countered in the upper atmosphere. This effect, coupled with the accompanying loss of aerodynamic lift unavoidably experienced in the headwind-to-tailwind swing, is what collectively creates the hazardous environment for an aircraft which encounters a microburst as it attempts to land in a thunderstorm.

Acknowledgments

This work was supported by NASA Langley through the American Society for Engineering Education Summer Faculty Research Program. The author enjoyed vigorous related discussions with Drs. R. L. Bowles, B. T. MacKissick, and K. Chuang, all of NASA Langley Research Center, and herewith acknowledges their collective participation in the completion of this work.

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Propeller Swirl Effect on Single-Engine General-Aviation Aircraft Stall-Spin Tendencies

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Introduction

THE considerable size and activity of the general-aviation fleet and its involvement in air accidents has focused attention on the safety of these aircraft. Among those accidents, the so-called "stall-spin" category accounted for more fatal and serious injuries than any other single type of accident.[1,2] The typical stall-spin occurs usually in low-airspeed maneuvers such as on final approach or following an engine failure. Because of the excessively low airspeed in these situations, the airplane operates close to its highest lift coefficient and any small lateral control input can result in a partial or full stall of one of the airplane's wings. Consequently, the stalled wing drops and creates larger drag which initiates the spinning motion of the airplane. On some aircraft, the stall-spin entry is so violent that most control surfaces are stalled and ineffective, and recovery is next to impossible with the available altitude. Therefore, estimating the propeller swirl effect on the lifting surfaces is critical since it introduces an asymmetric effect that is most pronounced in single-engine aircraft or in the "engine out" case of a twin-engine aircraft.

In this study, the effect of propeller slipstream on the stall pattern of a single-engine, untapered, low-wing aircraft was investigated. This asymmetric propeller influence can trigger an early stall of one of the wings and thereby can aggravate the spin-entry condition. Furthermore, it is shown that the combination of this propeller-induced effect with adverse sideslip can result in very large and abrupt changes in the rolling moment. This hazardous condition is likely to occur during uncoordinated, low-speed turning maneuvers, when the pilot yaws the aircraft to keep the wings level, instead of rolling it.

Discussion

Experimental development of stall-spin resistant general-aviation wings was sought by several research groups.[3-6] One of the methods investigated that showed partial success was to obtain gradual flow separation on both wings, thereby providing early stall warning as well as eliminating abrupt lift loss and violent changes in the rolling moment. The results reported here are the product of this effort, conducted at the NASA Ames 40×80 ft, full-scale wind tunnel.

The test airplane, as mounted in the wind tunnel is shown in Fig. 1. The airspeed was set to simulate the approach condition of about 124 km/h (77 mph), and the aircraft, piston-engine-driven propeller could be remotely operated. Further details on the experimental setup are reported by Feistel et al.[6]

The lift coefficient C_L and rolling moment coefficient C_R vs angle of attack α for the basic airplane with different power settings are shown in Fig. 2. The diamond symbols stand for the power-off data. The lift coefficient, in the lower section of the figure, shows fairly linear behavior up to an angle of attack of about 12 deg. In that region, the rolling moments are small and their scatter about the α axis is due to limited local separation at the wing's trailing edge (by the wing/fuselage junction). The triangular and circular symbols in Fig. 2 represent the data taken at 1800 and 2450 rpm, respectively, with flaps down ($\delta_f = 33$ deg). The case of 1800 rpm and flaps down corresponds to typical approach conditions, where stall-spin accidents are most likely to occur. The effect of flap deflection in the unseparated region of α is most pronounced on the lift curve (Fig. 2). The rolling-moment data, however, are almost unaffected, apart from a slight positive shift for the increased power setting.

The critical range of angle of attack for stall-spin alleviation for this particular aircraft is in the range of 10 deg $<\alpha<$ 16 deg, where the transition from attached to separated flow over the wing is developed. Figure 2 shows that through the stall region and beyond (10 deg$<\alpha<$16 deg), the rolling moment without the propeller effect is relatively small, whereas with increased power settings (constant pitch) the rolling moment increases violently in the negative direction. This is a result of the swirl caused by a clockwise propeller rotation (as seen from the pilot's point of view.) Therefore, because of the excess upwash at the left wing's root section, the flow over this wing separates first (at $\alpha \approx 13$ deg for 1800 rpm and $\alpha \approx 14$ deg for 2450 rpm), as shown by the inset of Fig. 2. Consequently, the negative rolling moment grows beyond control[6] (control limits are about $C_R \approx \pm 0.03$). After an additional increase of 3 deg in angle of attack, the right wing starts to stall, causing a reduction in the magnitude of the negative rolling moment. This process ended at about $\alpha \simeq 17$ deg with larger areas of flow separation on the right wing than on the left one. Flow visualizations (by tufts) verified this asymmetry of the stall pattern, which explains the second peak in the magnitude of the rolling moment (but this time to the positive direction).

Similar behavior of single-engine, low-wing aircraft was reported in Refs. 7–9. In Ref. 7, a large number of World War

Received Aug. 31, 1986; revision received Nov. 21, 1986.

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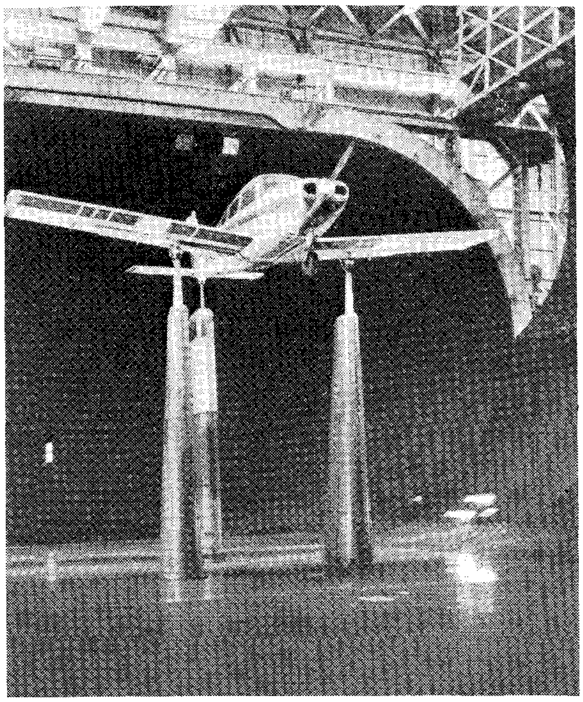

Fig. 1 Photograph of aircraft model as mounted in the NASA Ames 40×80 ft wind tunnel.

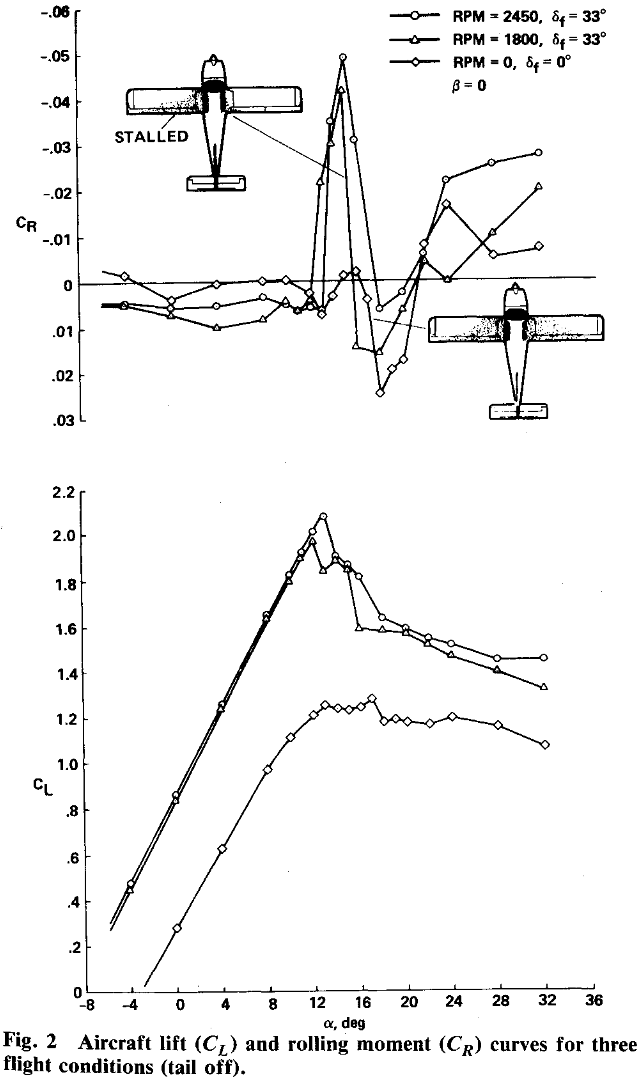

Fig. 2 Aircraft lift (C_L) and rolling moment (C_R) curves for three flight conditions (tail off).

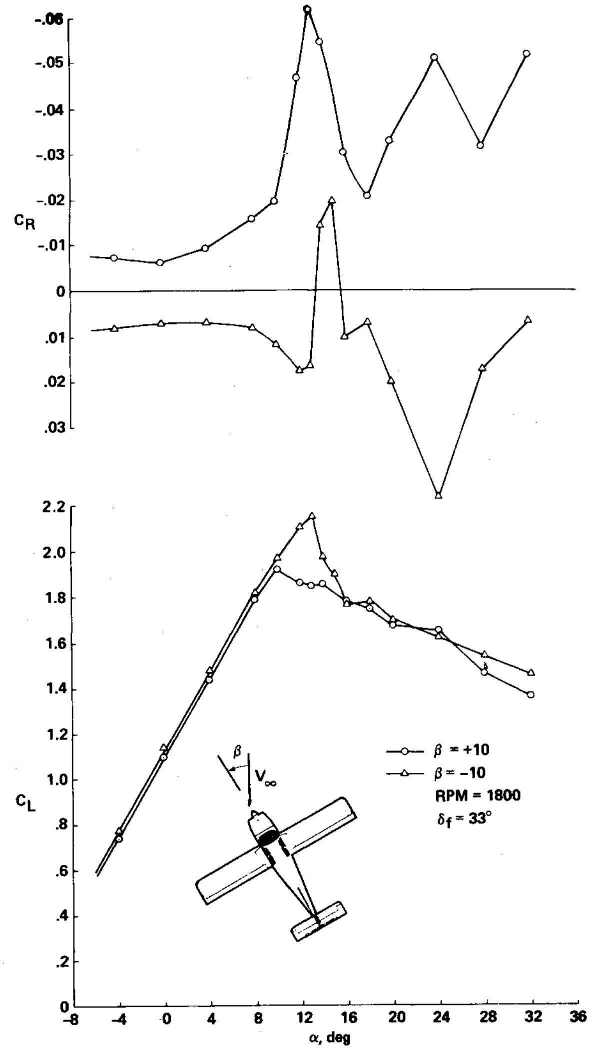

Fig. 3 Aircraft lift (C_L) and rolling moment (C_R) curves for two sideslip conditions (modified leading edge).

II aircraft were tested beyond stall condition, while Refs. 8 and 9 report on similar full-scale tests at the NASA Langley Research Center. These results are in agreement with the present data, but the negative rolling moments at the beginning of the left wing's separation are 20–50% smaller. This is probably a result of the tapered wings of the aircraft tested there, whereas the wing-tip lift of the current untapered wing (when the flow is still attached) is larger, causing the larger rolling moments.

For higher angles of attack ($\alpha > 20$ deg), the rolling moment has larger negative values for higher propeller power settings, but this region has no practical prespin significance since general-aviation aircraft are not flying in such extreme attitudes.

A typical high-risk stall-spin entry condition occurs when turning into final approach before landing.[2] Between the years 1967–1969, 36% of all such accidents occurred during landing, as shown by the survey of the National Transportation Safety Board.[1] A possible devastating situation under such a condition is when the airplane performs an uncoordinated turn with sideslip. However, if for some reason the pilot enters a positive sideslip condition (with lower banking angle when turning left), the additional effect of the propeller will cause the left wing to stall first. This effect is shown in Fig. 3; the airplane was tested under full-scale landing conditions (rpm = 1800, $\delta_f = 33$ deg) and the wings were equipped with leading-edge modifications to somewhat decrease the violent rolling moments beyond stall. In spite of these improvements, the combined unfavorable effects of both propeller and yawing initiated the left-wing stall at about $\alpha = 10$ deg, for the case of positive β (+10 deg). This corresponds to a left-turn situation as described above, resulting in a left yawing moment (into the turn) accompanied by a very high rolling moment extending beyond the control limits of the airplane.[6] The stall of the right wing is initiated only at above $\alpha = 13$ deg (Fig. 3) and the negative rolling moments are then reduced.

Because of the dihedral of the test airplane wing (5 deg), rolling moments on the order of ± 0.01 for both yaw conditions are measured at the lower angles of attack ($\alpha < 9$ deg in Fig. 3). On the other hand, because of the presence of the fuselage (the test aircraft had a low wing), the trailing half-wing section has a higher tendency to stall (in spite of the lower effective angle of attack). The combination of this effect with the propeller slipstream results in the considerable difference between the positive and negative yawing as shown in Fig. 3. That is, when yawing the aircraft to the right, the resulting rolling moment is within control limits, whereas, yawing it to left will bring the aircraft beyond its control limits.

Concluding Remarks

The study of propeller effect reported here shows that for a typical single-engine, low-wing, general-aviation aircraft with untapered wings, the propeller upwash on the left wing initiated separation at an angle of attack which is 3 deg smaller than the angle of attack at which the separation of the right wing occurred. When the aircraft was yawed, it was found that positive yaw angles resulted in a violent rolling moment and wing separation was initiated at smaller angle of attack. For the negative yaw condition, the separation occurred at 2–3 deg of angle of attack later, and the resulting rolling moments were within control limits. The above finding suggests that aircraft similar to the one tested, under positive sideslip condition, are likely to face a stall-spin entry when performing, for example, a low-speed final left turn with excessive rudder deflection before landing.

Acknowledgment

This work was done while the first author held an NRC Senior Research Associateship at NASA Ames Research Center.

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Applications of Similitude in Airship Design

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Introduction

THE Buckingham π theorem is often thought of simply as a tool for the reduction of the number of independent variables required in an experimental study of natural phenomena. Similitude is, therefore, often overlooked during the conceptual phase of engineering design. This Note describes two clarifications gained by implementing the Buckingham π theorem in a conceptual airship design study. First, a volume sensitivity parameter is obtained that permits a very close description of traditional airship performance characteristics in terms of a single curve. Second, the appropriate parameters for nondimensionalization of drag for an airship is discussed.

Airship Volume Sensitivity

The necessary airship volume V for a prescribed mission depends on the airship's altitude z, velocity U, payload W, and endurance t. Only three basic dimensions—mass, length, and time—are necessary to express the five variables dimensionally. Interpreting air density ρ to correspond to the effect of altitude on the airship performance, the functional relationship for the airship volume is

$$F(V,\rho,U,W,t) = 0 \tag{1}$$

The π theorem states that the number of variables ($n = 5$) minus the number of dimensions ($r = 3$) is equal to the number of independent parameters ($n - r = 2$) that characterize the problem. Classic dimensional analysis[1] leads one readily to find the two π parameters:

$$\pi_1 = V/U^3t^3 \tag{2}$$

$$\pi_2 = W/\rho U^4 t^2 = W/(\rho U^2)(Ut)^2 \tag{3}$$

Note the significance of the second term, which can be interpreted as the ratio of the useful load to the product of the dynamic pressure and the ferry range squared. From the π theorem,

$$F(\pi_1,\pi_2) = 0 \tag{4}$$

from which we define a new function, f, such that

$$\pi_1 = f(\pi_2)$$

so that a general relationship for airship volume is

$$\frac{V}{U^3t^3} = f\left(\frac{W}{\rho U^4 t^2}\right)$$

Received June 10, 1986; revision received Jan. 20, 1987.

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