Capabilities of In-Flight Thrust Reversing

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A program was conducted for the purpose of determining the performance capabilities and handling-quality characteristics of an aircraft equipped with a thrust reverser. The program was performed using a combination of fixed- and moving-base simulators. The thrust-reverser equipped airplane was compared with the clean airplane and the airplane equipped with speed brakes. Five types of thrust-reverser cockpit controls were used. Instrument landing approaches (ILS) were flown on the fixed-base simulator. The moving-base simulator was used to investigate gross deceleration maneuvers. The ILS simulation indicated that an airplane without thrust reverser was preferred for approaches on low-to-moderate-glide slopes. The thrust reverser did not sufficiently improve conditions during approaches of steep angles to make such approaches practical. The thrust-reverser equipped airplane was preferred for gross deceleration maneuvers.

Introduction

TODAY, aircraft are required to perform in expansive flight envelopes and execute a variety of missions. In many instances, then, conflicting requirements are imposed on the drag characteristics of the aircraft. Low drag is advantageous in maximizing the steady-state rate of turn but can be a disadvantage if the airplane is required to maximize a deceleration rate. During landing approaches, if sufficient lift can be provided, high drag or negative thrust is essential for steep-angle approaches. The case for high drag during ground rollout is self-evident. An attractive possibility under the aforementioned conditions would be to have an airplane with the capability of modulating thrust in such a manner as to provide the proper retardation when required. A fully modulated thrust reverser with small effect on the airplane drag when not deployed and capable of providing gross amounts of negative thrust when deployed would appear to provide an ideal method of matching the airplane "drag" to a particular situation. It was determined that present technology could allow a thrust reverser to be designed and installed with negligible trim change with use on an airplane. Hence, a simulation program could be conducted and certain significant conclusions arrived at regarding the usefulness of such a thrust reverser as a decelerating device. In using simulation to evaluate performance or handling-quality characteristics, judgment and interpretation are involved and decisions concerning the true flight environment are at times speculative. Nevertheless, it was felt that a useful exploratory investigation could be conducted using fixed-base and moving-base simulation. Thus, such a program was initiated. It consisted of fixed- or moving-base simulation utilizing a thrust reverser for several flight conditions. These included: 1) instrument approaches and wave-off, and 2) gross decelerations at constant altitude. These investigations are described in the following paragraphs.

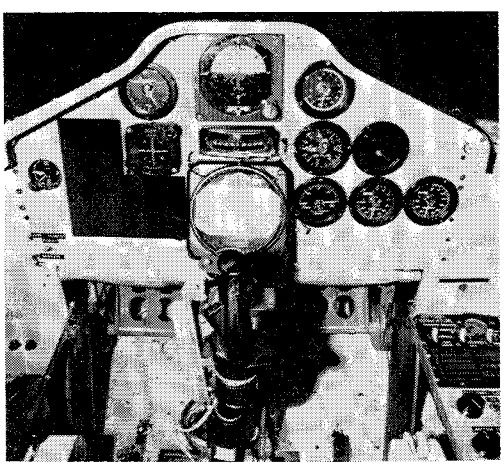

Fig. 1 Fixed-base simulator instrument panel.

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Simulator Description

Fixed-Base Simulator

The simulator used for the fixed-base simulation consisted of a cockpit with instrument panel display, normal flight controls, and five thrust-reverser controls.

The instrument panel included the following instruments: airspeed indicator, attitude director indicator (ADI), altimeter, rate-of-climb indicator, heading indicator, engine tachometers, course indicator, and thrust-reverser position indicator. The instrument panel is shown in Fig. 1.

The five thrust-reverser controls mechanized were as follows: proportional throttlelike lever, throttle-mounted beep control, stick-mounted beep control, throttle-mounted bang-bang control (on-off), and stick-mounted bang-bang control. The throttlelike control adjusted the position of the reverser doors at any position between full reverse and full forward thrust. The sense of the control was such that in the full forward position the reverser was off and in the full aft position it was in full reverse position. The beep controls enabled the reverser to be positioned in a manner similar to actuating a trim button. That is, the reverser doors opened or closed when the beep switch was held deflected and the doors remained in fixed position when the switch (spring-loaded to neutral) was released. The sense was again such that forward deflection was the direction of forward thrust and aft that of reverse thrust. The bang-bang controls did not allow for any intermediate thrust-reverser door positions. Pressing the button once resulted in full reverse thrust, and pressing it again resulted in full forward thrust. In none of the foregoing cases was the

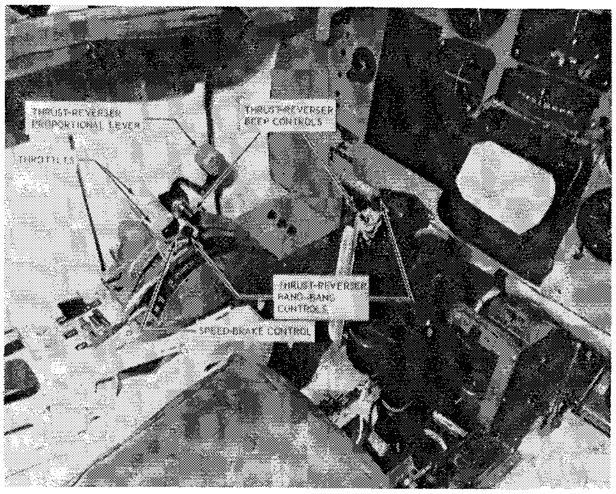

Fig. 2 Fixed-base simulator cockpit control.

level of engine thrust (engine rpm) adjusted by the thrust reverser controls. Only the throttle performed this function.

The cockpit controls are shown in Fig. 2. The thrust-reverser proportional lever is outboard of the throttles. The beep controls are the toggle switches mounted on the inboard throttle and on the stick. The bang-bang control on the throttle is the radio (mike) button. The stick-mounted beep control is the button on the upper left part of the stick grip. The speed-brake control is the black slide switch on the inboard throttle grip.

The pilot's task consisted of flying a simulated ILS approach. At a predetermined altitude, the pilot initiated a pullup to simulate a go-around or "wave-off" situation. The pitch and bank steering bars of the ADI were used to display ILS information. Thus the aircraft attitude and its position relative to the ILS localizer and glide slope were displayed on the same instrument. The steering bars were mechanized to display position information, not command steering information.

Moving-Base Simulator

The Northrop large-amplitude three-axis flight simulator was used to perform the moving-base experiments in this program. An external view of the simulator is shown in Fig. 3.

The motion system of the moving-base simulator employs a gimbaled cockpit suspended at the end of a beam, as shown in Fig. 3. The three rotational degrees of freedom are obtained through the gimbals. The beam is pivoted on a clevis and driven by front and rear hydraulic actuators to provide vertical translation. Lateral translation is derived through a pivoting mechanism between the clevis and the post, driven by hydraulic actuators. The external visual display consists of projector assemblies and a large projection screen (26 ft by 35 ft) located 10 ft in front of the cockpit. A separate operator control console completes the simulator hardware in the laboratory.

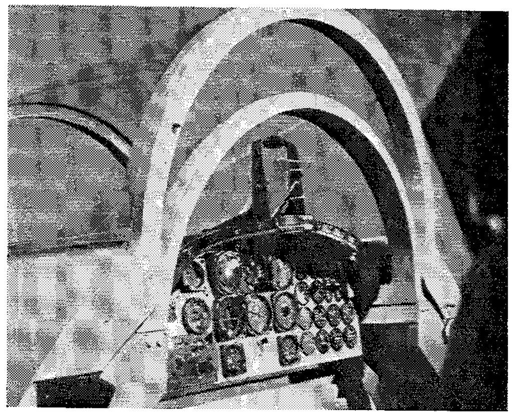

Fig. 4 Moving-base simulator instrument panel.

The instrument panel consisted of the following instruments: g-meter, elevator trim indicator, airspeed/Mach indicator, course indicator (not used), clock, attitude indicator, radio magnetic indicator, altimeter, vertical velocity indicator, thrust-reverser position indicator, rpm meters, and several dummy engine instruments. The instrument panel is shown in Fig. 4.

Three thrust-reverser controls were mechanized: a proportional throttlelike lever, a throttle-mounted beep control, and an integrated throttle/thrust-reverser control. The latter used the same cockpit lever as the proportional control. The proportional control adjusted the reverser at any position between full reverse and full forward thrust. In the full forward position the reverser was off and in the full aft position was in full reverse. The beep control allowed the reverser doors to open or close when the switch was deflected and to remain in a fixed position when it was released. Forward deflection was required for forward thrust and aft for reverse thrust. The integrated throttle/thrust-reverser control combined a throttle with the thrust-reverser control. The lever encountered a detent at approximately midrange in its travel. Forward of this detent, the lever functioned as a conventional throttle, controlling thrust from idle to military thrust. With the lever immediately aft of the detent, 100% rpm was obtained with the reverser positioned to produce approximately idle thrust. As the lever was moved progressively further aft, the thrust increased in the reverse direction.

The thrust-reverser, throttles, and speed-brake controls are shown in Fig. 5. The proportional lever is inboard of the

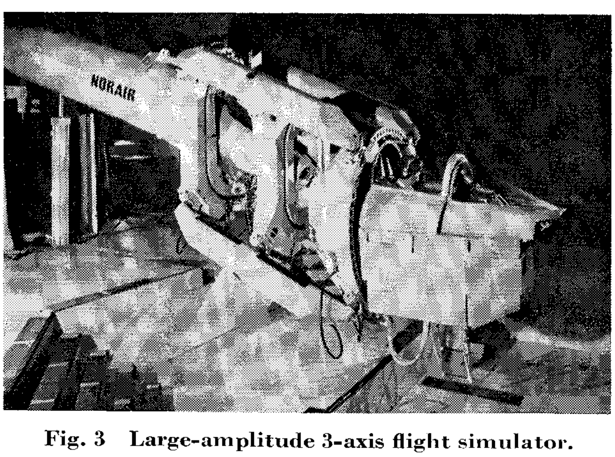

Fig. 3 Large-amplitude 3-axis flight simulator.

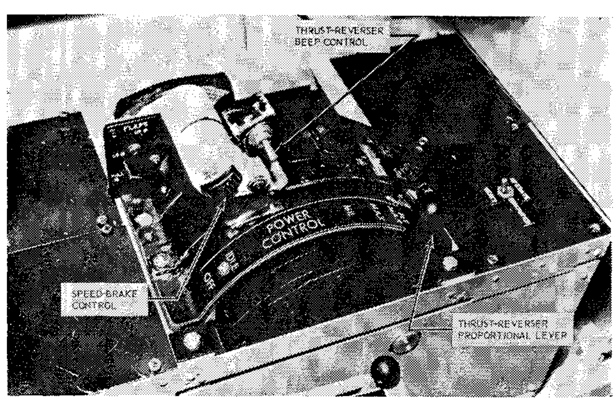

Fig. 5 Moving-base simulator thrust-reverser speed controls.

Table 1 Performance summary large-amplitude 3-axis flight simulator[a]

		Displacement	Velocity	Beam stationary Acceleration	Beam max accel Acceleration
Beam	Vertical	±10 ft	±16.2 fps	...	±5.8g
	Lateral	±4 ft	±21.6 fps	...	±2.2g
Cockpit	Pitch	±30°	±1.1 rad/sec	±24.4 rad/sec²	±14.4 rad/sec²
	Yaw	±30°	±1.5 rad/sec	±20.3 rad/sec²	±15.0 rad/sec²
	Roll	±45°	±2.7 rad/sec	±35.3 rad/sec²	±29.1 rad/sec²

[a] Performance is the same in each direction (±). Large roll acceleration is limited to 14 rad/sec² by pressure relief valves across actuator.

throttles. The beep switch is mounted on the inboard throttle. The speed-brake switch is on the inboard throttle grip.

There are five simulator motion drives: vertical and lateral beam drives, and cockpit pitch, roll, and yaw drives. The lateral beam motion was only used in the simulating of speed-brake and thrust-reverser buffet. The vertical beam motion was used for buffet and also to provide a vertical acceleration cue. The beam drive mechanisms require that acceleration, velocity, and position signals be supplied by the computers. In order that the simulator would not reach its physical limits of travel, the velocity and position signals were filtered with first-order lags to attenuate low-frequency signals. Velocity and position drive signals were not pure integrations of their respective next higher derivatives but were first-order lags of the signals. From the frequency response point of view, this causes a filtering of low frequencies; from the time response viewpoint, a step input is washed out.

The cockpit rotations were reduced to one third of the computed values in order to not exceed available motion travel. The remaining two thirds of the rotations were supplied to the external visual display.

A performance summary of typical simulator acceleration, velocity, and displacement characteristics is shown in Table 1. Typical vertical-acceleration time histories are shown in Fig. 6. The simulator vertical acceleration was recorded from an accelerometer mounted on the simulator. The command vertical acceleration was recorded at the pilot's station from the equations of motion. As stated previously, the velocity and position signals to the beam drive were filtered. This caused the simulator acceleration to be attenuated and centered about 1 g as compared with the commanded acceleration.

ILS Approaches

Operational Procedures

Normal airplane

The simulated normal airplane, equipped with speed brakes and without thrust reverser, was flown during instrument landing system (ILS) glide-slope approaches of 3°, 6°, 9°, and 15°. No pitching moment associated with speed-brake deployment was simulated in the landing approach portion of the program. The fixed-base simulation assumed that an ideal speed-brake/horizontal-tail interconnect system existed which completely eliminated all pitching moments associated with the speed brakes. No buffeting due to speed brakes was included. The fixed-base simulator could not adequately simulate buffeting in that no accelerations would be experienced by the pilot. Merely disturbing the instruments was not considered to provide a sufficiently realistic buffeting simulation. The approaches were flown in still air. No necessity existed to increase the difficulty of the approach task through the introduction of steady winds or turbulence. The initial, level approach to all of the glide slopes was flown at an airspeed of 175 knots. Speed brakes were opened while in level flight and before engagement of the glide slope on all approaches except those of 3°. Speed brakes were not required for the 3° approaches. Upon engagement of the glide slope, airspeed was reduced and held constant at 155 knots for the 3°, 6°, and 9° approaches. During the 15° approaches, airspeed increased from 175 knots to 210 knots while on the glide slope, even though speed brakes were fully open and throttles were at the idle position. The initial altitudes at which the glide slopes were engaged ranged from 1860 to 7460 ft, simulating engagement approximately five miles from wave-off. Wave-off altitude was established at 500 ft for all approaches except the 15° approaches. For these an increase in wave-off altitude to 750 ft was required.

Thrust-Reverser Equipped Airplane

The simulated thrust-reverser equipped airplane, without speed brakes, was flown during ILS glide-slope approaches of 3°, 6°, 9°, and 15°. However, buffeting associated with application of thrust reverser was not included primarily because the buffeting was not estimated to significantly influence either the performance or the handling qualities of the airplane while flying on glide-slope, and also as in the case of the normal airplane, buffeting is difficult to portray realistically on a fixed-base simulation. Initial level approach to the glide slope was flown at 175 knots. The air was assumed to be calm, i.e., no turbulence or steady wind. The airspeed was reduced to 155 knots and held constant on all of the glide slopes. Wave-off altitude was set at 500 ft for approach slopes of 9° or less, but was increased to 750 ft for the 15° approaches as in the case of the regular airplane.

Results and Discussion

Normal airplane

The normal airplane could be flown satisfactorily at glide slopes up through 9°, but the 15° glide slope was considered to be impractical. At wave-off altitude of 750 ft on this glide slope, the airspeed had increased from 175 to 210 knots.

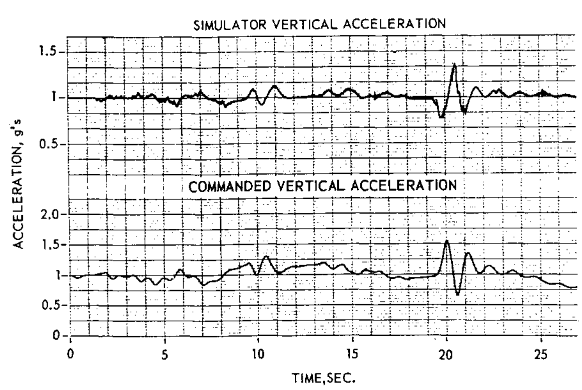

Fig. 6 Moving-base simulator typical vertical acceleration response.

The rate of the descent for 210 knots on a 15° glide slope was approximately 5500 ft/min. The rate was considered to be excessive for an instrument approach near the ground.

Thrust-reverser equipped airplane

The thrust reverser provided a precise control of airspeed and 155 knots could be maintained on all glide slopes with ease. However, the 15° glide slope was again considered impractical. The rate of descent in this case was approximately 4100 ft/min, which is still excessive for an instrument approach. At wave-off, power for climb was rapidly obtained because high engine rpm was maintained during the approaches.

It is of interest to note that even with the instrument-approach flight velocity reduced to 140 knots, i.e., a 10% reduction, the rate of descent would have been approximately 3500 ft/min, which is still considered to be excessive for an instrument approach near the ground.

The pitching moment associated with thrust-reverser deployment was immediately apparent to the pilots. However, once aware of it, pitching moment could be readily countered although it always was considered objectionable. The lateral-directional stability changes resulting from reverser actuation were too insignificant to be apparent.

It was readily apparent that the thrust-reverser equipped airplane could accomplish steeper approaches to an airfield while maintaining the recommended approach speed of 155 knots than could the normal airplane. This ability could be utilized at a destination where the ceiling was high enough to permit a steep descent to below the overcast and then a transition to a lower rate to a straight-in approach to a final landing, or to a normal circular approach to final landing. The advantage to this method is the slower approach or penetration velocity in the vicinity of the air base with its accompanying safety.

Preferred airplane

Although the thrust reverser offered advantages in airspeed control and wave-off, the normal airplane equipped with speed brakes was preferred to the thrust-reverser equipped airplane for glide slopes up through 9°. Airspeed could be readily maintained with the normal airplane and wave-offs could be safely executed. Further, the pilot had no unconventional controls to manipulate and, as simulated, no additional pitching moments to cope with.

The 15° glide slope was not considered practical with either airplane under ILS conditions.

Evaluation of various thrust-reverser cockpit controls

Throughout the evaluation, the thrust reverser was used to primarily control speed, and the stick to primarily control altitude. Five controls were evaluated: bang-bang, stick mounted; bang-bang, throttle mounted; beep control, stick mounted; beep control, throttle mounted; and proportional. The proportional control was preferred of the five controls available during ILS evaluation.

The bang-bang control, either stick or throttle mounted, was unsuitable as a velocity control. It lacked sensitivity, being either full on or full off, and consequently the airplane was in a state of almost constant acceleration for a given throttle position. When using the bang-bang as a speed control, the moment created with change of thrust-reverser position caused constant pitch attitude change and thus constant pilot correction. Further, at wave-off, the instrument panel had to be glanced at to determine the thrust-reverser position before possible reversing. An effort was made to use the bang-bang control with full thrust reversal selected; the throttle was then used as a vernier for speed. This was unsatisfactory because the pilot then had to "cross-control." To slow the airplane, the throttle was advanced; to speed up the airplane, the throttle was retarded. This was contrary to regular procedure and thinking. In addition, wave-off could be hazardous since, with the thrust reverser selected, an instinctive advance of throttle would slow the airplane.

The beep control was satisfactory as a vernier control for speed. The beep control mounted on the throttle was preferred to the beep control mounted on the stick. The beep control was deficient in that the only indication of thrust-reverser position was the gage positioned on the instrument panel. Because of the lag of the thrust-reverser positioning mechanism, the gage indicating thrust-reverser position had to be "led." Valuable seconds were lost because the thrust reverser could not be positioned with an initial placement of the thrust-reverser control button. Also, the control was insensitive for small corrections. A push of the thrust-reverser control button caused the position to vary over too great a range. This is the consequence of providing a beep control which is fast acting for its full range.

The stick-mounted beep control was unsatisfactory for use during a wave-off condition. The pilot used the hand on the control stick for a "cross-control" type operation. While the stick was being rotated aft to initiate the wave-off, the thumb was being used to rotate the beep button forward to gain maximum forward thrust. In addition, the thumb could not then be used simultaneously for trimming.

The throttle-mounted beep control was satisfactory during a wave-off condition. The throttle and beep button could be moved forward simultaneously with the left hand, while the stick and trim button could be controlled by the right hand.

The proportional control was the most natural to use and was preferred of the five controls available during the ILS evaluation. With the throttle fixed in position, the proportional control was used to control speed in the conventional manner; aft movement reduced speed and forward movement increased speed. During wave-off, both the throttle and proportional control could be moved forward easily with the left hand. Although the thrust reversing mechanism had a simulated mechanical lag, this could be compensated for easily by positioning the proportional handle quickly to a predetermined visual position and then minutely adjusted later.

The integrated throttle/thrust-reverser handle was added later in the program and was found to be the most natural to use and the most preferred of the thrust-reverser handles tested. The integrated handle was not utilized during the ILS phase. It is thought that the integrated type would have also been the most preferred during the 15° and during the 3° approaches. During the 15° approach, the thrust-reverser capability was continuously used because the added drag was required to fly at 155 knots. During the 3° approach, thrust-reverser capability was generally not necessary. However, there is a question that during a 6° or 9° approach, the engine may well have been operating in an area where the pilot may have been moving the integrated handle just in or out of thrust-reverser position. If this had occurred, and there had been delays or a dead band in the system, pilot reaction would have in all probability been negative and the control would have been unsatisfactory during the condition flown.

Use of reverser for speed control

During one of the approaches flown with varying stability changes, the pilot noted that the particular combination of values actually eased his flying task while on glide slope.

In a regularly equipped and normally stable airplane, as the pilot reduces thrust, the nose of the airplane will automatically lower to maintain speed if there is no change of elevator position, and the glide path is thus changed. If the pilot wishes to maintain the same glide path with a reduction of thrust, he must increase the elevator-up position to prevent the nose from lowering.

In this particular instance with an increase in thrust reverser to reduce speed, the thrust reverser imparted a slight pitch-up movement to the airplane which apparently increased the angle of attack of the airplane enough to compensate for the loss of lift associated with the loss of speed. Consequently, glide slope was actually easier to maintain since a change in elevator was not required. The situation was somewhat fortuitous in that values of other derivatives had to be of a combined value to cause the aforementioned effect.

It is of interest to note that, in Ref. 1, pilots commented favorably on a nose-down trim change when forward thrust was decreased by reverser deflection. However, in this reference, the pilots were assessing the thrust reverser for use as flight-path control rather than as a speed control device.

In Ref. 2 the author suggests that, when using thrust primarily for speed control, the effect of pitchup with thrust decrease might be attractive in a landing approach situation. Such was found to be true during this simulation.

However, in view of other comments in the report where the thrust reverser was being considered for use in operational situations besides instrument approaches, it is considered that thrust reverser application with zero associated moment is the most desired effect.

Summary

For an instrument landing system approach (ILS), the normal airplane with speed brakes is preferred to the thrust-reverser equipped airplane for glides of 3° to 9°. The pilot can fly the normal airplane and has no additional pitching moments or spurious aerodynamic changes to cope with as in the case of one equipped with a thrust reverser. A 15° or steeper instrument approach to landing does not appear practical because of the resulting high rate of descent at normal approach speed.

The thrust-reverser equipped airplane is capable of being flown at steeper glide angles to the vicinity of an airfield while in the landing configuration and at approach speeds. In view of the over-all operational use of the thrust reverser, it should be designed as carefully as possible to eliminate pitching moment with actuation.

Gross Decelerations

Decelerations were performed on the moving-base simulator from an initial trimmed supersonic airspeed and also from a subsonic airspeed. The performance and handling qualities of a thrust-reverser equipped airplane were compared with those of a speed-brake equipped airplane. The task was performed as an instrument flight problem, i.e., no external display was used. The pilot judged performance and handling qualities by motion cues and cockpit instrument readings.

Table 2 Normal acceleration and stick force during deceleration

Configuration change	Maximum incremental normal g from trim, 1st 5 sec	Maximum stick force from trim, 1st 5 sec, lb
	Pilot 1	
Speed brakes fully opened	0.30	11.4
Throttle reduced to idle power		
Full thrust reverser	0.13	4.6
	Pilot 2	
Speed brakes	0.20	10.4
Thrust reverser	0.20	3.0

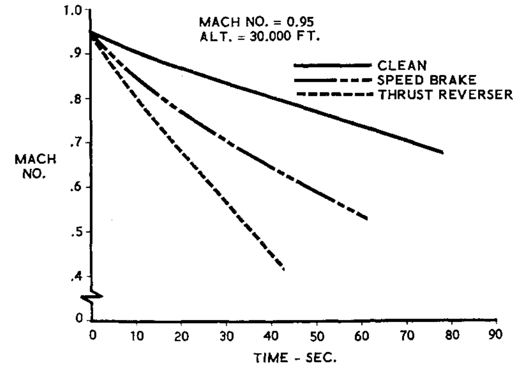

Fig. 7 Deceleration at 30,000 ft from $M = 0.95$.

Subsonic

The airplane was trimmed at 560 knots at 30,000 ft and then decelerated to 300 knots by these methods: 1) by deflecting speed brakes to the fully open position and simultaneously reducing the thrust to idle power, 2) by reducing the thrust to idle without opening speed brakes, 3) by actuating the thrust reverser to its maximum reverse position using the integrated throttle/thrust-reverser control.

Altitude was held constant during deceleration. As mechanized and flown on the simulator, the thrust reverser was a more effective drag device than speed brakes and provided superior handling qualities during deceleration.

The results in Table 2 may be compared with the requirements of Ref. 2, paragraphs 3.3.18 and 3.3.19. The maximum stick force and g's from trim obtained during the first 5 sec for speed-brake opening slightly exceeded the requirements of the specification of $\pm 0.25\ g$ and ± 10 lb. However, the qualities were not rated unsuitable for operational use by the pilots and were acceptable. In Fig. 7, deceleration times are presented for an initial Mach number of 0.95 and 30,000 ft. Data for three configurations are given: clean configuration, speed-brake equipped airplane, and airplane with thrust reverser. The data are shown as plots of Mach number against the time required to decelerate to that Mach number from the initial 0.95. The thrust reverser as mechanized is shown to provide superior performance, and for the task flown was the preferred deceleration device.

Supersonic

The airplane was trimmed at Mach 1.3 at 30,000 ft. It was decelerated to Mach 0.9 while holding altitude constant by two methods: first, by fully opening speed brakes with simultaneous reduction of thrust to idle, and second, by actuation of the thrust reverser to its maximum position. With the speed-brake method, back trim was required by the pilot both with initial opening of the brakes and with subsequent deceleration of the airplane. This trim was in the correct direction for speed stability. At approximately Mach 0.97, a severe pitchup occurred, requiring a large stick force and deflection to overcome it. To estimate the severity of the pitchup, the maneuver was repeated with the pilot trimming until approximately Mach 1.0 when he flew "hands off." The airplane pitched a maximum of $\pm 2.6\ g$'s at approximately Mach 0.97. The severity of this pitchup was rated unacceptable operationally by the pilot, although controllable. With the thrust-reverser method, initial actuation of the thrust reverser produced a slight pitchup requiring forward stick or trim to overcome. As the airplane decelerated, forward trim or stick had to be applied to hold constant altitude, indicating reversal of speed stability through the transonic region. The airplane, however, was trimmable and flyable through-

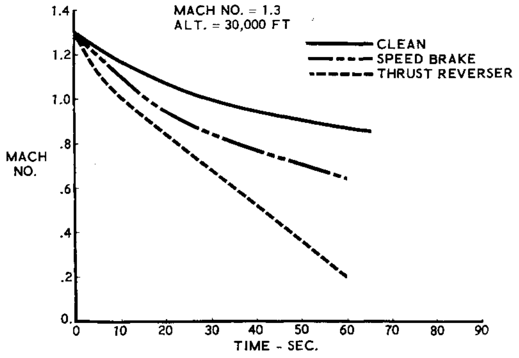

FIGURE 8 DECELERATION AT 30,000 FEET FROM M = 1.3

Fig. 8 Deceleration at 30,000 ft from M = 1.3.

out the region and was rated operationally acceptable by the pilots. The airplane was also decelerated from Mach 1.3 to 0.9 by reducing the throttle to the idle setting without deflection of a drag device. The airplane behaved in the same manner quantitatively and qualitatively as with application of the thrust reverser. However, time to decelerate was longer and there was no initial pitchup with reduction of throttle. Speed instability existed throughout the transonic area.

In Fig. 8, deceleration times are presented for an initial Mach number of 1.3 at 30,000 ft in the same manner as for the subsonic decelerations. Again, the thrust-reverser mechanization provided performance and handling qualities superior to those of the speed-brake equipped airplane.

Summary

The thrust-reverser equipped airplane was preferred over the clean or speed-brake configurations for deceleration because of the increased retardation available from the thrust reverser without adverse effects on the handling qualities.

Conclusions

1) In general, a thrust reverser could improve the over-all mission effectiveness.

2) In gross decelerations of both subsonic and supersonic speeds, an airplane equipped with a thrust reverser can provide performance handling qualities superior to an airplane equipped with speed brakes.

3) For an instrument approach under ILS conditions, the advantages of the thrust reverser in speed control and application of power at wave-off did not seem sufficient to balance the disadvantages of unconventional cockpit controls and possible pitching moments resulting from application of the reverser.

4) An integrated thrust-reverser/throttle controller was the most desired thrust-reverser control mechanism for all flight modes with the exception of the ILS approaches, where it was not employed.

References

[1] Anderson, S. B. et al, "Flight Measurements of the Effect of a Controllable Thrust Reverser on the Flight Characteristics of a Single-Engine Jet Airplane," Memo 4-26-59A, 1959, NASA.

[2] O'Hara, F., "Handling Criteria," *Journal of the Royal Aeronautical Society*, April 1967.

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Opening Time of Parachutes Under Infinite-Mass Conditions

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For the infinite-mass case, defined by the ratio of the suspended to the canopy included masses, equations have been developed which provide the canopy filling time for solid cloth as well as for ribbon and ringslot parachutes. Using newly established experimental data of the rate of canopy growth, the results obtained by this method agree satisfactorily with empirical information given in the *United States Air Force Parachute Handbook*.

Nomenclature

a,b = const
A = $t_f D_0^2/\pi$
B = $(\pi d_v/2D_0)^2$
C = u/v, coefficient of effective porosity
C_p = pressure coefficient
C_D = drag coefficient
C_DS = drag area
d = instantaneous diameter of parachute inlet
d_v = vent hole diameter
$D_{\max}$ = maximum diameter of parachute
D_0 = nominal diameter of parachute
D_p = instantaneous maximum projected diameter of parachute
D_{pc} = drag of parachute canopy
D_{ps} = projected diameter under steady-state condition
D_s = drag of suspended weight
$\dot{m}$ = actual mass flow, slugs/sec
m_a = apparent mass
m_i = mass of included air
$\dot{m}_i$ = ideal mass flow, slugs/sec
m_p = mass of parachute
m_s = mass of suspended weight
Δ_p = pressure differential
S_0 = total area of parachute
S_p = instantaneous projected area of parachute
t = time
t_f = filling or inflation time
T = t/t_f, dimensionless filling-time ratio
u = average velocity over the porous or slotted area
V = velocity; included volume of parachute canopy

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