Vortex Attenuation Obtained in the Langley Vortex Research Facility

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It has been shown by a new static airflow visualization method that a drogue device properly positioned downstream of the wing tip causes vortex breakdown. This same result has been obtained by mounting a jet engine simulator at the wing tip and directing the high-energy jet blast downstream into the vortex. These configurations, among others, are now under intensive investigation in the new Langley Vortex Research Facility. In this facility, a balance mounted vortex generating model is propelled along the 1800-ft track while a second model trailed at 160 ft (scale distance of 1 mile) measures the far-field rolling moment induced by the vortex of the generating model.

Introduction

THE lift-induced wing-tip vortex associated with the large wide-body jet transport aircraft of today has become a major problem in the terminal area resulting from the large upset rolling moment induced on smaller following aircraft in the vicinity of the ground. The persistent nature of this type of flow has also resulted in an unseen hazard during cruise flight long after the generating aircraft has passed. The wing-tip vortex, the strength of which is a function of lift for a particular aspect ratio and wing planform, has been in existence since the beginning of flight, becoming an ever-increasing problem as the weight of each succeeding generation of aircraft has increased. A large research effort is now underway to reduce or possibly eliminate this lift-induced vortex as a result of the urgent request of NASA by the Federal Aviation Administration, to determine some means to reduce the lift-induced wing-tip vortex intensity. Ideally, any such fix would be retrofitted to existing aircraft to cope with the vortex persistence problem.

An accelerated program has been initiated at the Ames Research Center, at Hydronautics under the direction of the Langley Research Center,[2,3] at the Langley Vertical Take-Off and Landing Wind Tunnel, and at the newly established Langley Vortex Research Facility. The discussion here will be limited to the research conducted in and associated with the Langley Vortex Research Facility.

Preliminary Vortex Research

To obtain a greater insight into the actual motions of the wing-tip vortex, a stationary airflow visualization method has been developed.[1] This method is based on the fact that the air molecules affected by the wing tip are set into circular motion with no longitudinal flow, with the exception of those molecules in the vortex core itself. To make this circular vortex motion visible, a screen of smoke is produced through which a model is propelled. As the model passes through the smoke screen, and for some time afterwards, it is possible to photograph the entire lift span of the vortex. (Although this same relative motion is present in the wind tunnel, the usual test section is not of great enough length to observe the full development of the vortex. The relationship of the observer to the flow in the wind tunnel does not lend itself readily to the study of aircraft wake because of the unreal longitudinal flow component which has been misleading in many cases in the past.) To determine the feasibility of this proposed method of wake investigation, tests were conducted using the basic wing panel, shown in Fig. 1, having a 5-ft span and a 13-in. chord mounted on the monorail catapult system in the Langley towing tank basin. A preliminary look was obtained of the vortex alleviating effect of a number of configurations which were essentially geometric modifications of the wing tip as the next three configurations shown on this figure. In studying these visual data, it became apparent that it is not likely that the vortex can be eliminated well downstream by merely reshaping the wing tip. A change in tip configuration may have a decided effect on the near-field vortex, resulting in an aerodynamic advantage through a reduction in induced drag. However, these configurations have only a small effect on the far-field flow, and are therefore considered no solution to the vortex persistence problem.

The author proposed that an unfavorable or positive pressure gradient applied just downstream of the wing tip may force the vortex to dissipate. This has been done by employing a decelerating chute at each wing tip shown in Fig. 1. Tests in the pilot test facility have shown that the vortex was virtually eliminated in this manner in both the near and far field. The mechanism behind the success of this approach is believed to be the result of the shearing stresses set up between the rotational vortex flow and the linear flow of the mass of air forced forward into each vortex core by the decelerating

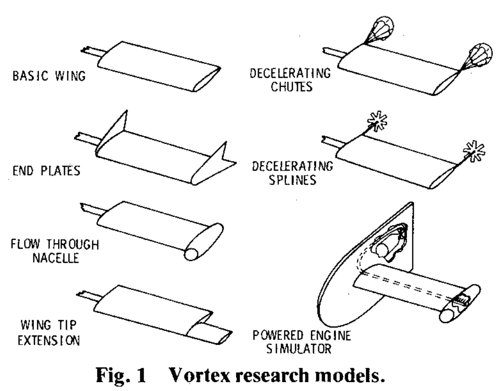

Fig. 1 Vortex research models.

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chutes. As a more practical application of this idea, a number of splines were probe mounted just downstream of each wing tip with the same vortex attenuating effect as the decelerating chute. The spline configuration has the advantage that it may be retracted during cruise flight and deployed during landing and takeoff.

Based on the results for the splines, and on the fact that the vortex created by a passing aircraft has little or no longitudinal movement except in the core itself, it should therefore be possible to produce the same results by forcing a mass of air into the vortex core from either direction. This would mean that a forced vortex breakdown may be accomplished, if not to a greater degree than by the splines, by mounting an engine at the wing tip and directing its high-energy jet blast into the core of the vortex. A model powered jet engine mounted on the tip of an unswept semispan model shown in Fig. 1 has been tested in the pilot facility. Thrust was produced by high-pressure air piped from a small air bottle attached to the catapult carriage to an engine simulator at the wing tip. The engine thrust coefficient produced was equal to that of one engine of a jumbo jet transport during the takeoff mode. These tests indicate qualitatively that the vortex rotation is greatly reduced by the engine blast. These data also indicated that a large thrust is required to obtain an appreciable vortex attenuation.

A similar test has been conducted in the Langley Transonic Aerodynamic Pressure Tunnel using a semispan model with a tip mounted power fan-jet engine and has been reported in Ref. 2. These data indicate a reduction in induced drag of approximately 30% for this unswept, untapered wing having a symmetrical airfoil section. The results of this investigation suggest that the nonrotating high-energy wake of the engine reduced the vortex strength such that the additional downwash behind the wing due normally to the vortex flow was reduced resulting in the reduction in drag due to lift.

Langley Vortex Research Facility

Based on these exploratory results, a vortex research facility has been established in the existing towing basin at the Langley Research Center. The stationary airflow visualization method is employed as in the earlier investigation, and in addition it is now possible to make force measurements of the vortex generating model and roll model position downstream of the lead model.

Facility Description

An overall view of the internal modification made to the towing tank in the transition from the model towing basin to a vortex research facility is shown in Fig. 2. The carriage is shown mounted on the 1800-ft overhead track with a 4-engine transport-type aircraft model blade mounted beneath this carriage. A following model is located at 160 ft downstream of the vortex generating model (a scale distance of 1 mile) through a series of trailers to measure the rolling moment resulting from the lead model vortex.

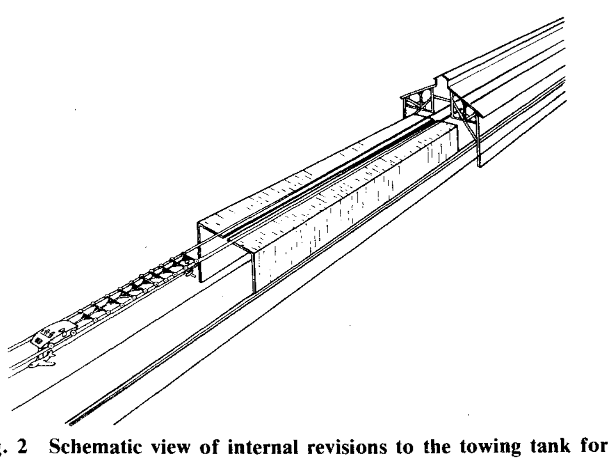

Fig. 2 Schematic view of internal revisions to the towing tank for vortex research.

The test section, constructed to isolate the wake of the carriage and trailers from the model wake, is 300 ft long with a 2-in. opening along the center of the ceiling to allow the model blade mounts to pass. The exterior of the building shown at the entrance of the test section encloses the entire length of the track.

The overhead track extends 1000 ft ahead of the entrance to the covered area where each test is begun. After the vehicle is launched, the automotive drive system accelerates through first and second gear to a velocity of 100 fps which is held constant by a cruise control throughout the length of the covered area. 100 ft inside the covered area is considered the test position where smoke (vaporized kerosene) is deployed for flow visualization. At this point, high-speed cameras are used to film the motion of the vortex produced by the generating model while the aerodynamic forces experienced by the model are recorded; 1.6 sec later the following model reaches this test point. The position of this model relative to the vortex core may be determined visually while the induced rolling moment is recorded. Caliper brakes are applied as the vehicle leaves the covered area bringing the vehicle to a 1 *g* stop over the next 250 ft of track.

Test Models

The vortex-generating model shown in Fig. 3, which represents a typical wide-body jet transport aircraft, is blade mounted on an internal 6-component strain-gage balance. High-pressure air is piped from a bottle field onboard the vehicle down the rear portion of the model blade mount to each engine nacelle for thrust simulation. The thrust of each engine is individually controlled to allow a difference in thrust level between the inboard and outboard engines. The model is equipped with both leading- and trailing-edge flaps to simulate the landing as well as the cruise configuration.

The following models used to measure the roll induced by the vortex of the lead model are shown in Fig. 4. The smaller of the two models is in the Learjet class while the other is similar in scale size to the DC-9 transport. The models include 2 swept and tapered wings plus 2 unswept untapered research wings having the same span and aspect ratio as the swept wings. The vertical and lateral position of the following

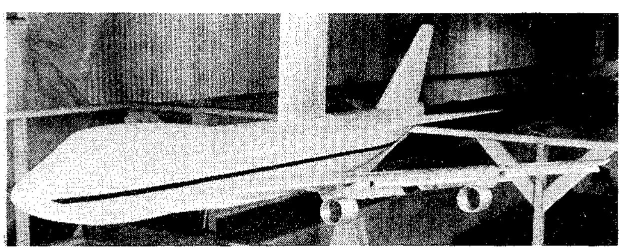

Fig. 3 Photograph of the model of a 4-engine wide-body jet transport aircraft used as a vortex generating model.

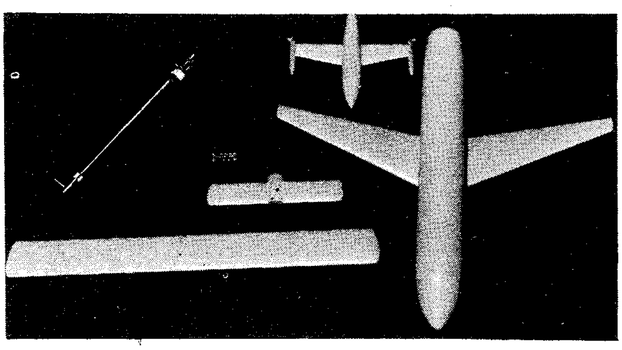

Fig. 4 Photograph of following models used for vortex induced roll measurements.

model may be varied to fix this model in the vortex generated by the lead model. This position of the roll model is recorded by a television camera to allow an instant replay of each test to determine the degree of vortex core penetration. The internal strain-gage balance used with these models is also shown in this figure.

Test Results

A sequence of photographs of the vortex flow created by a model of a typical wide-body jet transport aircraft in the Langley Vortex Research Facility is shown in Fig. 5. These photographs were taken at 1/5-sec intervals while the model traversed a distance of 3⅓ spans between each photograph. The clock in the lower right-hand corner of each photograph indicates this time interval. The height scale to the left of each photograph indicates the vertical travel of the vortex below the model in feet.

As the model penetrates the smoke screen, the vortex system produced by the model is made visible. The wing-tip vortex and the vortex produced by the outer edge of the outboard flap are shown for each wing panel in the first photograph. These two vortices produced by each wing panel orbit about a common axis forming into a single vortex within 4 spans, resulting in the classical vortex sheet emanating from a lifting wing rolling into a single vortex in the vicinity of each wing-tip, shown in the sequential photographs. These 2 vortices move downward under the influence of the wing downwash and the vortex cores become visible with time as a portion of the smoke material is induced upstream along the periphery of the vortex core. The smoke follows the vortex core as a result of the lower pressure associated with the more recently formed wake after the model has passed the smoke screen. Beyond the radius of the rotational flow of the vortex core, the irrotational potential flow region can be seen. In our effort to reduce or eliminate the vortex hazard through a reduction in vortex flow, it should be realized that the circulatory flow shown can only be eliminated by canceling the total lift of the aircraft. By converting the angular momentum of the persistent vortex flow into linear momentum, which has a shorter life span, the vortex-circulatory wake system may be caused to dissipate more rapidly, decreasing the separation distance between aircraft now required for safety.

The rolling moment induced by the vortex is measured by the following model as it penetrates the vortex shown in the eighth photograph taken 1.6 sec after the vortex generating model had passed the test position. The typical measured rolling moment experienced by this model is shown in Fig. 6. These data are presented against time in seconds as the model moves through the test area, starting at the moment the model enters the test area to the point the vehicle brakes are applied. This manner of presentation was chosen because a static condition cannot be established due to the meandering of the vortex core. The precent of the maximum rolling moment measured by the following model is dependent on how well the model is positioned relative to the vortex core; the maximum rolling moment value is obtained when the model is centered in the vortex core. Even though the model is centered visually in the vortex core at the smoke screen position, the data recorded at 20 points/sec indicate vortex meander throughout the test area. The rolling-moment coefficient of $C_\ell = 0.077$ as an average, disregarding the low-moment values, is above the roll capability of the medium class aircraft represented by the following model.

The measured effects of the spline configuration on the strength of the vortex are also presented in Fig. 6. Tests conducted on this device indicate that the maximum attenuating effect is obtained with the splines located at the 55% semispan wing position. These data indicate that the induced rolling moment experienced by the following model is approximately 20%, as an average, below that obtained for the unattenuated configuration. This attenuating effect may be increased by increasing the area of the spline if the associated drag can be tolerated, the drag representing the energy required for vortex

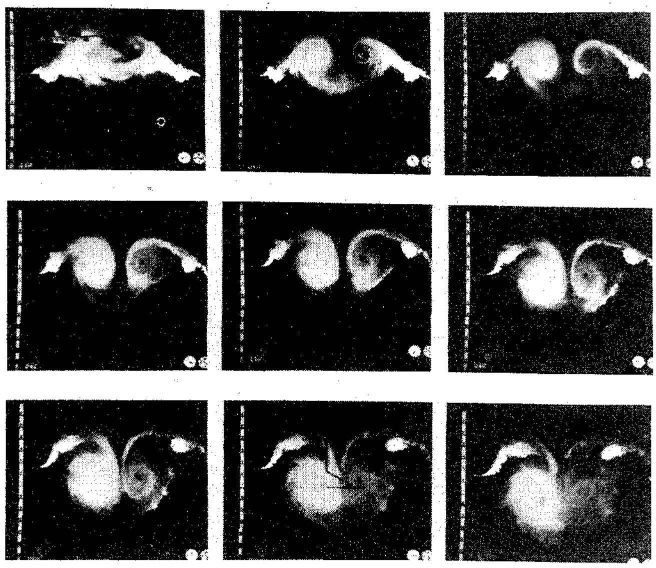

Fig. 5 Visual time history of the vortex system created by the vortex generating model in the test area of the Langley Vortex Research Facility. $C_L = 1.25$; flap deflection = 30°; photograph sequence = 5/sec.

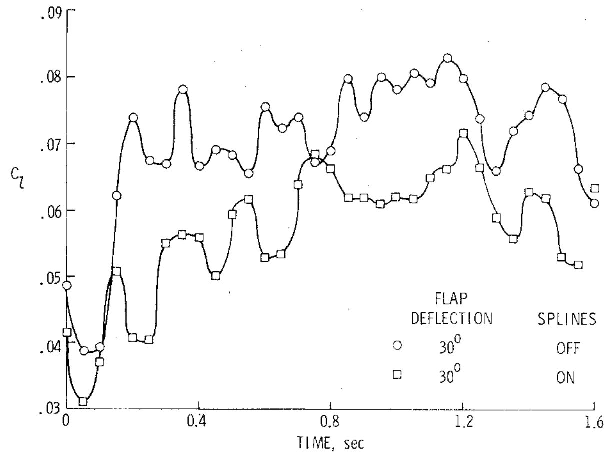

Fig. 6 Induced rolling moment measured at a scale distance of 1 mile behind the vortex generating model present against time with and without the spline vortex attenuating device installed. $C_L = 1.25$; flap deflection = 30°.

dissipation. The splines employed here are a minimum size for a 1-mile controllable separation with an accompanying increase in drag coefficient which is under 20% of total drag coefficient.

The data presented in Fig. 7 indicate visually the attenuating effect of the splines on the vortex flowfield. In comparing these data with those of Fig. 6, it is apparent that the vortex core flow is greatly affected in the near field with some reestablishment of the core in the far field. The attenuating effect of the splines on the circulation is more obvious in the high-speed motion pictures taken during this investigation.

The rolling moment induced on the following model as a result of the vortex system of the generating model including the effect of the thrust of the engine simulators is presented in Fig. 8. The simulators are operated at a static gross thrust level comparable to three-quarters of the maximum thrust obtainable by a wide-body jet transport aircraft of today. These data were obtained for a lift coefficient value of approximately 1.4, less the contribution of the thrust to the generating model lift, and are compared to the induced roll results obtained for the zero thrust case presented on this figure. Vortex strength is a direct function of lift for a particular aspect ratio and planform, therefore the resulting in-

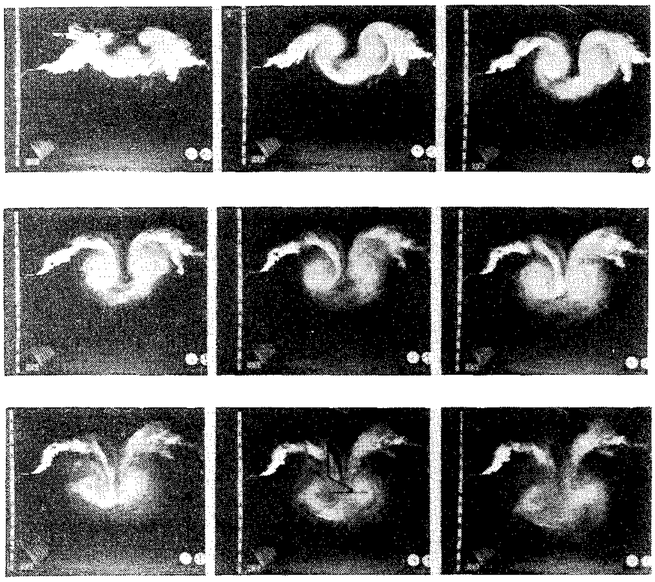

Fig. 7 Visual time history of the vortex system effected by the spline attenuating device. $C_L = 1.25$; flap deflection = 30°; photograph sequence = 5/sec.

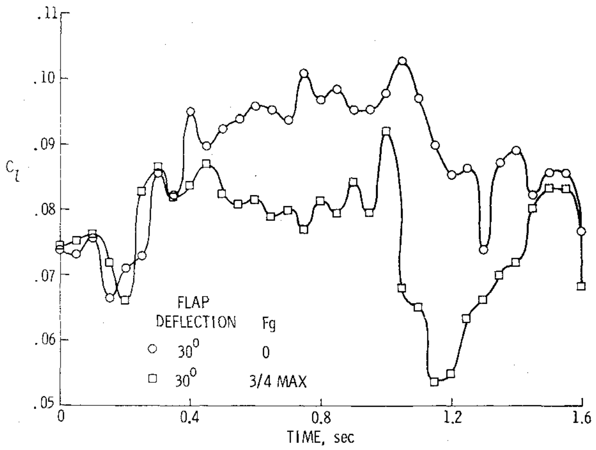

Fig. 8 Visual time history of the vortex system including the attenuating effect of the engine thrust. $C_L = 1.4$; flap deflection = 30°; maximum static gross thrust coefficient based on wing area $(F_g) = 0.33$.

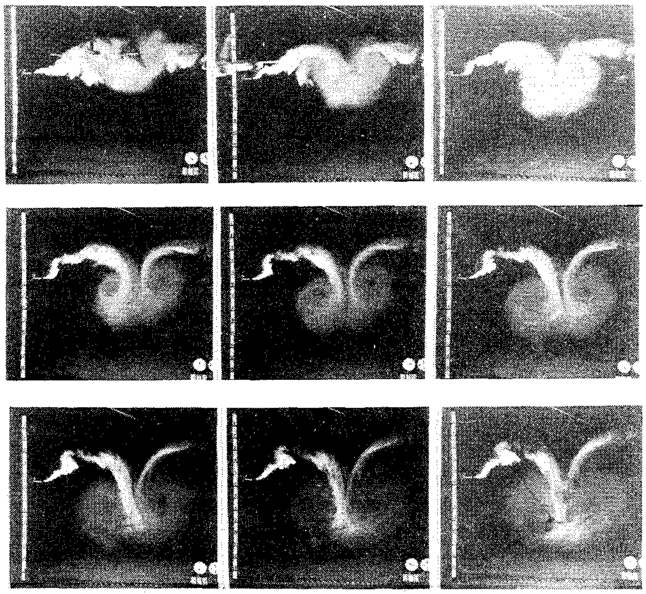

Fig. 9 Induced rolling moment measured at a scale distance of 1 mile behind the vortex generating model present against time with and without the attenuating effect of engine thrust. $C_L = 1.40$; flap deflection = 30°; static gross thrust coefficient based on wing area $F_g = 0.33$.

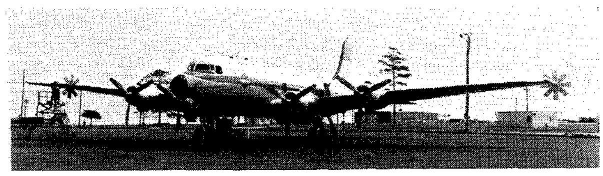

Fig. 10 Douglas C-54 with the vortex attenuating device mounted on each wing tip.

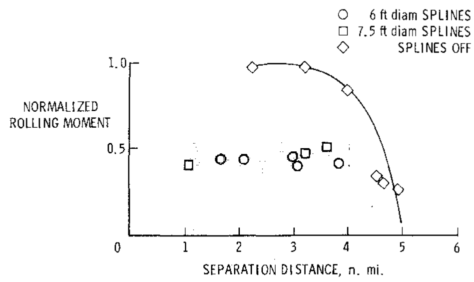

Fig. 11 Roll data measured by the Piper Cherokee chase aircraft behind the C-54 aircraft with and without attenuation.

duced roll increases with lift and the task of vortex attenuation increases as well.

The visual effects of engine thrust on the vortex formation are presented in Fig. 9. The wing tip and flap vortices do not appear as distinct as the high-energy jet blast from the inboard, and outboard engines are introduced on either side of the final vortex roll-up position which was found to be approximately 55% of the wing semispan during the spline investigation. The attenuating effect of the thrust should be greater than that of the splines because of the continued injection of an air mass from the engines into the vortex formed at a particular position along the flight path. The amount of engine exhaust that reaches the vortex, of course, decreases as the separation distance between the aircraft and the point in question increases. The attenuating effect of the engine wake continues for some time while the effect of the spline device is no longer present once this device has passed this point. The downwash produced by the wing is apparent in this figure as well as the circulatory field in the vicinity of each wing tip. The reformation of the vortex noted in the spline visual data does not seem to be present in these data.

The reduction in induced rolling moment resulting from the addition of thrust is approximately 18% based on an average of the largest induced rolling-moment values measured over a ¼-½-sec interval. This reduction in rolling moment is achieved without any alterations to the position of the pylon mounted engines relative to the wing. The results of tests conducted with an engine located at each wing tip, not presented here, had little or no effect on the vortex strength of the full landing flap configuration, indicating that the spanwise location of the engine should not be increased. This is in agreement with the results of the spline investigation which indicates that the final formation of the vortex system is even more inboard than the present outboard engine location.

Flight Test of the Spline Device

Before the Vortex Research Facility had been completed, flight tests were performed to determine if these visual data results from the ground facility would be similar under full-scale conditions. It would also be possible to obtain quantitative measurements of the attenuating effects of the splines using an instrumented following aircraft. The Douglas C-54 aircraft was used as the vortex generating aircraft and the

Piper Cherokee as the chase aircraft. The flight tests were conducted by Earl Hastings of the Flight Division of the Langley Research Center and Douglas Young located at the Wallops Station. The tests were performed at altitudes from 8000-10,000 ft above the Atlantic Coast over an uninhabited area along the shore line of Wallops Island.

The C-54, with a 6-ft diam spline probe mounted on each wing tip, is shown on Fig. 10. Because of the tapered wing of the C-54 aircraft, the most efficient position for the splines would be between 80-90% of the semispan. This had been determined from the flow visualization test performed using the C-54 model wing. Because of the structure of the C-54 wing and the fact that the aileron extends to the tip of the wing, it was necessary to locate the splines at the very tip of the wing. A series of 3 different sized splines were built: the 6-ft-diam set of splines in Fig. 10; a 7-½-ft-diam set of splines which is equal to 60% of the length of the mean chord of the wing, also determined vusially during the early development test to be the minimum size which might effectively reduce the vortex; and a 9.1-ft diam set of splines, covering a range from 25% below the predicted required size to 25% above.

The area of the 6-ft spline is equal to the area of one of the 3-bladed 13-ft-diam propellers of this 50,000-lb 4-engine aircraft. The flat-plate drag of one spline would be the same as that of one unfeathered propeller of the C-54.

Preliminary wind-tunnel tests indicate that the splines have little or no effect on the lift or the pitching moment and that the drag is equivalent to that of a flat plate of comparable area although it might be expected to be higher as a result of the complicated flow suspected to be associated with the spline configuration. C. Allen, the pilot of the C-54, stated that there was essentially no degradation in the performance or aircraft handling other than that due to the additional drag of the splines. Performance measurements[2] indicate that the takeoff distance was increased from approximately 1300-1500 ft while the rate of climb was decreased by approximately 25%.

To make the vortex visible during the flight test enabling R. Champine, pilot of the chase aircraft, to locate and penetrate the vortex, white powered chalk (diatomaceous earth) was forced by high-pressure nitrogen from a reservoir in the fuselage of the C-54 through a 1-in. pipe located below the right wing and expelled at the tip. It was possible to form a continuous stream of chalk for a duration of 30 sec creating a visible vortex for approximately 1 mile.

The rolling-moment data from these flight tests are presented in Fig. 11. The normalized rolling moment is presented against separation distance between the C-54 and the Piper Cherokee in nautical miles. Tests were begun with the Cherokee approximately 7 miles behind the C-54. Roll due to the lift-induced wing-tip vortex was first experienced at approximately 5 miles. As the separation distance was decreased, the rolling moment rapidly increased to a point beyond the control capability of the chase aircraft at approximately 3.5 miles. Data also shown in Fig. 11 for the various spline configurations indicate a reduction in rolling-moment coefficient of approximately 55% of that of the unattenuated aircraft allowing the Cherokee to fly within 1 mile behind the C-54.

Future Vortex Research

The research effort at the Langley Vortex Research Facility has been directed mainly toward investigation of the possibility of vortex alleviation by employing a spline device installed after the wing trailing edge as a retrofit configuration. A large effort is also directed toward the utilization of engine thrust to attenuate the lift-induced vortex as well as to improve the aerodynamic efficiency of the next generation of aircraft.

The Ames Laboratory has done extensive research in wing load variation to determine its effect on the vortex persistence problem, while the Langley Vertical Takeoff and Landing Facility has studied the effect of spoiler devices on the wing-tip vortex. Tests of Hydronautics[3] have determined the far-field effects in water for various devices from the different NASA facilities, for a number of spoiler configurations proposed by the Hydronautics, and for various wing-tip blowing configurations. The different approaches to vortex alleviation now being studied at the different facilities will be tested in the future at the Vortex Research Facility as well as those devices which will be developed through the present research.

Conclusions

The results of the present experimental investigation to determine some means to reduce the lift-induced wing-tip vortex intensity indicate the following conclusions: 1) The strength and relative position of the lift-induced vortex of a model aircraft configuration may be determined at a scale distance of 1 mile in a test facility such as the Langley Vortex Research Facility by the proper longitudinal, lateral, and vertical positioning of a following model. 2) The lift-induced vortex may be attenuated to a large degree by effecting the pressure field in the path of the vortex by a spline device located just downstream of the wing as a result of the shearing stress produced between the linear flow of the device and the rotational flow of the vortex. 3) Vortex attenuation similar to that obtained by the spline device may be accomplished by directing the high-energy jet engine wake into the vortex core. 4) The vortex of a Douglas C-54 class aircraft may be attenuated with the spline device to be considered nonhazardous to smaller following aircraft. 5) The scale effect on vortex attenuating devices from model results to full-scale results appear to be small if the model vortex is allowed ample room for full vortex development with minimum wall or ground interference.

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