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Recent Research on V/STOL Test Limits at the University of Washington Aeronautical Laboratory

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Shojiro Shindo and William H. Rae, Jr.
University of Washington
Seattle, Washington

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SUMMARY

Powered model testing of V/STOL aircraft presents a unique problem during the transition flight regime. This problem is associated with an interaction between the wind tunnel boundaries and the high downwash angles created by the model. The solution of this problem is the establishment of a low speed test limit. The low speed test limit is a function of the model size relative to the tunnel size and the downwash angle. When the low speed test limit is reached the aerodynamic forces and moments are neither reliable nor correctable to free air conditions.

The V/STOL low speed test limit was first recognized using rotors as powered models. Rotors represent a type of V/STOL aircraft that obtain vertical take-off lift by a distributed lift system. Representing the distributed lifting systems, a jet flap wing was also studied. Lift jets were examined as a representative model for concentrated lifting systems.

The lift jet low speed test limit obtained during the present research confirmed the criteria established by other researchers. The jet flap wing low speed test limit was found to be predictable using the results obtained earlier with the rotors.

It is concluded that during the low speed wind tunnel test of a V/STOL powered model all six aerodynamic components must be carefully examined to assume the validity of the data with respect to the low speed test limit caused by the phenomenon termed "flow breakdown."

SYMBOLS

C	wing chord, m (in.)
C_{L_t}	tail lift coefficient, $\frac{L_t}{qS_t}$
C_m	pitching moment coefficient, $\frac{M}{qSC}$
C_μ	momentum coefficient, $\frac{\dot{m}v_j}{qS}$
L_t	tail lift, N (lb)
M	pitching moment, Nm (in.-lb)
$\dot{m}$	mass flow rate, kg/s (slugs/s)
q	dynamic pressure, N/m^2 (psf)
S	wing area, m^2 (ft^2)
S_t	horizontal tail area, m^2 (ft^2)
v	free stream velocity, m/s (fps)
v_j	jet velocity, m/s (fps)
ϵ	downwash angle, deg
α	angle of attack referenced to wing chord, deg
$\alpha_{L=0}$	zero lift angle of attack referenced to wing chord, deg

INTRODUCTION

In the past two decades, a considerable degree of national effort has been expended to develop a V/STOL (vertical and/or short take off and landing) aircraft to provide a convenient and economical means of air transportation. V/STOL aircraft have been considered for commercial applications in addition to the proven military utilization. The potential values of this type of aircraft increased the national efforts toward conducting research and development of V/STOL aircraft.

However, since the V/STOL's benefit is predicated on the successful maneuver through vertical to horizontal flight, and vice versa, this flight regime became the unique problem of V/STOL aircraft testing. During transition flight, the V/STOL aircraft displays the distinctive feature of generating a large downwash. During wind tunnel testing of such a model, this large downwash interacts with the test section floor and the free stream velocity to produce a vortex on the floor. The existence of such a vortex-like secondary flow in the vicinity of the model does not represent the intended free-air configuration. The location and magnitude of this secondary flow determines the V/STOL low speed test limit condition termed "flow breakdown." When this test limit is reached, the flow in the test section does not resemble that of free air, and the data taken under this condition are unreliable and uncorrectable.

This report summarizes the results of experimental research conducted at the University of Washington to investigate the unique testing problem of V/STOL aircraft and describes the means of establishing an individual test envelope which will define the reliable test conditions.

REVIEW OF PREVIOUS WORK

Wind tunnel testing of powered V/STOL models in the transition region presents a unique problem due to the interaction of the model's wake with the tunnel boundaries. As previously stated, the data in the "flow breakdown region" is neither reliable nor correctable. As the model goes through the transition from forward flight to hover, the downwash angle of the lifting system increases from 1-3° to 90°. At a certain value of downwash angle, the forward or leading edge of the wake interacts with the flow at the tunnel boundary. These two flows roll up into a vortex-like flow opening parabolically to the rear. Furthermore, if the model is large relative to the test section, this vortex can move up the side walls of the tunnel.

The initial work, which defined flow breakdown as the point at which this secondary flow affected the model, used rotors for the powered lift source (ref. 1). The limit for rotors was shown to be a function of both the ratio of the model to tunnel cross-section momentum areas and the model downwash angle. It was also shown that corner fillets, and presumably curved walls, would reduce the allowable downwash angle.

Further work showed that, for a given model to tunnel size ratio, as the forward velocity decreased (increasing the downwash angle) the vortex-like flow on the floor would both become stronger and move forward in the test section. Thus, if the model had a lifting surface such as a horizontal tail aft of the rotor, the tail lift and hence the model's pitching moment, would be effected before the rotor's lift and drag. This effect on the tail also is a function of the vertical location of the tail relative to the rotor (ref. 2).

In an attempt to increase the size of the model for a given test section, a study was made of moving the rotor vertically relative to the tunnel centerline (ref. 3). This study showed that the best location was the centerline of the tunnel.

LATEST DEVELOPMENTS USING LIFT JETS AND A JET FLAP WING

As a contrast to both rotors and jet flap wings which are distributed lift systems, it was necessary to examine the low speed test limit using a model that had a discretely concentrated powered lift system. Such a system was designed and built using a pair of lift jets which were placed non-metrically near the model. This design separated the lift jet forces from the aerodynamic forces and moments on the wing and tail of the model. The V/STOL aircraft was simulated by a 0.91-m (3-ft) non-swept wing with a 0.15-m (6-in.) chord. The tail was 3-chord lengths behind the wing. Detailed design of the engine system, the V/STOL model, and the initial engine calibration results were reported in reference 4. The complete model was tested in three different tunnel configurations:

1. 2.44- by 3.66-m (8- by 12-ft) test section (Approximate free air)
2. 1.22- by 1.83-m (4- by 6-ft) insert (Model in wind tunnel)
3. 2.44- by 3.66-m (8- by 12-ft) test section plus a ground plane at the same distance below the model as in the 1.22- by 1.83-m (4- by 6-ft) insert (to simulate the floor of the 1.22- by 1.83-m [4- by 6-ft] insert)

The lift jet model in the 1.22- by 1.83-m (4- by 6-ft) insert shows that flow breakdown occurs at a velocity ratio of approximately 0.20 (ref. 5). At this velocity ratio, the wing angle of attack for zero lift, the wing lift coefficient at zero degree angle of attack, and the pitching moment coefficient about the quarter chord all show a divergence from the 2.44- by 3.66-m (8- by 12-ft) or free air case (figures 1, 2, and 3). The tests in the 2.44- by 3.66-m (8- by 12-ft) tunnel with the ground plane at the same distance below the wing also agree with the 1.22- by 1.83-m (4- by 6-ft) insert data down to a velocity ratio of 0.20. At a velocity ratio of 0.40, the data from all three tunnels are approximately the same. Thus the tunnel floor in the 1.22- by 1.83-m (4- by 6-ft)insert or the ground plane in the 2.44- by 3.66-m (8- by 12-ft) insert are affecting the flow from a velocity ratio of 0.40 to 0.20 (i.e., the model is in ground effect). At velocity ratios below 0.20, the data for the 1.22- by 1.83-m (4- by 6-ft) insert diverges from the ground plane data, indicating that the vortex-like flow on the tunnel floor is modified by the presence of the tunnel walls. The secondary flow has a major effect on the wing lift at velocity ratios of 0.18 in the insert and 0.14 with the ground plane (fig. 1 and 2). The tail (fig. 3), does not show the same change as the jet wake predominates in determining its flow field.

The data on the jet lift configurations is only applicable for a pair of jet engines in front of the wing. Caution must be used in applying these results to other engine-airplane configurations.

In conjunction with another NASA funded research program at this department, a 0.91-m (3-ft) span, A=4.05 jet flap wing equipped with a tail three chords behind the wing was designed and built (ref. 6). This model was tested in the 2.44- by 3.66-m (8- by 12-ft) test section and a 0.96- by 1.44-m (3.14- by 4.71-ft) insert to examine the flow breakdown phenomenon and the applicability of the existing wall correction theories. The model was tested in the momentum coefficient range of 0.2 to 6.0, and the representative results are included as follows in this paper.

Using the results of reference 1, the flow breakdown for this model in the 0.96- by 1.44-m (3.14- by 4.71-ft) insert was predicted at a momentum coefficient of approximately 2.1.

The effect of flow breakdown is shown in figure 4, which gives the variation of downwash angle (ϵ) with momentum coefficient (C_μ). The downwash angle in the insert follows the trend of the 2.44- by 3.66-m (8- by 12-ft) tunnel data (increasing ϵ with C_μ) up to C_μ of about 2.0, then the downwash in the insert decreases, rather than increases, as in the 2.44- by 3.66 -m (8- by 12-ft) tunnel or free air case. This same effect can be seen in figure 5, a plot of the variations of the lift coefficient of the tail (located 0.67-m [2.2-ft] behind the wing quarter chord) with C_μ. The 2.44- by 3.66-m (8- by 12-ft) test section data show an increase in tail lift coefficient with C_μ while the 0.96- by 1.44-m (3.14- by 4.71-ft) insert shows an increase up to a C_μ of a little less than 2.1 and then a decrease similar to the downwash variation in figure 4.

Lift coefficient variation with the angle of attack at momentum coefficients of 0.6, 1.02, 2.43, 3.44, and 6.01 are shown in figures 6a through 6e, respectively. These data are from the 2.44- by 3.66-m (8- by 12-ft) test section and the 0.96- by 1.44-m (3.14- by 4.71-ft) insert and are corrected by two available methods: 1) Glauert's classical method in which the model was represented by a pair of undeflected horseshoe vortices and 2) Heyson's method in which the model was represented by a single line of doublets which was allowed to linearly deflect downward until it strikes the floor (ref. 7 and 8). Thus, using Heyson's method, it is possible to correct tunnel velocity and consequently all forces, moments, and momentum coefficients. The proper wind tunnel interference factors were computed using the superposition techniques presented in reference 9. Reference 10 was used to compile a computer program suitable for the present model. These figures show that the lift coefficient of a jet flap wing model can be corrected reasonably well by Glauert's classical method at nearly all momentum coefficients examined during this study. Even at such a high value of momentum coefficient as 6.01, the classical wall correction method appeared to correct the wing data obtained in the 0.96- by 1.44-m (3.14- by 4.71-ft) insert to near free air configuration.

The lift data did not reveal any obvious indication of the adverse flow phenomenon at or near the predicted flow breakdown momentum coefficient. For this model, the flow breakdown effect is more clearly shown when the downwash at the tail is evaluated. Note, in figure 4, that the tail downwash variation in the 0.96- by 1.44-m (3.14- by 4.71-ft) insert with respect to the momentum coefficient, corrected by Glauert's method, diverge from the trend shown by that in the 2.44- by 3.66-m (8- by 12-ft) test section. The decreasing trend of the downwash with respect to the momentum coefficient in the 0.96- by 1.44-m (3.14- by 4.71-ft) insert indicates the incipient condition of flow around the model when the vortex-like secondary flow began to form on the floor. At the momentum coefficient of approximately 2.0, the location of this line of vortex is estimated, using the results of reference 1, to be in the neighborhood of 1.02-m (40-in.) downstream of the wing quarter chord. Since the tail was at 0.67-m (26.4-in.) downstream of the wing, the tail started to feel the upwash due to the vortex on the floor; thus reducing the downwash beyond a momentum coefficient of 3. The condition continues to affect the downwash by a further decrease as the momentum coefficient increases with the forward movement of the vortex-like flow.

If there was no flow breakdown in the insert, the wall correction applied to the insert data should be able to make the corrected insert data coincide with those of the 2.44- by 3.66-m (8- by 12-ft) test section. Therefore, subtracting from the 2.44- by 3.66-m (8- by 12-ft) data the increment of wall correction to the 0.96- by 1.44-m (3.14- by 4.71-ft) insert can provide an estimated expected trend of data in the insert, free from the flow breakdown phenomenon. This expected trend is shown by a dashed line in figure 4. Interestingly enough, Heyson's method applies an excessive correction to the insert data, but it seemingly accounted for the adverse effect due to the vortex-like secondary flow on the floor and walls.

CONCLUSION

This research resulted in identifying one of the most difficult aspects of wind tunnel testing of a powered V/STOL model. It is the low forward speed test limit, and is termed "flow breakdown" phenomenon. When the powered V/STOL model is tested in a solid wall wind tunnel, the flow in the vicinity of the model becomes grossly different from that of free air at some low forward speed. When this speed is reached, a vortex forms on the floor and walls. This secondary flow is caused by the interaction of the model wake and tunnel boundary layer. It affects the model's aerodynamic characteristics in such a fashion as to negate their reliability as correctable wind tunnel data.

The results with the jet flap wing show that the criterion in reference 1 for rotors is applicable to any powered lift system where the power is applied across the span of the lifting system. However, when one is testing a model with discrete concentrated lift sources, such as lift jets, the criterion of reference 1 will not work. Furthermore, since the lift engines can have a myriad of possible locations it would appear very difficult to develop a simple criterion to cover all configurations. In this case a possible solution would be to place tufts on the floor and side walls of the tunnel and observe them to discover the onset of a vortex-like flow that will be parabolic in shape opening downstream. Reference 11 presents a detailed discussion on this subject, and it established the low speed test limit due to the flow breakdown for lift jets. The test limit established for the present lift jet model in this report appears to agree with that shown in reference 11 within 5 percent of their value of the product of velocity ratio and nozzle height/diameter ratio.

Many other investigators have studied this phenomenon, and the results of some of them are found in references 12 through 14. The theoretical treatment of this phenomenon, using a rotor as the V/STOL model was reported in reference 15. Reference 16 established the flow breakdown criterion as the model wake impingement distance downstream of the model for lift jets and fan supported V/STOL models. Limited available information appears to verify this criterion. However, it is strongly emphasized that examination of all six aerodynamic components recorded during transition wind tunnel tests of a powered V/STOL model is necessary to identify the low speed test limit for that model caused by the "flow breakdown" phenomenon.

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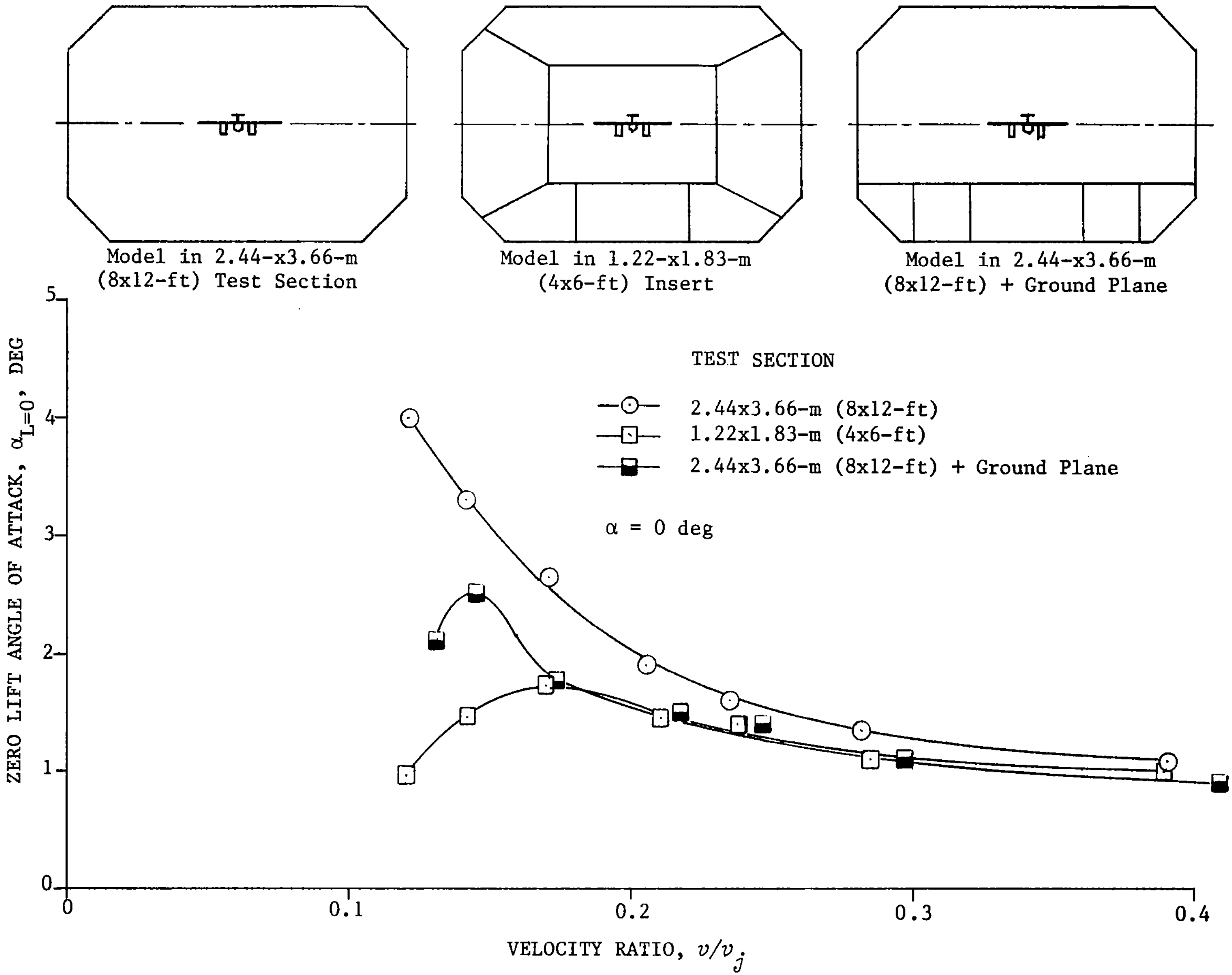


FIGURE 1. - Zero Lift Angle of Attack Variation with Velocity Ratio for Lift Jets.

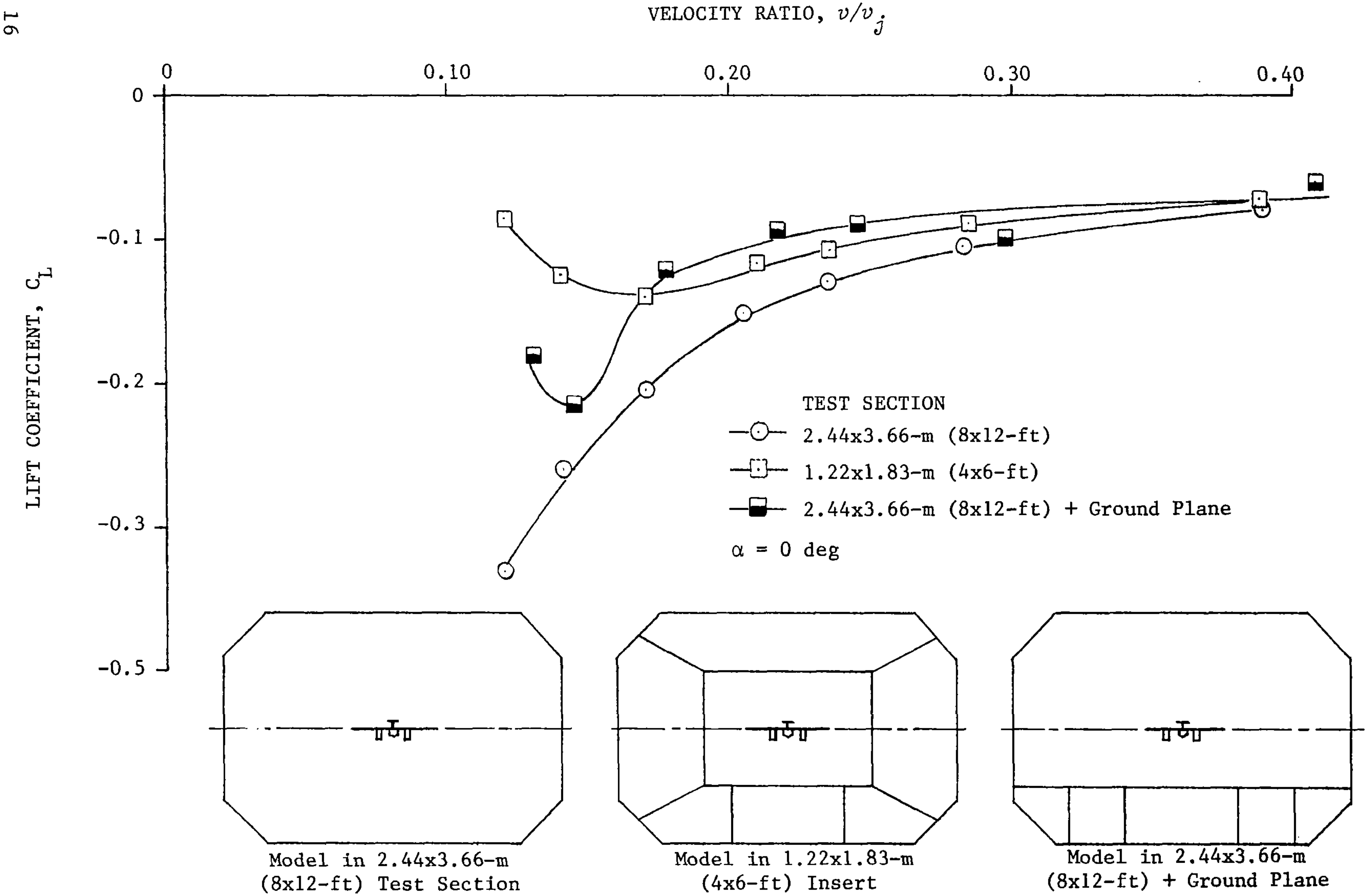


FIGURE 2. - Lift Coefficient Variation with Velocity Ratio for Lift Jets.

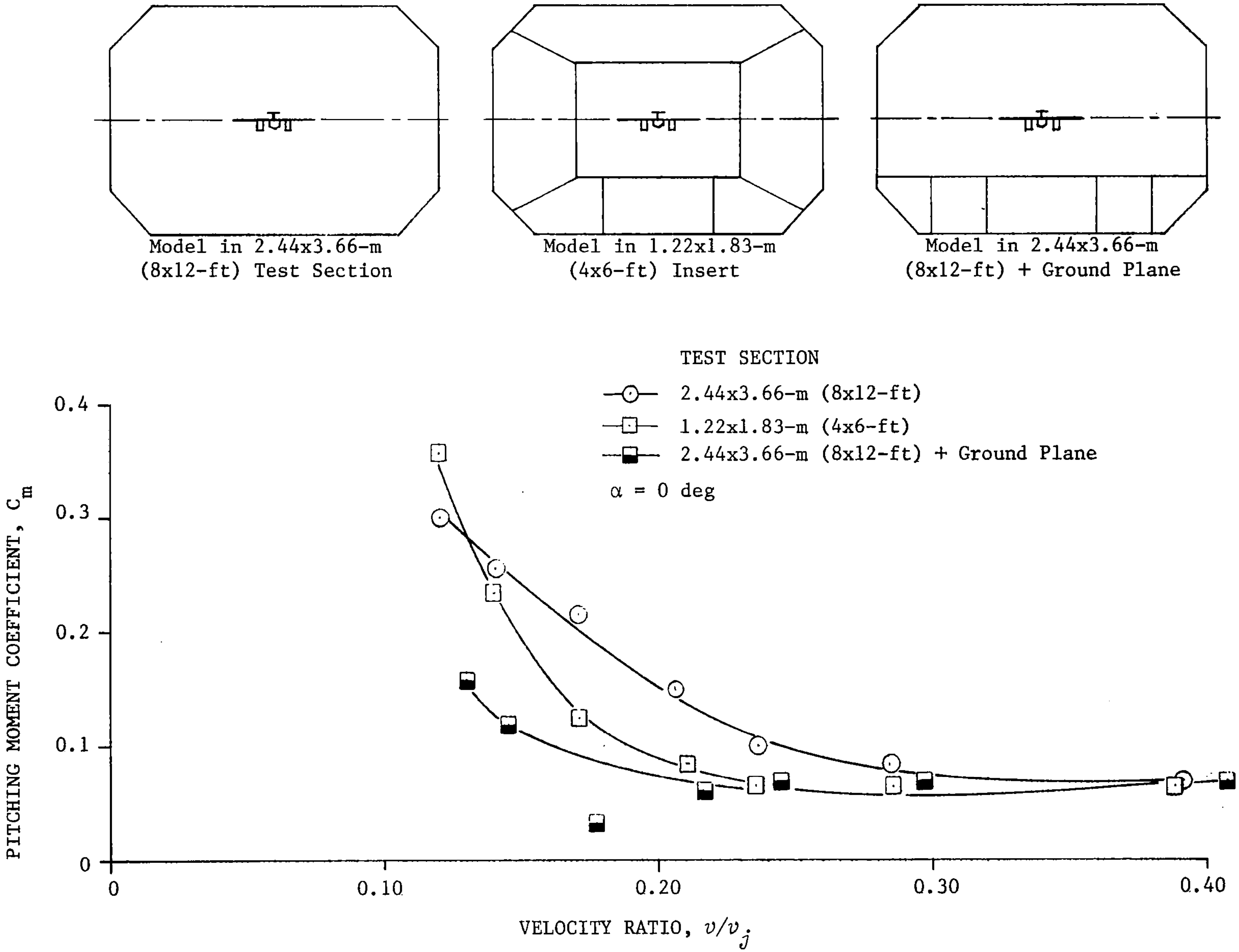


FIGURE 3. - Pitching Moment Coefficient Variation with Velocity Ratio for Lift Jets.

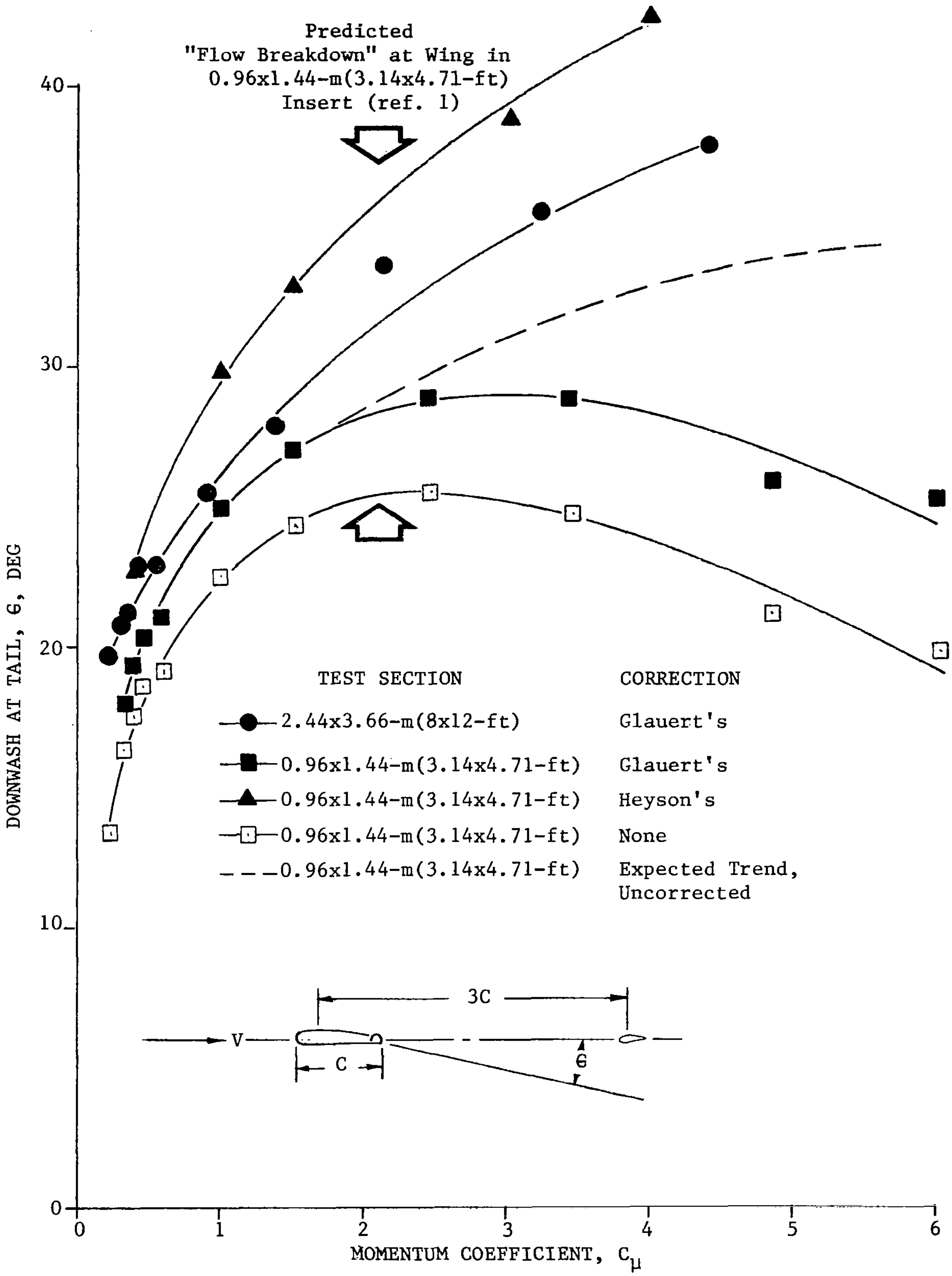


FIGURE 4.-Variation of Downwash Angle with Momentum Coefficient for Jet Flap Wing.

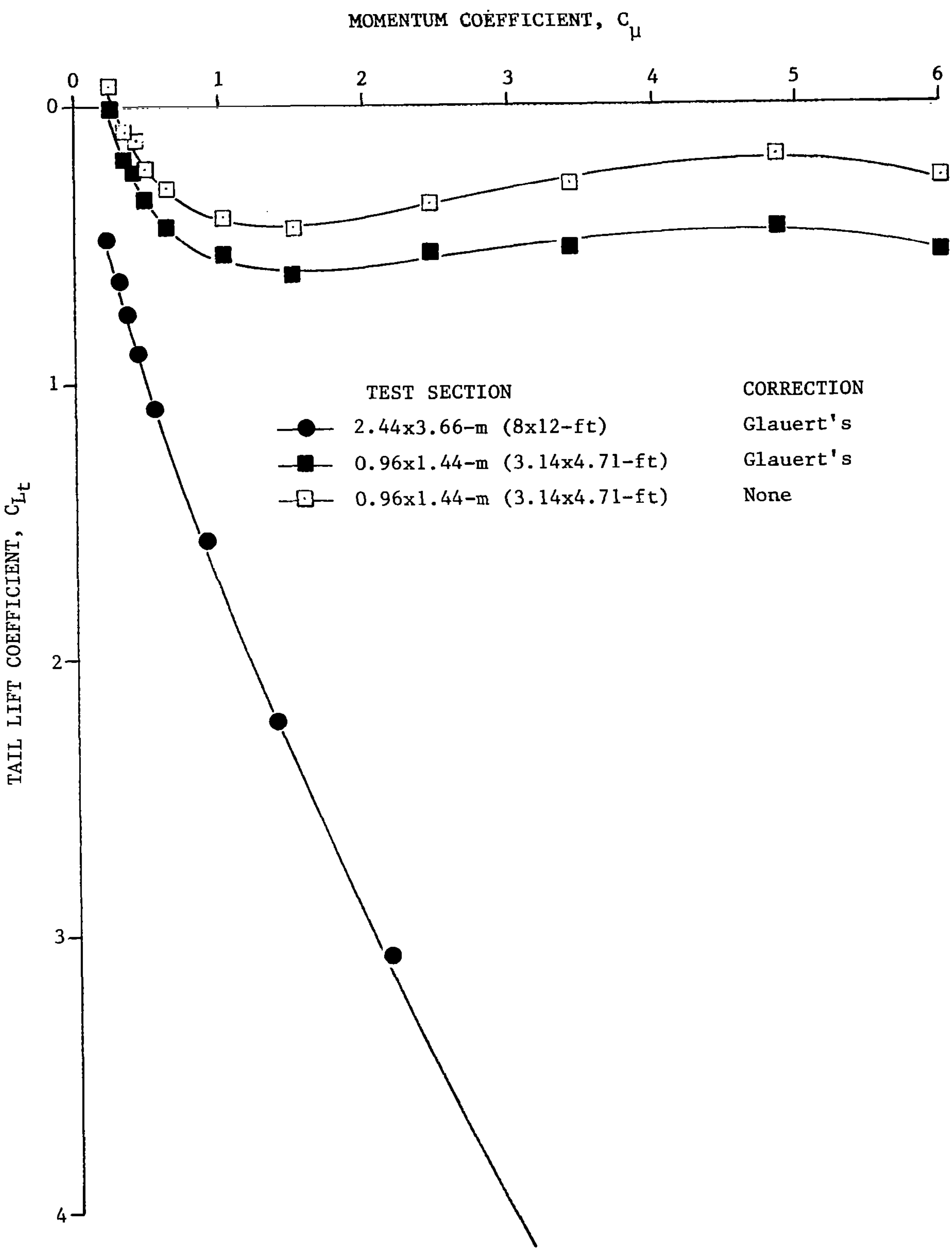
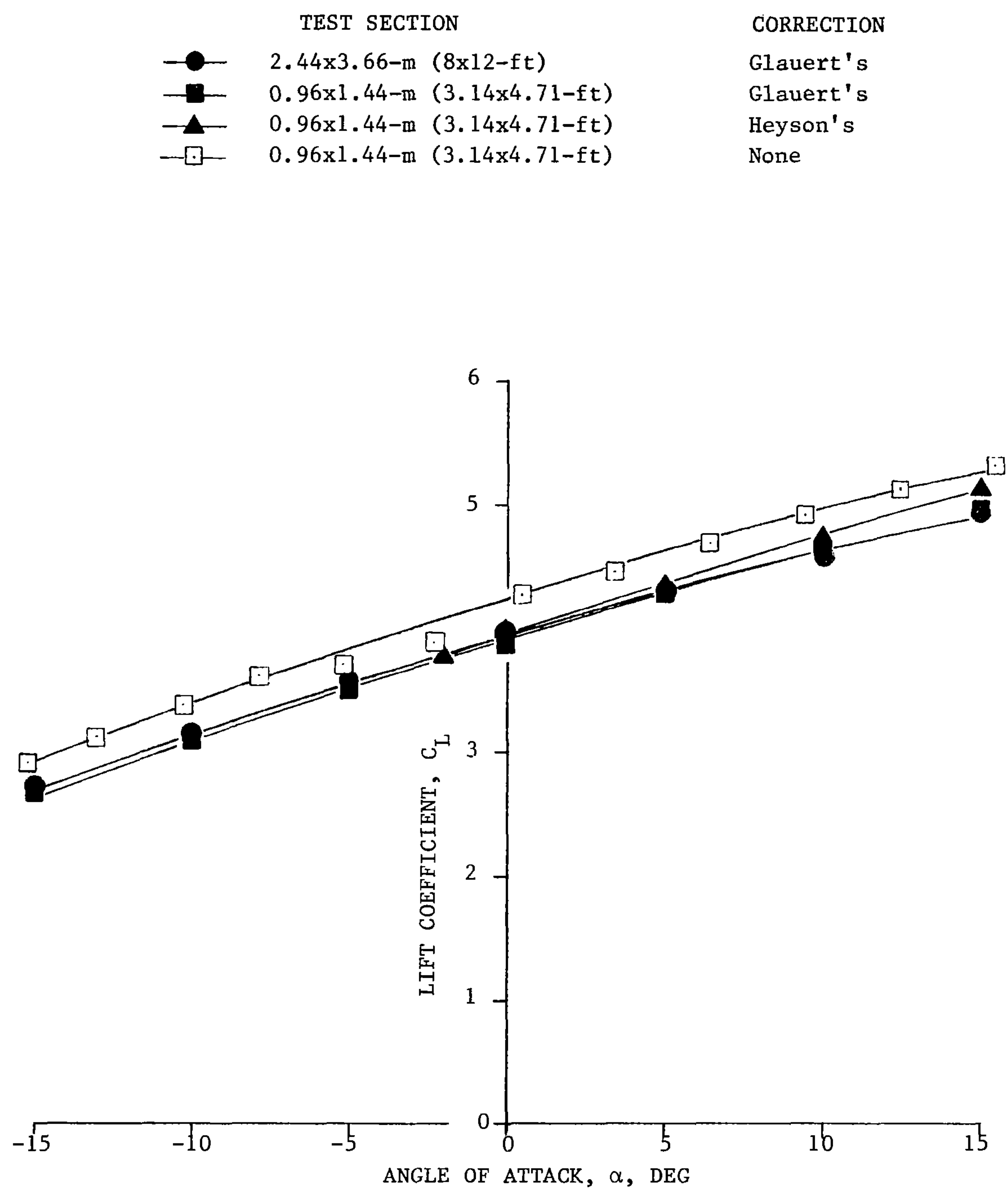
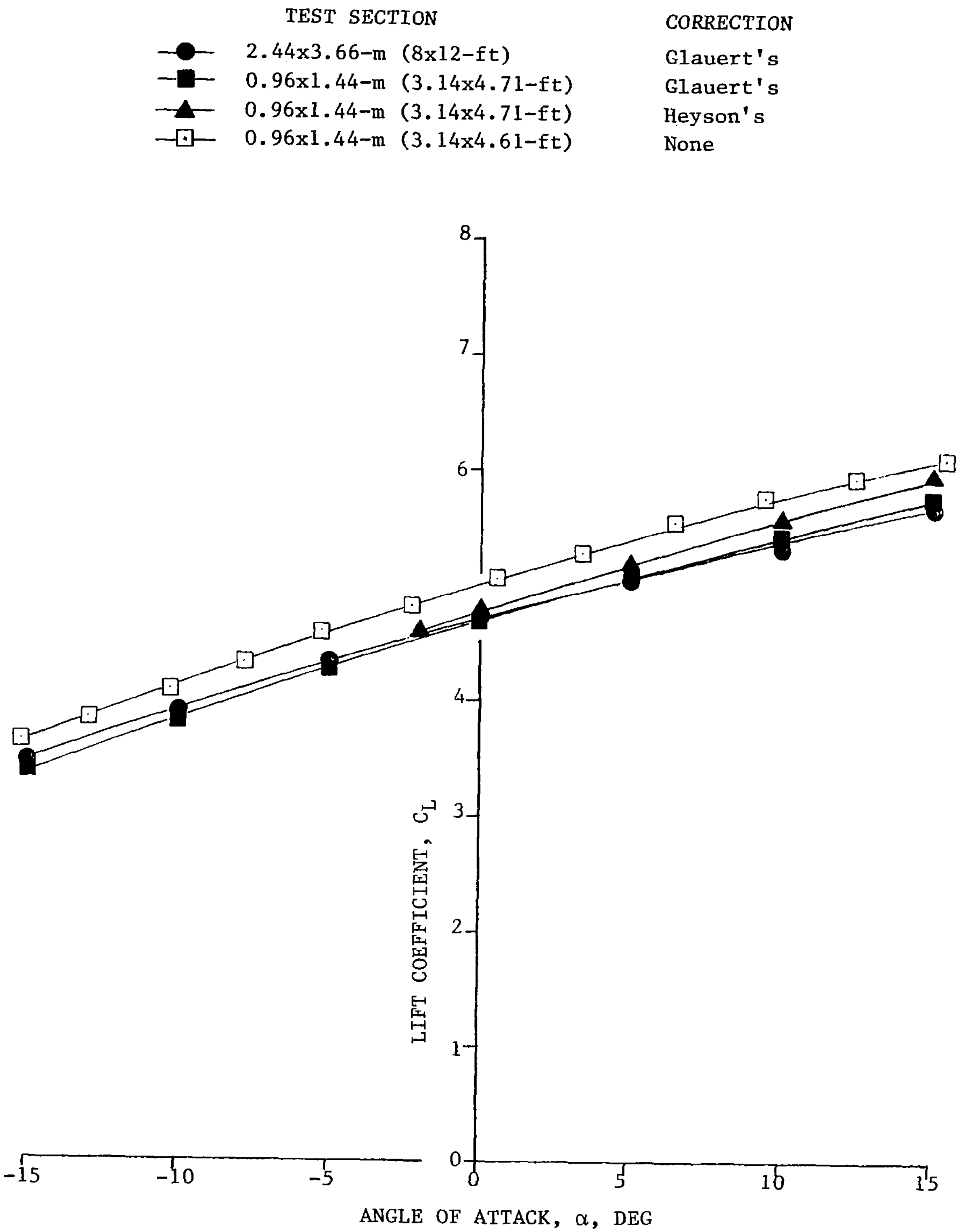


FIGURE 5.-Variation of Tail Lift Coefficient with Momentum Coefficient for Jet Flap Wing.



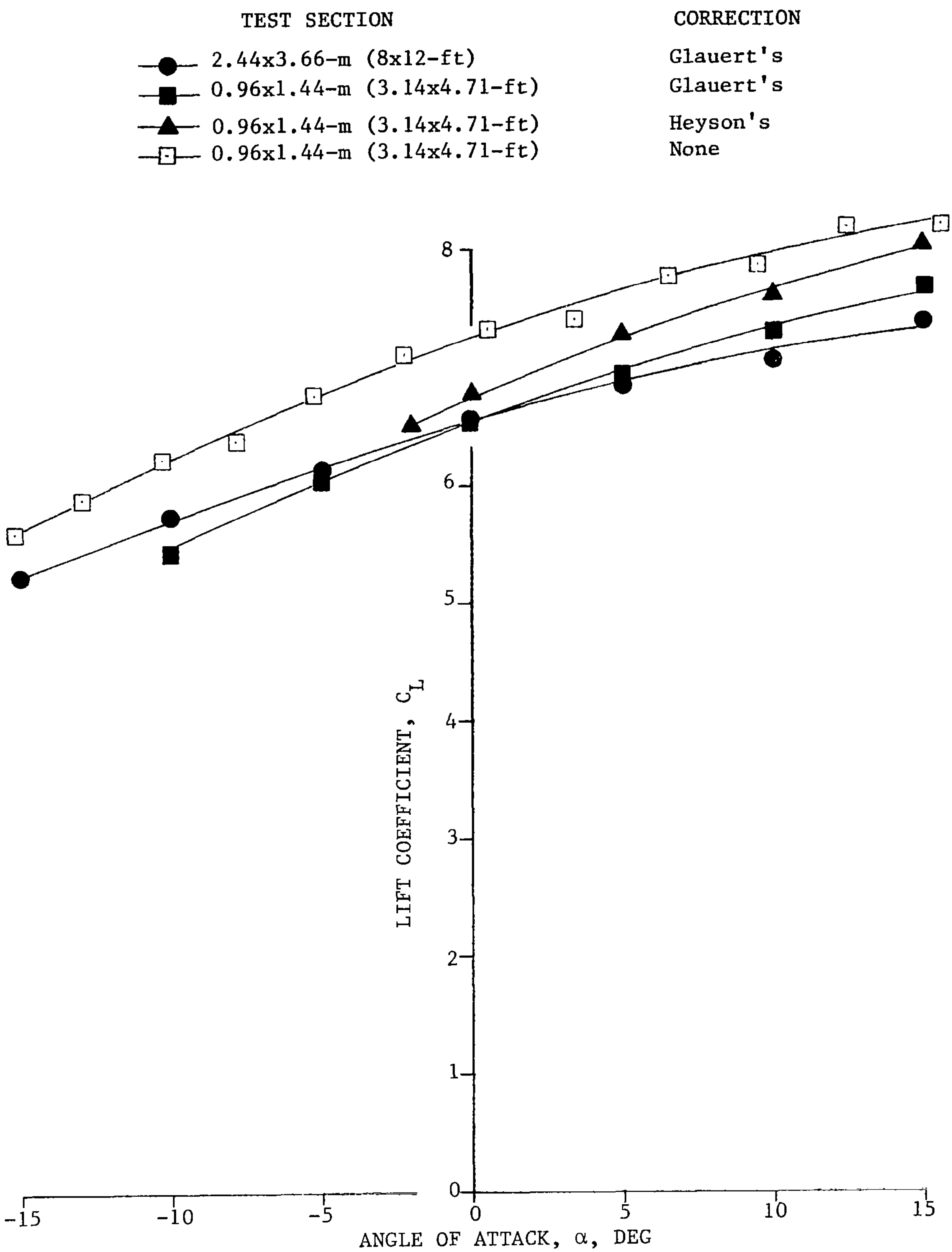
(a) $C_\mu = 0.6$

FIGURE 6.-Lift Coefficient of Jet Flap Wing.



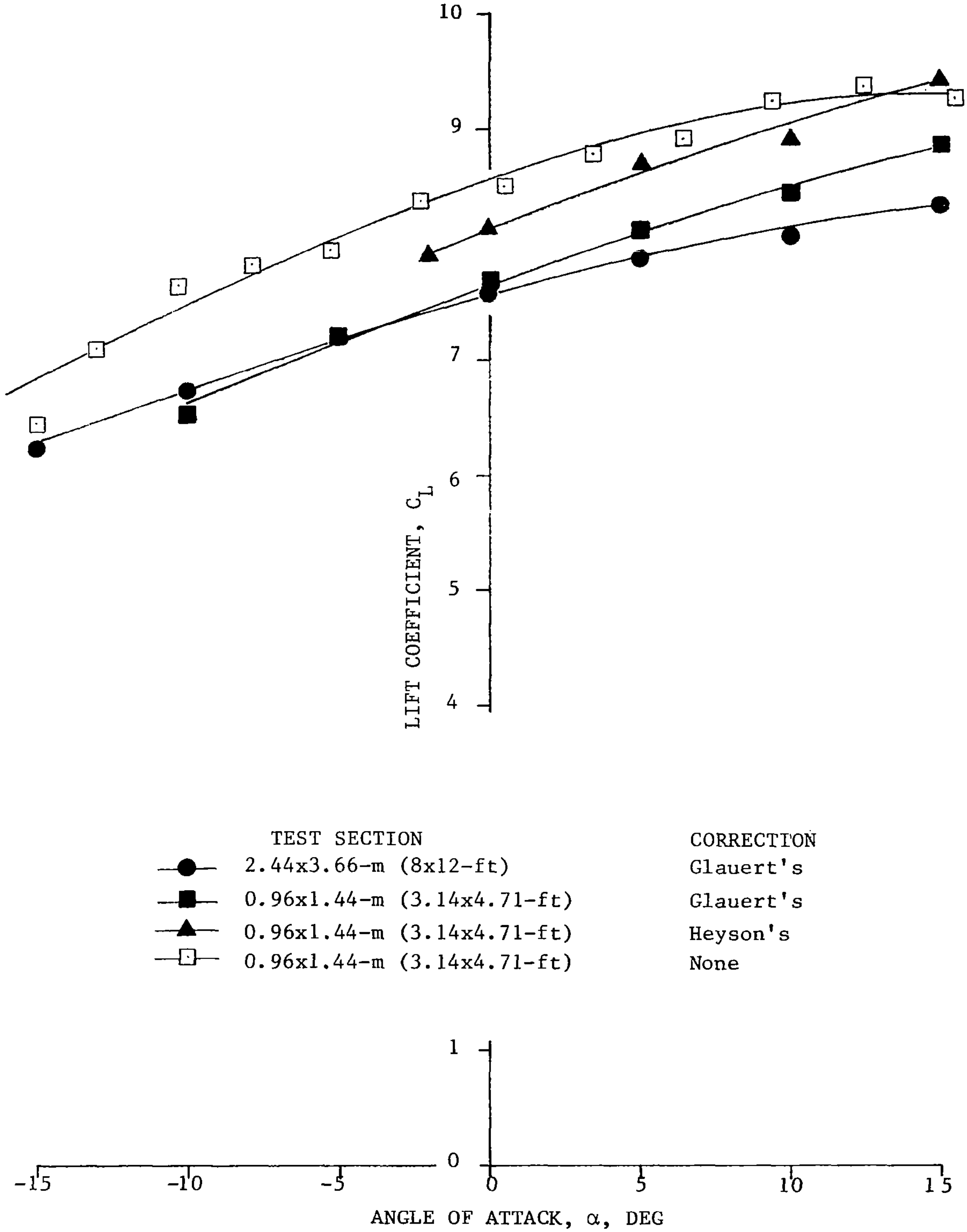
(b) $C_\mu = 1.02$

FIGURE 6.-Continued.



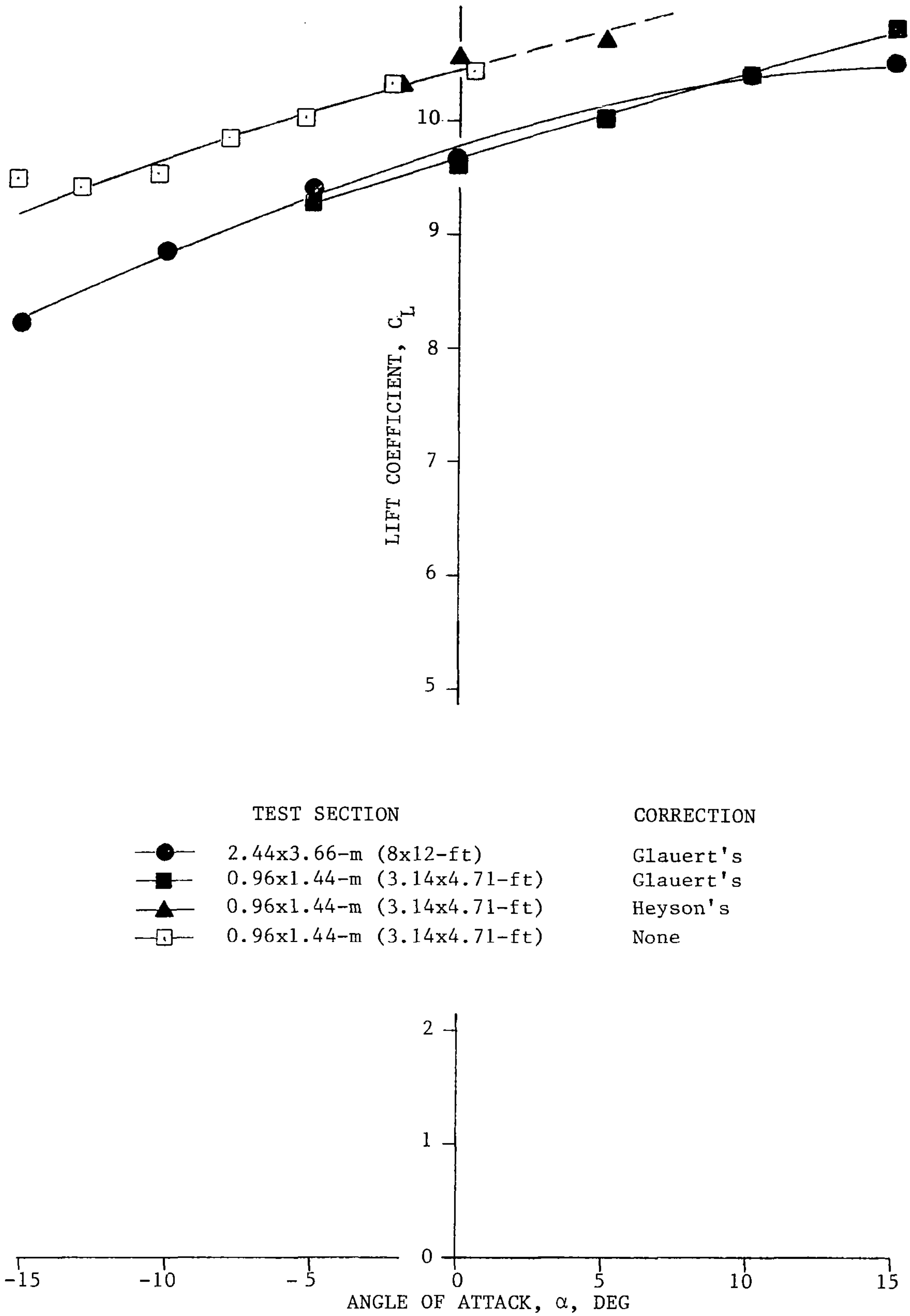
(c) $C_\mu = 2.43$

FIGURE 6.-Continued.



(d) $C_\mu = 3.44$

FIGURE 6.-Continued.



(e) $C_\mu = 6.01$

FIGURE 6. - Concluded.

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16. Abstract

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The V/STOL low speed test limit was first recognized using rotors as powered models. Lift jets were examined as a representative model for concentrated lifting systems.

The lift-jet low-speed test limit obtained during the present research confirmed the criteria established by other researchers. The jet-flap wing low-speed test limit was found to be predictable using the results obtained earlier with the rotors.

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