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# AN IN-FLIGHT SIMULATION OF LATERAL CONTROL NONLINEARITIES

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16. Abstract

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## SUMMARY

An in-flight simulation program was conducted to explore in a generalized way the influence of spoiler-type roll control nonlinearities on handling qualities. The roll responses studied typically featured a dead zone or very small effectiveness for small control inputs, a very high effectiveness for mid-range deflections, and low effectiveness again for large inputs. Given otherwise good handling characteristics, it was found that moderate nonlinearities of the types tested might yield acceptable roll control, but the best level of handling qualities is obtained with linear, aileron-like control.

## INTRODUCTION

Roll control spoilers have been used comparatively rarely on light airplanes, but they are now receiving new attention from researchers and designers intent upon displacing ailerons with full-span high lift devices (Reference 1). This activity has highlighted the long-known fact that the lift change, and hence the rolling moment, produced by a spoiler may be quite nonlinear with deflection. The typical form of the nonlinearity for a spoiler located ahead of a deflected flap is shown in Figure 1; it features little or no response for small spoiler openings, followed by a high level of effectiveness for the mid-deflection range and low effectiveness again for large deflections. The effectiveness varies somewhat with angle of attack, which accounts for the spread at high deflections.

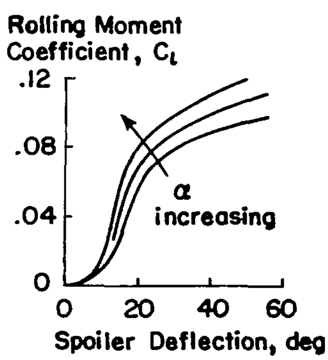



Figure 1 - Typical Spoiler Effectiveness Characteristics

If spoiler opening is directly proportional to cockpit control deflection, then the pilot will have to cope with a situation quite different from the familiar near-linear response furnished by conventional ailerons. Nonlinear control linkages may be provided to compensate for the irregular spoiler effectiveness; on the other hand, this is a complication which might be unnecessary if the nonlinear response will not seriously degrade the handling qualities of the airplane.

The in-flight investigation described in this report sought to explore in a generalized way the influence of these spoiler-type roll response nonlinearities on handling qualities. It was oriented toward small general aviation airplanes in terms of basic airframe characteristics and piloting task. Five pilots, most of them with considerable handling qualities evaluation experience, participated in the tests.

## DESCRIPTION OF THE EXPERIMENT

IN-FLIGHT SIMULATOR - The test vehicle was the in-flight simulator shown in Figure 2 and described in detail in Appendix 1. For this experiment it is sufficient to note that the evaluation pilot operates "fly-by-wire" cockpit controls which provide electrical signals to command the electro-hydraulic control surface actuators; electronic signal shaping was incorporated to provide various forms of nonlinear gearing between control wheel and aileron in addition to the normal linear mode of operation. For some cases the roll damping and roll control power were lowered to simulate a more sluggishly responding airplane.

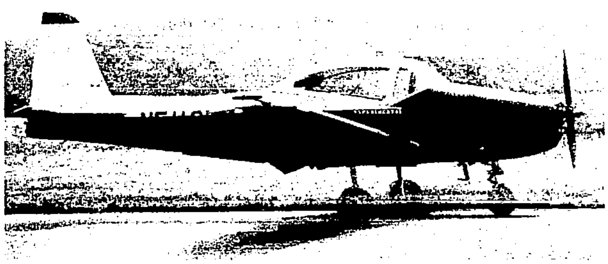


Figure 2 - In-flight Simulator

TEST CONFIGURATIONS - The notable features of the nonlinear response shown in Figure 1 are the dead zone or very small effectiveness for small spoiler (or wheel) deflections, the very high effectiveness of the middle region, and the decreased sensitivity for large control deflections. This type of nonlinear function was approximated in the test airplane with three straight line segments in the manner described in Appendix 2.

Preliminary flight trials indicated that the more important features to be explored were the extent of the initial region of small response and the slope, or sensitivity, of the mid region of highest effectiveness. Figure 3 shows the resulting seven test variations, idealized in terms of their straight line approximations. They may be described briefly as follows:

Configuration Zero (labeled "0") - Linear roll response (i.e., aileron only), used as the basis for comparison.

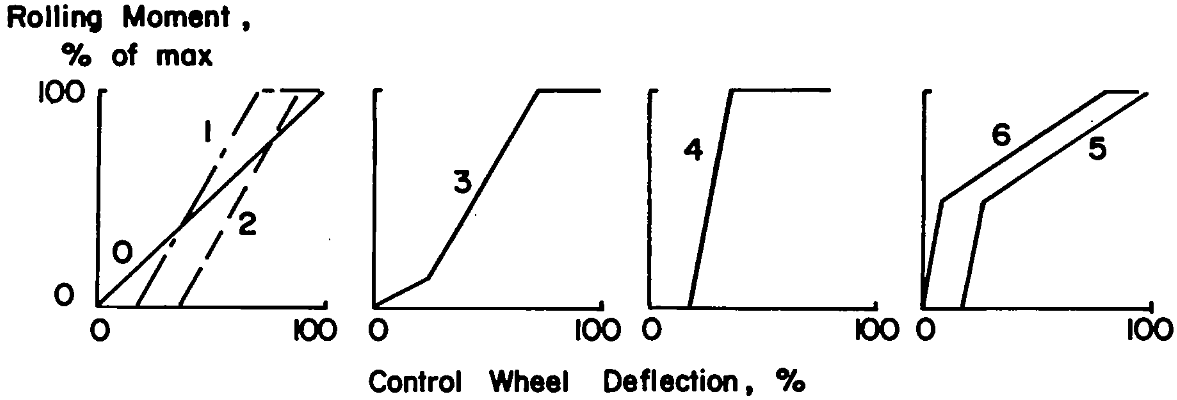



Figure 3 - Nonlinear Roll Response Configurations

Configurations 1 and 2 - Variations to determine the influence of the extent of dead zone (about 18% and 36%, or 14.5° and 29° of the available 80° control wheel deflection).

Configuration 3 - A variation of Configuration 1 to permit comparison of the case of a small initial response (one-third the gradient of the second segment) with that of a pure dead zone.

Configuration 4 - A variation to be compared with Configurations 1 and 2, to test the influence of a very high gradient for the second segment of the response.

Configuration 5 - A variation with an initial response resembling Configuration 4, but with lowered response for large wheel deflections, thus more closely resembling the Figure 1 characteristics.

Configuration 6 - A variation of Configuration 5, simulating the removal of the dead zone by symmetrical up-rigging of the spoilers.

Regardless of configuration, 100% of the available rolling moment was obtainable with maximum wheel deflection.

In addition to the above variations in the nature of the control, provision was made for two variations in the basic roll response of the airplane. These might best be described as "typically quick" and "comparatively slow" for light airplanes (Reference 2), corresponding, for example, to roughly doubling the rolling moment of inertia by filling outboard wing fuel tanks. In this situation both the available roll acceleration ($L_{\delta_{aw}}$) and roll damping ($L_p$) are decreased but the steady state roll rate for a given wheel deflection remains constant. The parameters defining the two cases are listed below for a nominal speed of 70 knots.

TABLE 1

Roll Control Characteristics

| Response Parameter | Response Type | |
|---|---|---|
| | "Quick" | "Slow" |
| Available Roll Acceleration $L_{\delta_{aw}} \delta_{aw_{max}}$ - rad/sec$^2$ | 4.66 | 1.91 |
| Roll Damping, $L_p$ - 1/sec | 4.11 | 1.68 |
| Roll Mode Time Constant, $\tau_r$ - sec | 0.24 | 0.59 |
| Maximum Steady Roll Rate - rad/sec | 1.14 | 1.14 |

Detailed information on the yawing moment characteristics of the spoilers was not readily available, so $N_{\delta_{aw}}$ was selected to be zero for the tests. The other lateral-directional characteristics were those of the basic test airplane. At 70 knots these were:

- Spiral Mode - slightly divergent
- Directional Stability - moderate ($\omega_d \cong 1.3$ rad/sec)
- Dutch Roll Damping - adequate ($\zeta_d \cong .15$)

A wheel-type cockpit roll control was used, with a maximum rotation of ±80°. Spring feel with no detectable breakout force and a gradient of 4.45N per 10° (one pound per 10°) of wheel deflection was provided. The outer surface of the hand grip was 14 cm (5.5 in.) from the center of rotation.

TEST PROCEDURE AND CONDITIONS - Testing was limited to approaches and landings, including actual touchdowns. The experiments were flown in natural conditions (that is, the on-board turbulence simulation system was not used), which ranged from calm weather to gusting 20 knot crosswinds with moderate to heavy turbulence.

The procedure called for the evaluation pilot to assume control on the downwind leg of the approach, and either turn to intercept the available microwave ILS localizer and glide slope or complete a normal visual landing pattern. The safety pilot resumed control after touchdown and during the climb reconfigured the airplane for the next run.

Primary data consisted of evaluation pilot commentary and ratings, following the standard Cooper-Harper system (Reference 3). In addition, time histories of control inputs and airplane motions were telemetered to the ground and recorded.

## RESULTS AND DISCUSSION

CRITICAL TASK - Initial plans called for the inclusion of ILS approaches in the evaluations, but a few trials indicated that the characteristics being examined were not critical in that task. Although control activity and overall workload did vary somewhat, control over average bank angle and heading was quite acceptable for all configurations and a uniformly high standard of localizer tracking could be maintained.

As a result of this finding, all further testing featured visual approaches, including brisk runway alignment maneuvers. Significant differences in handling qualities between configurations became apparent, however, only during the final phase of lineup and during the flare and touchdown. The following discussion will concentrate on the results for those phases of the landing.

GENERAL COMPARATIVE RESULTS - The general trend of the results may be seen in Figure 4, which presents pilot rating data for each of the variations flown. The plotted point represents in each case the average pilot rating and the vertical bar the range of rating. Five different pilots participated in the program; each variation shown was rated by at least two, and in most cases four of the five. Between two and five runs were usually flown before rating a given configuration. The data were obtained for weather conditions ranging from calm air to gusty crosswinds.

The linear control, "quick" responding airplane might be considered a baseline case; it was almost unanimously rated a very satisfactory 2.0-2.5 under all conditions by all five pilots. Precise control over bank angle could be maintained even in turbulence, and this quality led to good lateral positioning prior to touchdown.

Scanning over the other configurations in Figure 4 reveals a general, though not universal, degradation for the "slow" responding airplane compared to the "quick" one. The pilots usually felt that they needed more roll acceleration capability to quickly counter gusts and accurately position the airplane

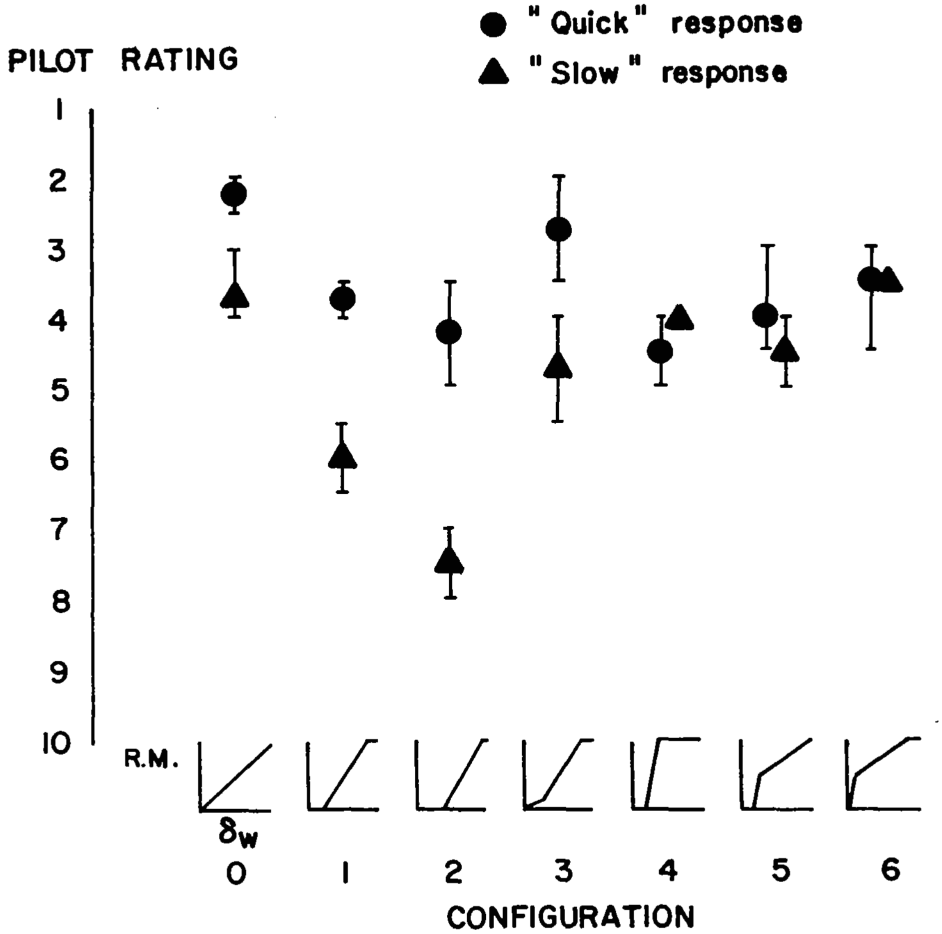



Figure 4 - Pilot Rating Results for Various Roll Response Configurations

prior to touchdown (the exceptional cases - Configurations 4, 5, and 6 - will be covered in a later section).

Also generally notable is the fact that an average rating of 3.5 or better (definitely satisfactory) is attainable only for cases without dead zone in the roll response - Configurations Zero, 3, and 6. The following sections cover the effects of the nonlinearities in detail.

EFFECT OF DEAD ZONE - The influence of an initial dead zone in the roll response may be seen by comparing the results for Configuration Zero (no dead zone), Configuration 1 (18%, 14.4°, 3.6 cm or 1.4" of dead zone), and Configuration 2 (twice the dead zone of Configuration 1).

The "quick" responding airplane is clearly satisfactory with no dead zone. A degradation is apparent for the successively larger dead zones, the main problem being notable deterioration in ability to attain or hold a desired bank angle, with consequent widening of lateral touchdown dispersion. The larger dispersion was not considered serious for normal runway operations with the "quick" airplane, however, since the estimated performance was ±.9m (±3 ft) compared to ±.3m (±1 ft) attainable without dead zone.

An increase in control activity was measured for increasing dead zone extent. This is shown in the time histories of Figure 5, which displays typical bank angle and wheel motions for the last 15 seconds before touchdown for the "quick" configurations. The bank angle excursions are seen to be generally less than 2°, but while 10° of wheel throw is seldom exceeded with the linear airplane, use of 30° or 40° is not unusual with dead zone present.

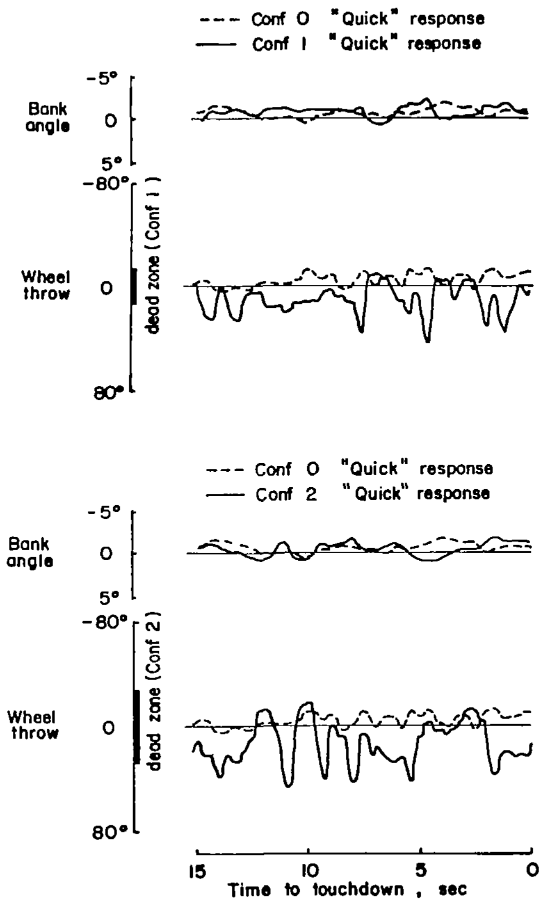



Figure 5 - Control Activity and Bank Angle Excursions with and without Dead Zone

Considerably more rating degradation due to dead zone occurred for the "slow" responding airplane; Figure 4 indicates that a marginally-satisfactory 3-4 rating for no dead zone becomes a seriously deficient 7-8 with 36% dead zone. Even though the steady state roll performance of the "slow" responding airplane was good, and the overall handling very adequate for turning maneuvers during the approach, the pilots noted an inability to quickly counter gust upsets and accurately position the airplane during the final stages of the landing. This is graphically evident in Figure 6, which compares "quick" and "slow" responding versions of Configuration 2 with its 36% dead zone.

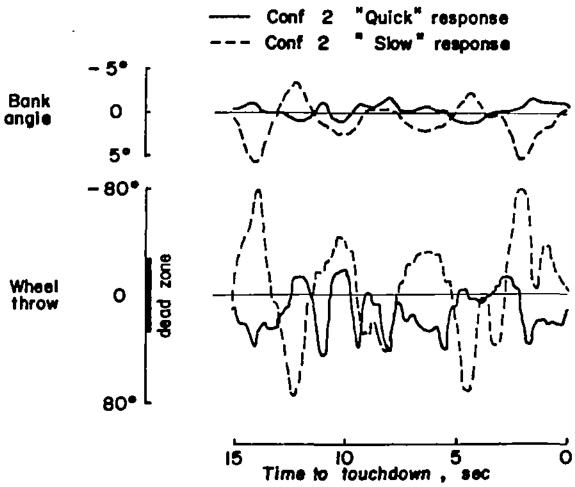



Figure 6 - Comparison of "Quick" and "Slow" Responding Airplanes with Control Dead Zone

IMPROVEMENT BY PROVIDING INITIAL RESPONSE - Configuration 3 featured an initial linear but low-sensitivity response, followed by moderate effectiveness after about 25° of wheel travel. As indicated in Figure 4, this was rated at the 3 level for the "quick" airplane and at the 4.5 level for the "slow" responding one; this placed it between linear Configuration Zero and Configuration 1 with small dead zone, as might be expected. The pilots commented that the small region of linear operation was appreciated even though the effectiveness was low; it was adequate for small or low rate bank angle changes and tended to soften the transition to the region of high effectiveness.

EFFECT OF CONTROL SENSITIVITY - The pilots indicated that the control sensitivity in the effective range of wheel motion for Configurations Zero, 1, and 2 was satisfactory. Since some wind tunnel results indicated the possibility of considerably higher gradients in this effective region, Configuration 4 was provided as a comparison with Configuration 1. Both had the same 16% dead zone, but the gradient (defined as percentage change in rolling moment for a given percentage change in wheel deflection) was increased from 1.73 to 5.66.

Figure 4 indicates that this increased control sensitivity degraded the "quick" response airplane from the 3.5-4 rating level down to a 4-5, while the "slow" responding machine was improved from a 5.5-6.5 rating to the 4.0 level. In the former case, the pilots commented on a reluctance to move vigorously into the effective region with high sensitivity because of the possibility of excessive or "jerky" response. This abruptness was softened by the dynamics of the "slow" response machine, and the ability to subdue upsets and maneuver with smaller control inputs than with Configuration 1 was appreciated.

OTHER CONFIGURATIONS - Configuration 5 had the 16% dead zone and high sensitivity of Configuration 4, but featured a lowered sensitivity for wheel travel beyond $25^{\circ}$, thus more closely approximating some of the wind tunnel results at large deflections. Configuration 6 had nearly the same gradients, but the dead zone was removed, simulating a symmetrical up-rigging of both spoilers.

The pilot rating results are again displayed in Figure 4, where these two cases may be compared with Configurations Zero and 4. Some small improvement over Configuration 4 may be noted, apparently because the large wheel deflection range could be used comfortably; complete removal of the dead zone raises the rating to the 3.5 level due to improvement in precision of control and ability to quickly suppress gust upsets. As with Configuration 4, there is little rating difference between "quick" and "slow" cases, the high effectiveness for reasonably small control deflections tending to make up for the deficiencies of the dynamic response.

## CONCLUSIONS

This report presents the results of an exploratory investigation of the effects of spoiler-type roll response nonlinearities on light airplane handling qualities. In order to simplify the experiment fixed-gradient linear control feel was used, spoiler-induced yaw was assumed to be zero, spoiler effectiveness was not changed as a function of angle of attack, and operations were conducted in actual (rather than simulated) winds and turbulence. However, it is felt that the general trends of the results are valid, and that the following conclusions may be drawn:

- Bank angle control and lateral positioning during landing flare and touchdown are critical roll control evaluation tasks. Approach maneuvering and ILS tracking are less demanding.

- Given otherwise good lateral-directional handling qualities, moderate response linearities of the types tested yield acceptable roll control. However, the best level of handling qualities is obtained with linear, aileron-like control.

- Rather large control dead zones can be tolerated but even a low effectiveness region for small wheel deflections is useful.

- Removal of the effectiveness dead zone (by spoiler up-rigging, for example) is helpful, even though the roll response for small control inputs may be large.

# REFERENCES

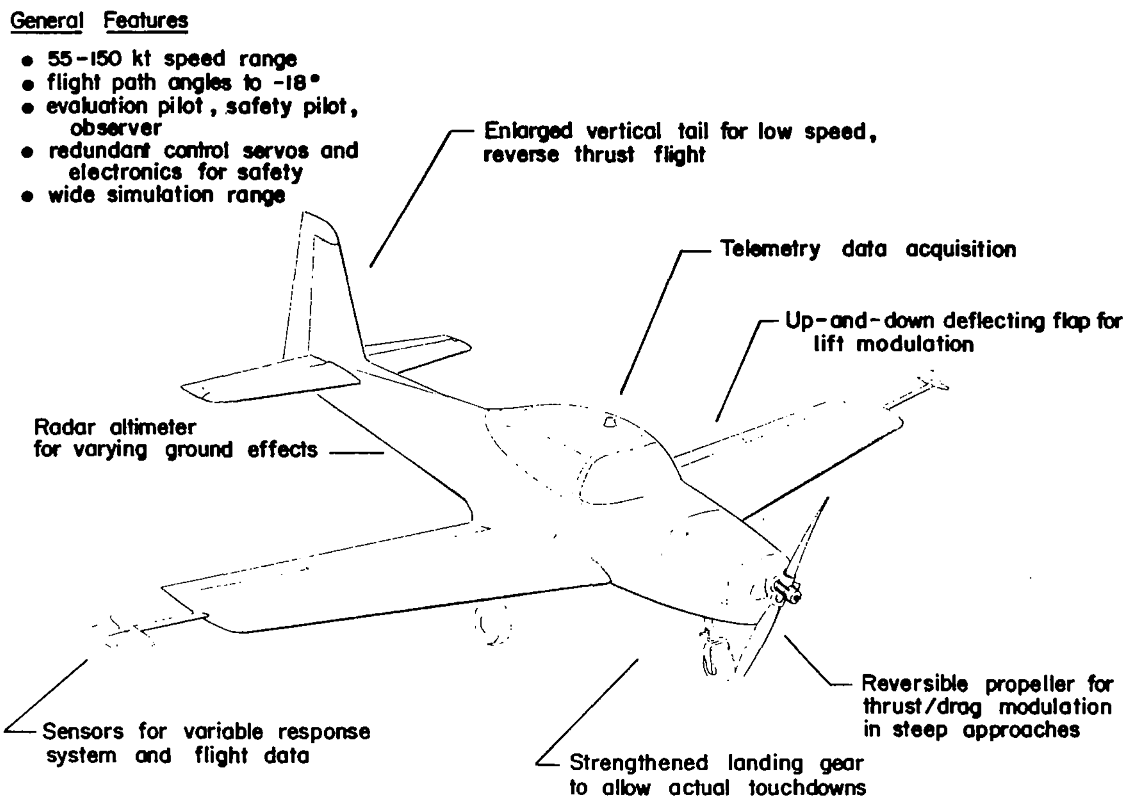

1. Roskam, J., Kohlman, D. L., and Wentz, W. H., Jr.: Spoilers for Roll Control of Light Airplanes. AIAA Paper 74-861, August 1974.

2. Ellis, D. R.: Flying Qualities of Small General Aviation Airplanes; Part 4, Review of Recent In-Flight Simulation Experiments and Some Suggested Criteria. FAA Report RD-71-118, December 1971.

3. Harper, R. P., Jr. and Cooper, G. E.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TND-5153, April 1969.

APPENDIX A

THE IN-FLIGHT SIMULATOR




## GENERAL DESCRIPTION

The In-flight Simulator is based upon a modified Ryan Navion airframe; the power plant is a Teledyne-Continental IO-520B engine of 212.6 kilowatts (285 hp) driving a Hartzell reversing propeller. Gross weight has been increased from the original 12230 to 14010 N (2570 to 3150 lb).

Two externally noticeable airframe modifications were made to improve the research capability of the machine:

The flap hinging and actuation were changed to allow up, as well as down, deflection over a ±30 deg range, resulting in increased lift modulation authority and smaller drag changes compared to the previous 0-40 deg down-only flap. Aerodynamics of the basic airframe and of this flap arrangement were explored in the full-scale wind tunnel tests reported in References A1 and A2.

The second change was an increase in vertical tail area made necessary by serious losses in directional stability when operating in the reverse thrust range. This was predicted by the wind tunnel tests and confirmed in flight. A 35.6 cm (14") extension, added to the base of the fin and bottom of the rudder, increased vertical tail area by nearly 50% and solved the problem, though at the expense of increased gust response and high rudder pedal forces in forward-thrusting flight.

The normal Navion main landing gear struts were replaced with those from a Camair twin (Navion conversion with nearly 40% increase in gross weight). Drop tests were conducted to optimize oleo strut inflation and orifice size, the final results indicating that the landing sink rate may be as high as 3.8 m/s (12.5 ft/s before permanent set will occur in the main gear or attaching structure. The original Navion nose gear strut was retained, but adjacent attachment fittings and structure were strengthened.

Other changes included redesign and relocation of the instrument panel, and incorporation of a single rear seat arrangement in place of the former bench seat in order to accommodate electronics and instrumentation equipment.

## VARIABLE RESPONSE CONTROL SYSTEM

The in-flight simulator utilizes what is now commonly known as a "fly-by-wire" control system, that is, power-actuated control surfaces commanded by electrical signals. The signals come from the various cockpit controllers and motion sensors, and when appropriately processed and summed, provide a net signal to each servo-actuator, and, hence, an airplane response of a particular character and magnitude. In this case, the servos are hydraulic, supplied by an engine-driven hydraulic pump delivering about .03 $m^3$/min at $5 \times 10^6$ N/$m^2$ (9 gpm at 725 psi pressure).

Independent control over the three angular and two of the three linear degrees of freedom is provided for - the missing one being sideways motion.

MOMENT CONTROLS - Control over pitching, rolling, and yawing are through conventional elevator, aileron, and rudder control surfaces. The full authority (that is, maximum travel) of each surface is available, and the maximum deflection rate in each case is about 70 deg/s. At a typical low operating speed of 70 knots, the available control powers are, respectively

Pitch: $\pm 4.4$ rad/s$^2$ (from trim)

Roll: $\pm 4.1$ rad/s$^2$

Yaw: $\pm 1.3$ rad/s$^2$

The presently available inputs to each of these controls are shown in Table A1.

NORMAL FORCE CONTROL - Independent control over normal acceleration is exercised through the Navion flap, modified to deflect up, as well as down, through a $\pm 30$ deg range. The upward motion provides increased lift modulation authority and tends to minimize the problems of drag and angle of zero lift changes.

Actuation is hydraulic, with a maximum available surface rate of 110 deg/s. At 70 knots, the available authority is slightly more than $\pm 0.5$ g.

Inputs presently available are shown in Table A2.

THRUST CONTROL - Thrust and drag modulation is by direct control of the blade pitch on the Hartzell reversing propeller, with the engine governed at 2300 $\pm$ 30 rpm by means of a tachometer feedback and throttle servoactuator. This system allows precise control over thrust and drag at flight path angles and/or deceleration rates well beyond the capability of the basic airplane with normal powerplant and closed throttle.

Propeller blade pitch is commanded through an electrohydraulic actuator connected to the mechanical-feedback servo which normally drives the reversing propeller when it is operating in its "Beta" mode. The blade pitch range presently used is +25 to -8 deg. With the engine governed at 2300 rpm, this provides performance ranging from modest climb (about 152 m/min or 500 ft/min) to steep descent ($\gamma \cong -18$ deg with V = 70 knots). Maximum blade actuation rate is about 20 deg/s.

Inputs to the thrust/drag modulation system are shown in Table 3.

INTERCONNECTS - It may be noted in the lists of inputs for the system (Tables A1-A3) that several coupling functions are provided. For some experiments, it is desirable to remove interacting effects in the basic airframe: lift and moment changes from thrust may be eliminated with interconnects between the propeller pitch sensor and the flap and elevator; and pitching moments due to flap angle and flap rate are countered with inputs to the elevator.

TABLE A1

INPUTS TO MOMENT CONTROLS

| Channel | Input | Function Varied |
|---|---|---|
| Pitch | Control column displacement | Control sensitivity |
| | Thrust lever | Simulated moment due to thrust |
| | Column thumbwheel | Simulated DLC moment |
| | Radar altitude | Ground effect moment |
| | Airspeed | Speed stability |
| | Angle of attack | Static stability |
| | Pitch attitude | Attitude hold sensitivity |
| | Pitch rate | Pitch damping |
| | Flap angle | Trim change from flap |
| | Flap rate | Moment from flap rate (approximate $M_{\dot{\alpha}}$) |
| | Propeller pitch | Moment due to thrust |
| | Integral of column displacement | Rate command gain |
| | Simulated turbulence | Turbulence response |
| Roll | Wheel displacement | Control sensitivity |
| | Sideslip | Dihedral effect |
| | Roll rate | Roll damping |
| | Yaw rate | Roll due to yaw rate |
| | Rudder pedal displacement | Roll due to rudder |
| | Simulated turbulence | Turbulence response |
| Yaw | Rudder pedal displacement | Control sensitivity |
| | Sideslip | Directional stability |
| | Yaw rate | Yaw damping |
| | Roll rate | Yaw due to roll rate |
| | Wheel displacement | Yaw due to aileron |
| | Simulated turbulence | Turbulence response |

TABLE A2

INPUTS TO NORMAL FORCE CONTROL

| Input | Function Varied |
| --- | --- |
| Control column displacement | Lift due to control (simulates elevator lift, or direct lift control integrated with column) |
| Thrust lever displacement | Lift due to thrust, direct lift control integrated with throttle |
| Column thumbwheel | Separate direct lift control |
| Radar altitude | Ground effect lift; wind gradients |
| Airspeed | Lift change with speed |
| Angle of attack | Lift response to angle of attack |
| Propeller pitch | Lift due to thrust |
| Simulated turbulence | Turbulence response |

TABLE A3

INPUTS TO THRUST/DRAG MODULATION SYSTEM

| Input | Function Varied |
| --- | --- |
| Control column displacement | Drag due to control (simulated control surface drag; drag due to direct lift controls integrated with column) |
| Thrust lever displacement | Thrust command/throttle sensitivity |
| Column thumbwheel | Drag change due to direct lift control (separate controller) |
| Radar altitude | Ground effect drag change; wind gradients |
| Airspeed | Drag change with speed |
| Angle of attack | Drag change with angle of attack |

Simulated interacting effects are handled by using inputs from the various cockpit controllers: pitching moments and lift changes due to power are provided by interconnecting the elevator and the flap with the thrust lever ($M_{\delta_T}$, $L_{\delta_T}$); and lift and drag changes due to pitch controller displacement are represented in $L_{\delta_s}$ and $D_{\delta_s}$. Other controllers may be similarly interconnected.

## SAFETY CONSIDERATIONS

By its very nature, landing research involves repeated exposure to minimum-speed, low-controllability situations, so special consideration was given to providing sufficient airframe strength and simulation system reliability to make the risk of damage from occasional hard touchdowns or control system failures acceptably low. The matter of strengthened landing gear was mentioned in an earlier section; the control system aspects will be discussed here.

SAFETY PILOT FUNCTION - Fundamental to the operation of an in-flight simulator is the concept that a safety pilot will continually follow the movements of the basic airplane controls, monitor the systems and the flight path, and be ready to disengage or override the evaluation pilot in case of a malfunction or unsafe condition. For disengaging, a disconnect switch on the control wheel is the primary cutout, with the main electrical and hydraulic controls providing secondary means of deactivating the system.

Manual override of the hydraulic servoactuators is possible for all controls except the flap. The force required is set through an adjustable poppet valve on each servo - 178N (40 lb) being typical.

Warning of system failures is provided by a flashing master warning light on the upper edge of the instrument panel in front of the safety pilot, with individual channel disengage warning on a panel slightly lower and to the right.

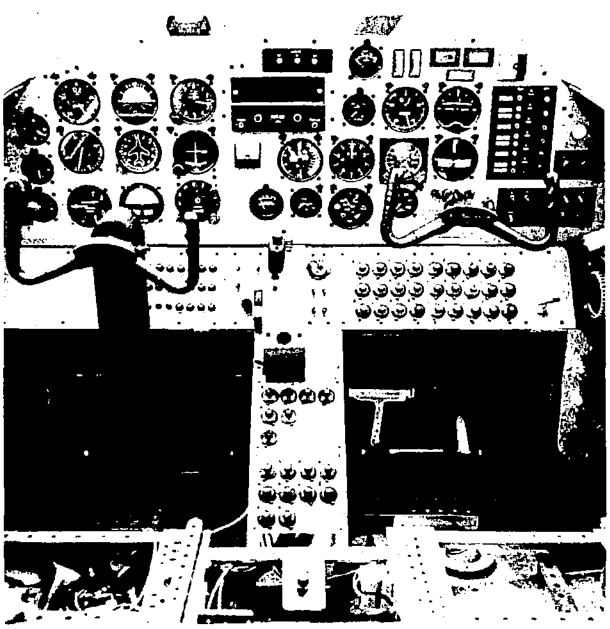
REDUNDANT CONTROL CHANNELS - The elevator, aileron, and throttle systems incorporate redundant control channels. The philosophy here is that hard-over control inputs resulting from system failures are particularly dangerous in this low-speed, low-altitude situation, and should be guarded against if possible. With the redundant channels, any substantial error between the commanded and actual control position is detected, and a switchover to a second servo is made. The evaluation pilot retains control during this process, but all inputs to the switched channel, except those from the control column, are eliminated, thus reducing the possibility that a defective transducer or signal path is causing the problem. Redundant sensors for the control input signal are incorporated; the other transducers are not duplicated. The fact that a channel has switched to the secondary servo is communicated to the safety pilot by the aforementioned warning lights, and he can then disengage the system and assume control.

The elevator is clearly critical with regard to failures which result in sudden full deflection, with the ailerons only slightly less so. Redundancy was incorporated in the throttle channel to reduce the possibility of a failure, which would apply power with the propeller blade pitch below the normal low-pitch stop, a condition which would overspeed the engine. Redundancy was not incorporated in the rudder or propeller pitch channels, because inadvertent disengages were felt to be less critical, and, since he follows pedal and Beta motions continuously, the safety pilot can very effectively override large-deflection failures. The flap channel was not duplicated because most failure modes are not hazardous - the surface trails aerodynamically at a 10 deg down position, and upon disengage, its return to this position from up-deflections is rapid. Down-flap deflections clearly pose no safety problem; up-flap hardovers could be hazardous due to the large lift loss, but this has proved to be a failure mode so instantly recognizable by the safety pilot that a disengage (with subsequent down-float of the flap) can be effected with very small altitude loss.

WAVEOFF AUTOMATION - To aid the safety pilot in recovering from an excessive sink rate situation, an "abort mode" system disengage can be used. Activated by pressing the disengage thumb switch, the flap travels at maximum rate to a 20 deg down position and power is automatically advanced to a climb setting; primary control reverts to the safety pilot. Using this system, recovery from a 70 kt, 6 deg approach (sink rate of 3.8m/s or 12.5 ft/s) with a simulated up-flap failure can be made with less than 3m (10 ft) altitude loss.

## COCKPIT AND EVALUATION PILOT CONTROLS

The instrument panel and controls are shown at left. The right seat is occupied by the safety pilot who operates the normal Navion wheel and rudder and the powerplant controls which have been relocated on the right side of the cockpit. Simulation system controls occupy the right side of the panel and the lower and middle consoles.



The evaluation pilot is seated on the left and provided with a standard flight instrument layout and conventional column, rudder, and throttle controls. Linear force gradients with no perceptible nonlinearities are incorporated. The gradients are ground adjustable by replacing springs. The values shown in Table A4 are currently being used.

## TABLE A4

## CURRENT VALUES FOR LINEAR FORCE GRADIENTS

| Control | Force Gradient | Travel |
|---|---|---|
| Pitch column | 7.9N/cm (4.5 lb/in.) | 7.6 cm forward (3 in.)<br>15.2 cm aft (6 in.) |
| Wheel | 2.6N/cm (1.5 lb/in.) | ±19.5 cm (±7.7 in.)<br>±80 deg |
| Pedal | 44N/cm (25 lb/in.) | ±6.3 cm (±2.5 in.) |
| Throttle | Adjustable friction | 13.3 cm (5.25 in.) |

Note: Three-axis trimming is provided.

Special controls presently installed include the following:

1. Direct Lift: Thumbwheel separate controller; integrated with pitch column; integrated with throttle. Adjustable moment and drag interconnects are available.

2. Pitch attitude command proportional to column displacement, with trimmable attitude hold.

3. Pitch rate proportional to column displacement with attitude hold.

Attitude hold may also be selected with any of the direct lift systems engaged.

## DATA ACQUISITION

Data acquisition is through telemetry, with 43 channels available. Airframe motion parameters (linear accelerations, angular rates, attitude, and heading), control inputs, and performance measures, such as localizer and glide-slope deviation, are normally recorded. Altitude and altitude rate are available from the radar altimeter.

Correlation of touchdown time with the other parameters is obtained through a recording of fore-and-aft acceleration of the main landing gear strut; wheel spinup loads produce enough strut motion to mark even very smooth landings.

## REFERENCES

A1. Shivers, J. P., Fink, M. P., and Ware, G. M., "Full-Scale Wind-Tunnel Investigation of the Static Longitudinal and Lateral Characteristics of a Light Single-Engine Low-Wing Airplane," NASA TND-5857, June 1970.

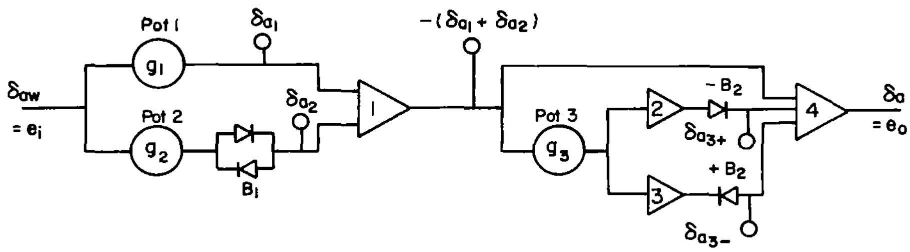
A2. Seckel, E. and Morris, J. J., "Full-Scale Wind Tunnel Tests of a Low-Wing, Single-Engine, Light Plane with Positive and Negative Propeller Thrust and Up and Down Flap Deflection," NASA CR-1783 and Princeton University Report 922, August 1971.

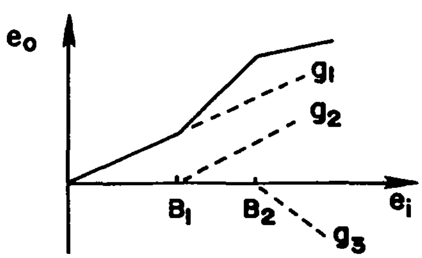
# APPENDIX B

## NONLINEAR FUNCTION GENERATOR

The control surfaces of the in-flight simulator are power actuated and commanded by electrical signals from various sensors and the evaluation pilot's cockpit controls. For this experiment the linear signal from the roll control wheel to the aileron was passed through a nonlinear function generator to produce a piecewise continuous approximation to the nonlinear control effectiveness curve shown in Figure 1, page 1.

The two sketches below illustrate the functioning of the nonlinear element of the system.




Potentiometer (Pot) 1 controls the magnitude of the initial slope $g_1$, while pot 2 controls the second segment slope which starts after the dead zone $B_1$ of the diodes. The two signals are summed by Amplifier 1. Pot 3 controls the third slope, $g_3$; Amplifiers 2 and 3 and their diode network change the sign of the signal and provide positive or negative components beyond breakpoint $B_2$. Finally, Amplifier 4 adds all of the segments to produce the desired curve. Although not indicated in the sketch, both breakpoints $B_1$ and $B_2$ are adjustable.

With reference to the measuring points on the sketch, the following relationships can be written:

1. $\delta_{a_1} = \delta_{aw} \times g_1$

2. $\delta_{a_2} = 0$ when $\delta_{aw} \leq B_1$

$= (\delta_{aw} - B_1)g_2$ when $\delta_{aw} > B_1$

3. $\delta_{a_3} = 0$ when $\delta_{aw} \leq B_2$

$= -[-(\delta_{a_1} + \delta_{a_2}) + B_2]g_3$ when $\delta_{aw} > B_2$

so that

4. $\delta_a = \delta_{a_1} + \delta_{a_2} + \delta_{a_3}$

$= \delta_{aw} \times g_1$ when $\delta_{aw} \leq B_1$

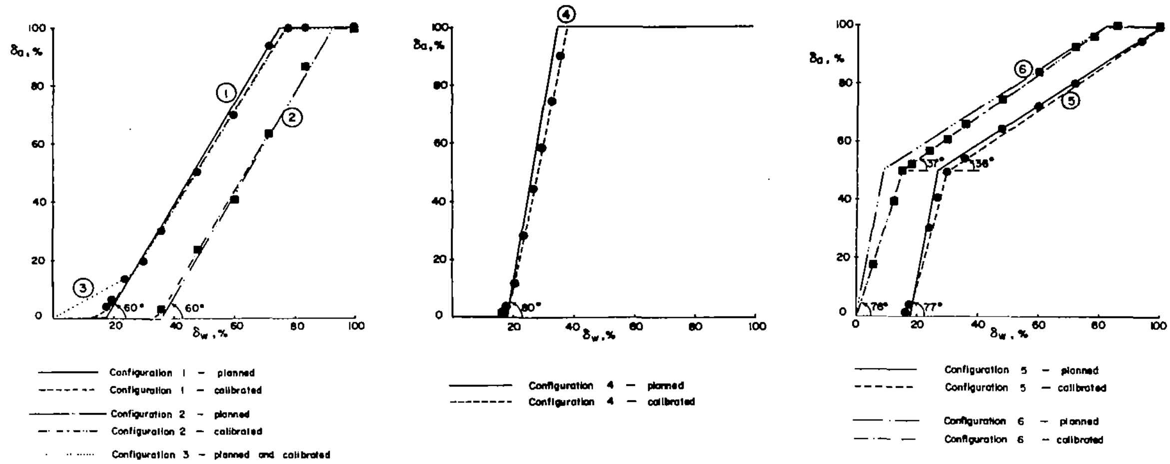
$= \delta_{aw} g_1 + (\delta_{aw} - B_1)g_2$ when $B_1 < \delta_{aw} \leq B_2$

$= \delta_{aw} g_1 + (\delta_{aw} - B_1)g_2$

$-[\delta_{aw} g_1 + (\delta_{aw} - B_1)g_2 - B_2]g_3$ when $\delta_{aw} > B_2$

Control Unit and Calibrations. The function generator was contained in a module which allowed in-flight access to the five controls needed to set the gains and breakpoints.

The unit was ground-calibrated to produce the six configurations discussed in the report. Except for Configuration 6 where a high gain limit was encountered, the planned functions were closely matched, and in that particular case it was felt that the deviation would not significantly affect the results. Calibration curves are shown in the following sketch.




Configuration Calibration Curves

The characteristics of the calibrated configurations are listed in the following table.

TABLE B1

| Configuration | Slope $G_1$ | Breakpoint $B_1$, % $\delta_{aw}$ | Slope $G_2$ | Breakpoint $B_2$, % $\delta_{aw}$ | Slope $G_3$ |
|---|---|---|---|---|---|
| 1 | 0 | 18 | 1.71 | 78 | 0 |
| 2 | 0 | 36 | 1.71 | 92 | 0 |
| 3 | 0.56 | 24 | 1.71 | 78 | 0 |
| 4 | 0 | 18 | 4.7 | 38 | 0 |
| 5 | 0 | 18 | 4.4 | 30 | 0.73 |
| 6 | 4.0 | 15 | 0.75 | 82 | 0 |

Note that the slope G differs from the electrical gain g used previously in describing the system; they are related by the following expressions:

$$G \equiv \frac{\text{Change in simulator aileron deflection, \% of maximum } \delta_a}{\text{Change in simulator control wheel deflection, \% of maximum } \delta_{aw}}$$

$$G_1 = g_1 \text{ for } \delta_{aw} \leq B_1$$

$$G_2 = g_1 + g_2 \text{ for } B_1 < \delta_{aw} \leq B_2$$

$$G_3 = g_1 + g_2 - [g_1 + g_2]g_3 \text{ for } \delta_{aw} > B_2$$

## APPENDIX C

## NOTATION

| | |
|---|---|
| $C_\ell$ | Rolling Moment Coefficient |
| ILS | Instrument Landing System |
| $I_x$ | Moment of Inertia in Roll, $kg\text{-}m^2$ ($slug\text{-}ft^2$) |
| $I_y$ | Moment of Inertia in Pitch, $kg\text{-}m^2$ ($slug\text{-}ft^2$) |
| $I_z$ | Moment of Inertia in Yaw, $kg\text{-}m^2$ ($slug\text{-}ft^2$) |
| $L$ | Rolling Moment, N-m (ft-lb) |
| $L_{\delta_{aw}}$ | Roll Control Effectiveness Derivative, $\frac{1}{I_x} \frac{\partial L}{\partial \delta_{aw}}$, $1/sec^2$ |
| $L_p$ | Roll Damping Derivative, $\frac{1}{I_x} \frac{\partial L}{\partial p}$, $1/sec$ |
| $M$ | Pitching Moment, N-m (ft-lb) |
| $M_{(\ )}$ | Pitching Moment Derivative, $\frac{1}{I_y} \frac{\partial M}{\partial (\ )}$ |
| $N$ | Yawing Moment N-m (ft-lb) |
| $N_{\delta_{aw}}$ | Yaw due to Roll Control Derivative, $\frac{1}{I_z} \frac{\partial N}{\partial \delta_{aw}}$, $1/sec^2$ |
| R.M. | Rolling Moment |
| $\alpha$ | Angle of Attack, deg or rad |
| $\delta_{aw}$ | Roll Control Deflection, deg, rad, or in. |
| $\delta_s$ | Pitch Control Deflection, cm (in.) |
| $\delta_T$ | Thrust Control Deflection, cm (in.) |
| $\tau_r$ | Roll Mode Time Constant, sec |
| $\omega_d$ | Dutch Roll Mode Natural Frequency, rad/sec |
| $\zeta_d$ | Dutch Roll Mode Damping Ratio |