Unique Flight Characteristics of the AD-1 Oblique-Wing Research Airplane

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Flight characteristics of an oblique-wing airplane have been studied with limited scope and complexity using the AD-1 research vehicle. The AD-1 is a low-speed, low-cost, manned airplane with an aeroelastically tailored wing that can be pivoted 0-60 deg asymmetrically. Aerodynamic forces and moments were shown to result in significant trim requirements, generally in all three axes. Wing flexibility in bending was designed to minimize roll trim requirements at a 60 deg sweep design condition. Aerodynamic derivatives, aeroelastics, stall characteristics, and inertial cross coupling of the asymmetric sweep configuration were also identified. The overall impact of sweep on the handling qualities at angles up to 45 deg was not great. At higher angles of sweep the handling qualities deteriorated rapidly. In a concurrent study using a ground-based simulator, a simple rate feedback control augmentation system was shown to significantly improve the flight characteristics at sweeps up to 60 deg.

Nomenclature

C_D = drag coefficient
C_l = rolling moment coefficient, referenced to unswept span
$C_{l_{\delta a}}$ = roll control derivative, deg^{-1}
C_{l_p} = roll damping derivative, rad^{-1}
C_L = lift coefficient
C_m = pitching moment coefficient, referenced to unswept root chord
C_n = yawing moment coefficient, referenced to unswept span
C_Y = sideforce coefficient
I_x = rolling moment of inertia, kg/m^2
I_{xy} = $X-Y$ cross product of inertia, kg/m^2
I_{xz} = $X-Z$ cross product of inertia, kg/m^2
I_Y = pitching moment of inertia, kg/m^2
$\dot{p}$ = roll angular acceleration, rad/s^2
$\dot{q}$ = pitch angular acceleration, rad/s^2
α = angle of attack, deg
β = angle of sideslip, deg
Λ = wing sweep angle, right wing forward, deg
φ = bank angle, deg

Introduction

ABOUT 10 years ago the oblique-wing configuration was proposed by Jones.[1] Subsequent studies of the concept have shown its improved transonic aerodynamic performance at Mach numbers up to 1.4 and the elimination of sonic booms in flight at Mach numbers as high as 1.2.[2] Subsonic, oblique-wing transport studies have also shown the potential for either increased range or reduced takeoff gross weight.[3] Common to both configurations are the anticipated, inherently low airport noise and generally better, low-speed performance characteristics. Although oblique-wing aerodynamic performance benefits occur at transonic speeds, many of the problems associated with asymmetry are not strongly tied to compressibility and thus (to a limited extent) can be evaluated at low speeds. An overview of oblique-wing technology is given in Ref. 4.

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The approach taken for the AD-1 was to design and fabricate a "one of a kind" low-speed, low-cost airplane to conduct research on many of the problems associated with an aeroelastic oblique-wing airplane. The "low-cost, low-speed" concept limited both the complexity of the vehicle and the scope of the technical objectives. Low speed allowed for the use of a simple structure, fixed landing gear, and a mechanical control system; however, it also limited the technical objectives. The specific technical objectives of the AD-1 were: 1) assessment of the unique handling and flying qualities of an unaugmented, low-speed, oblique-wing vehicle; 2) general appraisal of the nature and complexity of a flight control system on an oblique-wing configuration; 3) verification of the wing static aeroelastic design criteria; and 4) comparison of the flight-determined aerodynamic data with predictions.

From the limited measurements that were made, the total aerodynamic forces, moments, and derivatives were calculated at wing sweeps of 0-60 deg. These results were used to determine the incremental changes in performance, stability, and trim requirements. This paper presents results that highlight some of the unique flight characteristics of an oblique-wing airplane.

Vehicle Description and Instrumentation

The general layout of the AD-1 is shown in Fig. 1 and the physical characteristics are presented in Table 1. The airplane has a high-fineness-ratio fuselage, twin turbojet engines mounted on short pylons, fixed gear, and a high-aspect-ratio, aeroelastically tailored oblique wing that can be swept at 0-60

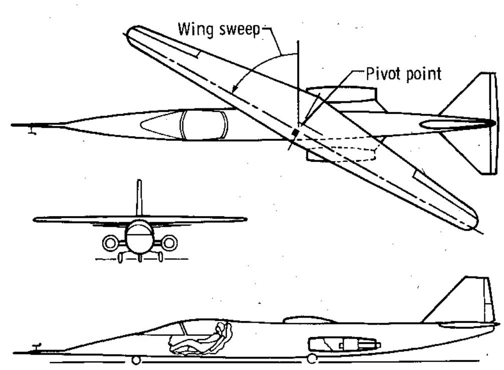

Fig. 1 AD-1 general configuration.

deg. The aircraft is constructed with a fiberglass-reinforced sandwich separated by a core of rigid foam.

The primary flight controls are an elevator, aileron, and rudder. The movable vertical surface is divided almost equally between a conventional rudder control and an electrically actuated directional trim surface. The primary controls are mechanical without boosts or interconnects.

Air data parameters, vehicle accelerations and angular rates, control surface positions, and throttle settings were measured in flight. The data were transmitted to a ground station and stored on tape for postflight analysis. Tufts were attached to the wing upper surface on some flights for flow visualization.

Predicted Data

Wind-tunnel tests that used a 1/6 scale model in the 12 ft pressure tunnel at NASA Ames Research Center provided most of the preflight data. Full-scale Reynolds number and aeroelastic wing bending were achieved during the tests. Damping derivative predictions were obtained using computational methods.[5] A six degree-of-freedom, fixed-base digital simulator was developed using these predictions for safety of flight and flight planning. A spin-tunnel test of a 1/13 scale model was also performed at the Langley Research Center.[6]

Flight Data

The aerodynamic derivatives were determined from dynamic flight maneuvers. A maximum likelihood estimation computer program, MMLE3, was used to estimate the best set of derivatives to match the known airplane response to a given control input.[7] The program was modified to include an aerodynamic model similar to that used in an oblique-wing remotely piloted research vehicle analysis.[8] This model separated the longitudinal- and lateral-directional equations of motion but included the effects of cross coupling.

Total untrimmed force and moment data were obtained by solving the equations of motion at discrete time points during quasi-steady-state flight maneuvers. Results of the derivative analysis were used to correct for sideslip, control inputs, and angular rate effects. The data were faired to give a continuous distribution with angle of attack. A complete set of forces and moments were obtained from analyzing 1 *g* flight maneuvers first. Load factor effects that result from wing aeroelasticity at elevated *g* were determined by analyzing windup-turn maneuvers.

Handling quality ratings for several piloting tasks were obtained during the flight tests using the Cooper-Harper rating scale.[9] The ratings were given based on the criteria for transport aircraft because oblique-wing technology may be most applicable to this type of airplane. Two pilots were used in the evaluation. Results were also obtained from 14 "guest pilots" who flew to 60 deg of sweep following a one-day ground school.

The fixed-base simulator was updated using flight-determined aerodynamic data and was then evaluated using pilot ratings. A simple, rate feedback control system was incorporated into the simulation to investigate the potential benefits. The feedback gain in each axis was adjusted in order to optimize the pilot ratings. This allowed control system augmentation to be studied, although it was never implemented on the flight vehicle.

Flight Characteristics

The AD-1 exhibits many strong aerodynamic effects as a result of oblique-wing sweep. Some of these effects, also present on conventional variable-geometry aircraft, will be discussed first. The asymmetric nature of the AD-1 results in other unique characteristics, such as unusual trim requirements, asymmetric stall, aeroelastic effects, and inertial coupling which will also be discussed.

Table 1 AD-1 physical characteristics

Length	11.8 m (38.8 ft)
Wing reference and actual planform area	8.6 m² (93 ft²)
Reference and unswept span	9.8 m (32.3 ft)
Reference and unswept root chord	1.30 m (4.28 ft)
Wing airfoil	NACA 3612-02, 40 (constant)
Wing pivot location	0.4 root chord
Gross weight	9540 N (2145 lb)
Powerplant	Two TRS-18-046
Thrust, each	979 N (220 lb)

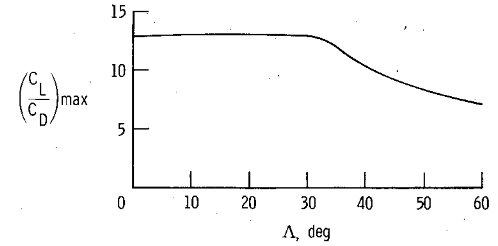

Fig. 2 Maximum untrimmed lift-to-drag ratio vs wing sweep angle.

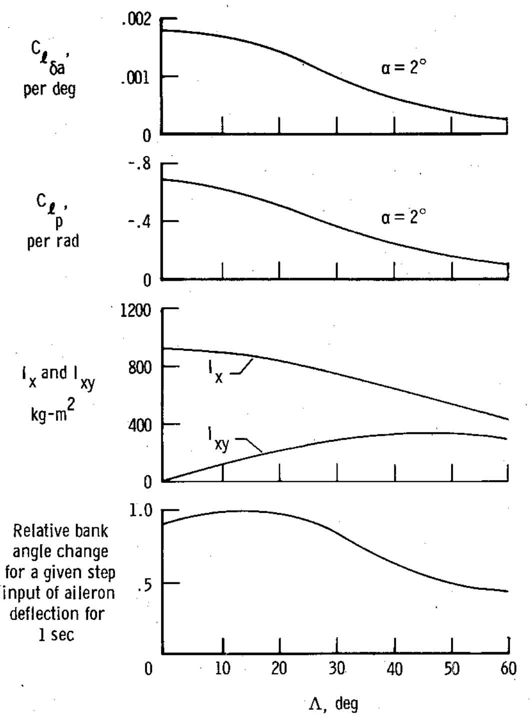

Fig. 3 Roll characteristics.

Maximum lift/drag ratio decreases steadily for sweep angles above 30 deg to about 55% of the level for low-sweep conditions (Fig. 2). These results were expected as the actual aspect ratio with sweep was reduced. Since verifying oblique-wing aerodynamic performance was never an objective of the program, the precautions (and expense) were not taken to minimize drag.

The reduction in the aileron roll control derivative $C_{l_{\delta a}}$, the roll damping derivative C_{l_p}, and the rolling moment of inertia I_x due to wing sweep are shown in Fig. 3. At 60 deg sweep, $C_{l_{\delta a}}$ is about 15% of its value at zero sweep, but with the concurrent reduction in C_{l_p} and I_x, adequate maneuvering roll authority is maintained. Also shown in Fig. 3 are the relative bank angles achieved for a given step input of aileron for 1 s.

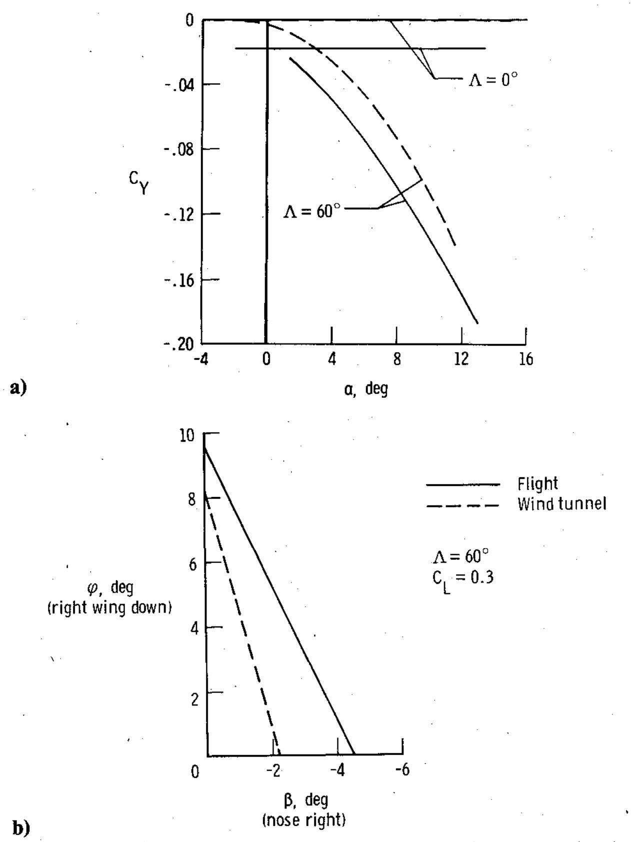

Fig. 4 Sideforce and corresponding trim requirements: a) wind-tunnel and flight sideforce coefficient results, b) trim requirements at design point.

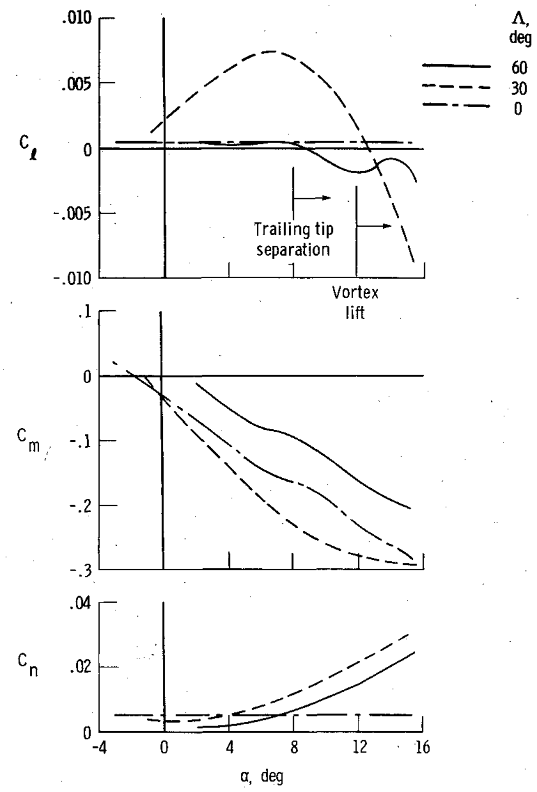

Fig. 5 Untrimmed moment coefficients at unity load factor, referenced to flight center of gravity.

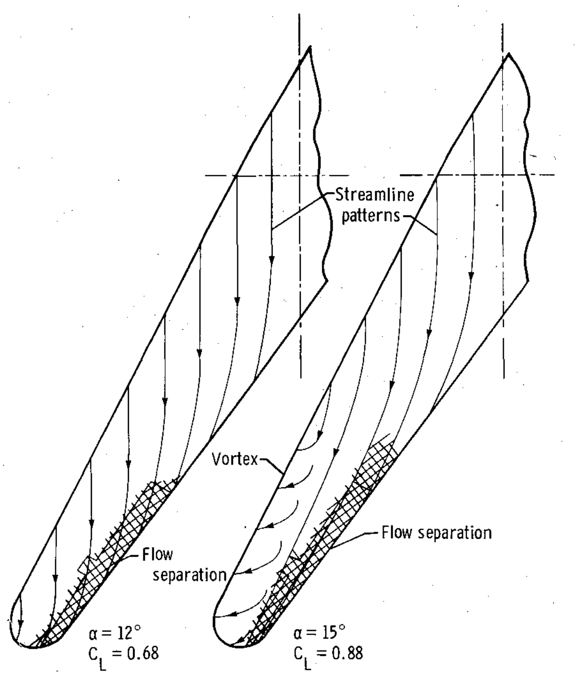

Fig. 6 Low-speed trailing-wing flowfield on upper surface at 60 deg sweep.

As the resultant aerodynamic force on a wing rotates forward with increasing angle of attack, the force rotates approximately perpendicular to the wing sweep angle. For an oblique-wing configuration, this effect creates a sideforce (Fig. 4a). To maintain a constant heading, the sideforce must be balanced by using either sideslip, bank angle, or both. An example of these trim requirements for 0.3 lift coefficient and 60 deg of sweep is shown in Fig. 4b. Although not understood at the time the AD-1 was designed, it would have been possible to eliminate most of the apparent sideforce and its trim requirements by tilting the wing pivot axis forward about 5 deg and increasing the wing incidence to maintain the same unswept geometry. This design would bank the wing when swept, thus allowing the fuselage to remain straight and level. Note that in Fig. 4a a bias on the order of 0.02 in C_Y exists in the flight sideforce data, resulting in larger trim requirements than were predicted. This bias can also be identified in the untrimmed moment coefficients at zero sweep and may be a result of inherent airplane asymmetry.

The static aerodynamic moments are shown in Fig. 5 to illustrate that trim is generally required in all three axes. For a rigid, oblique wing, when lift is increased, the untrimmed span-load centroid will translate toward the trailing-wing tip, while the converse happens for an overly flexible wing. A properly designed aeroelastic oblique wing will have a balanced span load at a design point. The AD-1 design point is 0.3 lift coefficient at 60 deg sweep which is a condition attained near an airspeed of 140 knots. This corresponds to an angle of attack of about 4 deg. As shown in Fig. 5, the roll trim requirement is nearly zero at these conditions.

At very slow speeds, nonpotential flow is initiated on the trailing wing and results in asymmetric response to stall. Figure 6 shows the trailing-wing streamline pattern for the upper surface at 60 deg sweep derived from tuft photographs. Spanwise flow and viscous separation begin at the trailing-edge tip and progress inboard as the angle of attack increases. The tufts indicated the formation of a spanwise vortex on the trailing wing at $\alpha > 12$ deg. Throughout the tests, the forward (right) wing exhibited attached flow. In Fig. 5, the roll coefficient data at 60 deg sweep reflect these trends. Negative values of C_l (left wing rolloff) at $\alpha > 8$ deg indicate trailing-wing flow separation. Vortex lift on the trailing wing alleviates this rolloff at $\alpha = 12$-14 deg. At higher angles of attack, the effect of separation is dominant, resulting in greater rolloff tendencies. This effect, combined with the loss of left aileron effectiveness, made complete wing stall in steady flight impossible. Rapid pullups to stall were not attempted. Spin-tunnel tests[6] indicated that the AD-1 model (wing swept) had a yaw-right established spin mode from which it was difficult to recover without first unsweeping the wing. Furthermore, with the wing highly swept, the model would not maintain a spin into the trailing wing (yaw left). Since the left wing began to stall first in slow-speed flight, the airplane rolled and yawed away from the potential spin problem. If the recovery was unchecked, indications were that the airplane would enter a steep spiral to the left.

Wing flexibility due to the load factor made a significant contribution to the aerodynamic moments of the airplane. The pitching moment at a 60 deg sweep is shown in Fig. 7 as a function of the angle of attack during both a level flight deceleration (constant 1 g load factor) and a windup turn (1.0-2.0 g normal acceleration). The incremental changes due to the load factor for all three moment components are shown in Fig. 8. These effects are detrimental to the handling qualities during rapid and high-load factor maneuvers such as windup turns. The positive pitching moment increment is analogous to a positive (destabilizing) increment in longitudinal static stability, and the negative rolling moment increment has the effect of resisting turns to the right and steepening turns to the left. Also, the negative yawing moment increment has an "adverse yaw" effect for right turns and a "proverse yaw" effect for left turns. Thus, right rudder was needed to coordinate either left or right turns.

The impact of the aeroelastic effects on the vehicle stability was aggravated by the flexibility of the wing structure. The use of fiberglass limited the maximum practical wing stiffness that could be obtained to about one-third of the desired stiffness. Although the AD-1 structure allowed completion of the technical objectives, the use of a stiffer material would have improved the stability characteristics by reducing the aeroelastic effects at elevated g.

At high wing sweeps, the I_{xy} cross product of inertia is of significant magnitude compared with the roll inertia (Fig. 3). An example of the pitch-roll inertial coupling at 60 deg sweep is,

$$\dot{p} = \frac{1}{I_x}\left[1.06\left(\begin{matrix}\text{rolling}\\ \text{moments}\end{matrix}\right) + 0.08\left(\begin{matrix}\text{pitching}\\ \text{moments}\end{matrix}\right)\right] \quad (1)$$

$$\dot{q} = \frac{1}{I_y}\left[0.73\left(\begin{matrix}\text{rolling}\\ \text{moments}\end{matrix}\right) + 1.06\left(\begin{matrix}\text{pitching}\\ \text{moments}\end{matrix}\right)\right] \quad (2)$$

These equations were simplified to illustrate only the pitch-roll coupling by deleting the roll-yaw coupling effects of the more common and much smaller I_{xz} term. Although the equations show significant roll coupling into pitch, the actual airplane response contained only minimal coupling. This is because of the very low I_x/I_y ratio, the low I_x, and low roll damping (Fig. 3). At high sweeps, the resulting vehicle motion is primarily in roll; therefore, the rudder was occasionally used at 60 deg sweep to augment roll control.

Aerodynamic cross-coupling derivatives were also determined in the data analysis; however, these were relatively insignificant compared with the inertial effects.

The aeroelastic effects and pitch-roll coupling contributed to poor handling quality ratings at high sweep angles. Pilot ratings[9] obtained in flight for windup turns, pushover/pullup maneuvers, aileron rolls, and straight-and-level trim were generally acceptable at sweeps below 45 deg; however, they deteriorated rapidly at higher sweeps. The windup turn ratings, which were the most difficult maneuvers to perform with precision, are shown in Fig. 9. The airplane tended to overshoot the intended bank angle when turning to the left, while it resisted bank angle changes to the right. Another factor that contributed to poor pilot ratings was the low directional stability that decreased with wing sweep and angle of attack.

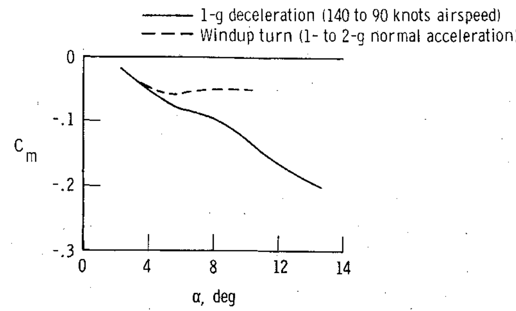

Fig. 7 Untrimmed pitching moment during 1 g and accelerated g flight, $\Lambda = 60$ deg.

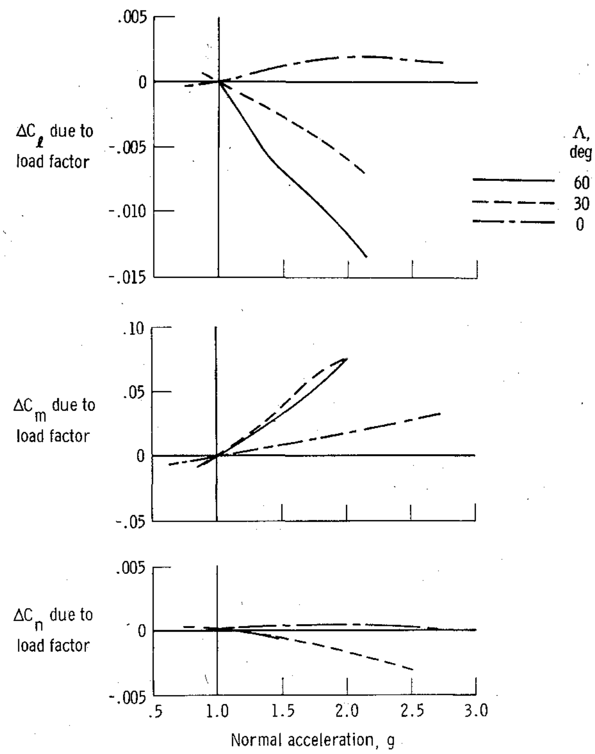

Fig. 8 Load factor effects on the moment coefficients.

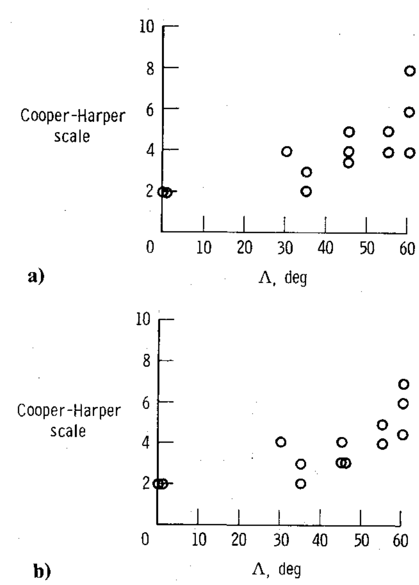

Fig. 9 Pilot ratings obtained in flight from windup-turn maneuvers: a) windup turn to the left, b) windup turn to the right.

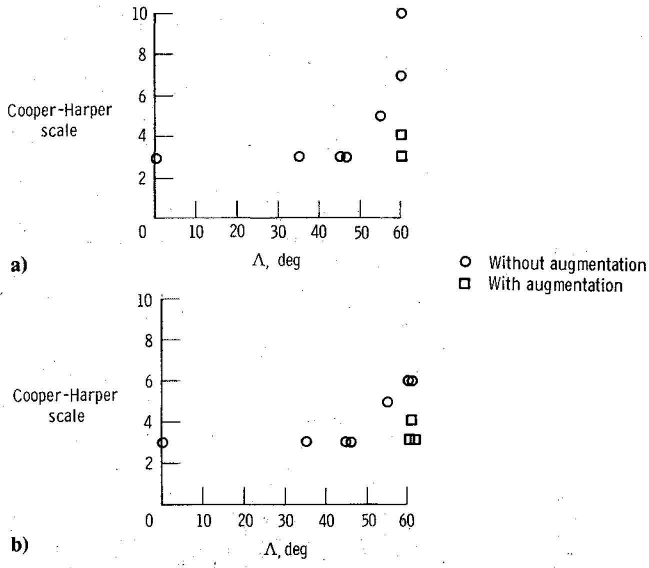

Fig. 10 Pilot ratings of a simulation of the AD-1 characteristics with and without control augmentation (pitch gain = 0.5 deg/deg/s, roll gain = 0.5 deg/deg/s): a) windup turn to left, b) windup turn to right.

In general, the handling quality ratings obtained in flight improved as the project pilots gained experience and developed pilot techniques in the airplane. Although considerable pilot compensation was necessary during flight at the high sweep angles, this did not interfere with the completion of the technical objectives. During the "guest pilot" program, 14 pilots demonstrated that the airplane could be flown without intensive preflight training.

The results of fixed-base simulator studies of a control augmentation system were favorable. Pilot ratings of windup turn maneuvers performed on the simulator at an airspeed of 140 knots are presented in Fig. 10. These ratings show that a control system utilizing pitch and roll rate feedback is sufficient to yield acceptable handling qualities ratings at all sweeps. Although not formally rated, simulation results for other airspeeds and maneuvers were virtually the same.

Conclusions

The AD-1 is an oblique-wing vehicle that exhibits many unique aerodynamic characteristics. Changes in the aerodynamic forces, moments, derivatives, and aeroelastics due to wing sweep have been shown to affect the performance, trim requirements, and stability of the airplane. Unusual stall characteristics and inertial coupling effects on the vehicle response were also observed.

Although the resulting handling qualities were adequate to complete the objectives of the program, the necessary pilot compensation increased at high wing-sweep angles. It was learned through fixed-base simulator studies that a simple control augmentation system could greatly improve these characteristics.

There is still a need for a transonic oblique-wing research airplane to assess the effects of compressibility, to assess a representative structure, and to define transonic flight performance.

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