pressure distributions

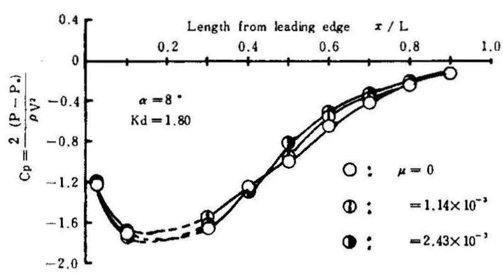

Fig. 9 Pressure distributions

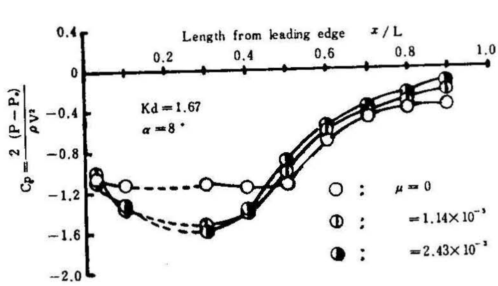

Fig.10 Pressure distributions

is about 2.20 for none supplied water. The value of K_i is decreased by supplied water except the range of large value of μ. Fig. 8 whose cavitation parameter is 2.88 shows the pressure distributions in the none-cavitation range. They are almost the same procedure as seen from the diagram, but at the just forward location of water supply, where is a low pressure region, the pressure somewhat increases by supplied water. This phenomenon is coinside with the decreasing of incipient cavitation parameter k_i . It is also significant considering development of cavitation as seen in the preceeding section. Fig. 9 is in the range of cavitation, and it develops about 50% of chord length for none supplied water. Pressure distributions are almost the same up to this range of cavitation where pressure water exists or not. Fig. 10 whose cavitation parameter is 1.67 also shows in the cavitation region. Cavitation develops on the hydrofoil about 75% of chord length for zero of μ. A scale of it is fairly decreased by supplied water. Change on pressure distributions indicates this phenomenon. Concerning with the relation between a scale of cavitation on the hydrofoil and supplied water volume will be shown more detailed in the preceeding section.

4. Effect of supplied water on cavitation development

Generally speaking, incipient cavitation occurs more easily by supplied water for small incident angle, but for large angle of incidence incipient parameter k_i decreases if supplied water volume is proper. Cavitation develops fairly rapidly as soon cavitation parameter as decreases from incipient value of k_i for none supplied water. On the other hand, when pressure water is supplied from the surface of the hydrofoil cavitation does not develop so easily as former. In this section, these relations will be shown.

Experiments have been made for four kinds of supplied water volume. They are

$\mu = 0.71\times10^{-3}$, 1.14×10^{-3} , 1.68×10^{-3} , 2.43×10^{-3}

To indicate a scale of cavitation development, a ratio of cavitation region's length along flow direction L' to chord length L will be introduced (see Fig. 11) ,i.e.,

$$\lambda = L'/L$$

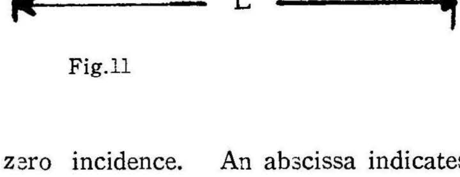

Fig.11

Fig. 12 shows for zero incidence. An abscissa indicates cavitation parameter K_d and an ordinate is of relative supplied water volume μ. In this diagram. the curves are drawn for constant values of λ. Incipient cavitation parameter increases gradually with supplied water volume, e.g.. the value of K_i is 1.28 for zero of μ, but 1.70 for 2.43×10^{-3} of it which is the maximum volume of supplied water in the experiments. Even though this, there are fairly long intervals between inception and some scale developments of cavitation when pressure water is supplied. For instance,

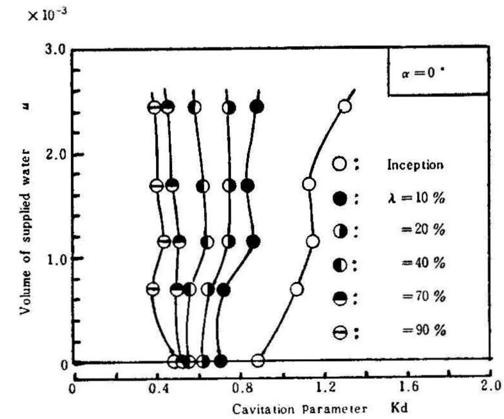

Fig.12 Relation between μ and K_d for constant value of λ

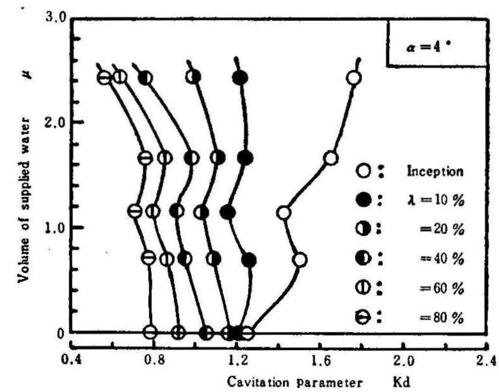

Fig. 13 Relation between μ and k_d for constant value of λ

a change of cavitation parameter K_d from inception to 10 percent development is 0.18 for zero of μ and 0.42 for 2.43×10^{-3} of μ. The curves of constant value of μ incline to right hand side below 40% of it, but two curves for 70% and 90% of λ incline to left hand side. This means that at the range of fairly developed cavitation, supplied water decreases the scale of it.

Fig. 13 is for 4 degrees of incident angle. Cavitation inception is promoted by supplied water as for zero incidence. In this diagram, inception curve is only one that inclination is to the light hand side. At the 10 percent development the slope of curve is nearly vertical, and above this value of λ the scale of cavitatation is decreased by pressure water supply. When K_d is 1.18, cavitation develops 80% for none supplied water, but it decays to 40% or less for 2.43×10^{-3} of μ at the same value of K_d.

Fig.14 is for 8 degrees and Fig. 15 is for 12 degrees of incident angle. Both of them, inclinations of inception curve are to left hand side except the range of large volume of supplied water. In the case of Fig. 14, the slope of the curve from vertical

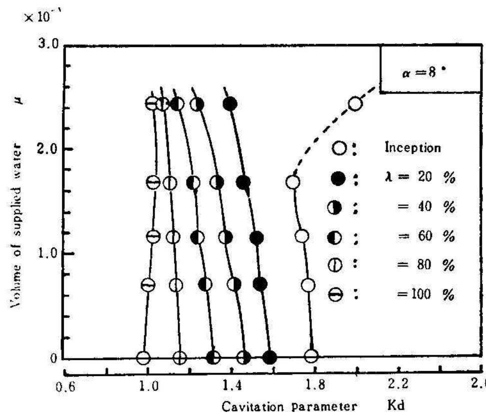

Fig.14 Relation between μ and kd for constant value of λ

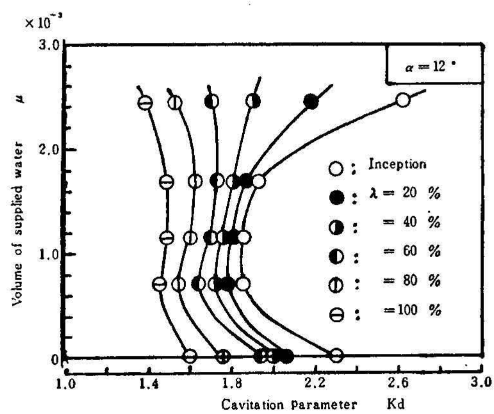

Fig.15 Relation between μ and kd for constant value of λ

line is small, but in Fig. 15, it is very large. An incipient value of K_i of the later is 2.5 for zero of μ, but when pressure water is supplied and if its volume is proper, the value of K_i goes down faily. For 0.17×10^{-3} of μ, K_i takes about 2.06.

Figs. 16, 17, 18, and 19 are written at constant volume of supplied water. In these

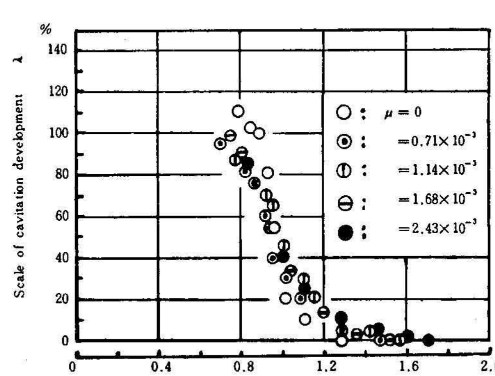

Fig.16 Relation between λ and Kd for constant value of μ ($\alpha = 0°$)

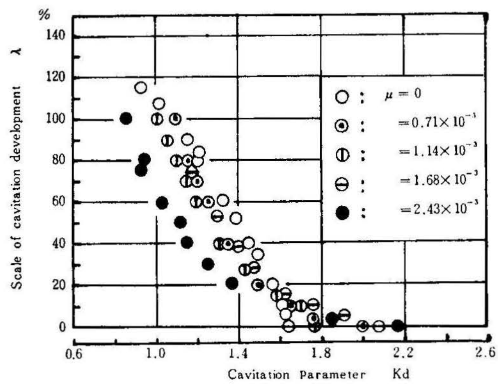

Fig.17 Relation between λ and Kd for constant value of μ ($\alpha = 4°$)

diagrams, an abscissa indicates cavitation parameter Kd and an ordinate is for a scale ratio of cavitation development λ (%) . Now the curves are drawn for constant value of μ. In Figs. 16 (zero of incident angle) and 17 (4 degrees) , measured values of λ for zero of μ are in the lower region or left hand side of the diagrams when μ takes relatively low value. As decreasing cavitation parameter, λ for zero of μ increases rapidly and goes ahead of it for other values of μ. The points that the former overtakes the later are at 60% of λ for zero incidence and at 20%for 4 degrees of incident angle respectively.

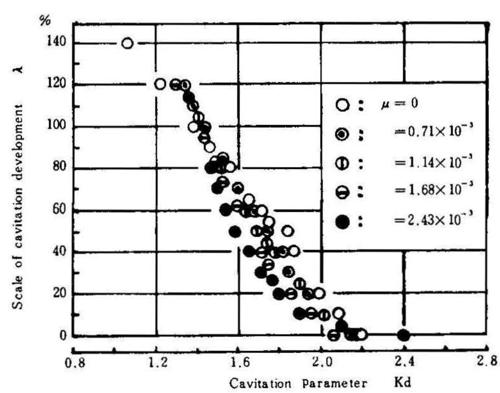

Fig.18 Relation between λ and Kd for constant value of μ ($\alpha = 8°$)

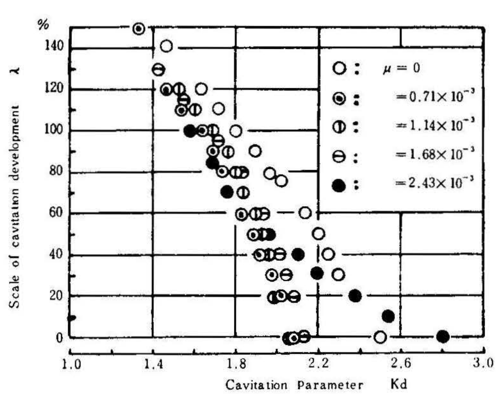

Fig.19 Relation between μ and Kd for constant value of μ ($\alpha = 12°$)

In Figs. 18 (8 degrees of incidence) and 19 (12 degrees), λ for zero of μ is left hand side of diagrams in almost all range of λ. In the case of Fig. 18 the scale of cavitation is decreased by pressure water supply up to 80% of λ, but above this value, the effect of supplied water is contrary. This is entirely reverse phenomenon compared with the case of in Fig. 16. In the diagram of Fig. 19, cavitation scale is always decreased by pressure water supply at any range of development within the experiments, except the neighbourhood of inception for the largest value of μ. For instance, when cavitation develops about 60% of λ without supplied water, it is entirely disappeared by supplied water. There is something in common through these four diagrams, that is, at the range of large volume of supplied water, cavitation inception is accelerated but the slope of development curve becomes low greatly.

5. Displacement of cavitation region by supplied water

Cavitation inception always occurs at the position of the lowest pressure in the flow. Pressure distributions on the hydrofoil are changed by supplied water as seen in section 3 . This means there occurs some displacement of cavitation region. Although the positions of the lowest pressure vary with incident angle of the hydrofoil, they are little down stream of leading edge when an angle of attack is positive. Therefore, cavitation inception occurs there if there isn't any water supply. On the other hand, when pressure water is supplied, inception is always at the position of water supply on the surface of the foil. The meaning of this may consider as follow; at the intersection of stream lines of main flow and supplied water, there occurs local pressure fall because of separation. Cavitation development is also made at the down

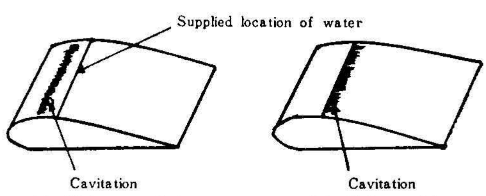

Fig. 20 Displacement of cavitation inception by supplied water

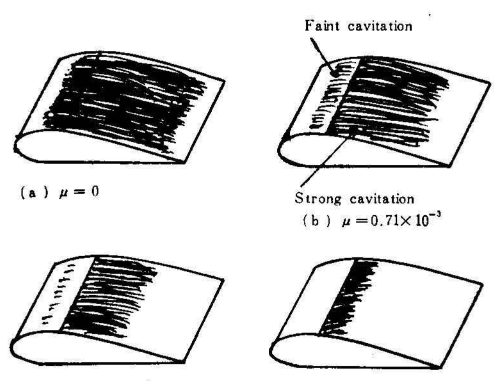

Fig. 21 Scale variation of cavitation by supplied water volume ($\alpha = 4°$ Kd $=1.25$)

stream region from this point except fully development. Displacement and a change of cavitation scale by supplied water are made a sketch in Fig. 20 and Fig. 21, for 4 degrees of incident angle. You may suppose from these figures, pressure of the upstream side on the hydrofoil from the position of water supply goes up compared with none water supply, then cavitation disappears there. Usually speaking, cavitation develops on a surface of the body where boundary layer develops. Considering this, if there is enough supplied water on the hydrofoil boundary layer development may be controlled, then cavitation does not develop on the hydrofoil. Fig. 20 indicates, this consideration is true.

Finally, what difference appears on lift of the foil will be shown. Coefficient of lift is shown in Fig. 22. The abscissa indicates caviation parameter K_d and the ordinate coefficient of lift C_L, where

$$C_L = \frac{2L}{\rho V^2 \ell}$$

and, L: A lift per unit width of the hydrofoil

ℓ : Length of chord

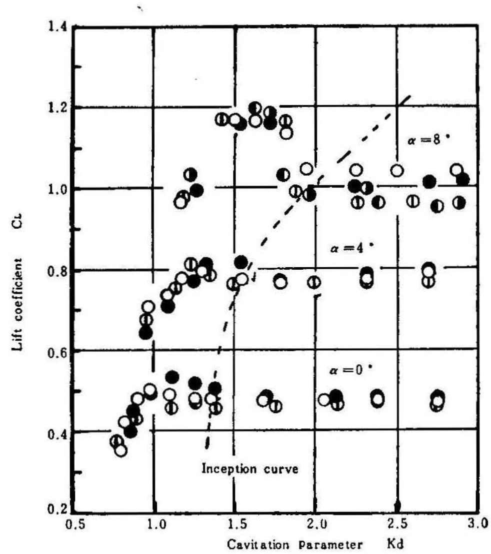

Fig.22 Variation of lift coefficient by cavitation parameter

In the range of non-cavitation, there isn't effective change of C_L by pressure water at the low angle of attack. At the high incident angle, C_L with supplied water somewhat drops than one of without. In the range of cavitation, there are nothing of remarkable change of lift coefficient in any incident angle. This means mainflow is little disturbed by supplied water.

In this paper, drag of the hydrofoil does not shown because of scattering of measured value. As a general tendency, drag coefficient increases to some extent at a low incident angle, but at a large angle it rather decreases by supplied water.

6. Summary and conclusions

The experimental results may be summed up as follows:

1. In the range of non-cavitation, pressure distributions on the upper surface of the hydrofoil are scarcely affected by the supplied water, especially at a small incident angle. In the case of large angle, there is a tendency of a little rising of pressure on the region of just upstream of water supply.
2. In the range of developed cavitation, the pressure on the hydrofoil without supplied water is almost constant at the downstream side from a starting point of cavitation, but when pressure water is supplied and if its volume is proper, a pressure dropping continues to the lowest pressure region on the hydrofoil, although cavitation parameter is the same.
3. Cavitation inception is facilitated by supplied water at a small incident angle, but at a large angle it is delayed if a volume of supplied water is proper. When its volume is large enough, incipient cavitation is always promoted at any angle of incidence.
4. At the range of developed cavitation, a scale of it is decreased by supplied water. The tendency of it is growing as increasing an angle of incidence. For instance, at 12 degrees, cavitation entirely disappears by supplied water when it develops to about 60% of chord length without supplied water.
5. In the range of relatively small scale of cavitation, small volume of supplied water is rather effective to decrease or to extinguish the cavitation, but for fully developed cavitation, large volume of the water is more effective.
6. Cavitation inception always occurs at the location of water supply at any angle of incidence, because there occurs local pressure drop caused by separation at a intersection of mainflow and supplied water flow.

All of experiments have been made at the same position and flow direction of supplied water measured from the testing hydrofoil itself. If another position and flow direction was tested, it may be obtained different results. Considering the experimental results of myself, it will be obtained more good results if a supplied position of water is a little down stream than this, particularly for small angle of incidence, because the lowest pressure is at somewhat down stream region compared with it for large angle.

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