Handling Characteristics in Roll of Two Light Airplanes for Steep Approach Landings

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A flight test program has been conducted to measure experimentally the roll control and spiral stability characteristics of two general aviation airplanes and to relate these characteristics to the increase in pilot's workload associated with preserving a level wing attitude during steep landing approaches. A DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane were used in the investigation. Values of measured roll control and stability parameters are compared with current handling qualities criteria. Rates of roll are compared with values calculated using lifting-line theory. The experimental results show that the problem of reducing the pilot's workload is not dependent upon improving the roll control characteristics of the airplanes tested, but appears to be mostly dependent upon providing additional spiral stability and reducing cross coupling. The requirement for additional spiral stability needed during the landing approach conflicts with the need for neutral spiral stability during the turning maneuver. Comparisons of roll control parameters with current handling qualities criteria show that both airplanes are within the range for satisfactory operation.

Introduction

THE rapidly expanding need for greater utilization of general aviation airplanes has challenged the manufacturers to offer improved designs with special capabilities. However, in many cases, advances in design have also resulted in increased requirements and the need for greater piloting skill during the landing phase of flight. Additionally, the pilot is finding that air traffic procedures for landing at an airport are demanding more of his attention. Considering that more demands are placed on the pilot and his margin of error is less during the landing than any other phase of flight, future improvements in the utility of general aviation airplanes depend greatly upon reducing the workload during the landing. To date, general aviation still lacks adequate limits for handling qualities and pilot workload related to the task of landing an airplane. The obscurity of these criteria is mostly related to the absence of actual flight test information.

The investigation at the Flight Mechanics Laboratory has focused on relating excessive pilot workloads to the handling characteristics of general aviation airplanes and on investigating methods for reducing the pilot's workload associated with the steep landing approach. The investigation is being conducted in three phases. The first two have recently been completed and the third is currently being conducted. The objectives of the first phase were to obtain a measure of the pilot's workload during a typical steep visual approach and to show where reductions for general aviation airplanes are essential.[1] With areas of excessive workload identified from the first phase, the objectives of the second phase of testing were 1) to evaluate stability and control parameters, 2) to determine if available airplane handling qualities criteria are adequate for general aviation airplanes and 3) to point out deficiencies in both airplane and available criteria. The objective of the third phase which is currently being conducted is to establish new criteria that could affect a reduction of pilot's workload.

Initial flight test measurements of pilot's workload parameters using a Beechcraft T-34B airplane showed that excessive workload resulted from the task of preserving a level wing attitude during visual landing approaches. These results were presented at the AIAA Guidance, Control and Flight Mechanics Conference in August 1971.[1] A second series of tests similar to those using the T-34B were conducted using a DHC-2, DeHavilland Beaver airplane. The test with the DHC-2 airplane investigated only the steep approaches and the only instrumentation used was a camera to photograph stick motions. Although quantitative measures of the pilot workload were not obtained as in the case of the T-34B airplane, observations of the pilot's motion during the steep approach indicated the same trend as in the case of the T-34B. The major difficulty was maintaining a wings level attitude throughout the approach. The photographic results clearly showed that small bank angle corrections at low speeds produced large heading errors. As a result the pilot had difficulty in landing on a predetermined point on the runway. Flight test results for both the T-34B and DeHavilland Beaver airplanes have shown that increases in workload during the landing approaches are, for the most part, a consequence of preserving a level wing attitude.

Four pilots, new to flight testing and with different levels of experience, were used in this phase of the investigation. The approximate accumulated flight time of each pilot was: 200, 500, 2500, and 5000 hr.

A second phase of testing was then conducted to evaluate the roll control and stability parameters in order to determine handling characteristics for the landing approach and to determine if available criteria are adequate for current general aviation airplanes. This paper presents the results of the second phase of flight testing conducted to determine the rolling characteristics of these two airplanes. Results include data on roll control power, roll sensitivity, spiral stability, and cross coupling parameters for each aircraft in various landing configurations. Values of each parameter

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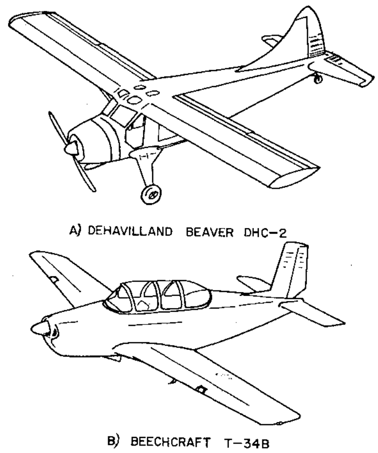

Fig. 1 Test airplanes.

are compared with existing handling criteria to evaluate airplane acceptability and to determine where existing criteria could be improved.

Flight Test Program

Test Airplanes

Two aircraft were used in the investigation, a DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane. The DHC-2 is a high wing, single engine airplane and is characteristic of a typical short field takeoff and landing (STOL) general aviation aircraft. The T-34B is a low wing, single engine airplane and is characteristic of a conventional general aviation aircraft. Sketches of the two aircraft are shown in Fig. 1.

Measurements

A photographic method was used to measure roll angle variations with time. The equipment consisted of a motion picture camera and a plexiglass plate with etched grid lines. The center line of the camera was mounted parallel to the fuselage center line (aircraft roll axis) and located in a position to view the horizon through the grid on the plexiglass plate. The roll angle of the airplane was measured from the included angle between the actual horizon and the horizontal lines on the grid. The grid was mounted perpendicular to the fuselage center line and was located near the aircraft's windshield approximately three feet forward of the camera. Both a clock mounted on the plexiglass grid and the frame speed of the camera were used to record time.

Stick motions for aileron control were limited to deflections of 0.5, 1.0, and 2.0 in. by mechanical stops. These mechanical stops could be removed instantaneously by the pilot. Mechanical stops installed by the aircraft manufacturer (5.5 in. for the T-34B and 9.0 inches for the DHC-2) were used for maximum stick deflection.

Test Procedure

Flight tests were conducted for various airplane landing configurations and airspeeds. A summary of the test conditions is given in Table 1.

Most flight tests were conducted during calm air conditions. Some tests were conducted during turbulent conditions for investigating spiral instabilities; however, only pilot observations were recorded. The tests were conducted at airspeeds representing 1.40, 1.58, and 1.75 times the flaps up stalling speed of the T-34B airplane and 1.32, 1.67 and 2.05 times the flaps up stalling speed of the DHC-2 airplane.

Before each maneuver the aircraft was trimmed for straight and level flight. Except for spiral stability tests, measurements were made for abrupt rudder-fixed aileron rolls. Data were recorded from level flight to roll angles of approximately 90°. For spiral stability measurements the airplane was rolled to a small bank angle (approximately 10°) by the ailerons. After the desired bank angle was obtained the ailerons were returned to a neutral position. Measurements were then recorded with the stick and rudder pedals in a fixed position.

Table 1 Summary of test conditions

Airspeed, mph	Flap position, deg	Control stick displacement in.
A) Beechcraft T-34B (landing gear down)		
80	0,30	0.5, 1.0, 2.0 and 5.5
90	0,30	0.5, 1.0, 2.0 and 5.5
100	0,30	0.5, 1.0, 2.0 and 5.5
80	0,30	10 deg. roll; stick, rudder fixed
90	0,30	10 deg. roll; stick, rudder fixed
100	0,30	10 deg. roll; stick, rudder fixed
B) DeHavilland Beaver DHC-2		
Airspeed, mph	Flap position, deg	Control stick displacement in.
80	14,58	1.0, 2.0 and 9
104	14,58	9
127	14,58	1.0, 2.0
80	14,58	10 deg. roll; stick rudder fixed

Results and Discussion

The roll response characteristics of the two airplanes tested were principally defined by the roll angle time histories obtained from three basic types of flight maneuvers: 1) a full displacement of the aileron control to obtain control power characteristics 2) displacement of aileron control to several limited positions to obtain control sensitivity characteristics 3) a displacement of the aileron to perturb the airplane to a small bank angle for obtaining stability characteristics.

A study of the available references[2-12] resulted in the selection of two sets of handling qualities criteria for comparison with the experimental flight test data obtained in this investigation. One set of values[2-8] corresponds to criteria that were most likely used during the design and development of current general aviation airplanes. The other set is more recent and was obtained from military specifications[9-12] published in August 1969 and July 1970.

Roll Control Power

Typical flight test results obtained for the variation of roll angle with time using maximum stick deflections for the T-34B and DHC-2 airplanes are shown in Figs. 2 and 3. Results show that for both the T-34B and DHC-2 airplanes, changes in flap position did not affect a change in the maximum rolling characteristics of the airplane. Although the two airplanes have entirely different geometric configurations, both exhibit nearly the same maximum roll angle variation with time as shown by the curves in Figs. 2 and 3. It should be noted that left aileron rolls for the DHC-2 airplane resulted in larger roll rates than those to the right.

Control power is a term used to describe the effectiveness of the control to maintain a steady equilibrium state or to produce various maneuvering states. The requirements for maximum roll control power obviously vary with the operations of the aircrafts; but, in general, the maximum obtainable roll angle and/or rolling moments must be sufficient: 1) to recover to a level wing attitude in gust conditions or from self generated disturbances 2) to maintain a bank angle in cross wind landings and take-offs 3) to maintain

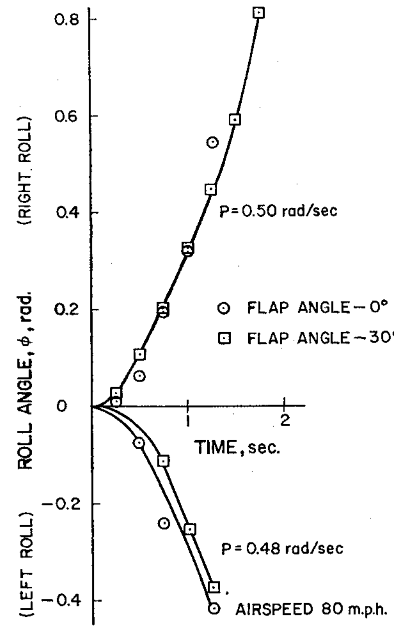

Fig. 2 Variation of roll angle with time for the T-34B airplane with maximum stick deflections.

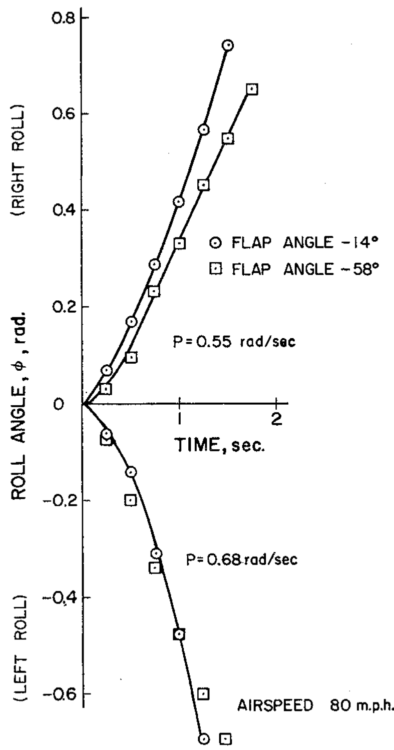

Fig. 3 Variation of roll angle with time for the DHC-2 airplane with maximum stick deflections.

heading for various asymmetries due to aerodynamic and/or power conditions 4) to perform all required turning maneuvers.

A measure of the available control power can be expressed in terms of angular velocity, bank angle after a specified length of time, and roll angular accelerations. Results obtained for the T-34B and DHC-2 airplanes along with current handling qualities criteria are summarized in Table 2. Comparisons of flight test values with handling qualities criteria given in Table 2 show that the results obtained for the two airplanes are within levels for satisfactory operation. Except for the current military specification,[9] the values for each airplane far exceed available criteria. On the other hand, additional parameters may also be required to assess the amount of control power needed during the landing approach as suggested by Ashkenas.[3] For example, the gust response of each airplane configuration is different, which suggests that a more useful parameter would be the time to recover from a gust induced roll attitude. Flight tests to investigate this parameter are currently being conducted in the third phase of the over-all program.

The helix angle and maximum roll rate criteria given in military specifications[13] for the general aviation type (weight) of airplane are even less restrictive than the values of parameters given in Table 2. It should be noted, however, that some

Table 2 Roll control power requirements[a]

Parameter	Control power	Minimum levels satisfactory operation	Beechcraft T-34B	DeHavilland Beaver DHC-2
Roll angular velocity (max.) deg/sec	Landing	>15	80 mph 27.5–28.7 90 mph 30.4–32.7 100 mph 26.4–26.9	80 mph 31.5–38.0 104 mph 28.1–37.2
Bank angle after 1 sec/deg	General Maneuvering	2–8	80 mph 17 90 mph 22 100 mph 20	80 mph 23 104 mph 24
Bank angle[a] in 1.3 sec/deg	Landing	30	80 mph 22 90 mph 28 100 mph 29	80 mph 35 104 mph 38
Bank angle[a] in 1.7 sec/deg	General Maneuvering	60	80 mph 46 90 mph 45 100 mph 43	80 mph 50 104 mph 47
Roll angular acceleration, rad/sec^2	General Maneuvering	0.1–0.6	80 mph 1.5 90 mph 1.8 100 mph 1.5	80 mph 2.5 104 mph 2.5
Roll angle acceleration rad/sec^2	Typical range used by STOL aircraft	0.3–2.5	80 mph 1.5 90 mph 1.8 100 mph 1.5	80 mph 2.5 104 mph 2.5

[a] Obtained from military specification Ref. 9 all other values obtained from Ref. 2–8

Table 3 Comparison of predicted with measured roll angular velocities

Airspeed	Predicted roll angular velocity, deg/sec	Measured roll angular velocity, deg/sec
A) Beechcraft T-34B		
80	33.0	27.5–28.7
90	37.2	30.4–32.7
100	41.2	26.4–26.9
B) DeHavilland Beaver DHC-2		
80	23.7	31.5–38.0
104	29.8	28.1–37.2

general aviation airplanes tested by NASA[14] did not have sufficient control power to obtain values given by these specifications.

Theoretical Predictions

An abrupt aileron roll produces motion mainly about the longitudinal wind axis of the airplane. Thus, a good approximation to the initial roll response can be obtained by considering only the rolling degree of freedom. Calculated values of angular velocity in roll and values measured in flight tests of the DHC-2 and T-34B airplanes are given in Table 3 for comparison. Values of roll rates predicted by theory for the T-34B airplane given in Table 3 were consistently larger than those obtained by flight tests. This difference probably resulted from the effects of dihedral and sideslip angles during the rudder-fixed aileron rolls. A loss in roll rate will occur when the rudder is not used to counteract the yawing moments of a wing with positive dihedral.[16]

In general, predicted values of roll angular velocity given in Table 3 show reasonable agreement with values obtained in flight tests. The use of simple lifting-line theory provides an adequate means of analysis for preliminary design and optimization of the general aviation aircraft.

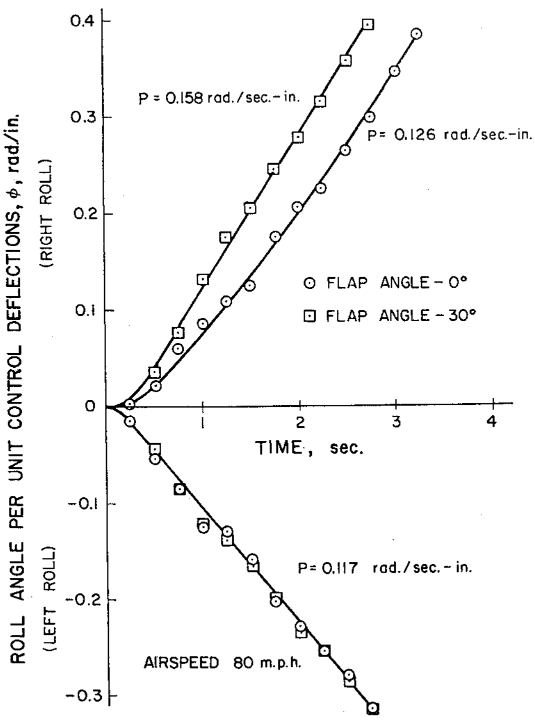

Fig. 4 Variation of roll angle per unit control deflection with time for the T-34B airplane.

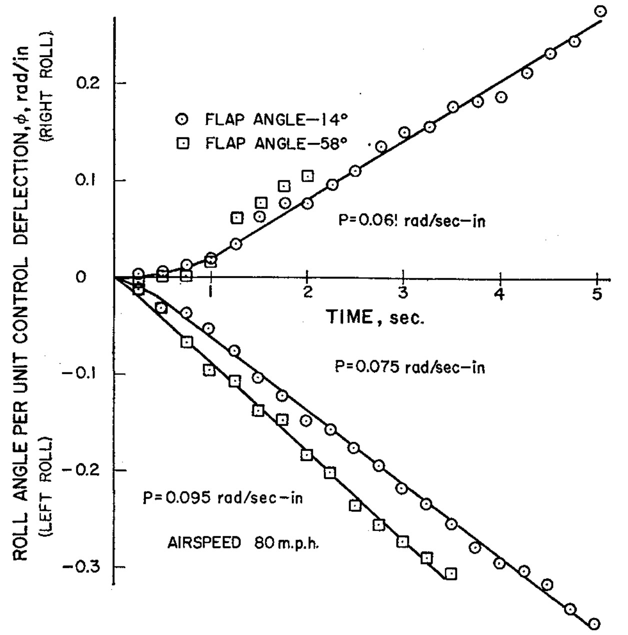

Fig. 5 Variation of roll angle per unit control deflection with time for the DHC-2 airplane.

Control Sensitivity and Lag

Typical results for a unit controlled deflection are given in Figs. 4 and 5. The results obtained for control deflection of 0.5, 1.0, and 2.0 in. showed that the roll rates for aircraft tested were linear with control deflections. In addition, results for maximum control deflection (Figs. 2 and 3) are in agreement with the results obtained for a unit control deflection and indicate that the roll rates were approximately linear throughout the displacement range of the control stick. The pilot uses control displacement as an indicator of the margin available to perform various turning maneuvers and to correct for roll disturbances. When an abrupt increase or nonlinearity in roll rate occurs with control surface deflection, precise adjustments for roll attitudes are extremely difficult and, in general, the pilot tends to over control. Thus, it is not likely that the excessive roll control motions used by the pilot for steep approaches in the T-34B and DHC-2 airplanes were a consequence of nonlinearities in roll rate.

The study of pilot's workload for steep approaches using the T-34B airplane[1] showed that during the approach the pilot moved the aileron control less than 1 inch and at a rate of approximately 2 to 3 times per second. Comparisons of these numbers with results shown in Fig. 4 indicate that these motions by the pilot did not produce large changes in the roll attitude of the airplane.

Table 4 shows comparisons of flight test results with minimum levels of control sensitivity and lag for satisfactory operations.[2–8,11] In general, the levels of roll control power (Table 3) and sensitivity (Table 4) far exceeded most criteria for satisfactory operations and indicate that the more restricted handling quality criteria given by current military specifications[9–12] should be considered for use in evaluating future general aviation type airplanes.

Comparisons of the experimental results with current criteria indicate that the problem of reducing the pilot's workload is not necessarily a problem of improving the roll control characteristics of the airplane tested.

However, another possibility that must also be considered when viewing satisfactory levels of handling quality criteria is that the existing handling quality parameters may not provide the proper assessment needed in reducing pilot workload during the landing approach. As noted, the control characteristics of both airplanes were approximately the same and were with satisfactory limits, but the span loading and wing

Table 4 Roll control sensitivity and lag requirements

Parameter	Minimum levels for satisfactory operation	Beechcraft T-34B	DeHavilland Beaver DHC-2
Sensitivity, roll angular acceleration per unit control deflection rad/sec/in.	0.5–0.25	80 mph 0.42–0.76 90 mph 0.20–0.5	80 mph 0.6–0.27 127 mph 0.50
Response,[a] deg/in. in one sec or less V/STOL aircraft	4.0 min. 20.0 max.	80 mph 6.3 90 mph 4.0 100 mph 4.6	80 mph 2.5 127 mph 2.6
Linearity, variation of roll angular acceleration with control deflection	Constant or no abrupt increase or sign	Constant all speeds	Constant all speeds
Lag, time from control input to 63% of peak angular acceleration	<0.3	<0.2	<0.1
Lag,[a] time from control input to maximum angular acceleration	<0.3	<0.2	<0.1

[a] Obtained from military specifications Ref. 11.

loading of the two aircraft were different, and the airplane response to gust as felt by the pilots flying the two aircraft were entirely different. Thus, the important features when landing could be the airplane's response to control movements and the stability characteristics during a gust-induced roll. To date, research data pertaining to the assessment of roll performance needed to counter the response to atmospheric disturbances for general aviation airplanes are very limited.[10]

Spiral Stability

The amount of aerodynamic spiral stability is important during the landing approach. Large turn rates associated with small bank angles at low airspeeds can produce large heading errors which develop quickly when the pilot's attention is diverted momentarily. As a consequence, poor spiral stability characteristics can easily result in excessive pilot workload.

Roll angle variations with time, following a small bank angle input for the T-34B and DHC-2 airplanes, are shown in Figs. 6 and 7. For satisfactory handling characteristics no roll angle buildup is desired, and in no case should the angle double in less than 20 sec.[2,9,11] The T-34B airplane is unstable, as shown by the results in Fig. 6. For each airspeed and airplane configuration the variation of roll angle with time diverged to twice the initial angle during an interval of time of much less than 20 sec. This instability is probably a major contributing factor in the increased physical effort required to maintain a level wing condition for the T-34B airplane during steep landing approaches.[1] Most of the results obtained for the DHC-2 showed that the airplane is spirally stable as indicated in Fig. 7. For some test conditions the airplane exhibited a tendency to be neutrally stable.

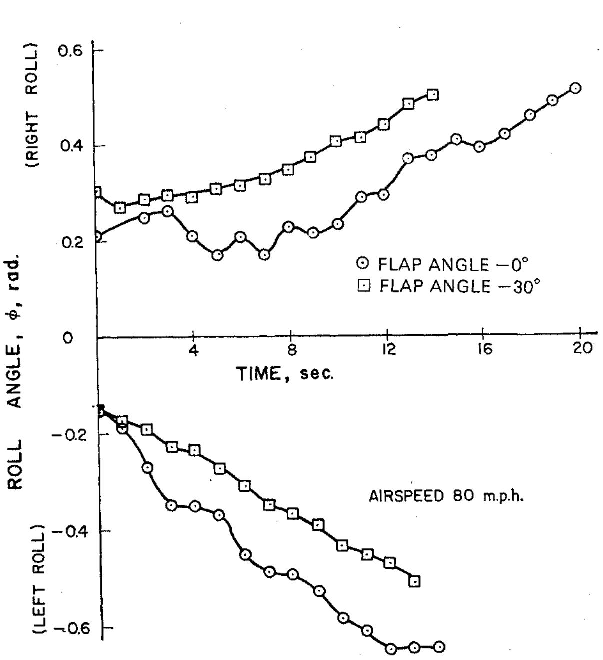

Fig. 6 Variation of roll angle with time for the T-34B airplane, initially disturbed about roll axis.

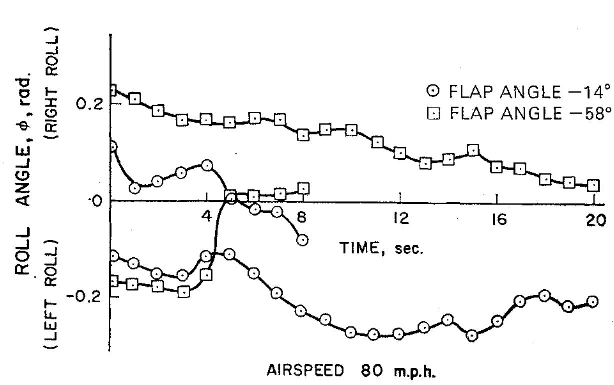

Fig. 7 Variation of roll angle with time for the DHC-2 airplane, initially disturbed about roll axis.

Measurements of pilot's roll control motions for both airplanes indicate that the number of roll control motions associated with the DHC-2 airplane during steep approaches were much less than that for the T-34B airplane.[1] This reduction in pilot's workload during the landing approach for the DHC-2 airplane as compared to the T-34B airplane is apparently related in part to the increase in spiral stability and indicates that an additional increase in stability could result in more workload reduction. Although these results indicate the need for spiral stability, too much spiral stability is undesirable. Excessive stability results in unsatisfactory lateral control characteristics in a turn. If the aircraft is left unattended for a short period of time, the wing has a tendency to return to a level position and the pilot has difficulty in maintaining a desired bank angle and in obtaining the desired heading change. This difficulty was noted during the flight test of the DHC-2 airplane. The aircraft requires additional attention from the pilot for turns under instrument conditions. The T-34B airplane also requires additional attention; however, the situation is the reverse of that for the DHC-2 airplane. In the case of the T-34B, the airplane tends to tighten the turn when left unattended whereas in the case of the DHC-2 the airplane tends to level itself. For this reason neutral spiral stability is recommended as a criterion in most references. However, this conflicts with the requirements for the landing approach. A solution to these conflicting requirements is not apparent and is the subject of further study.

Cross Coupling

Aileron deflection and the rolling motions of the airplane can also produce moments about the pitch and yaw axes resulting in a change of both sideslip and pitch angles. Probably the most severe are the yawing moments due to aileron deflection (adverse yaw) and the yawing moments due to roll rates. Motion picture photographs of the DHC-2 airplane roll maneuvers with zero flap angle deflection indicate no detectable adverse yaw and that the maximum sideslip-to-bank-angle ratio was very small. With flaps fully deflected to 60° some adverse yaw was noted. Additional flight tests were later conducted using rate gyros mounted at the center of gravity of the DHC-2 airplane. These results showed that the maximum adverse yaw rate was 4°/sec which resulted in a maximum adverse yaw angle of 2.5° for the zero flap angle configuration. For the 60° flap angle configuration the maximum yaw rate was 9.8°/sec and the resulting maximum adverse yaw angle was 7.3°. These angles are less than the maximum allowable adverse yaw angle of 10° (Ref. 14). Results for the T-34B airplane indicate significant adverse yaw and the large sideslip angles due to roll rate. Although more accurate measurements using rate gyros were not made, estimates from the motion picture photographs indicate that the angles are less than the recommended maximum values of 20° of sideslip and 10° adverse yaw in maximum aileron deflection rolls.[14]

Changes in pitch attitude for the DHC-2 airplane were negligible; however, changes for the T-34B airplane were quite noticeable. For most test conditions an increase in pitch accompanied the initial rolling motion of the airplane. Following the increase in pitch angle, a rapid objectionable nose down motion occurred which persisted throughout the remainder of the maneuver.

Significant cross coupling occurred for both airplanes and this is probably an additional contributing factor in increasing the pilot's workload during the landing approach. Negligible cross coupling effects would be more desirable and can be obtained for general aviation airplanes. One possible solution to the problem of adverse yaw during the landing approach is the use of spoilers for roll control.

Roll Damping

The only parameter evaluated in this investigation relating to roll angular velocity damping was the number of control reversals required to stabilize the aircraft in a rolling maneuver. For both airplanes not more than two reversals were needed which is within the recommended range for satisfactory operation.[2]

The amount of roll angular velocity damping needed is a function of the amount required for lateral quick stops to avoid an overshoot of the desired bank angle. Excessive damping could produce objectionable roll upsets in atmospheric gusts. Additional testing is being conducted to establish a suitable range for flight in atmospheric gusts.

Concluding Remarks

Comparisons of roll control parameters with current handling qualities criteria show that both the DHC-2 airplane and the T-34B airplane are within the range for satisfactory operation. On the other hand, the problem of reducing the pilot's workload during the landing approach does not appear to be dependent upon improving the roll control characteristics of the airplanes tested. This problem appears to be mostly dependent upon providing additional spiral stability and reducing the amount of cross coupling. Cross coupling can be removed by design considerations; however, the requirement for additional spiral stability needed during the landing approach conflicts with the need for neutral stability during the turning maneuver.

Although a previous study showed that the number of stick motions by the pilot was excessive during the landing approach, results of this investigation showed that the small amplitude of these motions would not produce large changes in the roll attitude of the airplane. It is possible that these motions were used by the pilot to obtain a feel for the degradation in airplane stability at lower airspeeds during the landing approach. Thus, it is also possible that the pilot will have to be assured of sufficient stability to maintain both heading and approach angle before a reduction in the workload can be obtained.

In summary, additional criteria are needed for the steep landing approach to obtain improvements in design of future general aviation airplanes. Results of these flight test studies indicate that improvements are needed in the following areas: 1) criteria based on the gust response of the airplane, 2) suitable spiral stability criteria for both the landing and maneuvering phases of flight and, 3) relationships between criteria and design parameters of the airplane such as wing loading, span loading and power loading requirements.

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