EXPERIMENTAL STUDY OF THE EFFECT OF A GAP CLEARANCE ON THE PERFORMANCE OF A FULLY CAVITATING FLAT PLATE WITH AND WITHOUT A FLAP

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EXPERIMENTAL STUDY OF THE EFFECT OF A GAP CLEARANCE ON THE PERFORMANCE OF A FULLY CAVITATING FLAT PLATE WITH AND WITHOUT A FLAP

by

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ABSTRACT

Experimental results are presented for the effect of a hinge gap on the fully cavitating performance of a flat plate hydrofoil without and with a flap. From the results of the tests it is concluded that for the zero flap deflection, no significant effects of the gap are apparent for the range of the parameters investigated. However, for a 20% flap-to-chord ratio and a 20° flap deflection a significant drop occurs in the lift and moment coefficients for a given gap ratio. This effect increases with increase in gap width. The drag on the other hand is unaffected for the range of values tested.

Certain qualitative effects of the jet, arising from the gap, on the cavity appearance are discussed. Comparison of the experimental results for zero gap, with established non-linear theories, show very good agreement.

NOMENCLATURE

A	plan form area of model
c	chord length
C_L	lift coefficient $= \dfrac{L}{A \rho V^2/2}$
C_D	drag coefficient $= \dfrac{D}{A \rho V^2/2}$
C_M	hinge moment coefficient $= \dfrac{M}{A c \rho V^2/2}$
D	drag force
g	gap width
L	lift force
M	hinge moment
p_o	upstream static pressure
p_k	measured cavity pressure
V	velocity
ρ	density of fluid
σ	cavitation number $= \dfrac{p_o - p_k}{\rho V^2/2}$

Introduction

With the advent of hydrofoil boats, high speed turbo-machinery and propellers, a knowledge of the performance characteristics of hydrofoils operating in both the non-cavitating and cavitating regions, is of great practical interest.

Many theoretical and experimental studies have been made in this field with a view to obtaining necessary design criteria for the engineer. As in the case of the airfoil the necessity for control devices of one form or another in the use of hydrofoils is obvious. Thus it becomes essential for the designer to have some idea of the performance and efficiency of any such device. The most widely used and practical control device is the flap. The use of a flap in practice, depending on the mechanical design involved, may give rise to a certain hinge gap between the main foil body and the flap when the latter is in use. The effect of this gap clearance on the performance of hydrofoils in cavitating flow is therefore of importance. Furthermore, in fully cavitating flows it is feasible that the utilization of the jet arising from such a hinge gap may be used to the benefit of hydrofoil performance.

The purpose of the present experimental study is to gain some insight into the qualitative and quantitative effects of such a gap on the performance of a fully cavitating hydrofoil both without and with a flap. The tests were conducted in the two-dimensional high speed water tunnel at the California Institute of Technology.(1), (2)*

Description of Experiments

The model used for the tests was a flat plate, in the form of a

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[*] Numbers in parentheses designate References at the end of the paper.

wedge with a 10° apex angle and a 4" chord, as shown in Fig. 1. Two flap configurations were tested, one having zero flap angle and the other having a flap angle of 20°. The flap-chord ratio in each case was 20%. The flap on both models was designed so that the gap could be varied from zero to approximately 10% of the chord. The method of adjusting the gap, by sliding the flap in its base mounting, is seen in Fig. 2. This method of mounting necessarily restricted the flap movement to a line parallel to the wetted side of the foil. The tip of the flap was tied to the main body of the hydrofoil so as to avoid any relative bending and twisting of the two under load, causing a possible variation in gap width along the span of the model. The gap width between the main foil (fore body) and the flap could be varied from zero to 10% of the chord length (0.040").

Pressure taps were provided in both the fore body and the flap to measure cavity pressures, which were recorded with respect to atmospheric pressure on mercury manometers. The line to the cavity was kept clear of water by constant purging with a small amount of air. The accuracy and repeatability of this method of recording cavity pressures has been described previously. (3)

The forces on the model were monitored on the tunnel three-component force balance. (4) The lift, drag and total moment about the hinge point were recorded. Due to the method used in mounting the model, the force measurements include a small tare force which arises from the frictional drag on a circular fairing plate attached to the model and set flush to the tunnel wall. This tare force is primarily a drag force and has negligible effect on the lift and moment. Consequently, only the drag data was corrected for this effect.

The necessary pressure measurements for the determination of the tunnel static pressure and the dynamic pressure across the tunnel nozzle were recorded on an absolute mercury manometer and a differential pressure gage respectively.

These pressure measurements were both recorded at a point well upstream of the hydrofoil (viz. 30'' or 7.5 chord lengths) in the tunnel nozzle. The effects of the presence of the model on the pressures recorded at this point were deemed sufficiently small to be negligible. In order to correlate the readings taken at this station with those existing in the working section, a clear tunnel calibration was undertaken prior to the tests.

Finally, the nature of the cavitation on the body and consequently the cavity length, was photographically recorded by means of a 35mm recording camera.

A view of the experimental set-up is shown in Fig. 3, the tunnel working section together with the various recording equipment also being seen in this photograph. The mercury manometers for the pressure measurements are seen to the right in the picture and the force gage console is shown to the left in front of the tunnel nozzle.

Experimental Procedure

The experiments were limited to the fully cavitating range of operation, i.e., where the cavity length is greater than the chord length of the model. A further limitation on angle of attack was imposed in stipulating that the cavity spring from the sharp leading edge of the model. This requirement necessitated operating the model at angles of attack of 8° or more in the case of zero flap angle and 6° and greater for the 20° flap deflection. The maximum angle of attack investigated in either case was 15°. All the experiments were run at a constant tunnel velocity of approximately 25 feet per second, corresponding to a Reynolds number of 8.5×10^5 based on chord length.

The procedure used in all runs was the same—after fixing the hydrofoil angle of attack at the desired value, the tunnel velocity was adjusted to the above value. The static pressure in the tunnel which was held at atmospheric pressure whilst the tunnel velocity was set, was then lowered until a cavity slightly longer than the chord was obtained. With these conditions established, the data recording was started.

For each value of tunnel static pressure the readings of the forces on the model and the differential pressure across the nozzle to the calibrated section were photographically recored as was the cavity length. The cavity pressure on the fore body and on the flap were read together with the tunnel static pressure at the calibrated pressure tap in the nozzle. For each setting of tunnel static pressure, three separate data readings were taken to average out any slight fluctuations occurring in the tunnel conditions.

The test run was then continued by systematically lowering the tunnel static pressure until the fully choked condition was reached (very long cavity). The pressure was then raised in successive steps with further readings being taken. This procedure enabled the fully cavitating range of operation to be covered twice thus allowing a sufficient number of data points to be obtained for each angle of attack. The test was then repeated for angles of attack varying from 8° to 15° in the case of the zero flap angle model and 6° to 15° for the 20° flap model in 2° increments. This procedure was again adopted to investigate the various gap conditions. The gap ratios (gap width/chord) used were 0%, 1%, 2%, 3%, 5% and 10%.

The behavior of the jet of water flowing through the gap into the cavity was checked carefully for each data point, to obtain a comprehensive qualitative picture of the effect of this jet on the cavity.

Results

(a) Flap angle 0°

Figure 4 illustrates the lift, drag and moment coefficients of the flat plate model with zero flap angle as a function of cavitation number. It is seen from all these curves that the gap has no perceptible effect on the preformance of the hydrofoil for the range of values tested.

The cavitation number referred to in these curves is that based on the cavity pressure measured on the fore body. Little or no difference was found in the two cavity pressures measured on the fore body and on the flap, hence only the one reading was used in the data plotting.

Also shown in these figures are theoretical curves obtained from the non-linear theory of Wu(5) for a fully cavitating flat plate hydrofoil. As can be seen good correlation is found between the experimental results and the theory. Since no correction has been incorporated in the test data for wall effects it is to be expected that for any given angle of attack, the deviation from the theoretical curves, which hold for unbounded flow, will be greater at the lower cavitation numbers where blockage effects are more predominant. This trend is quite apparent from the lift data. Furthermore, this discrepancy between the experimental results and theory increases with increased angle of attack due once again to the increased blockage.

Although no quantitative effects are evident due to the existance of a gap in the flat plate, certain important qualitative aspects are of interest. It was noticed that under all the conditions of cavitation so far tested the water jet through the gap tended to purge and stabilize the cavity upstream of the jet; that is to say, whereas with no gap the cavity under certain conditions, was frothy and somewhat unsteady, with a gap it became clear and glassy and the unsteadiness diminished. This effect, it is felt would be of some value in the so-called transition region between partial and full cavitation where this unsteady phenomenon is most prevalent. The clearing of the cavity is illustrated in the photographs in Fig. 5 where this effect is shown for two angles of attack.

Figure 6 illustrates the cavitation number as a function of cavity length for different angles of attack. Here again it is seen that for the flat plate with no flap the gap has no evident effect on the results. Shown on these graphs are the theoretical curves again obtained from Wu's theory. In this theory no cavity length as such is defined. It is felt, however, that the constant pressure "near wake" region used in the model for the flow is representative of the cavity length. The exact relationship used in the present comparison is to define the cavity as being twice the length of this constant pressure region. The justification for this assumption, however, can only be found in the correlation between theory and experiment. According to the model used in the theory two possible cavity lengths may be defined on the above basis. Since these two lengths differ only slightly from one another, the theoretical cavity lengths shown plotted are an average of the two values. As can be seen from these results there is good agreement between theory and experiment for the shorter cavity lengths. As this length becomes larger, there is a systematic deviation between the theory and experiment. Since blockage effects become more prevalent under these circumstances this discrepancy is not unexpected. However, the correlation achieved would indicate that the theory may be used to predict cavity lengths.

(b) Flap angle 20°

Once again no significant difference was observed in the measurement of the two cavity pressures on either side of the jet. Consequently, only the cavitation number based on the fore body reading will be used in the data presentation.

Figure 7 illustrates the force coefficients as functions of cavitation number for the range of angles of attack investigated. It is seen from these curves that a significant gap effect exists on the lift and moment coefficients. The drag coefficient, however, is unaffected. For the sake of clarity only the results of the 3% and 10% gap ratios are shown in the graphs. The results for the other gap ratios, however, lie between the values shown.

Also shown in these figures are theoretical curves obtained from Wu and Wang(6). Once more it is seen that for the zero gap case fairly good agreement exists between theory and experiment. Again the effects of tunnel blockage are evident on the lift and moment coefficients.

Figure 8 illustrates the effect of a 10% gap ratio on the performance of the flap model. The values in this figure were obtained from cross plots of the preceeding experimental data. It is seen that there is quite a significant decrease in the performance of the hydrofoil due to the gap.

The qualitative effects of the jet on the cavity are no longer the same in this case as they were with the flat plate. Due to the relatively higher pressures now occurring at the hinge point the jet has associated with it a larger momentum. This causes the jet to impinge on the cavity boundary with sufficient force to cause the cavity boundary to deform and to become irregular both in the upstream and downstream directions. Consequently, there is a tendency here for the cavity to become frothy rather than clear as was the case for the flat plate. These effects are illustrated in Fig. 9 for two angles of attack.

Figure 10 shows the behavior of the cavitation number with cavity length. Here again the tunnel effects are evident when the data is compared with the theoretical curves obtained from Wu and Wang, where as previously discussed, an average value of the two possible cavity lengths is shown plotted. It will be seen from these curves that there is no visible gap effect on the cavity length—cavitation number relationship.

The appearance of the jet and its effect on the cavity is well illustrated in Fig. 11 where several views are shown of the jet under different conditions of cavitation. The disturbance of the cavity surface with the subsequent splashing of the jet in the cavity can clearly be seen.

Finally, in Fig. 12 the values of the lift and drag coefficients for choked flow and the choking cavitation number are shown plotted as a function of angle of attack for the flat plate model with no gap. Shown on the graph are the theoretical values of these quantities as calculated by Ai and Harrison(7) using non-linear theory. The value of W, the channel height to chord ratio for the present case is 7.5. As is seen from the curves, good correlation exists between the experimental values and theory except at the lower angles of attack. The discrepancy in this case, especially in the choking cavitation number, is due to the fact that at the smaller angles a very low static pressure was necessary in the tunnel to obtain choking conditions. This very low static pressure gave rise to cavitation on the top wall of the working section, thus causing added blockage. It is seen that the drag readings consistently lie slightly above the theoretical curve, which fact can be accounted for by the skin friction on the model. If an estimate of this frictional drag is made for the present model assuming a turbulent boundary layer, a value of 0.005 is obtained for C_f, which is of the correct order of magnitude to possibly account for this discrepancy.

The discrepancy in the cavitation numbers can be accounted for in the technique used to measure this quantity. Due to the small air flow rate used to keep the pressure line to the cavity clear, there exists a small pressure drop between the point of measuring the cavity pressure and the cavity itself. Hence the actual reading of cavity pressure is always slightly higher than its actual value, thus lowering the cavitation number somewhat from its true value.

Conclusions

An experimental investigation of the effect of a hinge gap on the performance of a fully cavitating hydrofoil has been presented. From the results obtained it can be concluded that the gap has no effect on the performance of a hydrofoil with zero flap angle. However certain advantageous qualitative effects arise due to the gap jet. The cavity over the fore body tends to be stabilized by the jet and unsteady effects that usually occur for short cavities slightly longer than the chord, are effectively reduced.

In the case of the flap hydrofoil studies, the gap has a marked effect on the lift and total hinge moment. The drag, however, seems unaffected by the gap effect. Qualitatively the effect of the jet in this latter case does not have the stabilizing effect mentioned above. On the contrary, due to the higher momentum of the fluid jet the cavity boundary is greatly distorted by this jet.

Comparison of the experimental results obtained in the present investigation with those results predicted by various non-linear theories shows very good agreement and the theoretical prediction of the wall effects, at least in fully choked flow, is seen to be very well established.

Acknowledgment

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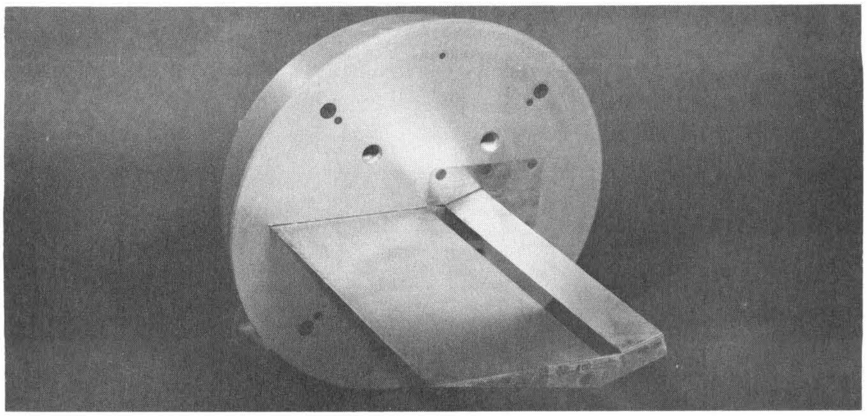


Fig. 1 View of model with 20° flap angle and 10% gap ratio.

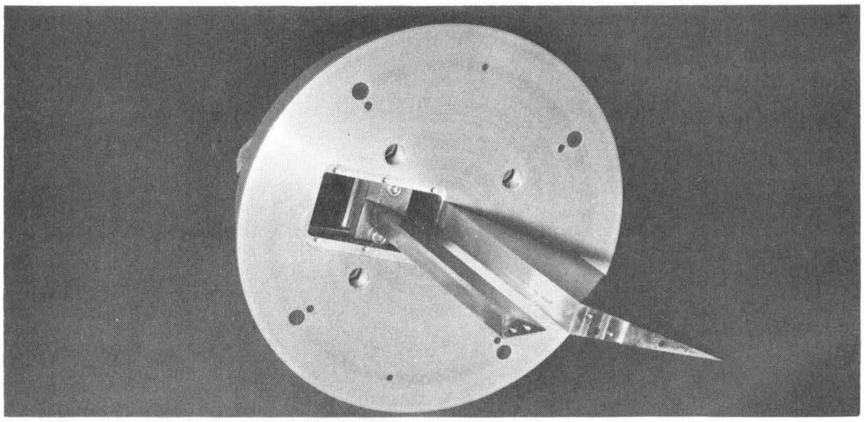


Fig. 2 Illustration of method of supporting flap and varying gap ratio.

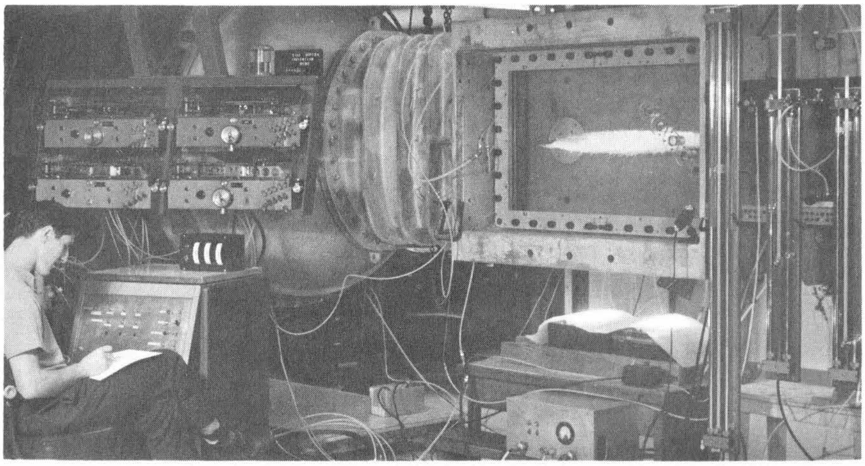


Fig. 3 General view of working area illustrating two dimensional test section, force gage console and mercury manometers.

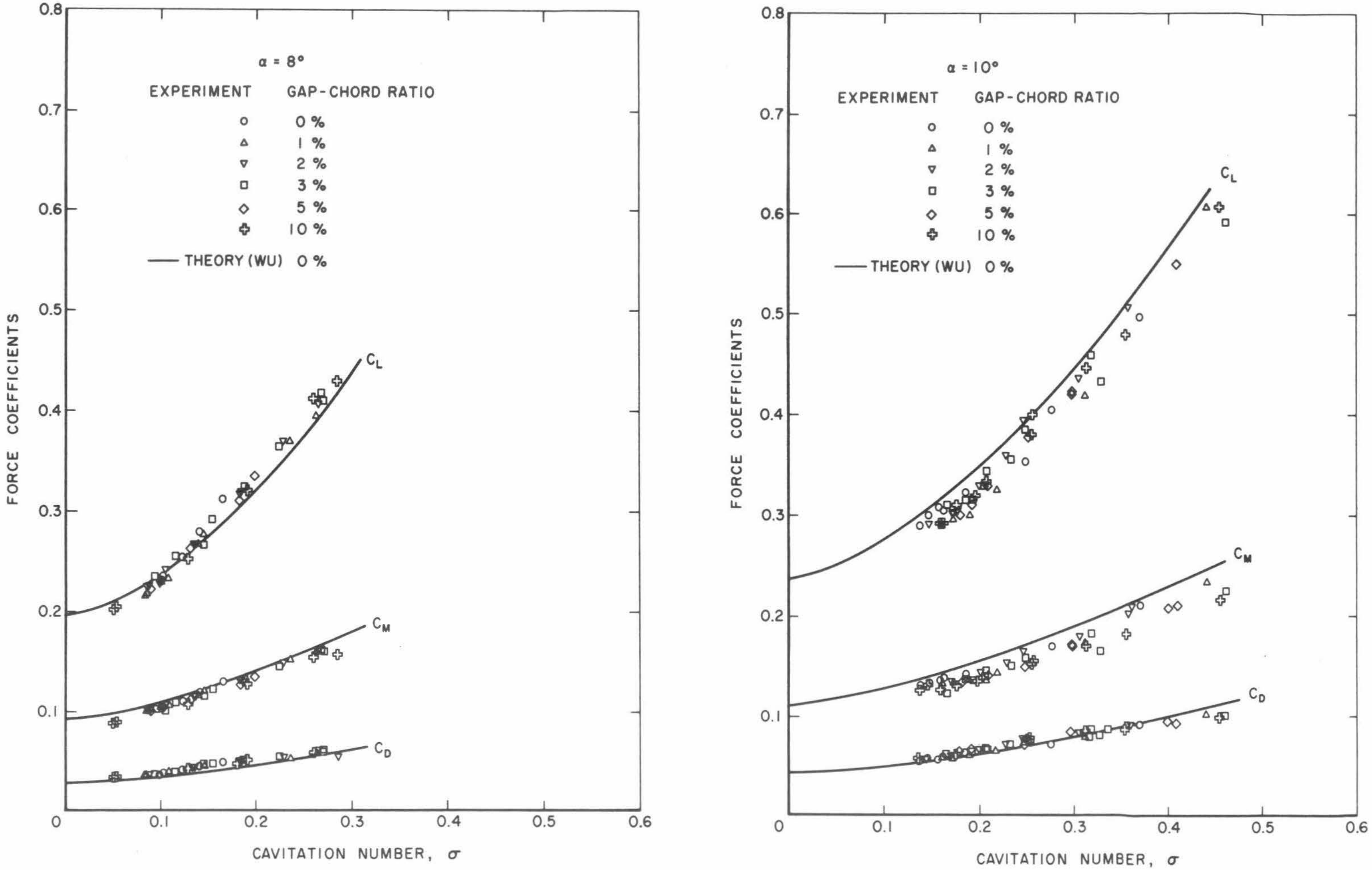


Fig. 4-1 Force coefficients as functions of measured cavitation number for flat plate with zero flap angle for varying hinge gap ratios at a constant angle of attack.

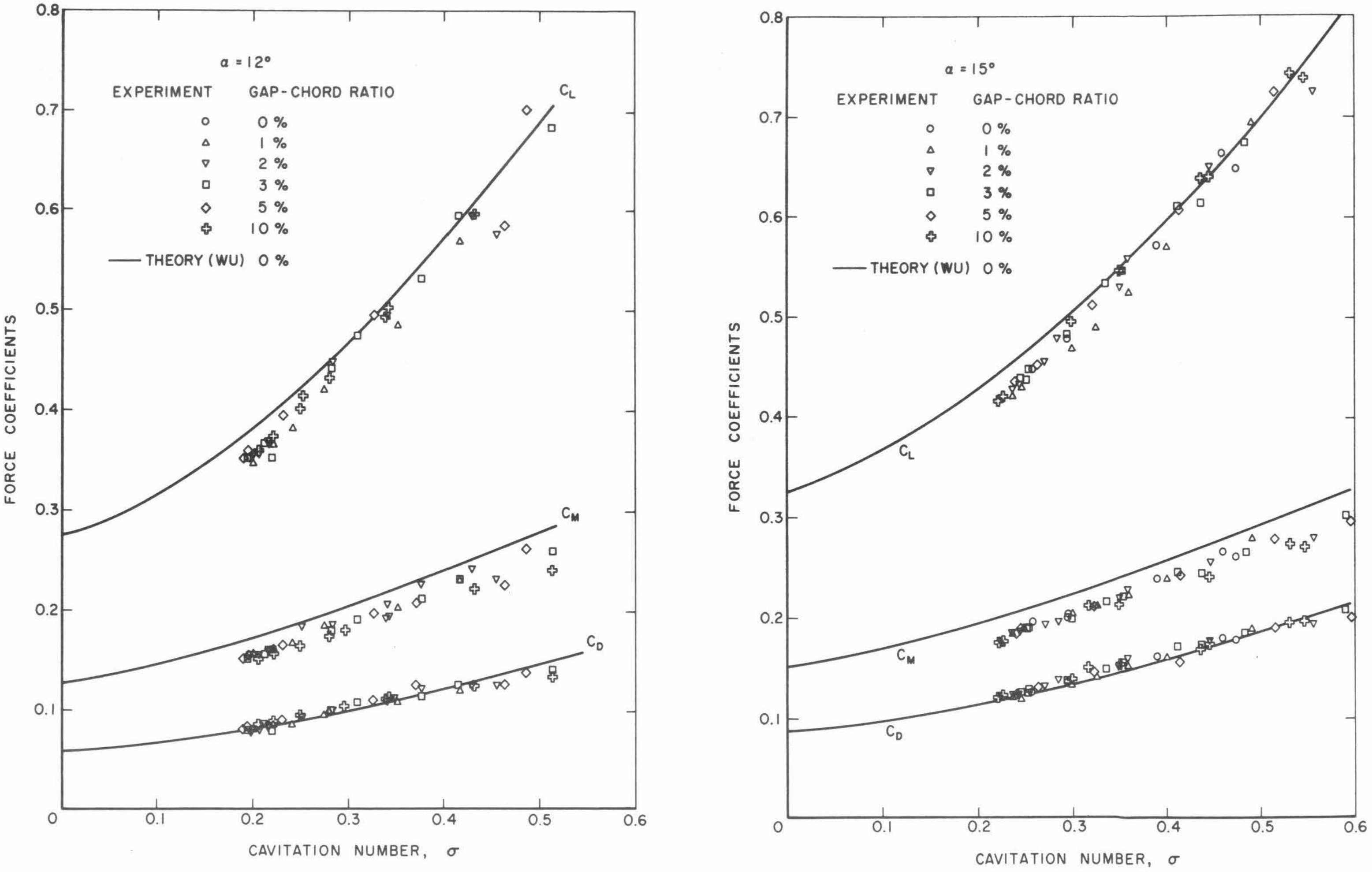
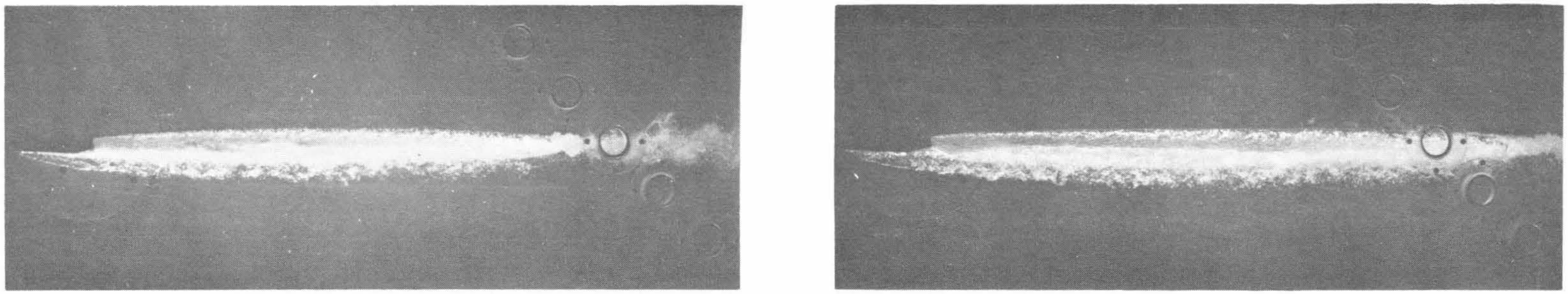
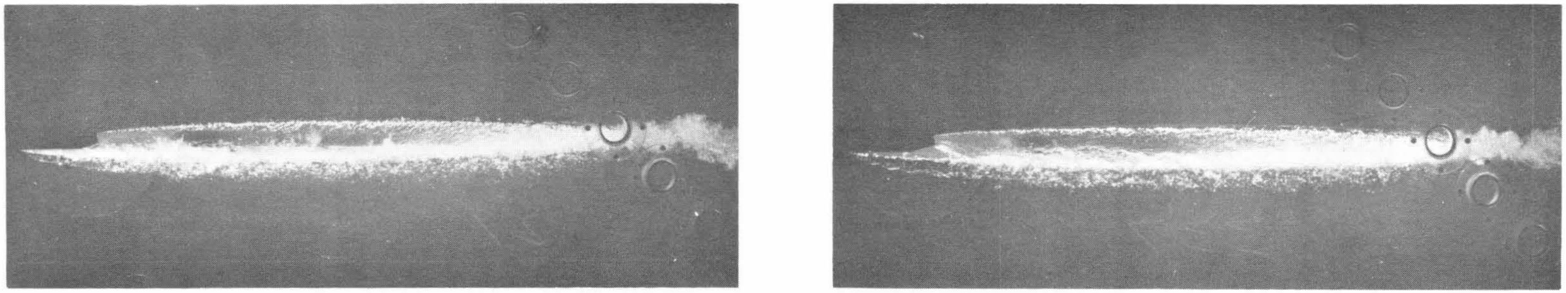


Fig. 4-2 Force coefficients as functions of measured cavitation number for flat plate with zero flap angle for varying hinge gap ratios at a constant angle of attack.



$\alpha = 8^\circ$, $g/c = 0\%$, $\sigma = 0.1$

$\alpha = 8^\circ$, $g/c = 10\%$, $\sigma = 0.1$



$\alpha = 10^\circ$, $g/c = 0\%$, $\sigma = 0.16$

$\alpha = 10^\circ$, $g/c = 10\%$, $\sigma = 0.16$

Fig. 5 Photographs illustrating the effect of the jet in purging the forward section of the cavity for the flat plate hydrofoil.

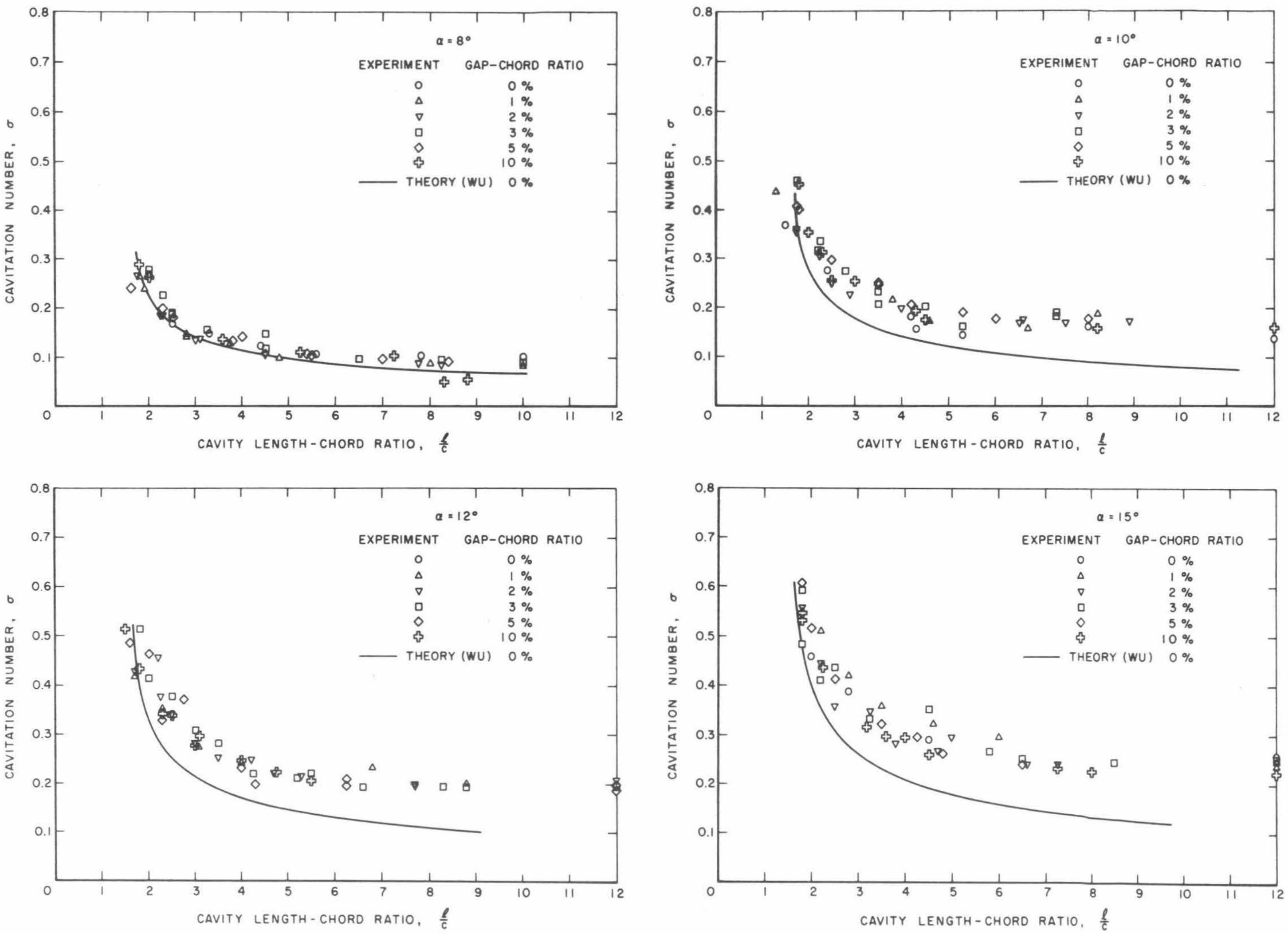


Fig. 6 Variation of measured cavitation number with cavity length for the flat plate with zero flap angle for varying hinge gap ratios at constant angle of attack.

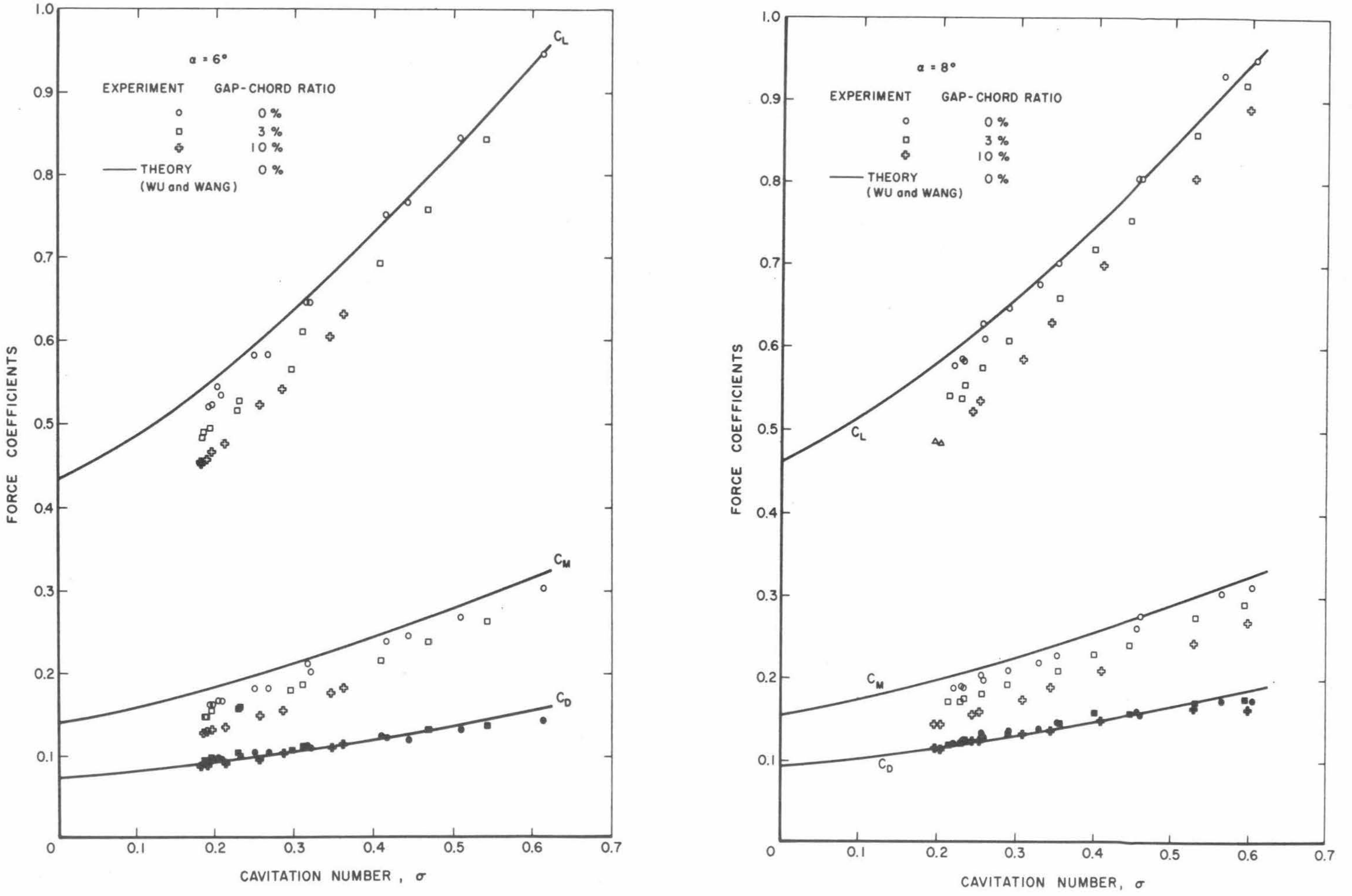


Fig. 7-1 Force coefficients as functions of measured cavitation number for hydrofoil with 20% flap-chord ratio and 20° flap deflection for different hinge gap ratios at a constant angle of attack.

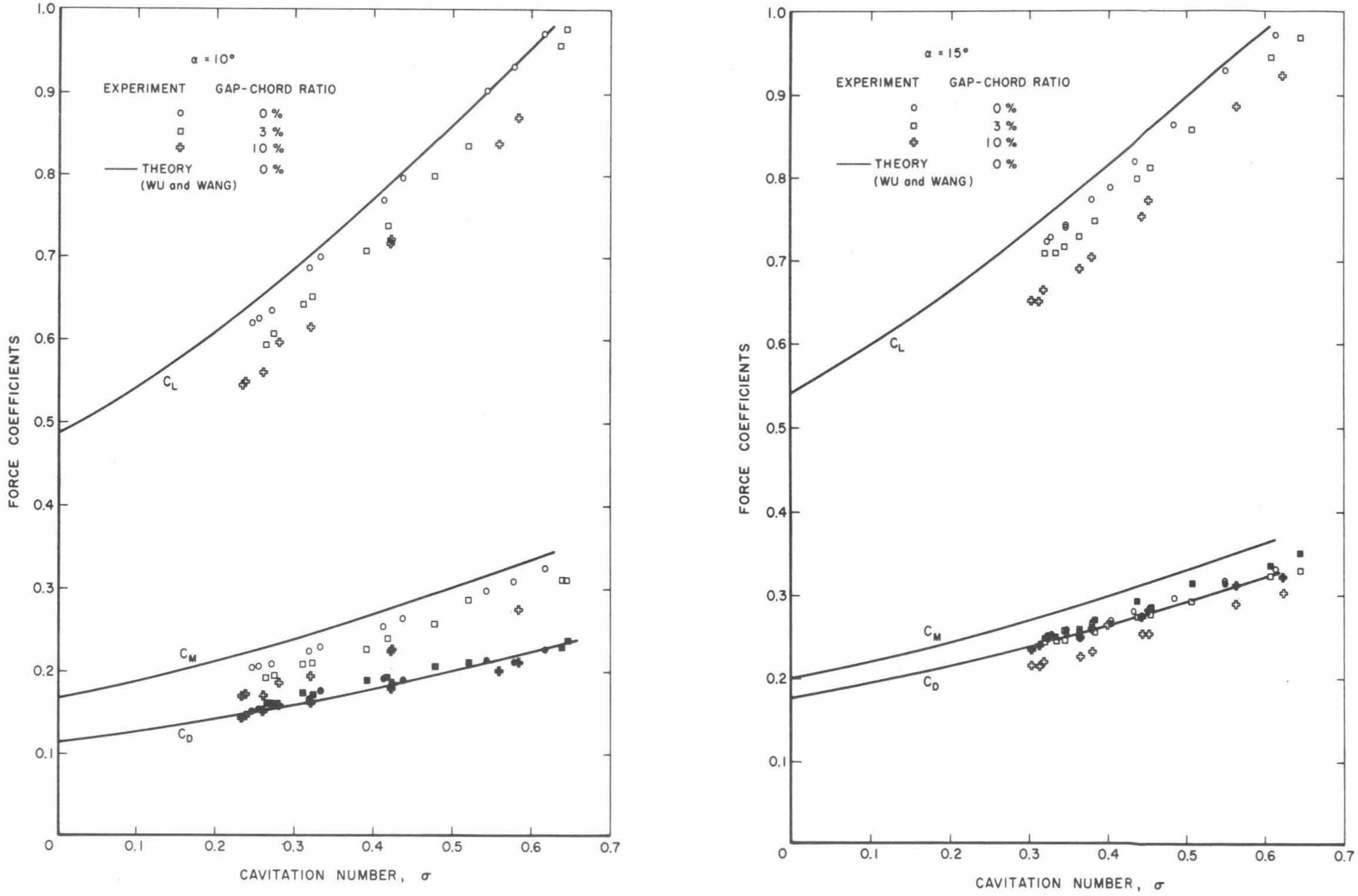


Fig. 7-2 Force coefficients as functions of measured cavitation number for hydrofoil with 20% flap-chord ratio and 20° flap deflection for different hinge gap ratios at a constant angle of attack.

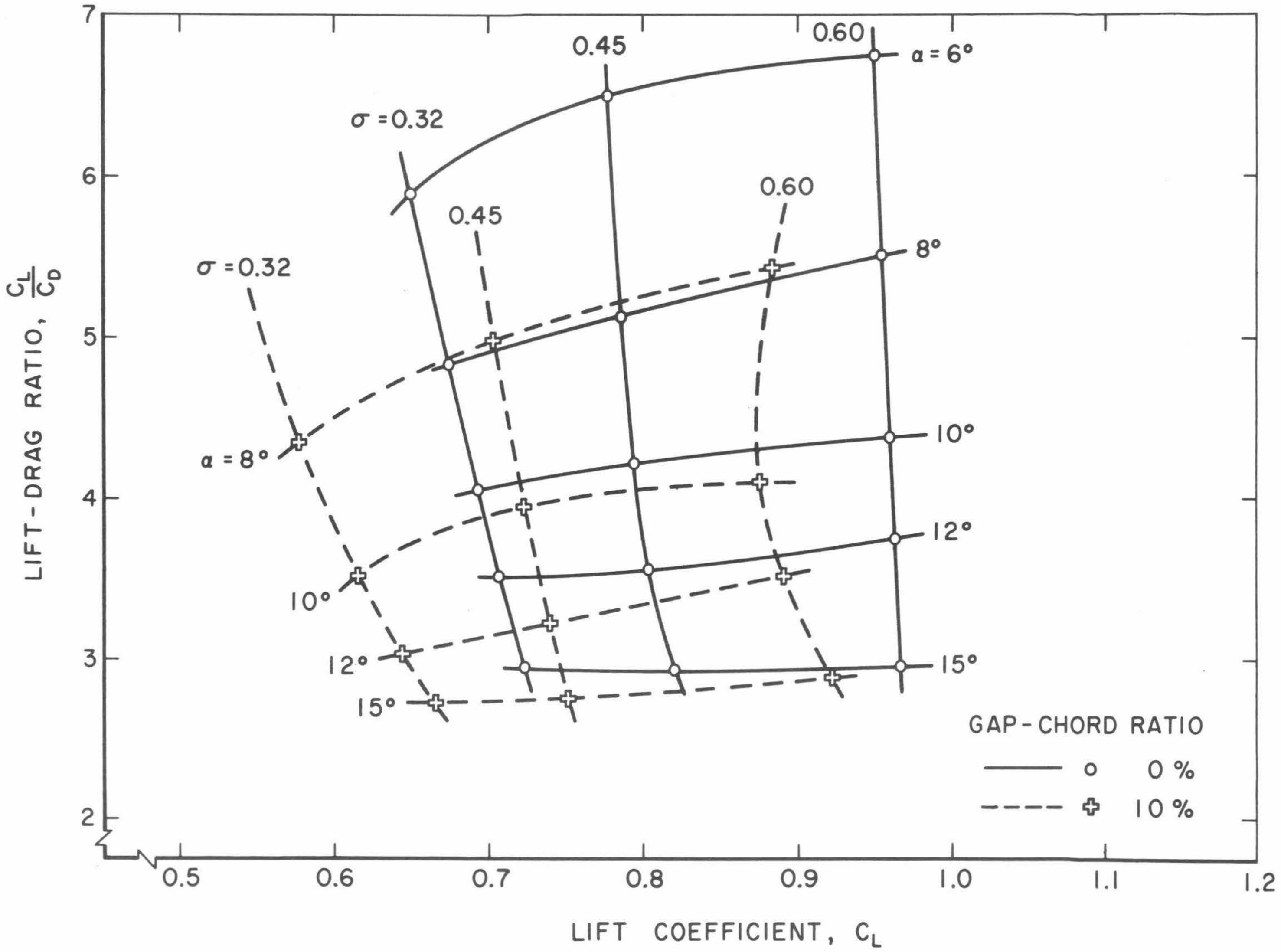
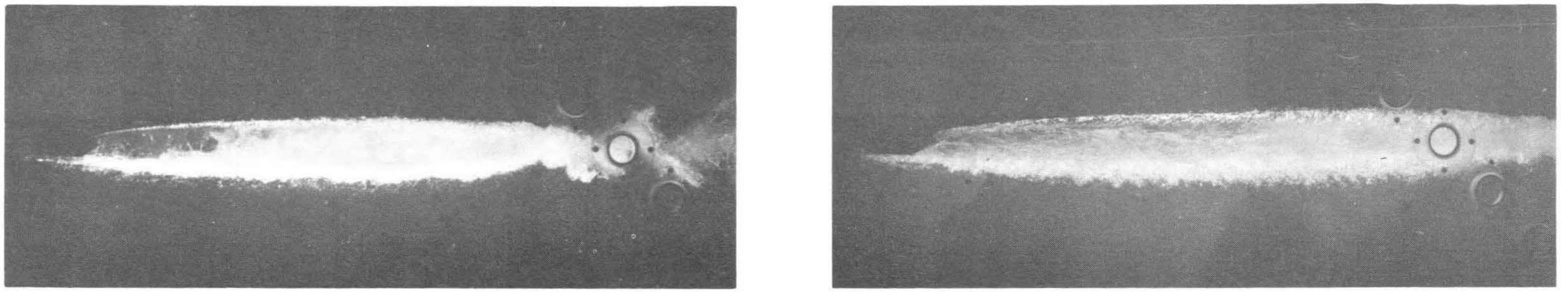


Fig. 8 Effect of a 10% hinge gap ratio on the performance of the flap hydrofoil from the zero gap condition.



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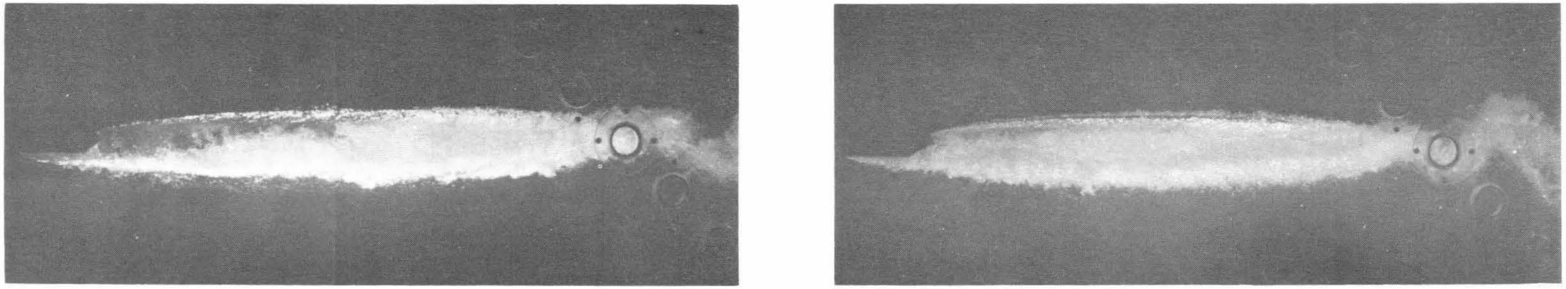


$\alpha = 10^\circ$, $g/c = 0\%$, $\sigma = 0.25$

$\alpha = 10^\circ$, $g/c = 10\%$, $\sigma = 0.24$

Fig. 9 Photographs illustrating the effect of the hinge gap jet on the cavity for the flap hydrofoil.

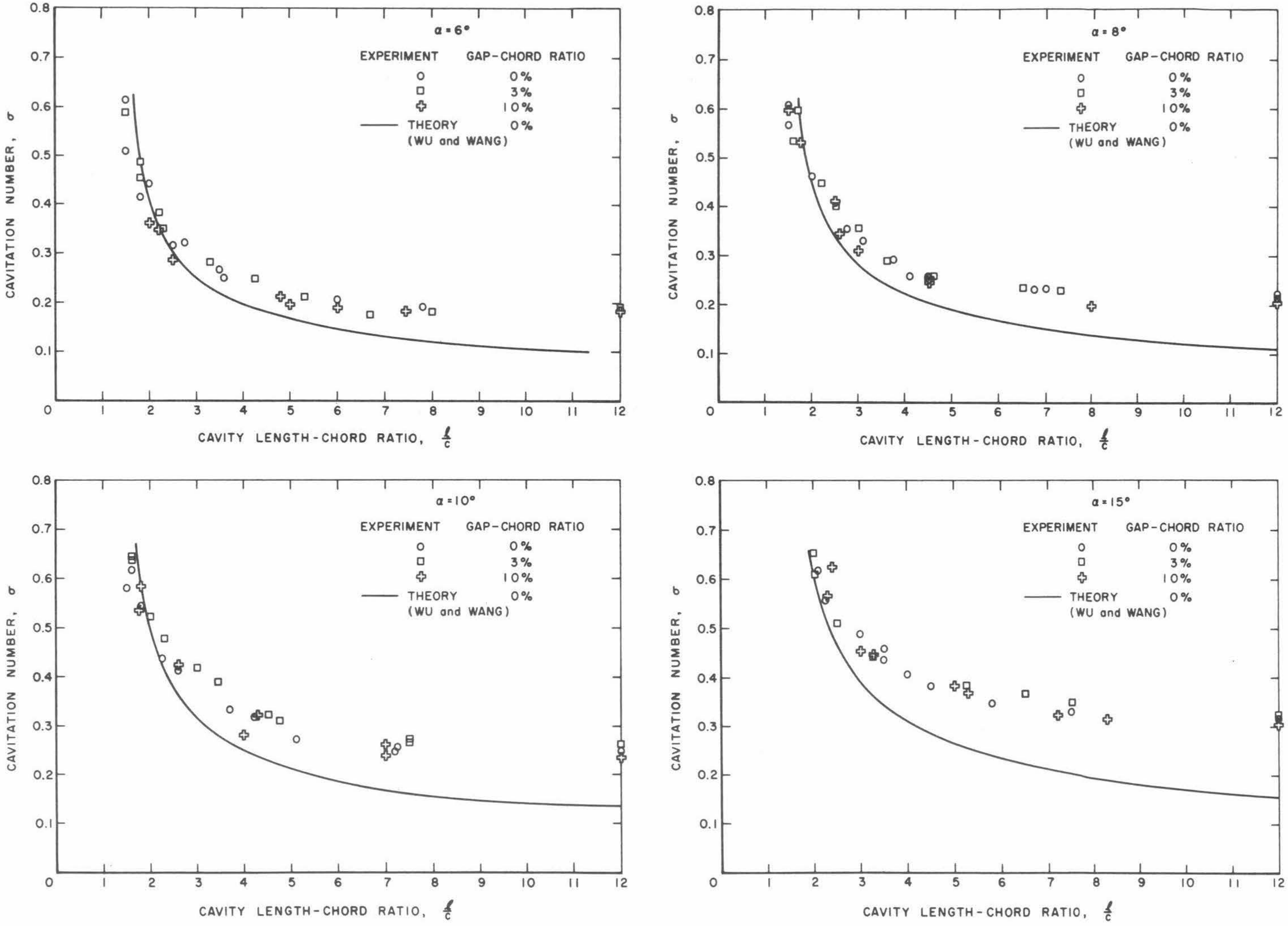
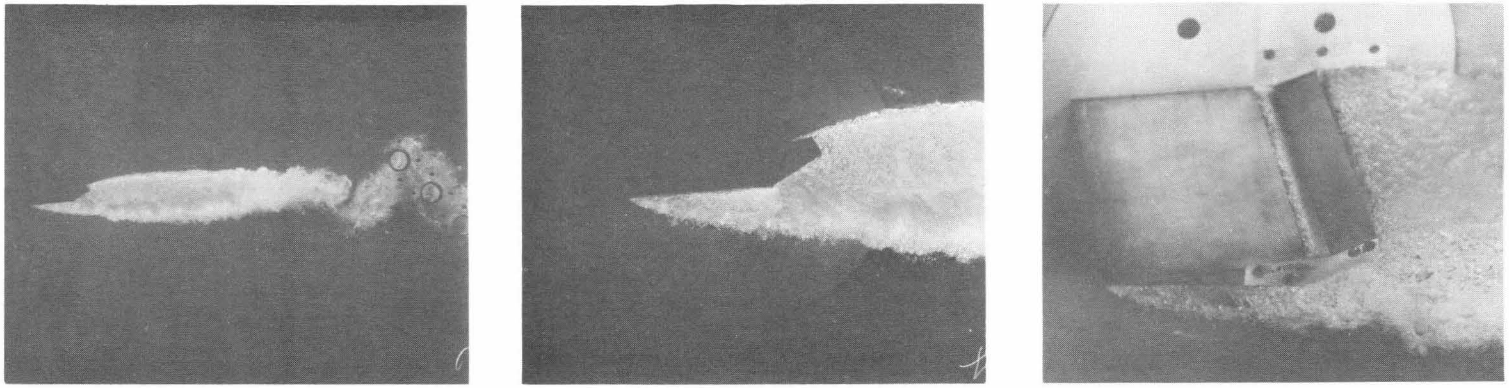
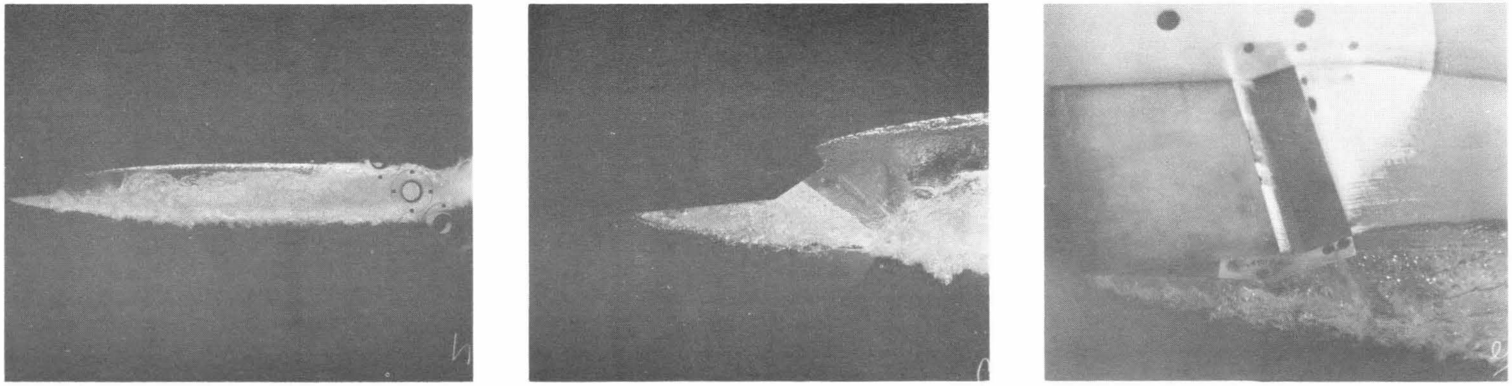


Fig. 10 Variation of measured cavitation number with cavity length for the flap hydrofoil for different hinge gap ratios at constant angle of attack.



$\alpha = 15^\circ$, $g/c = 10\%$, $\sigma = 0.45$



$\alpha = 15^\circ$, $g/c = 10\%$, $\sigma = 0.31$

Fig. 11 Several views illustrating the behavior of the hinge gap jet for the flap hydrofoil.

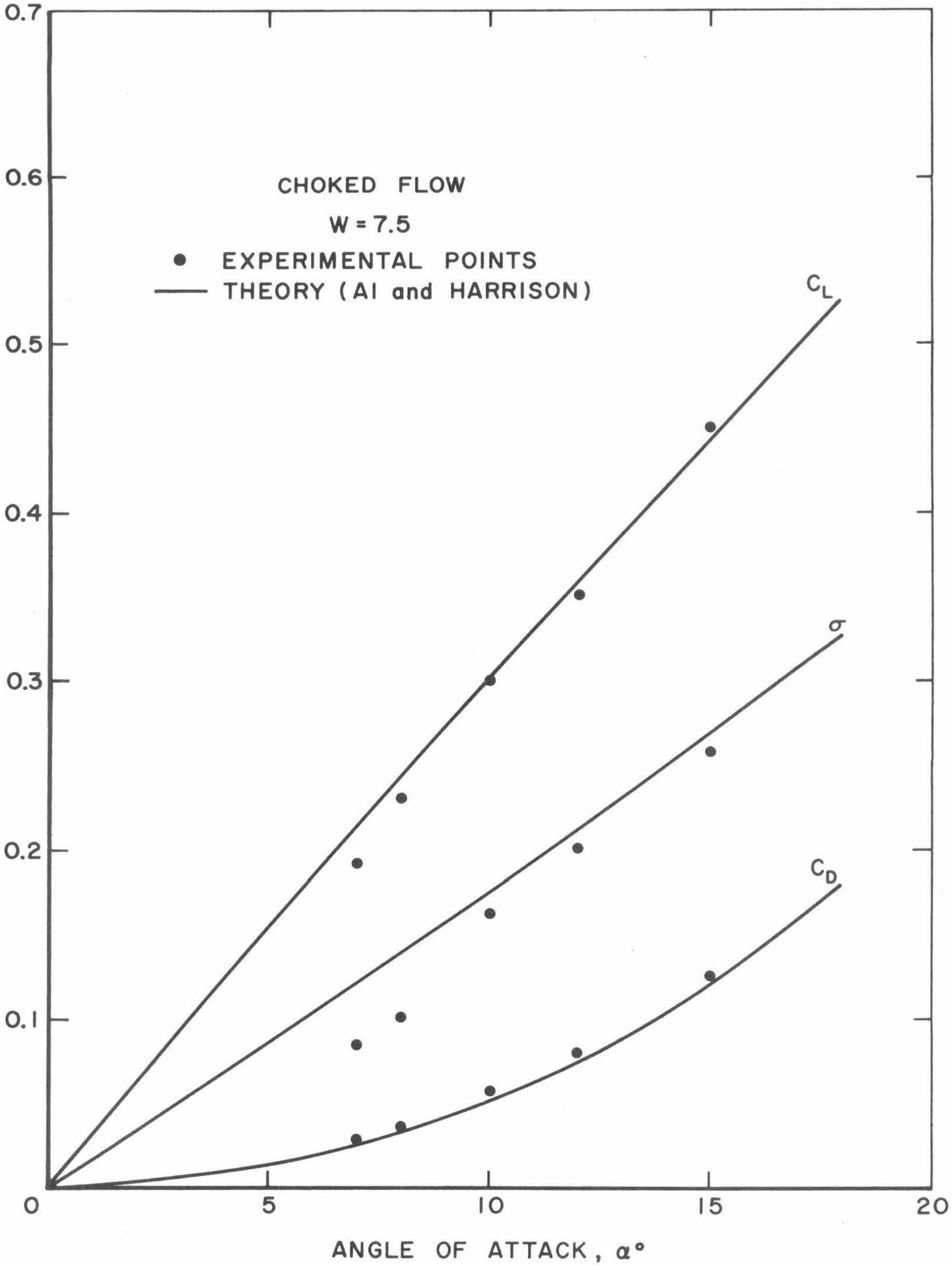


Fig. 12 Comparison of the experimental results of the flat plate hydrofoil with zero gap with theory for choked flow conditions.

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Experimental results are presented for the effect of a hinge gap on a fully cavitating performance of a flat plate hydrofoil without and with a flap. From the results of the tests it is concluded that for the zero flap deflection, no significant effects of the gap are apparent for the range of the parameters investigated. However, for a 20% flap-to-chord ratio and a 20° flap deflection a significant drop occurs in the lift and moment coefficients for a given gap ratio. This effect increases with increase in gap width. The drag on the other hand is unaffected for the range of values tested.

Certain qualitative effects of the jet, arising from the gap, on the cavity appearance are discussed. Comparison of the experimental results for zero gap, with established non-linear theories, show very good agreement.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Hydrofoils						
2. Cavitation						
3. Hinge gap effects						

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