EXPERIMENTAL INVESTIGATION OF WING-TIP VORTEX ABATEMENT

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Abstract

Detailed measurements of aerodynamic forces and downstream velocity distributions of a model airplane with and without vortex abatement device have been made in the NASA-Langley V/STOL wind tunnel. Time-mean-average velocity components were measured, using a triple-sensor hot film probe, at 1/2-chord and 5-chord distances behind the trailing edge of the wing.

The results of these tests clearly indicate that not only does the vortex abatement device reduce greatly the size of the wing-tip vortex but also the strength of the vortex core. The effect of the vortex abatement device also results in a considerable increase in lift and decrease in drag.

Nomenclature

b	wing span
c	wing chord
C_D	drag coefficient
C_L	lift coefficient
C_ℓ	rolling moment coefficient
C_μ	jet momentum coefficient formula $\left(J\Big/\rho\,\frac{U_\infty^2}{2}\,bc\right)$
D	total drag of the model
J	total jet reaction or momentum flux
L	total lift of the model
R_e	Reynolds number based on chord
u	time-mean-average velocity in x-direction
U_∞	free stream wind tunnel velocity
v	time-mean-average velocity in y-direction
w	time-mean-average velocity in z-direction
x	coordinate in the free stream direction
y	coordinate in the spanwise direction
z	coordinate perpendicular to y and x
$(\ )_{TW}$	trailing wing
α	angle of attack
ρ	density

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I. Introduction

In a paper published in 1894,[1] F. W. Lanchester stated that the high pressure beneath the wings of a finite span would roll up into two main trailing vortices of opposite sign, one located behind each tip (Fig. 1). Three years later Lanchester secured a patent covering the use of end plates at the wing tips to minimize the spillage there; however, experimental results showed that tip vortices are generated at both upper and lower edges of the end plate. During the past few decades numerous researchers[2] have devoted a great deal of time in studying the problems relating to the behavior of wing-tip vortices which include the areas of vortex generation, motion, and decay; vortex control; stability of vortex pair; vortex breakdown; and flight measurements including detection and visualization. But the results of these investigations have yielded very little quantitative information with regard to the abatement of wing-tip vortices.

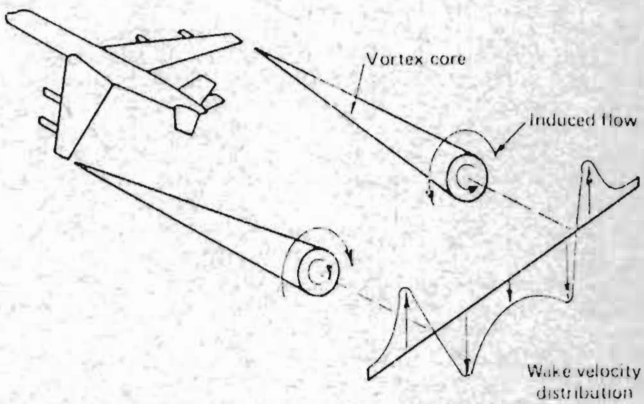

FIGURE 1. AIRCRAFT VORTEX WAKE HAZARD.

The trailing vortices generated at the wing tip of an aircraft possess potential hazards to light aircraft which follow in the wake of heavier aircraft. The severity of this hazard to the lighter aircraft usually results in structural failures or loss of control, and on occasions severe and even fatal accidents have occurred. The advent of "jumbo" jets, coupled with an increase in the number of smaller aircraft, has turned the problem of trailing wing-tip vortices into a serious concern of the aviation community.

Current solutions to the problems of trailing-vortex hazards are merely wide aircraft separation in time and space. As a result of a DC-9 which crashed following in the wake of a DC-10 in 1972, the Federal Aviation Administration has required a seven-mile spacing between all aircraft in enroute flight and a three-minute separation between two aircraft in the final approach stage. The slow down requirement to permit greater separation between aircraft would not only interfere with high-volume operations common at major airports, but would also impose severe economic penalties at such airports.

Recently, several research programs of reducing the trailing-vortex hazard on existing aircraft by artifically inducing the vortices to break up have been undertaken. These methods consist of mounting a spoiler on the upper surface of the wing,[3,4] mass flow injection into the core of the vortex,[5] and the induction of the Crow instability.[6] These investigations were summarized in a recent article[7] entitled, "Vortex in Aircraft Wakes," as insufficient to be considered acceptable for current transport airplanes. They are either aerodynamically intolerable, especially during take-off, or incapable of alleviating the vortex hazard.

The present research is concerned with an experimental investigation of a unique system for abating the wing-tip vortices. The system consists of a small circular tube with a series of multiple apertures or a continuous slot extending outward in the spanwise direction, near the trailing edge of the wing tip for blowing a jet sheet of air through the apertures in the downward direction, approximately perpendicular to the free stream velocity (Figs. 2 and 3). Previous tests which were conducted in the subsonic wind tunnel of The George Washington University revealed the effectiveness of this system for abating the wing-tip vortex in the near wake region behind the wing.[8] Simultaneously, a considerable increase in lift was obtained for the wing with this system in comparison with that of a conventional wing.

The objective of this investigation was to verify the effectiveness of the vortex abatement system in the near wake region behind the wing and to determine whether this system can abate the wing-tip vortices in the far wake region behind the wing. Simultaneously, the aerodynamic performance of the wing with this system was thoroughly investigated. In order to accomplish these objectives, experimental measurements were made on a wing-body model with a tube tip vortex abatement device in the NASA-Langley Research Center V/STOL wind tunnel. The data obtained include forces acting on the model as well as velocity profiles and rolling moment of a trailing model in the wake of up to 40-chord length downstream of the trailing edge of the test model.

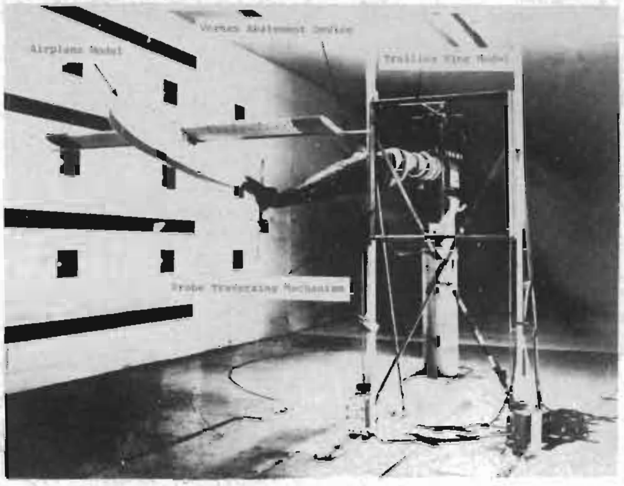

FIGURE 2. NASA V/STOL WIND TUNNEL FOR WING–TIP VORTEX ABATEMENT TESTS.

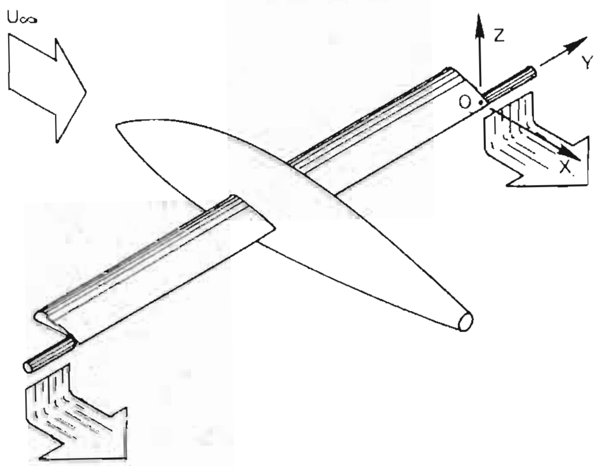

FIGURE 3. WING–BODY MODEL WITH WING–TIP VORTEX ABATEMENT DEVICE.

The test results presented in this paper indicate that not only does the proposed vortex abatement system reduce the strength of the wing-tip vortex but also results in a considerable increase in aerodynamic performance of the aircraft.

II. Description of Experiment

Test Model

The general view of the installation (Fig. 2) shows the wing-body combination with the vortex abatement device in the test section of the NASA-Langley V/STOL wind tunnel. The basic wing has a rectangular planform with the following geometric details:

Span	69 in. (175 cm)
Chord	10 in. (25.4 cm)
Section	NACA 0018-64
Aspect Ratio	6.9

The tip of the basic wing was modified and equipped with the vortex abatement device which consists of a small circular tube extending outboard from the vicinity of the trailing edge of the wing tip in the spanwise direction (Fig. 3). A single row of holes was made along this approximate 1/2-chord length tube for blowing a jet sheet of air in the downward direction perpendicular to the free stream velocity.

Compressed air was used to provide jet blowing for the wing-tip vortex abatement device. The mass flow rate for the blowing jet was measured by a choked venturi to an accuracy of ± 1%.

The wing-body model was sting mounted in the NASA-Langley V/STOL wind tunnel, which has a test section of 14.5 ft. high and 21.75 ft. wide (Fig. 2). The tunnel is of the continuous-flow, closed-circuit type, capable of a maximum velocity of 230 mph. The V/STOL wind tunnel is equipped with SEL data acquisition system, which has the capability of taking both steady state and continuous mode data on magnetic tape. All force and pressure measurements were processed and recorded through this data acquisition system. All wake measurement instrumentation was mounted on a two-dimensional probe traversing mechanism which was capable of traversing in the y and z directions up to approximately 1 1/2-chord length in either direction from the center of the y-z plane (Figs. 2 and 3). The traverse mechanism was driven by a variable speed electric motor.

Wake Rolling Moment Measurements

Measurements of wake rolling moment were obtained from a small trailing model wing of rectangular planform with an aspect ratio of 6.7. The model was secured on a rolling moment strain gage balance which in turn was mounted on the traverse mechanism. Full-scale deflection of the balance was 25 in-lb_f.

The rolling moment data of the trailing model wing was taken on steady state SEL mode where a ten-second time average was performed. At a given downstream position behind the wing tip of the wing-body model and a given free stream velocity the trailing model wing was traversed horizontally and vertically until the position of maximum rolling moment was located. The SEL system digital channel display was used to monitor the rolling moment readout during this phase. With the position of maximum rolling moment established, a pattern of data points was taken in the region surrounding the maximum. This procedure was carried out for the tests of the wing-body model with and without the wing-tip vortex abatement device. In order to obtain rolling moment data at different downstream positions the traverse mechanism must be manually disengaged and reassembled at that position.

Wake Velocity Measurements

Wake velocity profiles were measured with a three-component split film anemometer which has the capability of measuring three components of velocity. The split film probe was mounted on the traverse mechanism in a manner similar to tnat of a trailing model wing. For a given downstream position behind the wing tip trailing edge of the test model and a given free stream velocity a pattern of data points was taken about the center of maximum rolling moment previously measured. The SEL system was put on continuous mode, and five-second time averages at a fixed position were used for each velocity data point. The process was carried out for the tests of the wing-body model with and without the wing-tip vortex abatement device at different downstream positions.

Force Measurements

Measurement of the force and moments acting on the test model were obtained from a six-component strain gage balance with the following full-scale deflections:

Normal Force	=	500 lb_f
Axial Force	=	100 lb_f
Side Force	=	300 lb_f
Pitching Moment	=	3,000 in-lb_f
Rolling Moment	=	1,000 in-lb_f
Yawing Moment	=	2,000 in-lb_f

Accuracy of the balance was ± 1/2% of full-scale deflection. The angle of attack was measured by a calibrated pendulum inside the model to an accuracy of ± 0.05 degrees.

The force data were taken on steady state SEL mode where a ten-second time average was performed. The test model was positioned through an angle of attack range of -2° to +22°, and data points were taken in two-degree intervals. This procedure was carried out for the tests of the wing-body model with and without the wing-tip vortex abatement device at a wind tunnel velocity of 87 feet per second.

III. Results and Discussion

Rolling Moment of Trailing Model Wing

Measurements of the trailing model rolling moment were made at downstream positions of 2-, 5- and 40-chord lengths behind the trailing edge of the test wing-body model. For all tests the Reynolds number based on the wing chord was 5.4 x 10^5 (wind tunnel velocity was about 87 feet per second) and the wing angle of attack was 10.5°. The air requirement for the tube tip blowing jet was measured and reduced to the form of the jet momentum coefficient C_μ. Although a range of C_μ between zero and 0.043 were tested, the results presented here are limited to C_μ = 0 and 0.02, as no significantly different results were obtained for a C_μ value greater than 0.02.

The contours of constant values of the trailing model rolling moment coefficient $C_{\ell_{TW}}$ are shown for all the test conditions in Figs. 4 through 9. In the figures, the positive y coordinate denotes the outboard region of the test wing and the positive z coordinate indicates the region above the wing planform. Figures 4 and 5 represent the contours of the constant rolling moment coefficient of the trailing model at 2-chord length behind the test model with and without the vortex abatement device on, respectively. The results of these tests clearly indicate that the vortex abatement device considerably reduces the strength of the wing-tip vortex in the core region as well as in the region surrounding the core. Similar results were obtained for the reduction of the rolling moment of the trailing model at 5-chord and 40-chord lengths behind the test model with the vortex abatement device on in comparison with the device off. The comparison of these results are given in Figs. 6 and 7 for $\frac{x}{c}$ = 5, and in Figs. 8 and 9 for $\frac{x}{c}$ = 40, respectively. These figures show that the vortex abatement device results in a reduction of 39%, 42% and 33% of the strength of the wing-tip vortex core at $\frac{x}{c}$ = 2, 5 and 40, respectively.

As mentioned in the previous section, the rolling moment data of the trailing model wing were taken on a steady state SEL mode where a ten-second time average was performed. At positions 2- and 5-chord lengths behind the test wing trailing edge all rolling moment data were believed to be repeatable within the specified time average. However, the data recorded at 40-chord length downstream were rather unsteady, due to the meandering phenomenom. It is believed that this may explain the lower rolling moment reduction at 40-chord length downstream.

Velocity Distribution in the Trailing Vortex

Spanwise distributions of normal time-mean-average velocity w obtained from hot film probe measurements are shown in Fig. 10 where the y′coordinate is measured from the centerline of the wing-body model. At 1/2-chord length behind the trailing edge

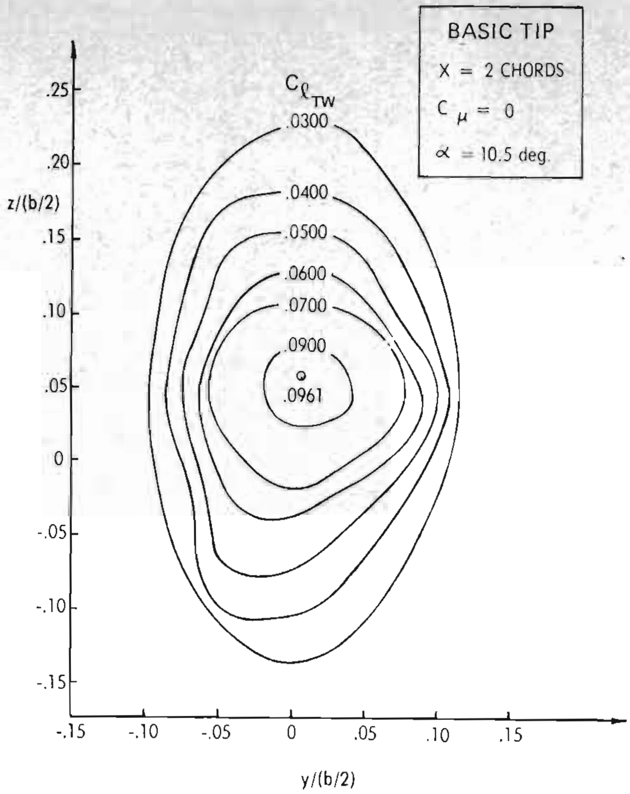

FIGURE 4. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

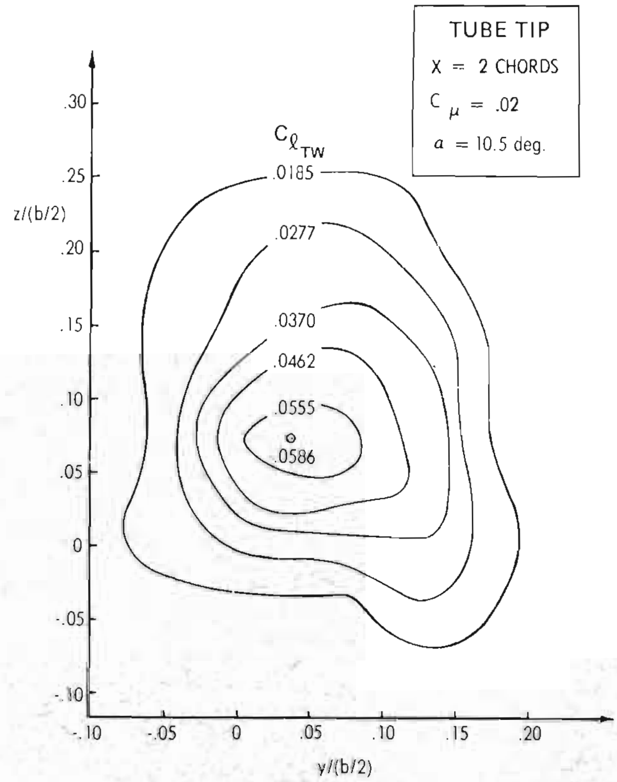

FIGURE 5. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

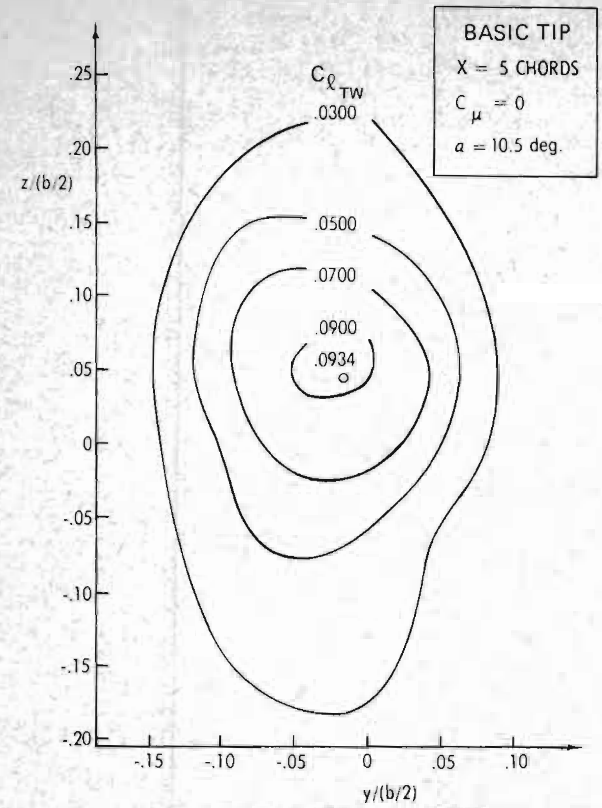

FIGURE 6. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

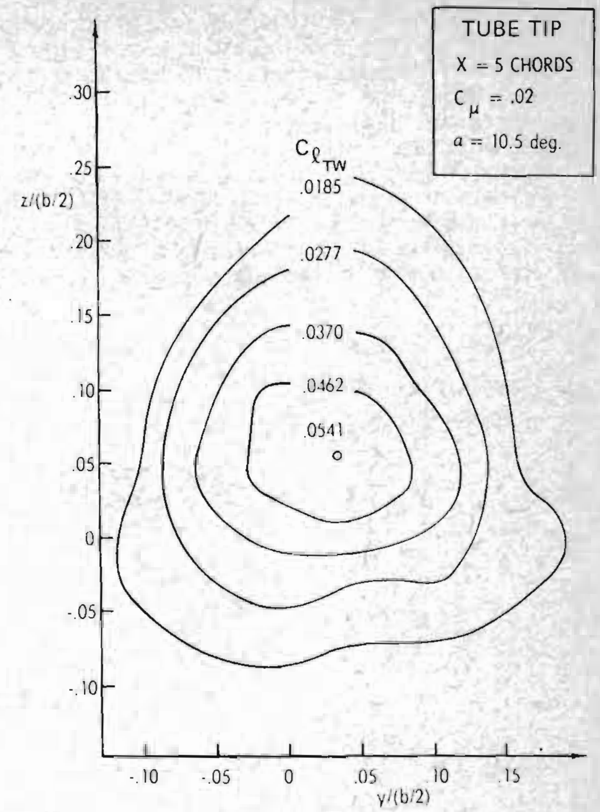

FIGURE 7. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

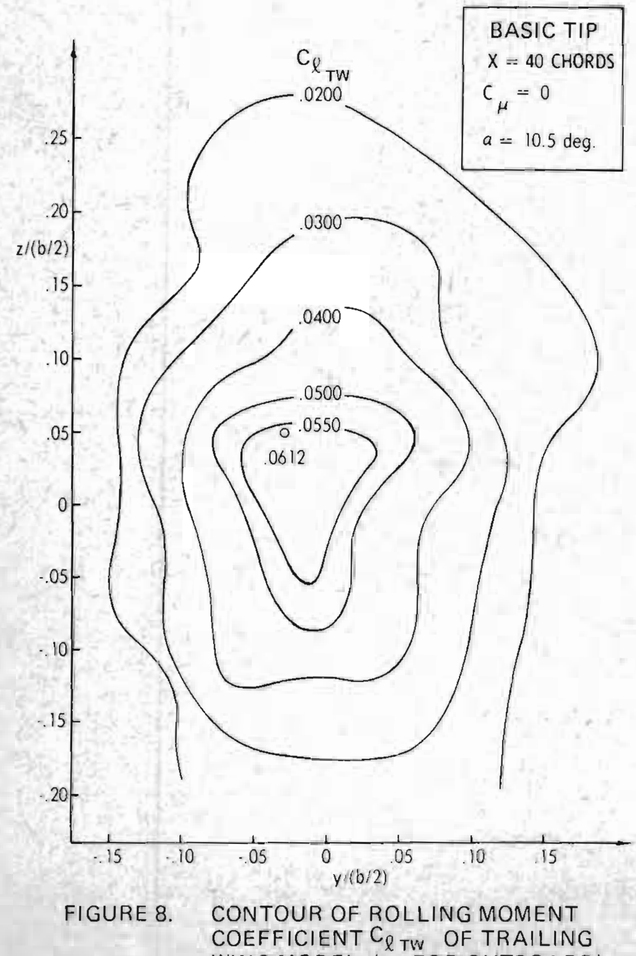

FIGURE 8. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

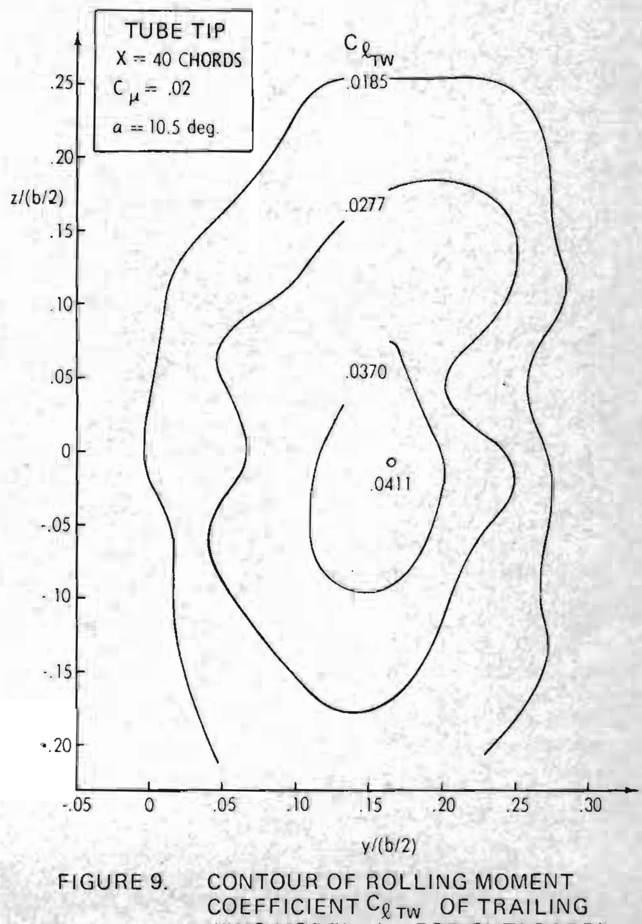

FIGURE 9. CONTOUR OF ROLLING MOMENT COEFFICIENT $C_{\ell_{TW}}$ OF TRAILING WING MODEL. (+y FOR OUTBOARD)

of the test wing, the results indicate that the downwash velocity for both cases are almost uniformly distributed in the inboard region of the wing tip and upwash velocity occurs in the outer portion beyond the wing tip. However , for the case with the vortex abatement device on, the downwash velocity occurs again in the outer portion of the wing tip which is believed mainly due to the strong downward jet velocity from the tube tip blowing. This explains the considerable decrease of wing-tip vortex strength at 1/2 chord length downstream when the vortex abatement device was engaged.

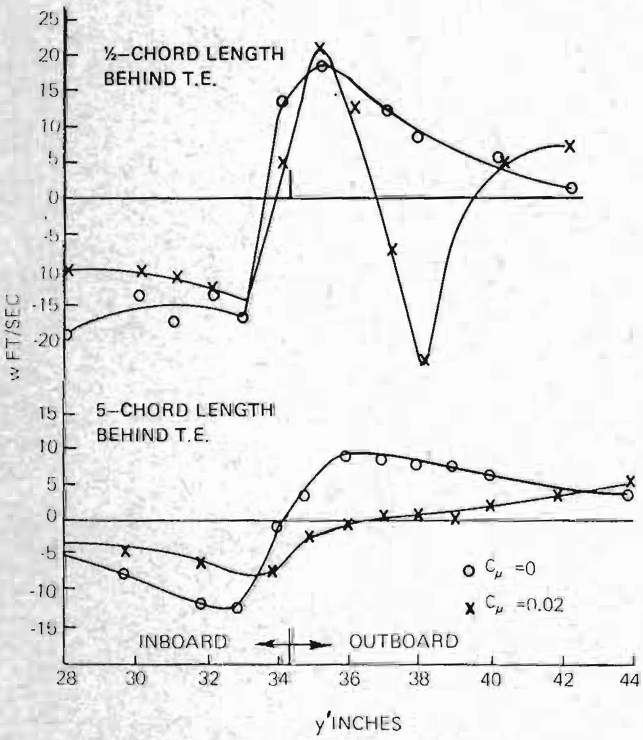

FIGURE 10. SPANWISE DISTRIBUTION OF NORMAL VELOCITY **(MEASURED FROM FUSELAGE ℄)**

At 5-chord length behind the trailing edge of the test wing the spanwise distribution of normal velocity obtained from the basic wing tip was almost anti-symmetric about the wing tip location. It is believed that a complete rollup of wing-tip vortex at this position has occurred. On the other hand, with the vortex abatement device on, the results show that upwash velocity outboard from the wing tip was largely diminished and the downwash velocity inboard from the wing tip was greatly reduced compared to the case with the vortex abatement device off.

Figures 11 and 12 show a comparison of the distributions of velocity vectors of v and w at a 1/2-chord length behind the trailing edge of the test wing model with and without the vortex abatement device, respectively. The orientation of the velocity vectors shows the direction of the vortex flow in a plane perpendicular to the free stream direction. Although the rollup process of the wing-tip vortex at this downstream position is incomplete, the random orientation of the velocity vectors for the case in Fig. 12 clearly indicate that the wing-tip vortex strength has been significantly reduced. It is also noted in Fig. 12 that a weak second vortex was present but had disappeared further downstream. It is believed that the occurrence of this vortex is due to the rollup of the jet sheet.

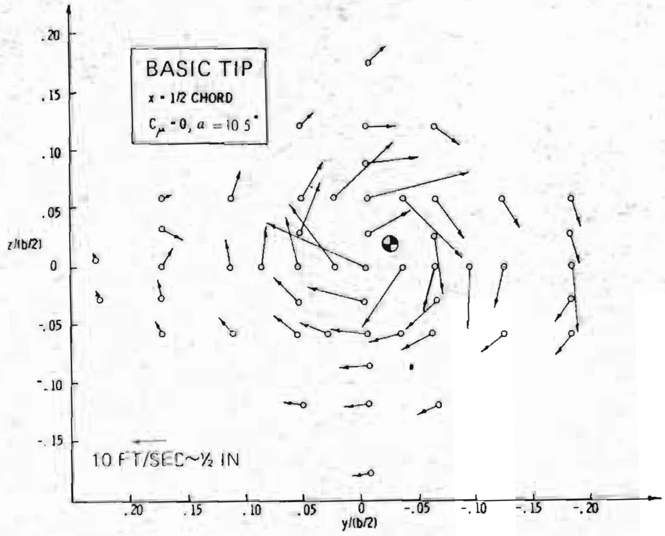

FIGURE 11. DISTRIBUTION OF VELOCITY VECTOR IN DOWNSTREAM WAKE. (—y FOR INBOARD)

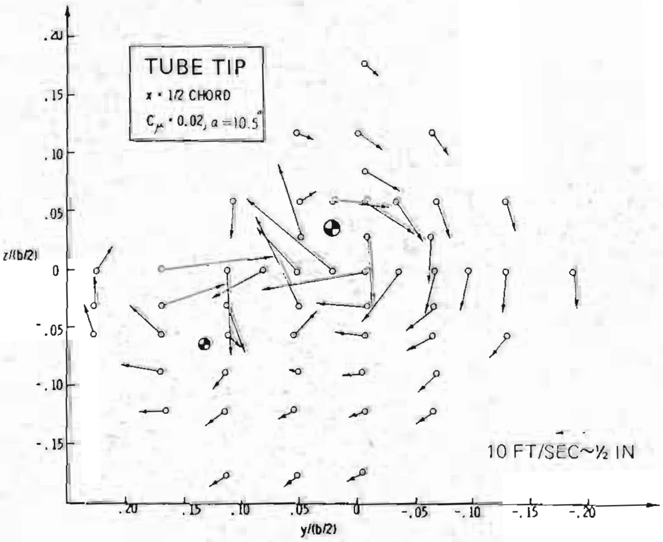

FIGURE 12. DISTRIBUTION OF VELOCITY VECTOR IN DOWNSTREAM WAKE. (—y FOR INBOARD)

The distribution of velocity vectors of v and w at 5-chord length behind the trailing edge of the basic wing tip is shown in Fig. 13. It can be clearly seen that a strong wing-tip vortex rollup appeared at this downstream position. The maximum velocity vector around the vortex core in this case is about 18% of the mainstream velocity.

Figure 14 depicts the distribution of velocity vectors of v and w at a 5-chord

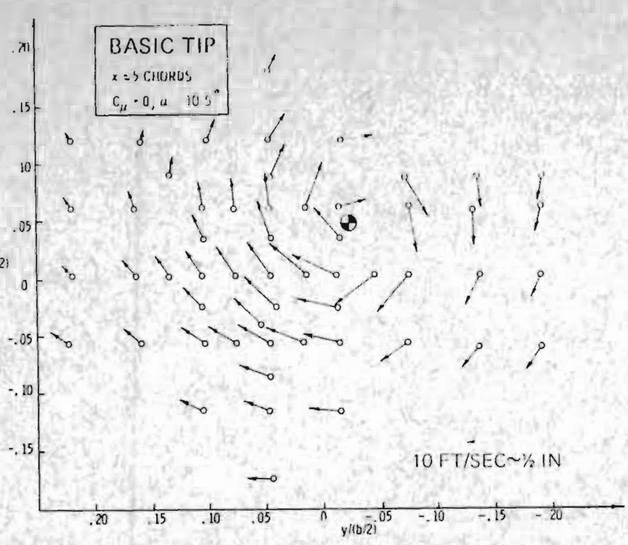

FIGURE 13. DISTRIBUTION OF VELOCITY VECTOR IN DOWNSTREAM WAKE. (−y FOR INBOARD)

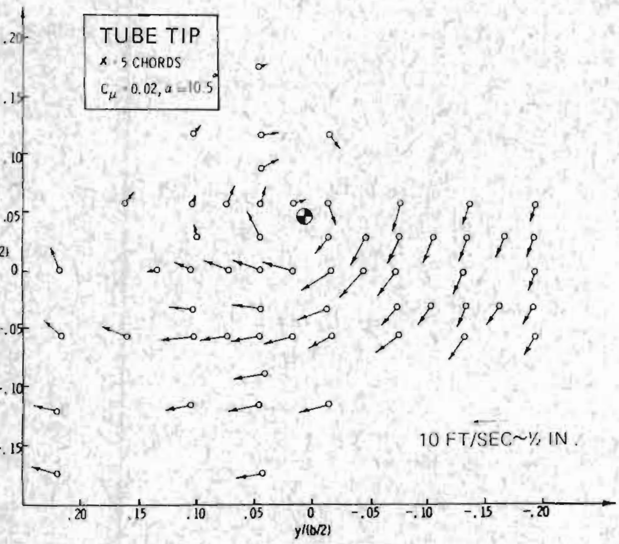

FIGURE 14. DISTRIBUTION OF VELOCITY VECTOR IN DOWNSTREAM WAKE. (−y FOR INBOARD)

length behind the trailing edge of the wing model with the vortex abatement device. The velocity vectors outboard from the wing-tip location in this case tend to sweep away in the spanwise direction instead of rolling upward. However, a vortex rollup appears near the vortex core but the magnitude of the velocity vectors is less than 10% of the mainstream velocity. The results also indicate that the vortex roll-up is confined to a rather small region. It can be concluded that the results obtained from the split film anemometer data confirm that of the rolling moment data from trailing model wing at this downstream position.

Lift and Drag

Figure 15 shows the very encouraging results obtained from the force measurements data of the test wing-body model with the vortex abatement device. The results for lift and drag coefficients are shown in the figure as a function of angle of attack with jet momentum coefficient of 0, 0.008 and 0.043. Since all force measurements of the test model were made for the wing tip with tube attached, the drag of the test model with an equivalent basic wing tip was calculated by subtracting the drag of the tube (based on C_D = 1.0) from the drag obtained for the test model for C_μ = 0. This modified drag coefficient curve is assumed to represent a model with a conventional wing tip. In Fig. 15 it can be seen that for C_μ = 0.043 the maximum lift coefficient (at α = 16°) of the test model with the vortex abatement device on increases by almost 12% over that of the model without the device. Simultaneously, the total drag reduction of the model with the vortex abatement device is about 11% in comparison with the model having a conventional wing tip. At an angle of attack of 6° (minimum drag condition) the total drag reduction is about 95% while the increase in lift is about 20% when the vortex abatement device is employed.

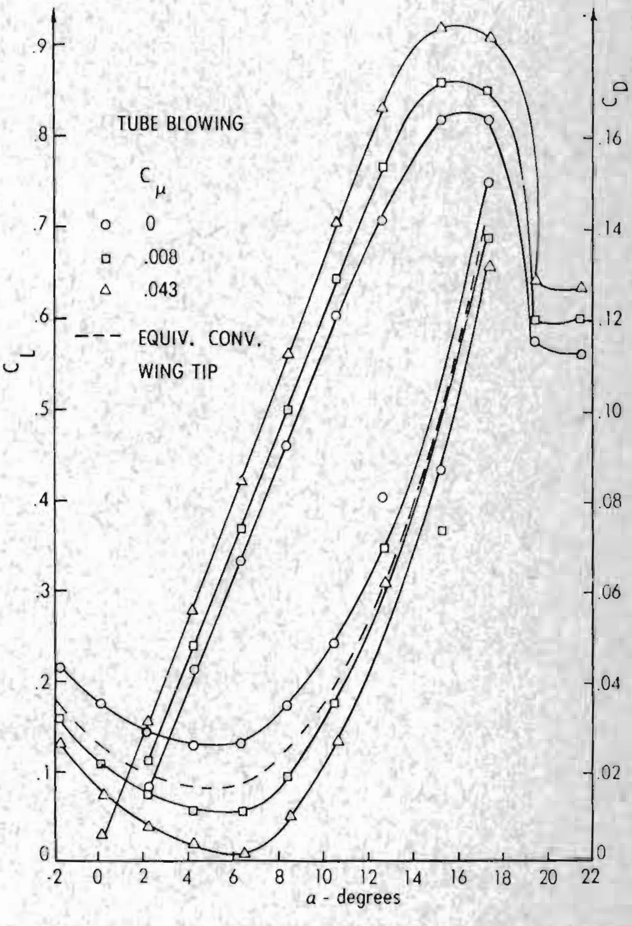

FIGURE 15. LIFT AND DRAG COEFFICIENTS VERSUS ANGLE OF ATTACK.

The considerable increase in lift of the model with the vortex abatement device on can be understood from the potential flow theory since the two stagnation points of the circular tube coincide at the bottom point of the tube where a strong jet is emitted. The measured lift coefficient of 10 was obtained for the tube tip with the jet blowing (C_μ = 0.043) during present tests. The decrease in drag of the model with the tube tip blowing is believed to be due to jet thrust recovery.

The lift-over-drag ratio plotted against angles of attack is shown in Fig. 16. The results indicate that the value of L/D of the test model with the vortex abatement device on increases by 70% (at α = 7°) over that of the model with a conventional wing tip. At an angle of attack of 16° the corresponding increase in L/D ratio is about 8%. The jet momentum coefficient C_μ = 0.008 was used here.

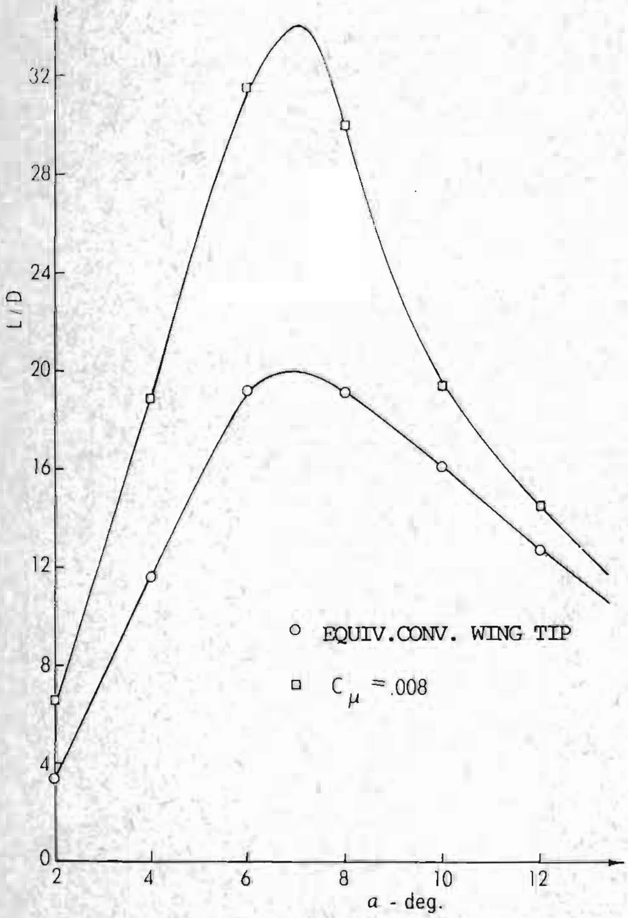

FIGURE 16. LIFT AND DRAG RATIO VERSUS ANGLE OF ATTACK.

IV. Conclusions

Experimental results obtained for a wing-body model with a unique system for abating the wing-tip vortices in the NASA-Langley V/STOL wind tunnel are in good agreement with previous data of vortex abatement visualization and force measurement taken from a small wind tunnel.[8] Measurements of the trailing model rolling moment behind the trailing edge of the test model indicate that, with the vortex abatement device on (as compared to the case with the vortex abatement device off) the wing-tip vortex core strength at $\frac{x}{c}$ = 2, 5 and 40 is reduced 39%, 42% and 33%, respectively. Velocity distributions in the trailing vortex obtained from a three-component split film anemometer clearly indicate that the wing-tip vortex strength has been significantly reduced. The results are in good agreement with that of the rolling moment data from the trailing model wing at the same downstream position.

Encouraging results were obtained from the force measurements data of the test model with the vortex abatement device. The results reveal that, for a jet momentum coefficient C_μ = 0.043, the maximum lift coefficient (at α = 16°) of the test model with vortex abatement device on increases by almost 12% over that of the model without the device. Simultaneously, the total drag reduction of the model with the vortex abatement device is about 11% in comparison with the model having a conventional wing tip. The results further indicate that the value of lift-over-drag ratio (C_μ = 0.008) of the test model with the vortex abatement device on increases by 70% (at α = 7°) over that of the model with a conventional wing tip. Hence, the important application of this unique system for abating the wing-tip vortex and improving performance to aircraft, hydrofoils and rotor blades is evident.

Acknowledgements

This research was supported by the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F 33615-73-C-3097. The authors wish to thank George Kurylowicz of the Air Force Flight Dynamics Laboratory, Alexander Hammond, Richard Margason and Delwin Croom of the Aerodynamics and Performance Branch, NASA-Langley Research Center, for many helpful suggestions and discussions.

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DISCUSSION

V.L. Marshall (British Aircraft Corporation, Weybridge, U.K.): I noted from the movie-film that there was a considerable interaction between the forming tip vortices from the main wing and the junction with the cylinder when blowing was applied. Some entrancement appeared to exist there which disseminated the primary tip vortices.

My question is therefore, has any attempt been made to evaluate the function of a passive tip fence, such as rear planform tip stretching, which might produce the desired effects (or some of it).

S.W. Yuan: As mentioned in my paper, several research programs of reducing the trailing-vortex hazard on existing aircraft by introducing artificial inducing vortices have been undertaken during the past few years. One of these methods consists of mounting a spoiler on the upper surface of the wing which is like a tip fence as you have suggested. According to test results made by NASA, the spoiler would serve as a moderately effective means to break up the wing-tip vortices. However, it has been proven to be impractical due to the intolerable increase in drag, especially during take-off. The results also show that the spoiler has little effect on lift.