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UNSUCCESSFUL CONCEPTS
FOR AIRCRAFT WAKE VORTEX MINIMIZATION

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ABSTRACT

This report describes exploratory concepts investigated by the National Aeronautics and Space Administration to achieve a reduction in the vortex-induced rolling upsets produced by heavy aircraft trailing vortexes. The initial tests included the use of mass injection, oscillating devices, wingtip shape design, interacting multiple vortexes, and end plates. Although later refinements of some of these concepts were successful, initial test results did not indicate a capability of these concepts to significantly alter the vortex-induced rolling upset on a following aircraft.

INTRODUCTION

The National Aeronautics and Space Administration has been conducting an extensive program to find methods for the reduction of the operational constraints imposed by trailing vortexes from large jet aircraft during terminal-area operations. The research program has involved model tests (refs. 1 to 11), theoretical studies (refs. 12 to 16), and flight tests (refs. 17 to 20) of concepts and techniques that would reduce the rolling upset on a smaller following aircraft. During the course of the research program, several areas were identified as having some success in reducing the upset on a following aircraft. The injection of turbulence into the vortex has been shown to alter the vortex structure by premature aging and dissipation (refs. 17 and 21). The combined effects of the turbulence and momentum impulse from jet engines have been shown to change the vortex structure (ref. 22). In addition to turbulence injection, the far-field structure of trailing vortexes can be affected by alteration of the span-load distribution to shed multiple vortexes (refs. 9, 23, and 24), which mutually interact to reduce the vortex strength. The combined effects of turbulence injection and span-load alteration were investigated through the use of spoilers (refs. 9, 10, 20, and 25).

During the development of these promising techniques, several concepts and ideas investigated were shown to alter the trailing vortex structure in varying degrees without significantly altering the upset experienced by a following aircraft. This paper summarizes the numerous concepts investigated that did not meet the primary program objective of achieving a reduction in the vortex-induced rolling upset on a following aircraft.

SYMBOLS

b_f	wingspan of following model used to measure rolling moment, m
b_g	wingspan of vortex generator model, m
c	local wing chord, m
$C_{\ell,f}$	rolling-moment coefficient on following model, $2M/\rho S_f b_f V_0^2$
$C_{\dot{m}}$	mass rate coefficient, $\dot{m}/\rho S_g V_0$
C_μ	momentum coefficient, $2\dot{m}V_j/\rho S_g V_0^2$
$\dot{m}$	mass rate, kg/s
M	measured rolling moment, N-m
r	distance from center of vortex, m
S_f	wing area of following model used to measure rolling moment, m^2
S_g	wing area of vortex generator model, m^2
V_j	jet velocity, m/s
V_0	free-stream velocity, m/s

V_θ tangential velocity in a vortex, m/s
X downstream distance behind the vortex generator model, m
ρ fluid density, kg/m^3

PRESENTATION OF RESULTS

In general, the investigation of a particular concept began with a preliminary evaluation through the flow visualization of the vortex pattern with and without the vortex-alleviation concept. All of the test facilities used in the vortex minimization program (wing tunnels and water and air tow facilities (ref. 26)) provided an adequate visual assessment of the vortex alleviation capabilities of a particular concept. If the initial flow visualization indicated a change in the vortex structure, a quantitative assessment of the effectiveness was undertaken. The quantitative assessment was obtained by detailed velocity measurements or, as described in reference 26, by a determination of the vortex-induced rolling moment imposed on a trailing wing model.

It was assumed during flow-visualization studies that, in order for a concept to be effective in reducing the vortex rolling upset on a following aircraft, a large visual change in the vortex flow would be detectable. Several concepts were eliminated from further consideration on their inability to visually alter the vortex flow pattern. Conversely, some concepts were found to visually alter the flow while causing a measurable change in the vortex velocity distribution, without significantly reducing the rolling upset on a trailing wing. Additionally, certain techniques that were evaluated on straight wings were found to be less effective when applied to the multiple, diffuse vortex system shed by a flapped, swept, large transporttype wing.

Many of the concepts described in this paper, although unsuitable for minimization of the vortex hazard behind a large transport aircraft, may have other vortex-related aerodynamic benefits. Two possible benefits are the reduction of vortex-induced helicopter blade loads caused by the impingement of the preceding-blade vortex (blade slap) and the reduction of aircraft cruise drag. It may be possible to further refine some of the techniques described to achieve an acceptable reduction in vortex-induced upset. In fact, some of the unsuccessful concepts explored were later refined to the stage of successful application.

The concepts and techniques describe have been divided into two broad categories for discussion: (1) active devices and (2) passive devices. The active devices attempted to alter the vortex by emitting either a sheet or jet of air at various positions on the wing, or through oscillating devices to create an instability in the shed vortex sheet. The passive devices attempted to alter the vortex by controlling or altering the flow about the wing.

Active Devices

Blowing Concepts

Use of mass injection or air blowing was explored in many different forms. The simplest form of blowing consisted of an air jet located so as to inject air in the vortex axial direction. This concept, as it was evaluated on a straight wing, is shown in figure 1. Flow visualization studies conducted during the initial evaluation of this concept (ref. 27) indicated a visual alteration in the vortex structure as blowing increased. Hot-wire anemometer measurements of the vortex tangential velocity distribution, with and without blowing, are shown in figure 2. The data indicate a significant reduction in peak tangential velocity; however, rolling-moment measurements of the vortex-induced roll on a following model, using the technique described in reference 26 and shown in figure 3, indicated no apparent reduction as blowingincreased. Although a significant reduction in the vortex imposed rolling moment could not be achieved with this concept, the achievable reduction in peak vortex tangential velocity (fig. 2) may be significant when applied to the vortex impingement blade-slap problem of helicopters.

The jet blowing concept was evaluated on a swept-wing transport model. It was envisioned that the jet would be provided by a small engine located on the wingtip. The wingtip-mounted engines, shown on the transport model in figure 4, were small compared to the propulsion engines and would provide only about 8 to 10 percent of the thrust required for cruise. No detectable reduction in vortex-imposed rolling moment was measured during the evaluation of the wingtip-mounted engines. Because the large mass flow and thrust levels of the jet engines of transport aircraft have been shown to alter the character of the trailing vortex system (ref. 22), one of the reasons for the inability of the wingtip-mounted engines (fig. 4) or the jet blowing (fig. 1) to reduce the vortex hazard was the relatively low mass flow and momentum coefficients used for these tests ($C_{\dot{m}} = 0.0008$ and $C_{\mu} = 0.02$).

Several techniques for blowing a sheet of air from a wingtip to inhibit the formation of the vortex have been tried. Figure 5 illustrates two techniques that were evaluated on a straight-wing model to inhibit the wingtip vortex formation. Figure 5(a) illustrates the means by which a chordwise sheet of air was blown downward from the wingtip, while figure 5(b) shows how a tube was extended from the trailing edge of the wingtip to blow a sheet of air downward in the spanwise direction. Vortex-induced rolling-moment measurements obtained on a following model 7.5 span lengths behind the generating model, with these two techniques, are shown in figure 6. Spanwise blowing was found to be the most effective. The results of a detailed study of the spanwise blowing concept (fig. 5(b)) are described in reference 28. As reported in reference 28 and shown in figure 7, the spanwise blowing provided a significant improvement in the wing lift/drag ratio.

The spanwise tip blowing concept was evaluated on a large jet transport model in the manner illustrated in figure 8. The spanwise blowing concept was found to provide an improvement in the clean wing (cruise configuration) lift-to-drag ratio of the jet transport model, as shown in figure 9. However, the measured improvement in lift-to-drag ratio was not as large as that found for the straight-wing tests of reference 28. In addition, no significant change in the lift-to-drag ratio of the flaps-down (landing approach) configuration of the transport model due to spanwise blowing was noted. The vortex-induced rolling moment on a small-wing model ($b_f/b_g = 0.182$) behind the transport model, for both the flap-down and clean-wing configuration, as a function of increased spanwise blowing is shown in figure 10. The data show a small reduction in rolling moment as blowing is increased for the cruise configuration; however, no effect was noted for the flap-down configuration. Because the flap-down configuration creates a complex vortex structure made up of wingtip and flap vortexes, it was expected that spanwise blowing at only the wingtip might not influence the large flap vortex. Some tests were conducted using a crude implementation of the spanwise blowing concept on the outboard edges of the flaps. These tests did not show a reduction in rolling moment for the flap-down configuration.

Other variations of blowing techniques have been investigated and are illustrated in figure 11. Hot-wire measurements behind these configurations (ref. 6) indicated a reduction in the peak tangential velocity for the cruise configuration, but no reduction was noted for the flaps-down configuration. The inability of the configurations shown in figure 11 to alter the vortex structure for the flap-down configuration is probably due to the low momentum and mass flow used and the implementation of these concepts at the wingtip.

Oscillating Devices

Introduction of a cyclic disturbance into the shed vortex sheet was investigated in an attempt to trigger a dynamic instability within the flow field that would lead to its collapse. Velocity measurements of the jet mass-injection technique (fig. 2) indicated an ability to alter the details of the vortex core, and effects of cyclically varying the jet by turning it on and off with a highly responsive valve were investigated. The jet could be pulsed to provide a jet on time of 2 to 14 wingspans behind the model and a jet off time of between 2 and 60 span lengths behind the model. The mass flow and momentum of the jet for the time the valve was open were similar to those used in the test setup of figure 1. The pulsating jet did not appear to induce a visual instability in the vortex.

Tests were conducted of a small oscillating spoiler on a large transport model, as illustrated in figure 12. The spoiler could be cyclically deployed so as to introduce a disturbance wave of 1.5 to 13 spans behind the vortex generator model. This spoiler was located in a different position and was smaller than the successful spoiler concept reported in reference 25. The oscillating spoiler was found ineffective in altering the vortex pattern shed by the transport model in a flaps-down landing approach configuration. Apparently, because of its position on the wing, the disturbance shed by the spoiler was not being introduced into the vortex system for the flap-down configuration. The oscillating spoiler altered the vortex pattern shed by the transport model in a flaps-up cruise configuration, as illustrated in figure 13. While the spoiler was deployed, the vortex core diameter was apparently increased; and while the spoiler was down, the vortex core was unaffected. As shown in figure 13, the oscillating spoiler produced a vortex of varying core diameter immediately behind the aircraft. The effects of the spoiler were washed out beyond about six spans behind the aircraft. The rolling moment on a trailing aircraft model was found to be reduced over the test range of 6 to 45 spans behind the transport aircraft; however, the reduction was independent of the frequency of oscillation. The same reduction also could be achieved by leaving the spoiler in the deployed position. Tests were unsuccessful in exciting a vortex instability.

These two oscillating techniques introduced longitudinal disturbances in the vortex. Cyclic variation of the load distribution, so as to oscillate the centroid of vorticity of the wing to produce a variation of the vortex spacing and provide a lateral disturbance, has been investigated. The results of these tests are presented in reference 29. As reported in reference 29, the Crow instability (ref. 30) can be initiated. It is felt that for the modest shifts in load distribution that can be obtained on operational aircraft, the shift in vortex spacing would be small and the time required for the instability to continue to linking and vortex breakup would be too long to significantly alter the vortex hazard.

Passive Devices

The use of end plates and variations of the end-plate concept have been investigated. Figure 14 shows three end-plate concepts evaluated. During flow visualization studies, the basic end plate (fig. 14(a)) was found to slightly inhibit the rollup of the vortex sheet shed by the wing; however, after the rollup was complete, the vortex structure did not appear to be different than without the end plate. A variant of the end plate is the body of revolution (fig. 14(b)) that had an opening in the center to allow a mixing of the flow which passed through the center with the exterior flow. This device was observed to alter the vortex only slightly. To increase the mixing between the fluid that passed through the body of revoluion and exterior flow, turning vanes (fig. 14(c)) were placed inside the body of revolution to impart a swirl opposite the vortex. The turning vanes did not visibly alter the vortex.

A very efficient end-plate design known as a "winglet," which was developed for improved cruise efficiency, was evaluated to determine its effect on the trailing vortex structure. Figure 15 is a photograph of winglets as installed on the large jet transport model. Results indicate that for their intended design a reduction of cruise drag of about 8 percent was achieved on a second-generation transport model. Tests conducted in the Langley Research Center's Vortex Research Facility (ref. 26) indicated that the winglets reduced the rolling moment on a trailing wing 10 to 15 percent for the transport in a clean-wing cruise configuration. Tests conducted with the transport model in a flaps-down landing approach configuration showed no reduction of the vortex system due to the wingtip-mounted winglets. No attempt was made to implement the winglets on the flap system of the transport aircraft.

Reduction of the loading gradient at the wingtip has been investigated using the wingtip design (ogee tip) shown in figure 16. Figure 17 shows the reduction in peak tangential velocity measured at one span behind the ogee tip. Simple strip-theory calculations from the vortex velocity distribution (fig. 17) of the vortex-imposed rolling moment on a trailing aircraft showed very little reduction in rolling moment. Consequently, the concept was not considered suitable for minimization of the wake vortex hazard. However, the ogee tip, along with other concepts that reduce the vortex-peak tangential velocity without reducing significantly the vortex imposed rolling moment on a trailing aircraft, may have other vortex-related applications. In particular, the blade-slap problem for helicopter operations is related to the passage of a rotor blade through the large velocity gradients associated with the vortex from a preceding blade. The ogee tip has shown some promise in reducing helicopter blade slap.

Another technique investigated for vortex alleviation was to extract rotational energy from the vortex system by trailing a set of large fixed-crossed blades attached to the wingtip to inhibit the vortex rotation (fig. 18). Velocity distributions obtained 2.5 spans behind the crossed blades are shown in figure 19. The alteration in vortex velocity distribution (fig. 19) would not produce a significant reduction in the vortex-imposed rolling moment on a trailing aircraft.

Initial tests of wingtip devices and vortex generators to produce multiple vortexes that will interact have been conducted (fig. 20). Flow visualization studies on a straight-wing model, of the two techniques shown in figures 20(a) and 20(b), indicated little beneficial effect from the interaction of multiple vortexes. Rolling-moment measurement obtained on a model behind the multiple vortex system, shown in figure 20(c), indicated no reduction in the vortex hazard. Later, more successful tests of the interaction of multiple vortex systems, obtained by alteration of the lift distribution (ref. 24), indicate a requirement to maintain the proper vortex strength and spacing to produce successful interactions of vortexes. The theoretical efforts described in reference 16 provide an indication as to the required relationship for spacings and strengths of multiple vortexes to achieve vortex merging and dissipation.

CONCLUDING REMARKS

During the conduct of the NASA program to develop vortex minimization schemes, numerous concepts were evaluated that were not capable of achieving a significant reduction of the vortex-imposed rolling moment on a trailing aircraft. Early tests indicated that the use of mass injection at momentum and mass flow levels significantly lower than that used for cruise propulsion would not significantly reduce the vortex hazard. Initial tests also indicated that the beneficial interaction of multiple vortexes required the proper relationship between spacing and strength. Although several concepts were not capable of achieving a significant reduction of the vortex hazard, they were shown to be capable of reducing the induced drag for cruise performance improvement. Tests to date have been unable to excite a dynamic instability of the vortex system by using a cyclic-disturbance input.

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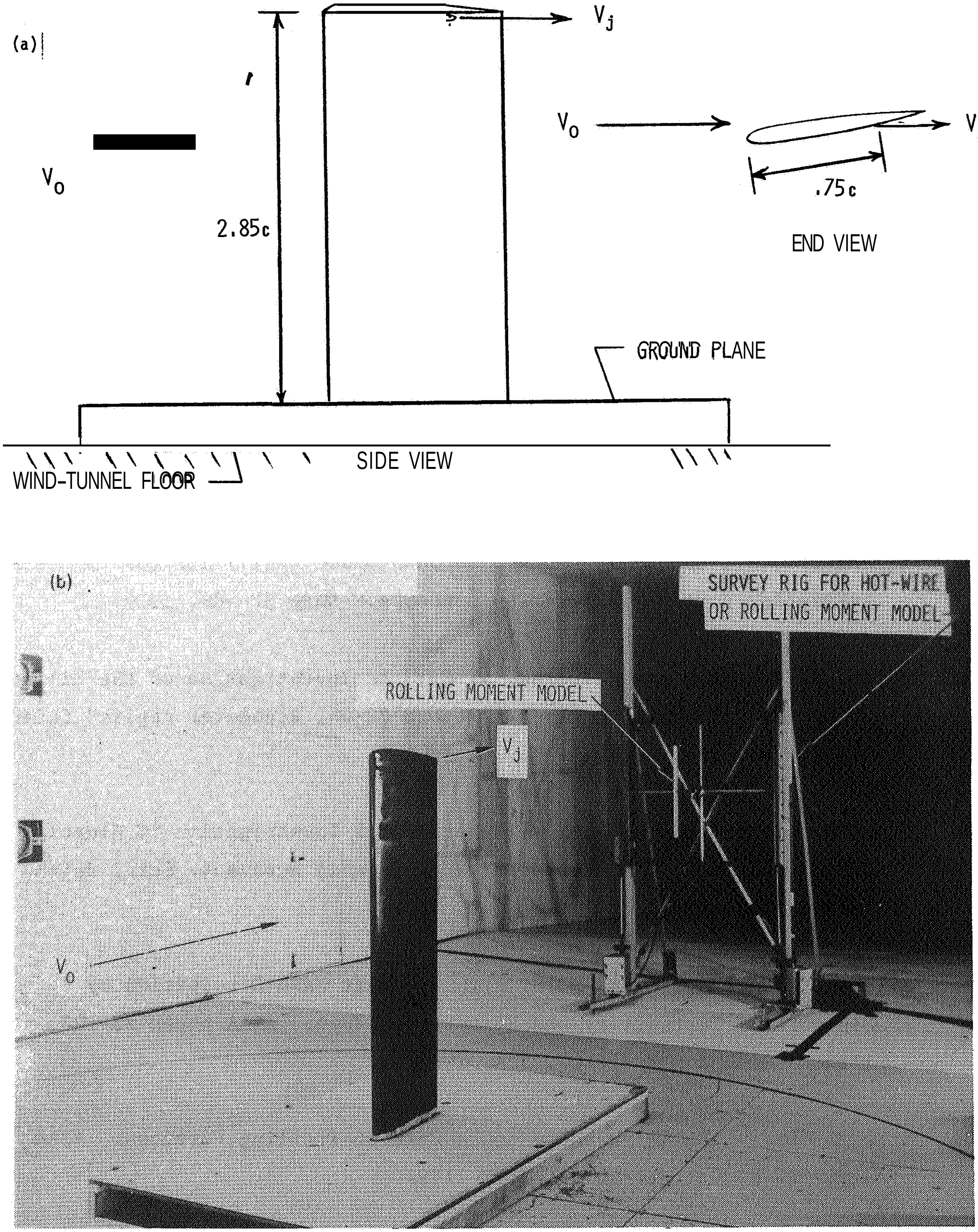

Figure 1.––Model and test setup used for the evaluation of axial mass injection. (a) Diagram of model. (b) Photograph of test setup.

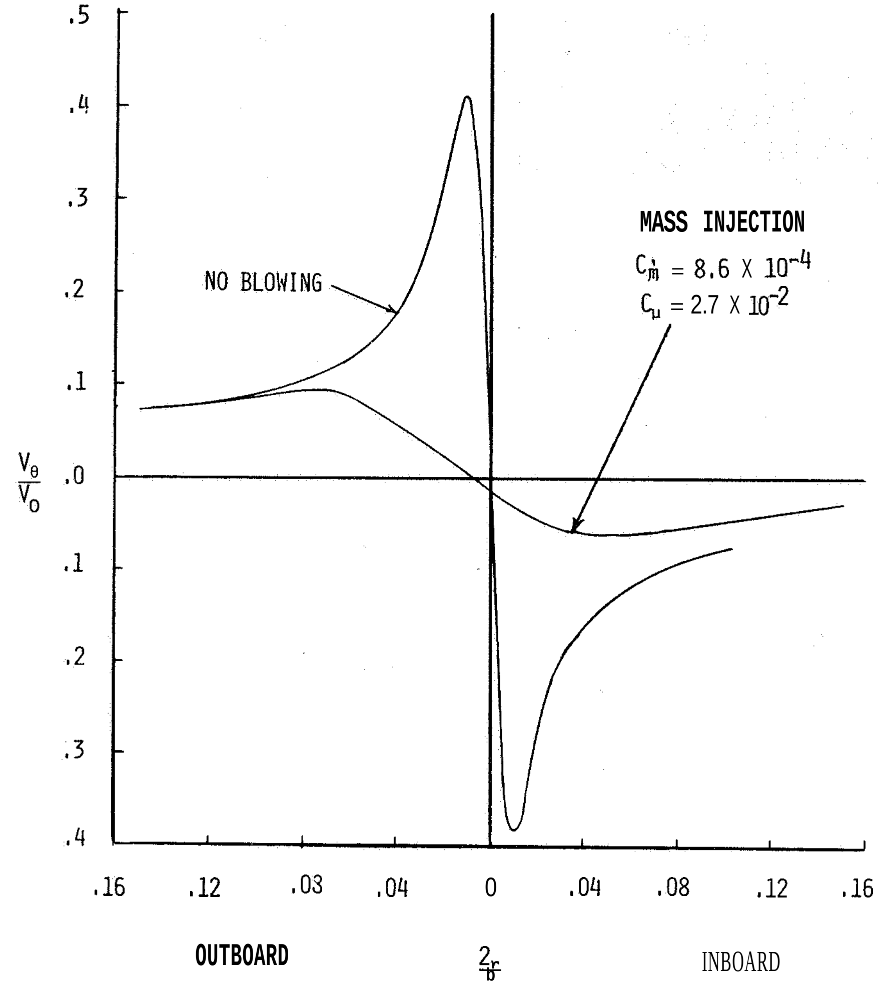

Figure 2.--Effect of mass injection on vortex velocity distribution.

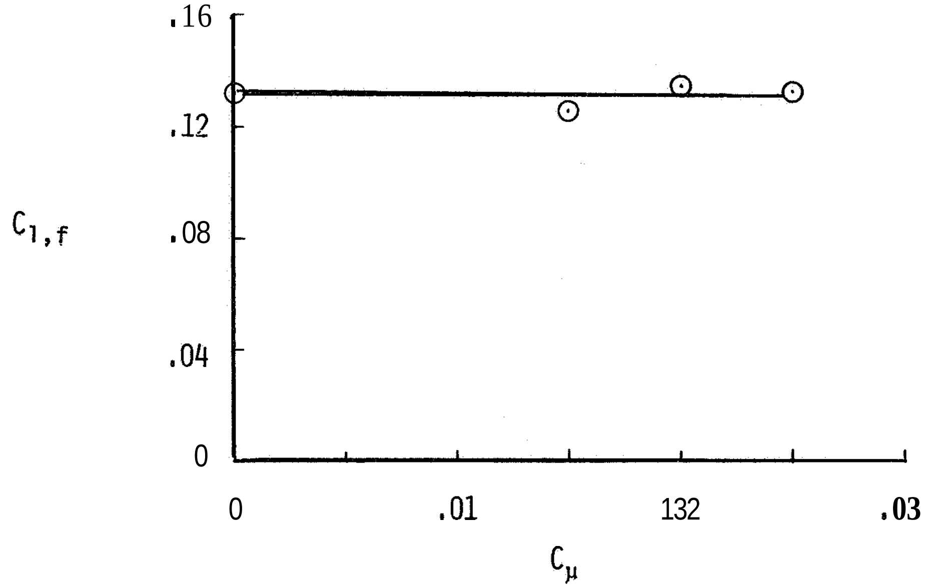

Figure 3.--Measured rolling moment on a following wing model as mass injection is increased. Lift coefficient = 0.73 on the vortex generator; $b_f/b_g = 0.18$; $X/b_g = 6.67$.

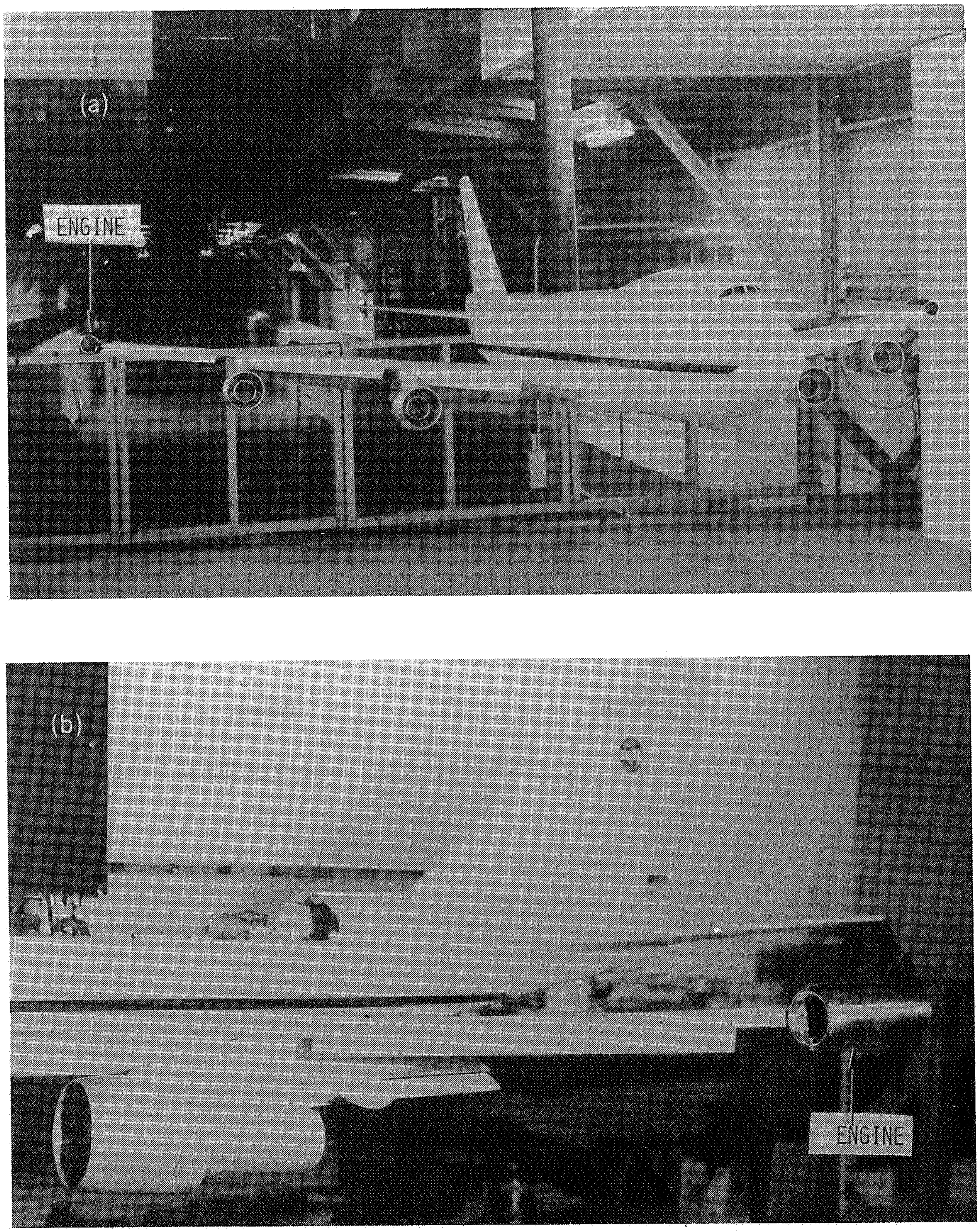

Figure 4.--Photographs of wingtip-mounted engines on transport model. (a) Front view. (b) Side view.

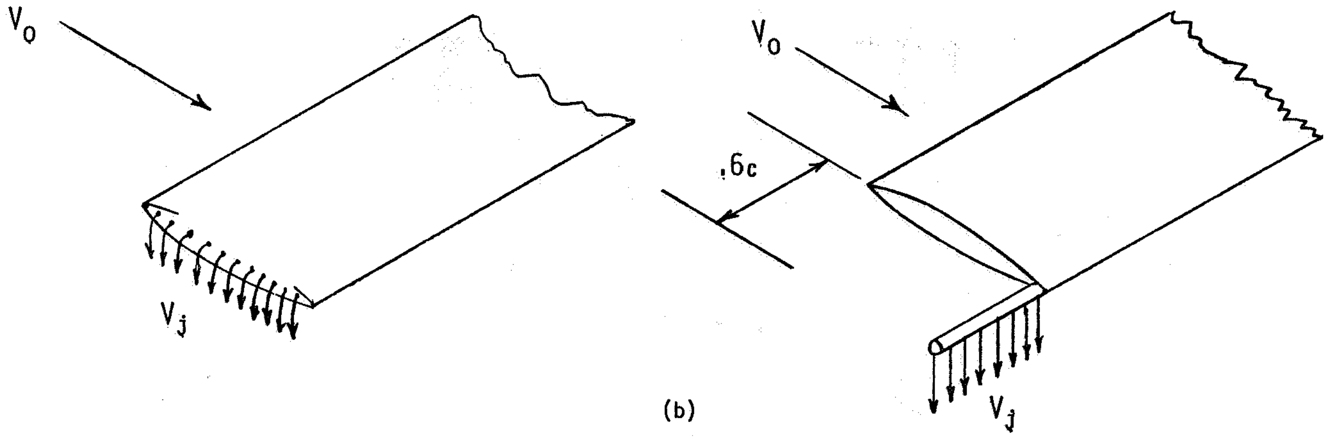

Figure 5.--Two techniques used to direct a sheet of air downward from the wingtip. (a) Chordwise blowing downward from a rounded wingtip. (b) Spanwise blowing downward from an extended tube.

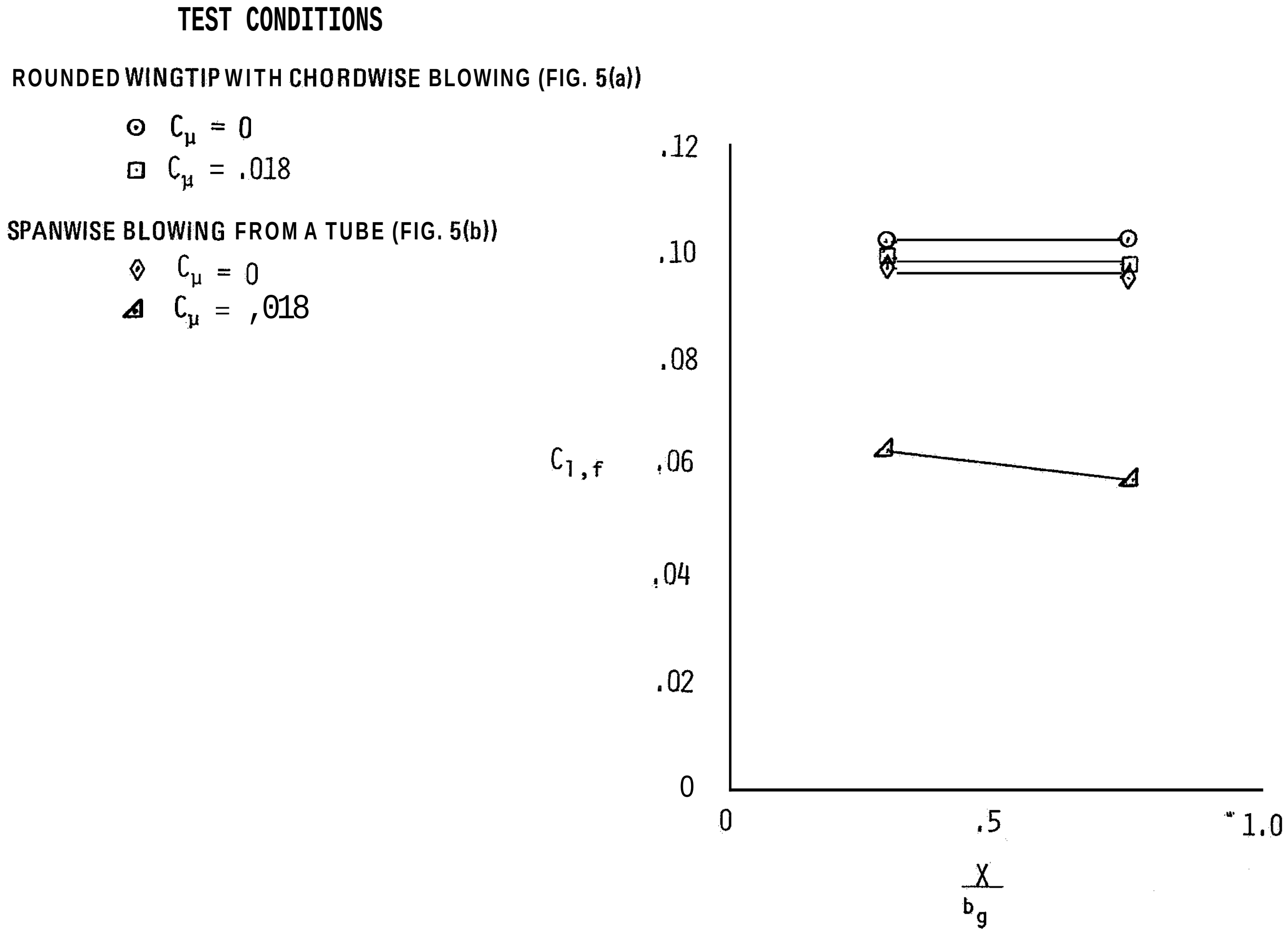

Figure 6.--Rolling moment measurements behind a straight wing of aspect ratio 6.8.

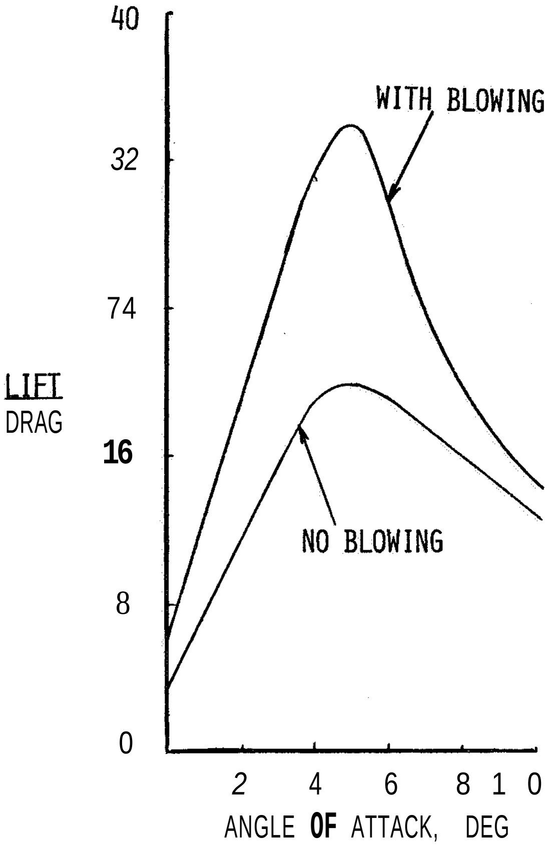

Figure 7.--Change in lift-drag ratio with spanwise blowing (fig. 5(b)). (Data from ref. 28.)

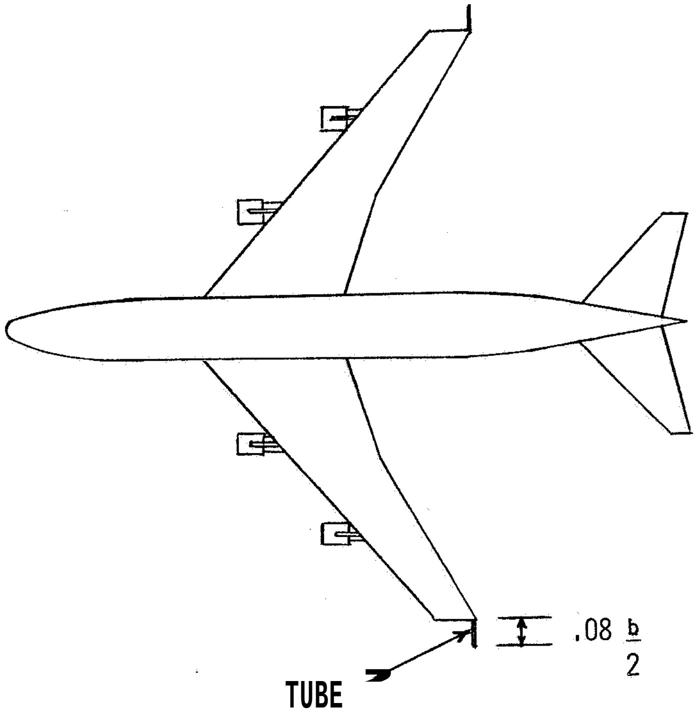

Figure 8.--Spanwise downward blowing at the wingtip of a transport aircraft model.

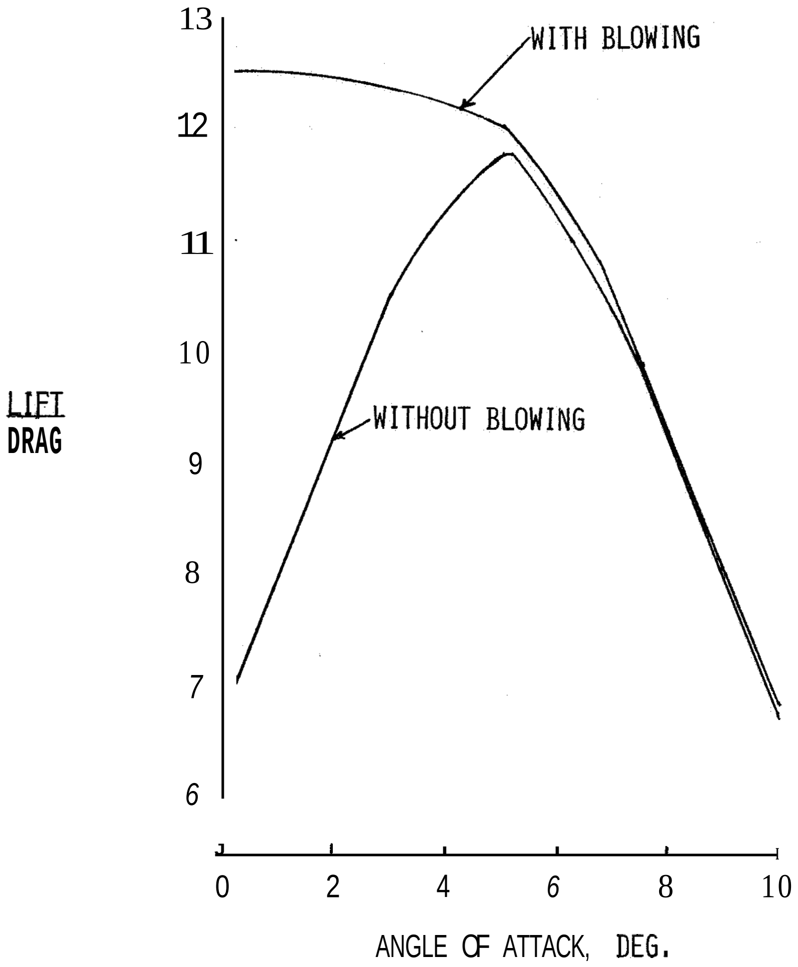

Figure 9.--Change in lift-drag ratio with spanwise downward blowing at transport model wingtip in cruise configuration.

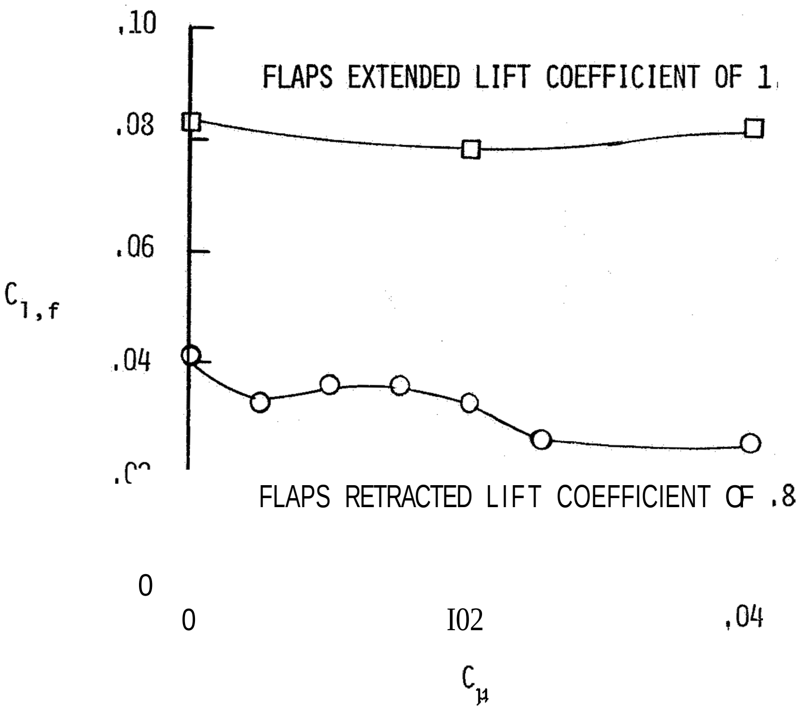

Figure 10.--Rolling moment measured by small-wing model (b_f/b_g = 0.182) at 7.5 spans behind a transport-aircraft model with spanwise downward blowing at the wingtip (fig. 8).

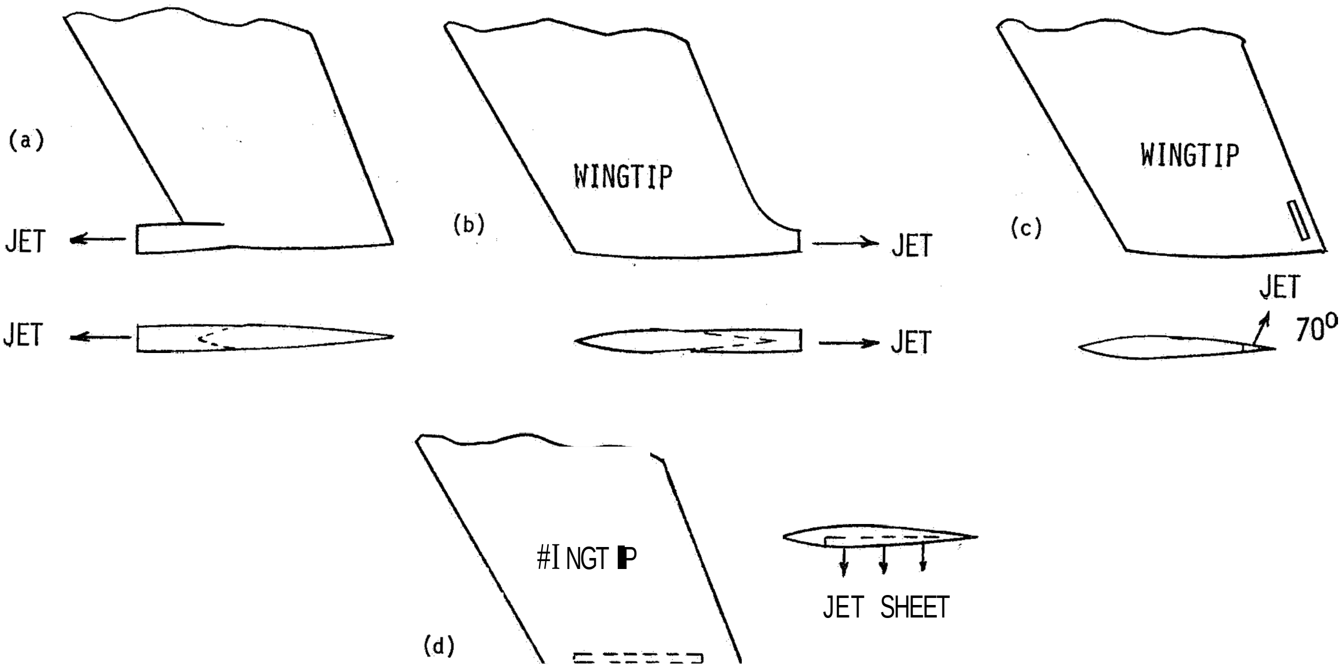

Figure 11.--Blowing devices investigated on the wingtip of a large transport model. (a) Forward blowing jet. (b) Rearward blowing jet. (c) Upward deflected jet. (d) Downward jet sheet.

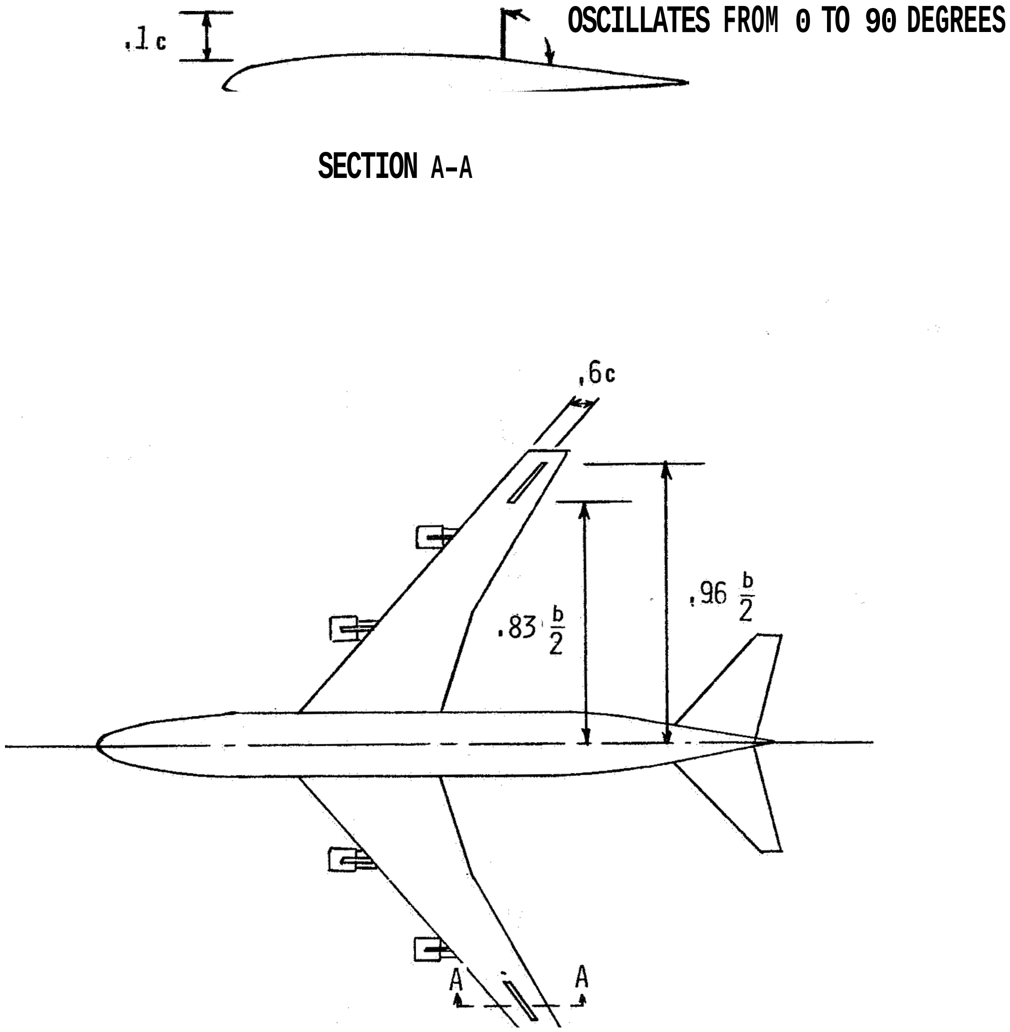

Figure 12.--Oscillating spoiler device on large transport model.

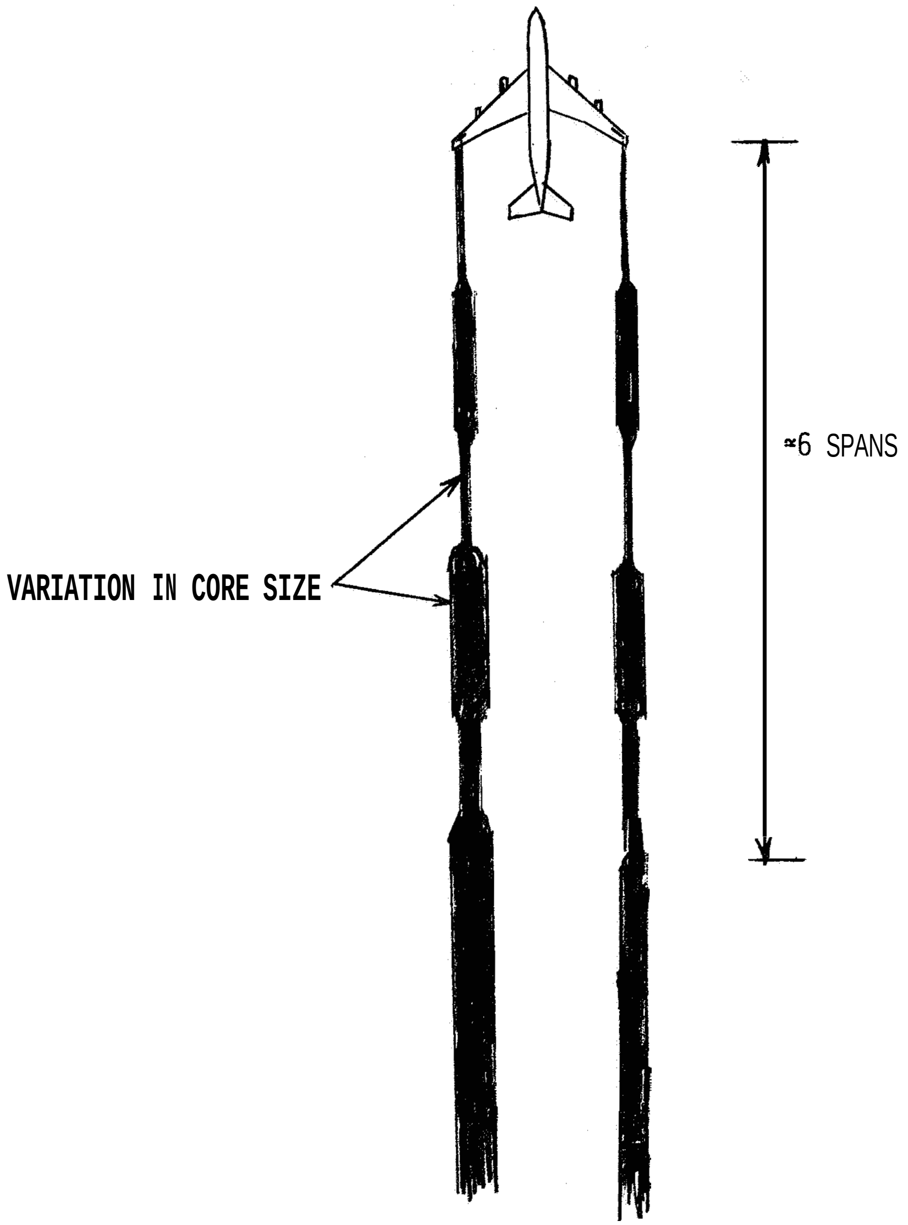

Figure 13.--Effect on an oscillating spoiler on transport-model trailing vortices, in cruise configuration.

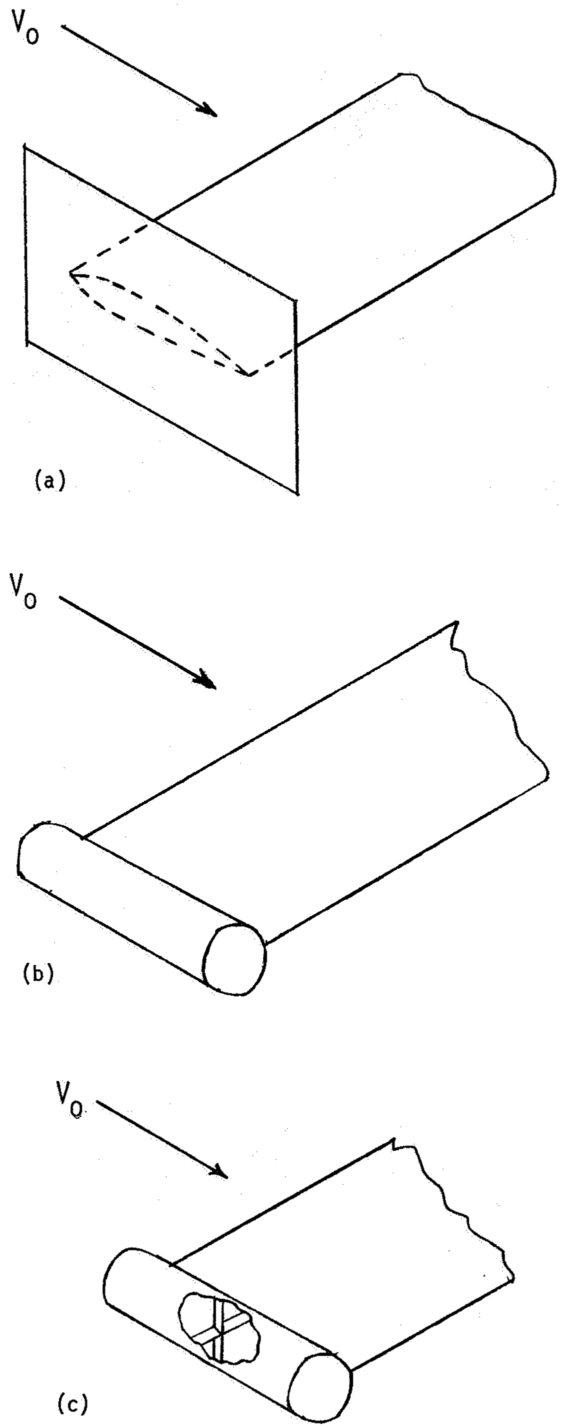

Figure 14.--The three types of wingtip end plates evaluated. (a) Sheet end plate. (b) Body of revolution with flow through center. (c) Body of revolution with turning vanes in center.

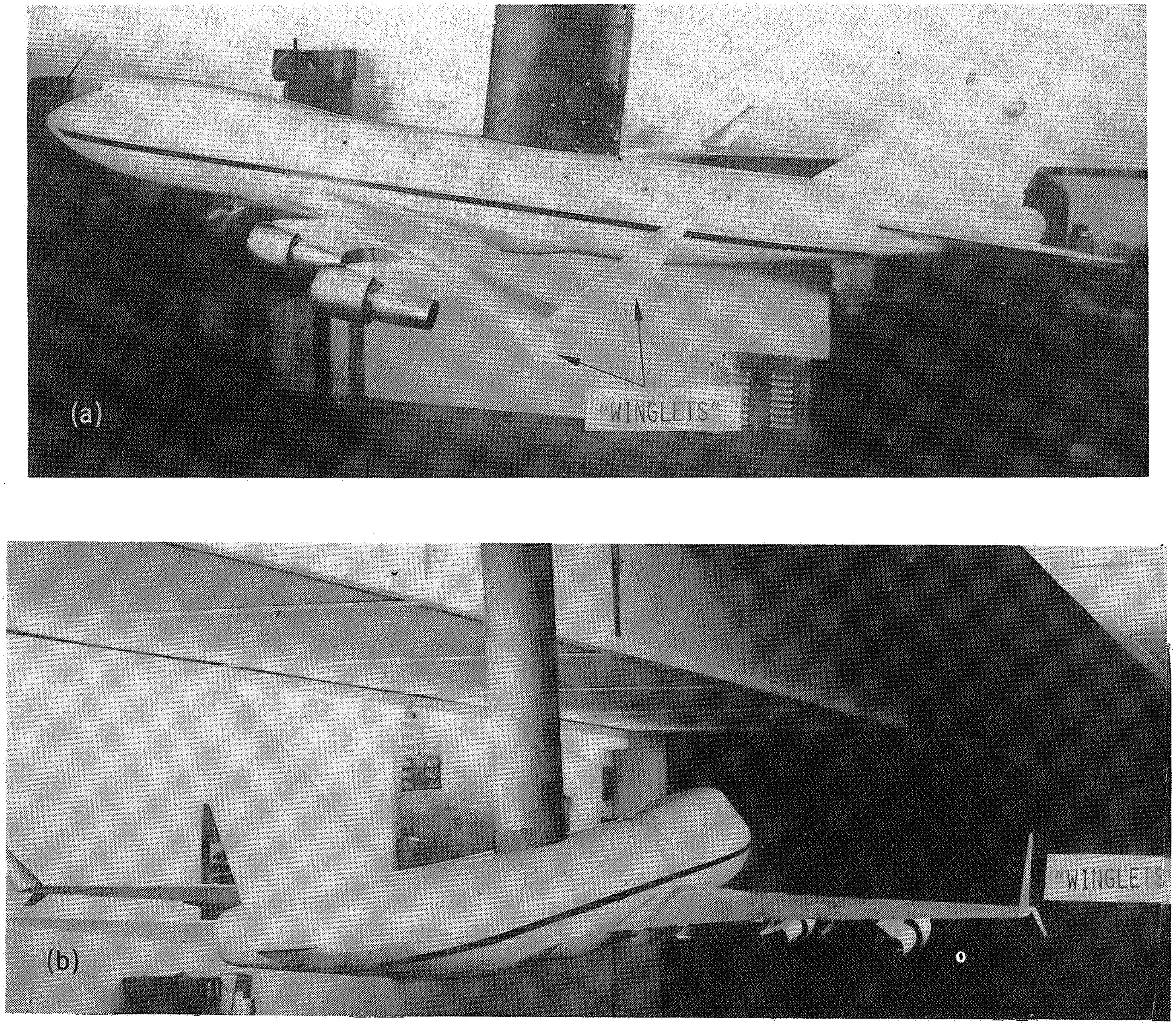

Figure 15.--Photographs of wingtip-mounted winglets on transport model. (a) Side view. (b) Rear view.

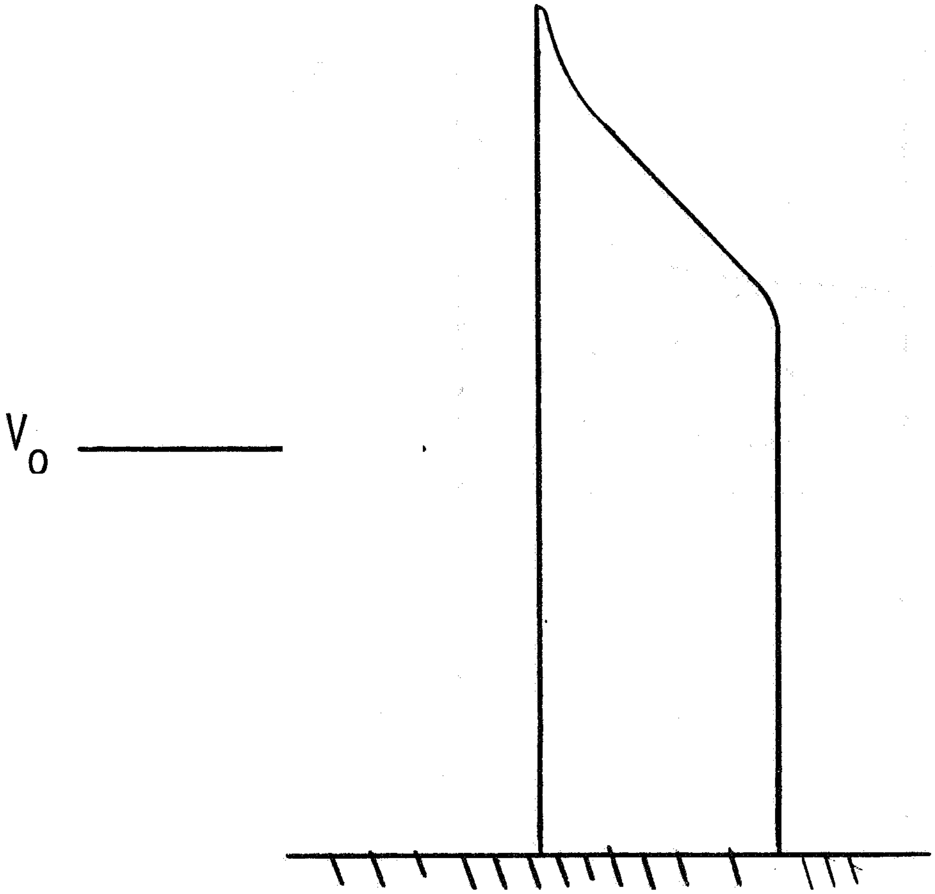

Figure 16.--Modified wingtip shape (ogee tip).

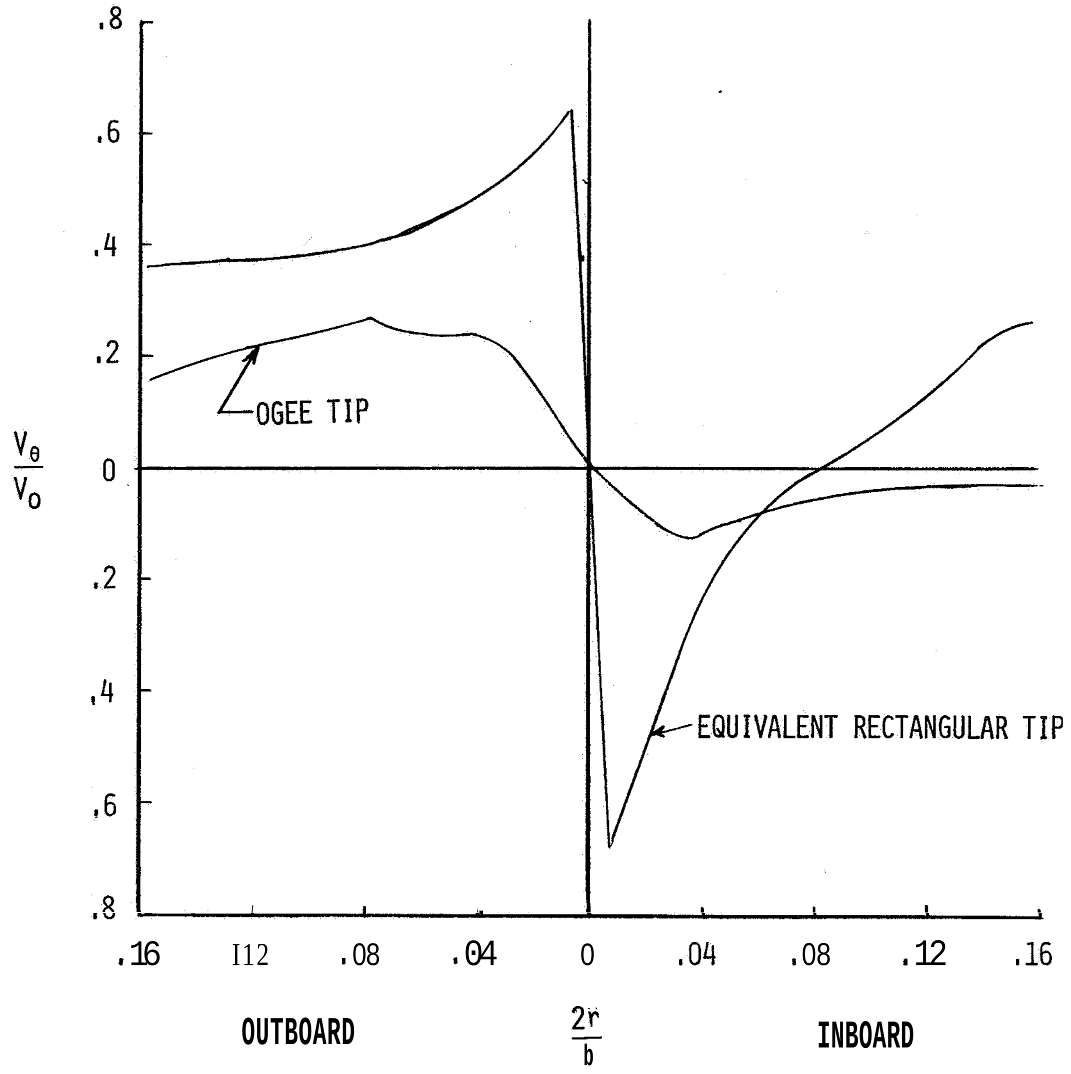

Figure 17.--Effect of modified wingtip, shape (ogee tip) on vortex dissipation.

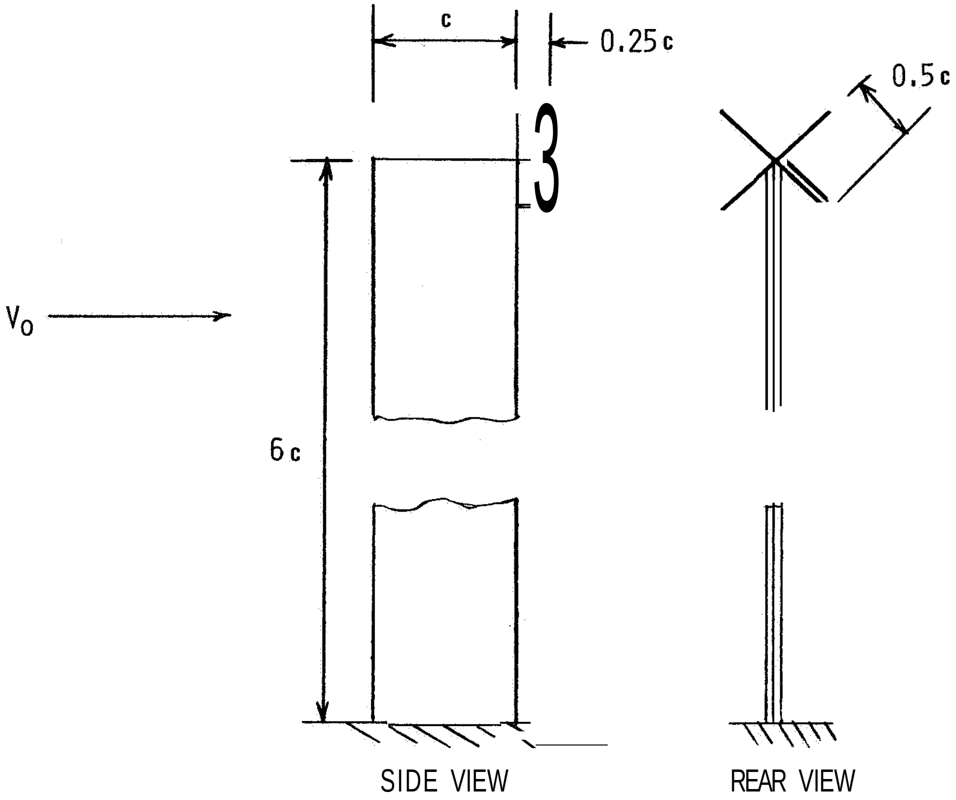

Figure 18.--Arrangement of crossed blades to inhibit vortex rotation.

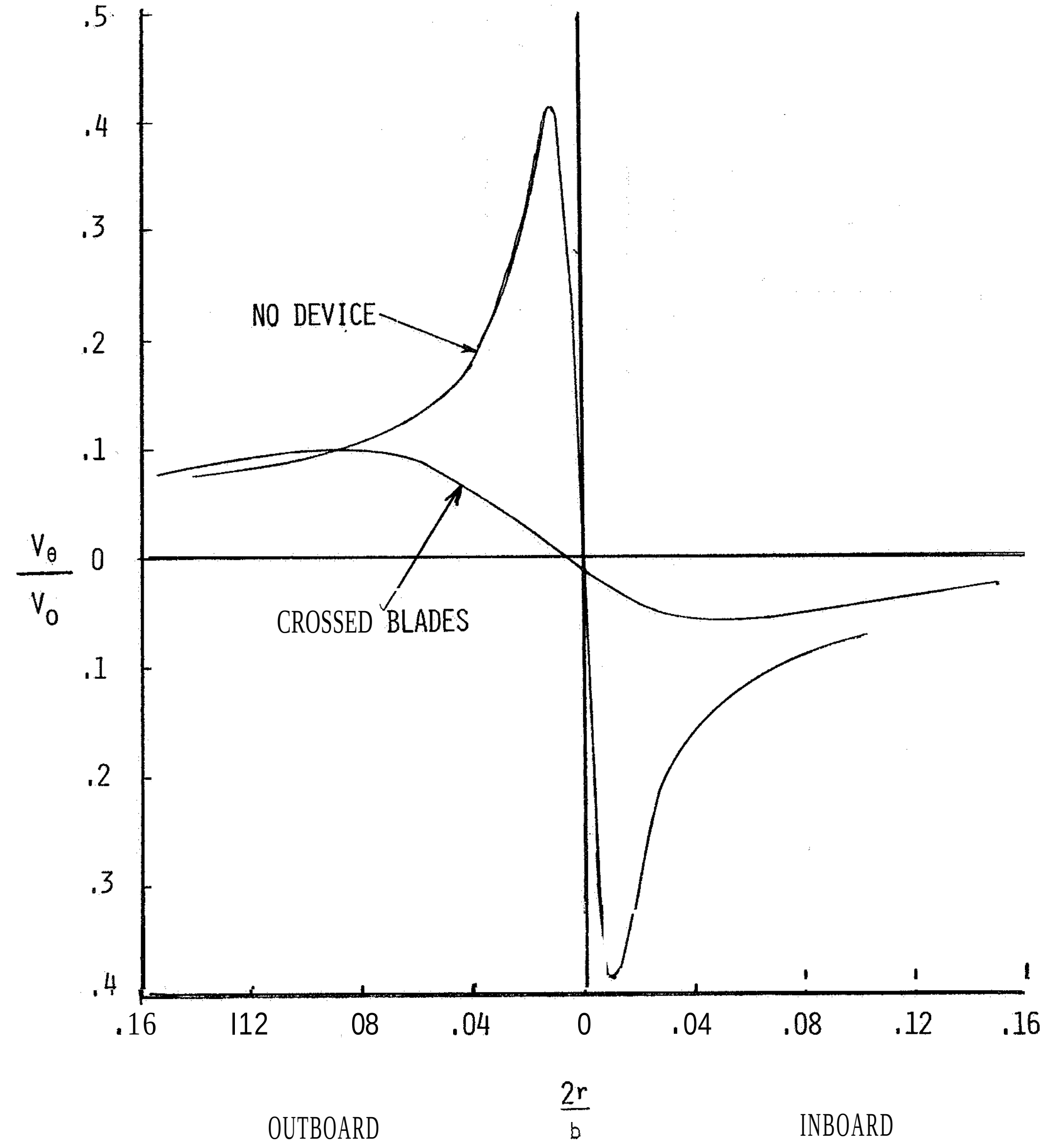

Figure 19.--Effect of crossed blades (fig. 18) on vortex velocity distribution.

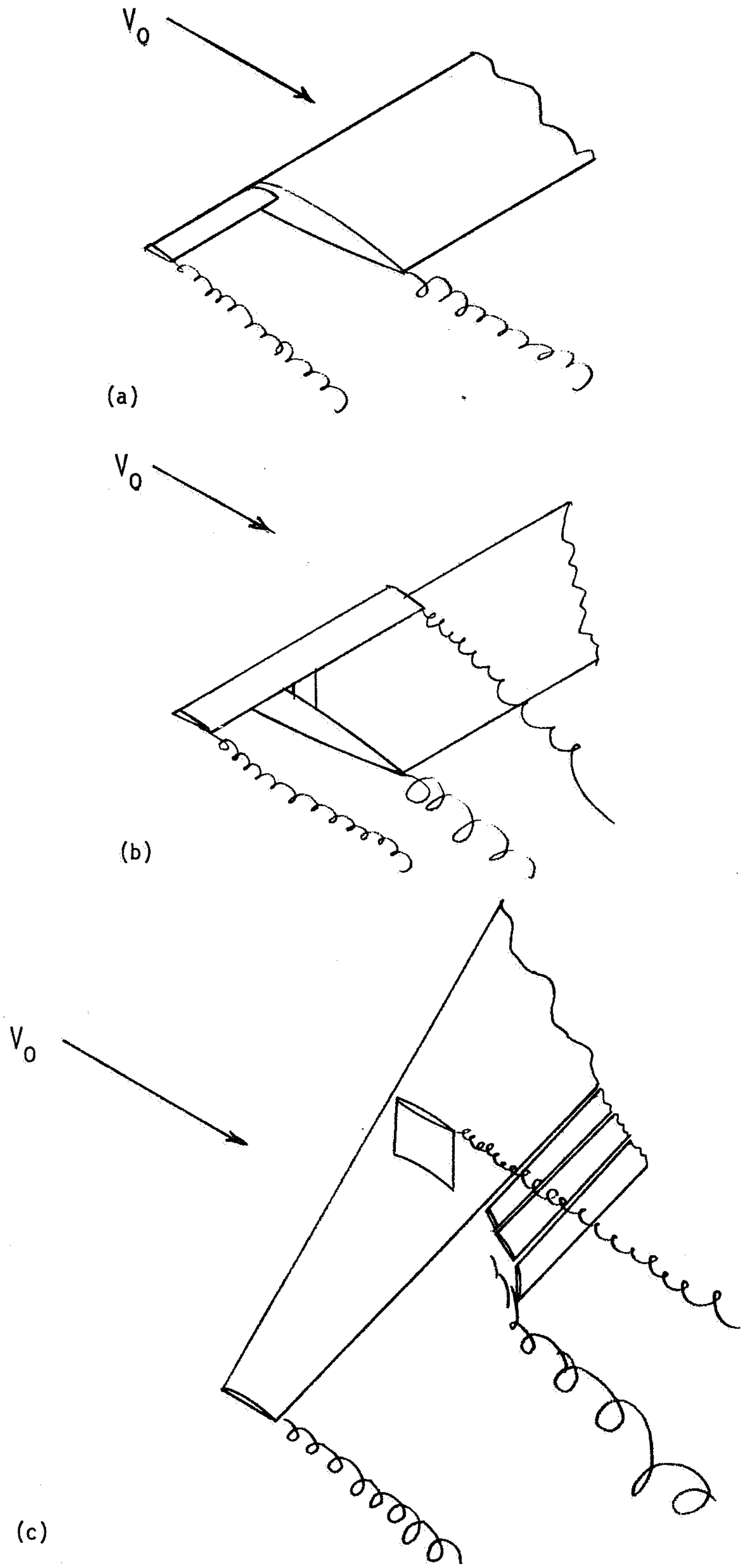

Figure 20.--Techniques used to investigate interaction of multiple vortices. (a) Wingtip extension. (b) Biplane wingtip. (c) Large vortex generator on transport aircraft model.