Engineering Notes

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Correlation of Force Measurements and Separated Flow Regions on Surface Piercing Struts

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Introduction

THE effects of separation on force coefficients are well-known for most types of aerofoils in two-dimensional flow situations, and correction factors are available for finite spans. The complications introduced by the free surface for a surface piercing foil have not previously been examined nor have the effects of the associated ventilation. This Note presents the results of force measurements on four different surface piercing foils and compares them with the separation patterns obtained using an oil smear technique. Results are presented only up to the point of steady ventilation inception, since full face ventilation or cavitation produced surprisingly complex force patterns which were the subject of a separate study.[1] Thus the diagrams do not show the discontinuities and hysteresis effects typical of ventilation.

Apparatus

The work was carried out in a variable pressure water channel of 14 in. square working section.[2] A three component balance,[3] constrained by air bearings, was used to evaluate side force, drag, and turning moment components. Interactions were virtually eliminated, typical errors noted during calibration ranging from zero to 0.5% of the largest force acting.

An oil smear technique[4] was used to ascertain the extent of the separated flow regions. To cover the range of separation modes expected in practice, four foil shapes were chosen: a sharp nosed biogive with a thickness chord ratio of 10% and a nose radius 0.1% of chord; a blunt nosed biogive of the same over-all shape but with the nose radius 1% of chord; and a NACA 0012 and a NACA 16-021. All foils were of 4-in. chord.

Results

Side force, drag, and turning moment were measured at 1° intervals at an aspect ratio of 2 for increasing and decreasing incidence angles up to the point of ventilation. The incidence angle was varied in both directions to eliminate alignment errors and the procedure was repeated for four water velocities: 5, 10, 15, and 20 fps. In two cases, results could not be obtained at 20 fps because the lift forces were beyond the range of the balance.

Significant differences were observed in the curves of the lift and moment coefficients as the speed was changed. Typical examples of the different types of curves obtained are shown in Table 1. When interpreting results, it is helpful to remember that an increased gradient in the lift curve results from any event which increases the area enclosed by the pressure curve. Similarly, the positive gradient of the turning moment curve corresponds to a clockwise moment of the foils as drawn. Thus all foils have a moment which acts to turn the foil to greater angles of incidence. An increase in the gradient of this curve implies an increase in the area of the pressure curve at the nose of the foil or a decrease in the enclosed area near the tail.

Analysis was carried out of photographic color transparencies taken of the oil smear patterns on both foil surfaces for the same range of speeds and incidence angle as the force measurements. In doubtful cases, the direction of flow was established by further tests in which only selected regions of the foil were coated with the oil/pigment mixture. Details of the separation characteristics are given in Table 1; it may be noted that the biogival foils both exhibited the nose bubble type of separation and the remaining two foils tail separation. The separation characteristics of the NACA 16-021 were unusual in that the flow appeared to be on the point of separation over much of the mid-chord section for certain incidence angles, yet was clearly attached at the nose and the tail. As the angle of incidence was increased, the stagnant region moved forward and developed into a "short" or "shrinking" type of nose bubble. Subsequent study showed that this "quasi-bubble" is theoretically possible and the required pressure distribution is close to that expected on the NACA 16-021.

The lift slopes were deduced approximately using the expression

$$dC_L/d\alpha = 2\pi(4a/c)(1 + t/c) \times [A/(A + 2.17)] \text{ viscous efficiency}$$

where c is the chord, A the aspect ratio, t the maximum thickness, and a the radius of the circle in the transformed plane. The aspect ratio dependence is from Breslin,[5] who uses a loading such that the circulation is continuous. The viscous losses decrease with increasing Reynolds number but are expected to be about 20% at a Reynolds number of 3×10^5 (see Ref. 6), which coincides with a channel speed of 10 fps and the viscous efficiency was therefore taken to be 80%. The estimates are indicated by the broken lines in the lift diagram of Table 1.

Discussion

Comparison of the lift curves with those accepted for two-dimensional flow shows that the three-dimensional flow and curtailment of the curve by ventilation, mask the characteristics which enable the mode of separation to be deduced from the lift curve. The influence of tail separation is less than for two-dimensional flow at low aspect ra-

Received March 19, 1973; revision received November 30, 1973. The assistance of Defense Research Establishment Atlantic, Halifax, Nova Scotia, in providing funds for this work, is gratefully acknowledged.

Index categories: Hydrodynamics; Marine Hydrodynamics, Vessel and Control Surface.

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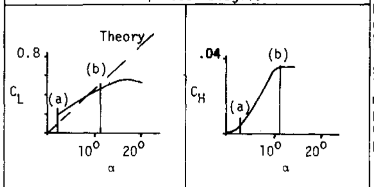
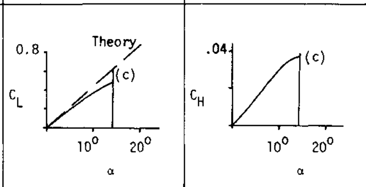
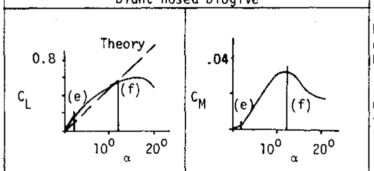
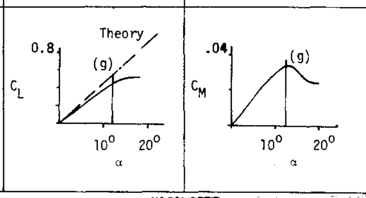
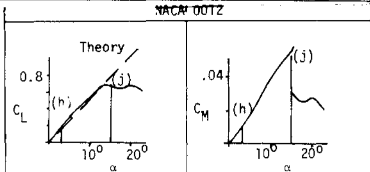
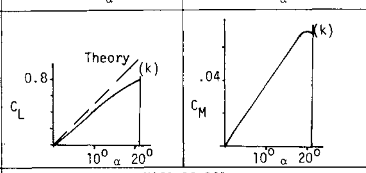
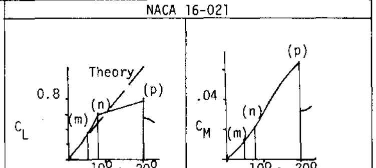
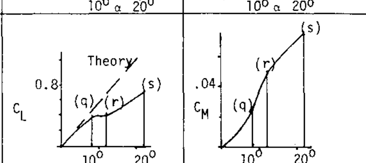
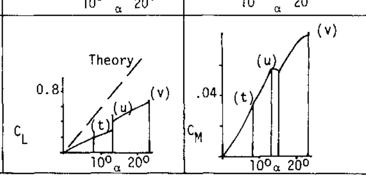
Table 1 Comparison of force and separation characteristics

Speed	Schematic Drawings: Lift coefficient	Schematic Drawings: Turning moment	Separation characteristics
	Sharp nosed biogive		
(i) 5 ft/s			Long bubble emerges at 2° on low pressure (a) face. Rapid bubble growth at 8° leading to thin aerofoil stall (b) resulting in large loss of turning moment due to unusual pressure distribution. Complete stall at 15° precedes ventilation by 6°.
(ii) 10ft/s 15ft/s 20ft/s			Development of long bubble as at 5 fts^{-1} but curtailed by ventilation (c) before complete stall.
	Blunt nosed biogive		
(iii) 5 ft/s			Long bubble emerges at 2° on low pressure face. Rapid bubble growth leading to thin aerofoil stall (f) and loss of lift especially near leading edge. Complete stall at 16° precedes ventilation by 3°.
(iv) 10ft/s 15ft/s 20ft/s			Development of long bubble as at 5 fts^{-1} but full thin aerofoil stall occurs before ventilation (g) except at 20 fts^{-1}.
	NACA 0012		
(v) 5 ft/s			Laminar tail separation on both faces initially. Reattachment (h) on high pressure faces reduces lift slightly. Partial ventilation (j) on low pressure face.
(vi) 10ft/s 15ft/s			Turbulent tail separation starting about 12° moving forward to give full stall at 20°. Ventilation occurred 1° later.
	NACA 16-021		
(vii) 5 ft/s			Laminar tail separations on both faces initially, moves forward on low pressure face. Quasi-bubble (n) at 8° but no turbulent reattachment. Partial ventilation (p) on low pressure face.
(viii) 10ft/s			As at 5 fts^{-1} until turbulent separation at tail at 10° which causes rapid shrinking of bubble (r) ahead of it. Ventilation (s) occurs when flow separated over 50% of chord.
(ix) 15ft/s			Very similar to 10 fts^{-1} but limited ventilation (v) on high pressure face.

tios because the area of the separated flow is reduced by the presence of the free surface and by the tip vortex. In these experiments, tail separation was observed at an incidence angle about 5° less than that at which it was detectable by the force measurements. The small chord length and early emergence of the nose bubble on the biogival foils also hide the characteristic kink in the lift coefficient which marks the initiation of the bubble. Thus nose and tail separation are indistinguishable by consideration of force diagrams alone.

At 5 fps the behavior of all foils is anomalous and a full explanation cannot be offered. The Reynolds number at this speed is only 1.5×10^5 and these results are not of much practical significance.

The behavior of the NACA 16-021 is unusual for reasons which do not seem to be entirely connected with the free surface and the finite span. The concept of a quasi-bubble seems to be justified by the force measurements, the separation patterns, and the theoretical analysis. Only a few foil profiles will show this mode of separation. Further irregularities in the lift and moment curves are produced by the partial ventilation which occurs on the high pressure face at high angles of incidence. This unusual feature will only occur with foils of high thickness/chord ratios.

Some discrepancies are to be expected between calculated and theoretical lift coefficients because of the influence of the separated regions. Other deviations will arise for the following reasons:

a) The aspect ratio is ill-defined because of the three-dimensional flow. The error could be as high as ±10%.

b) The effective freestream velocity is not known exactly because of the reduction in channel area due to the presence of the foil and also the unknown influence of the foil on the speed recorder. Estimated error after suitable experiments ±5%.

c) The wall effects of the channel have been estimated theoretically as ±3%.

Conclusions

It is not possible to deduce separation characteristics from a knowledge of force measurements for a surface piercing foil, although satisfactory correlations can be made if both the separation and force characteristics are known. A mode of separation has been observed on a thick foil in which a large mid-chord region of near stagnant flow persists until near the trailing edge. As the angle of incidence increases, this region develops into the more usual "short" or "shrinking" bubble. A comparison of theoretical and measured lift coefficients showed some discrepancies, some of which are due to the limitations of this method of testing.

References

[1]McGregor, R. C., Wright, A. J., and Swales, P. D., "Explanation of Forces on a Surface Piercing Strut after Ventilation," *Journal of Hydronautics*, Vol. 7, No. 3, July 1973, pp. 132–133.

[2]Hunter, B., Swales, P. D., and Cole, B. N., "Variable Pressure Recirculating Water Channel," *The Engineer*, Vol. 225, 1968, pp. 515–9.

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[5]Breslin, J. P., "The Hydrodynamic Characteristics of Surface Piercing Struts, Part II: The Side Force Developed in the Absence of Ventilation," SIT ETT Rept 597, 1956, Stevens Institute of Technology, Hoboken, N.J.

[6]Goldstein, S., *Modern Development in Fluid Mechanics*, Dover, New York, 1965.