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DYNAMICS OF HIGH-BYPASS-ENGINE THRUST REVERSAL USING A VARIABLE-PITCH FAN

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16. Abstract

The unique reverse-thrust performance requirements of a variable-pitch-fan propulsion system for future short-haul aircraft required the early full-size engine demonstration that rapid forward-to-reverse-thrust transients could be performed. The test program demonstrated that successful and rapid forward- to reverse-thrust transients can be performed without any significant engine operational limitations for fan blade pitch changes through either feather pitch or flat pitch. For through-feather-pitch operation with a flight inlet, fan stall problems were encountered and a fan blade "overshoot" technique was used to establish reverse thrust. Variable-pitch fans offer a potentially attractive means of providing rapid reverse-thrust capability for future short-haul aircraft.

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DYNAMICS OF HIGH-BYPASS-ENGINE THRUST REVERSAL USING A VARIABLE-PITCH FAN

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SUMMARY

During the past several years, there has been a concerted effort to develop the technology necessary to meet the unique reverse-thrust performance requirements of a variable-pitch-fan propulsion system for future short-haul aircraft. A significant portion of this effort involved the testing of a full-size, variable-pitch-fan engine to demonstrate rapid forward-to-reverse-thrust transients. This report presents the results of this effort, which encompassed approach-power thrust reversals, in both through-feather-pitch and through-flat-pitch modes of operation as well as aborted-takeoff transients. Tests were performed with both a bellmouth and a flight inlet. This program has demonstrated that rapid approach-power thrust reversals can be accomplished without any significant engine operational limitations for fan blade pitch changes through either feather pitch or flat pitch. Also, the aborted-takeoff operational mode has been satisfactorily demonstrated. For through-feather-pitch operation with a flight inlet, however, fan stall problems were encountered, but a fan blade "overshoot" technique was used to establish reverse thrust. High fan blade vibratory stresses relative to forward-thrust values occurred during through-feather-pitch transient operation but were well within acceptable limits. In conclusion, this program has shown that variable-pitch fans offer a potentially attractive means of providing rapid reverse-thrust capability for future short-haul aircraft.

INTRODUCTION

For the past several years, the development of advanced technology for a quiet, clean, high-bypass-ratio turbofan engine to be used on future short-haul aircraft has been pursued. At the NASA Lewis Research Center, a major portion of this effort is the Quiet, Clean, Short-Haul Experimental Engine (QCSEE) Program. A status report on this program is presented in reference 1. The reduced field lengths envisioned for short-haul aircraft operation have made reverse-thrust performance a critical part of the propulsion system's design requirements. Noise requirements for short-haul aircraft dictate that a low-pressure-ratio, high-bypass-ratio fan be used, especially for under-the-wing engine installation. For such installations, engines designed with variable-pitch fans for reverse thrust have been shown (refs. 2 and 3) to be superior to those with fixed-pitch fans and conventional reversers. The potential advantage of using variable-pitch fans is the elimination of the conventional heavy, high-maintenance, target or cascade thrust-reversal hardware plus the added benefit of improved thrust response time (refs. 2 and 3). Obtaining reverse thrust with a variable-pitch-fan engine involves a new mode of engine operation. Therefore, early in the QCSEE program, collecting information on the feasibility of this approach as well as gaining operating experience was considered imperative. An overview discussion of the status of reverse-thrust technology for variable-pitch-fan systems is presented in reference 4.

Investigative tests were undertaken on a full-scale, high-bypass-ratio, variable-pitch-fan engine developed by the Hamilton Standard Division of United Technologies Corp. Steady-state aerodynamic and acoustical performance, including net thrust and external exhaust velocity profiles, was determined for both forward- and reverse-thrust modes, with both bellmouth and flight inlets.

Transient tests were performed in the "through-feather-pitch" (stall) and "through-flat-pitch" (zero lift) operational modes with both inlets. In addition to the normal transient operation of approach power to reverse thrust, the aborted-takeoff transient operation was also investigated.

This report discusses the results of the transient test program that was performed under NASA contract at Hamilton Standard and at the Lewis Research Center. Detailed discussions of the Hamilton Standard testing are presented in references 5 to 8.

APPARATUS AND PROCEDURES

The initial transient tests were conducted at the Hamilton Standard Hilltop Test Facility as described in references 7 and 8. Transient testing was resumed later at the NASA Lewis Test Facility. The Lewis facility, test hardware, and experimental methods used are described here.

Test Facility

The Lewis test facility shown in figure 1 is an outdoor test facility capable of testing turbofan engines up to a maximum thrust level of 133 500 newtons. The large tripod structure supports the cantilevered overhead thrust-measuring engine mount with the engine centerline at 2.9 meters above ground. The area around the test stand is paved with concrete to provide a flat, consistent ground surface. The engine support and thrust-measuring system can be rotated to allow the movable shelter to be rolled in place over the test stand.

A 37.85-cubic-meter fuel tank is located underground adjacent to the movable shelter, which is positioned approximately 90 meters from the test stand. In the same area above ground is a large high-pressure gaseous nitrogen storage tank used for fire protection. An instrumentation vault housing signal conditioners and amplifiers is located near the test stand. The control room is approximately 120 meters away from the test stand. A digital data acquisition system is capable of recording pressures, temperatures, and other engine parameters and, together with a computer system, can print out engineering parameters in the control room.

Test Hardware

The variable-pitch, gear-driven fan engine that was tested is shown installed at the Lewis test facility in figure 2. The structure beneath the engine provided a stiff mounting support for the thrust cell, which resulted in improved real-time thrust response measurement. These measurements are discussed later. The variable-pitch-fan engine, described in references 5 to 8, was supplied by Hamilton Standard and included the fan, the gearbox, the hydraulic equipment, the computer control system, and the engine cowling. The NASA Lewis Research Center supplied additional inlet and nozzle hardware. The fan is driven by an Avco Lycoming T55-L-11A turboshaft engine. Table I lists the main design characteristics of the fan and the engine.

Cross-sectional views of the cowling hardware are illustrated in figure 3. Several combinations of inlets and exhaust ducts were tested, but the standard fan nozzle was not used when the engine was generating reverse thrust because reverse-thrust performance is severely degraded with that configuration (refs. 7, 8) Instead a bellmouth-shaped inlet was used to simulate the open position of a variable-area fan nozzle, called an exlet (ref. 9). The flight inlet was tested primarily to assess its effect on reverse-thrust performance. Its characteristics are presented in figure 4. The flight inlet was designed with the same inlet lip contour to be used on the QCSEE engines (ref. 10).

The programmable digital computer control system allowed for the changing of the control parameters; a simplified schematic is presented in figure 5. The different research inputs listed could be changed between test points and are defined later in the text. The control system interpreted the requests and controlled the fan blade pitch and power lever position during the transient.

Experimental Methods

Generally, steady-state aerodynamic instrumentation was located in the planes identified in reference 5. Specifically, inlet wall static pressures were added for the Lewis Research Center tests, located as shown in figure 6. The pressures, temperatures, and other outputs were received as millivolt signals, digitized, and then transmitted to a remote data collector system. A computer then reduced the data to appropriate engineering parameters.

The following transient instrumentation was used:

(1) Ambient pressure, P_0
(2) Ambient temperature, T_0
(3) Fan speed, N
(4) Engine speed, NC
(5) Engine torque, $\mathcal{T}$
(6) Power level position, PLA
(7) Fan blade angle, β
(8) Engine fuel flow, WF
(9) Engine thrust, F
(10) Compressor inlet total pressure (ref. 5), P_{T2}
(11) Compressor discharge pressure, P_{S3}
(12) Low-pressure-turbine inlet temperature, T_5
(13) Fan strain gages (located 36.2 cm from blade tip)

Excitation of the overhead engine support structure at its natural frequency during thrust reversal was a significant concern. The result would be to obscure the actual real-time engine thrust value measured by a load cell. The amplitude of the vibration was significantly reduced and the natural frequency increased by using a secondary support and incorporating a bidirectional load cell. The secondary support located beneath the engine is shown in figure 2. The secondary support was available and used only for the through-feather-pitch portion of the transient program.

The real-time transient data signals were transmitted as millivolt signals to a remote high-speed digitizing system. The data were digitized at a rate of approximately 5000 samples per second. The digitized signals were transmitted to a computer for appropriate calculations, and the final engineering data were presented at a rate of approximately 50 samples per second.

RESULTS AND DISCUSSION

Steady-State Aerodynamic Performance

Forward thrust. - To better understand the transient tests, steady-state forward-and reverse-thrust aerodynamic performance is discussed first. Figure 7 presents the forward steady-state aerodynamic performance as a plot of corrected thrust versus corrected fan speed. Various fan-blade-angle operating lines are shown. The three solid symbols indicate the selected takeoff and landing approach operating conditions. These points were used as the starting conditions for all transients. The landing approach thrust level of 60 percent of takeoff thrust was selected based on the short-haul aircraft study discussed in reference 11. For forward-to-reverse-thrust transients through feather pitch from the approach power setting, 100-percent fan speed was selected for good waveoff thrust response. But for some of the reverse transients through flat pitch, the initial fan speed was reduced to approximately 75 percent of takeoff speed to allow a greater fan overspeed margin. The transients were conducted with the bellmouth-shaped exlet and not the standard fan nozzle (fig. 3) to provide a better airflow path for reverse thrust. This change had little effect on the starting thrust level (less than 5 percent) because the effective nozzle area of the exlet was essentially equal to the standard nozzle area.

Reverse thrust. - A basic concern in the operation of a variable-pitch fan is the direction in which the fan blade pitch should be changed to develop reverse thrust. The two possible ways are illustrated in figure 8. Cross sections of two fan blade shown in their normal forward-thrust position are at the top of this figure. From this position, the blades can be turned through flat pitch, a condition of zero lift, to the reverse-thrust position as shown on the left in figure 8. Two things should be noted for this approach. First, adjacent blade leading and trailing edges must pass each other during the transition through flat pitch. This requires that the blade solidity be less than 1 at all radii. This constraint can limit fan performance, especially at the hub. Second, while the blade leading edge remains the same relative to the airflow, the blade camber is wrong for reverse-thrust operation.

The alternative approach is to turn the blades through feather pitch, passing through a separated flow or stall condition. This is shown on the right side in figure 8. In this case, the blade camber is correct in the reverse-thrust position, but the leading and trailing edges are reversed. During the transition the flow over the blades separates and then reattaches in reverse thrust, moving in the opposite direction relative to the blade. With this approach the blade solidity may exceed 1, which allows more freedom in the blade design. The blade twist and camber can still limit the hub solidity to some extent.

In figure 9 the steady-state reverse aerodynamic performance is presented as a plot of corrected thrust versus corrected fan speed. Various relative reverse fan blade angles for through feather pitch and a single angle for through flat pitch are shown. The solid symbols indicate the selected reverse-thrust operating conditions. The reverse through-feather-pitch fan blade angle was selected based on obtaining the required thrust with the lowest fan speed operating line tested. Attempts to test on a lower fan speed operating line ($\Delta\beta = -88^\circ$) were limited by high fan blade vibratory stresses. This approach results in the largest thrust increase capability for emergency operations. A reverse-thrust level of 35 percent of takeoff thrust has been established as the required reverse thrust for short-haul aircraft, as discussed in reference 12. For thrust reversals with the bellmouth the fan speed was increased to maintain the 35-percent reverse-thrust requirement. Even though through-flat-pitch reverse thrust does not meet the reverse-thrust requirements for short-haul aircraft, an understanding of this mode of operation was considered valuable should future considerations require this mode of operation. A reverse-thrust fan speed of 90 percent was used to allow some margin for fan overspeed.

Approach-Power Transient Performance

Reversal through feather pitch - bellmouth inlet. - Before discussing the results of the through-feather-pitch transients, a discussion of the real-time variations during a transient is desirable. In figure 10 are presented characteristics during a typical reverse-thrust transient through feather pitch. The selected transient parameters are shown plotted as a function of time. Data obtained using the high-speed transient data system are shown with a solid line faired through the points. At the start of the transient the power lever was immediately raised to the level required for the selected ending condition. Fan blade angle (fig. 10(a)) was changed at approximately 130 degrees per second and reached the final position is less than 1 second. Fuel flow (fig. 10(b)) increased as a result of the power lever change, followed by a few rapidly damped oscillations in fuel flow. Thrust, torque, and fan speed should be viewed collectively (figs. 10(c), (d), and (e)). The initial change in fan blade pitch increases the aerodynamic loads on the blades. As this happens the fan speed is lowered as the fan rotational energy is converted into a thrust increase. As the blade pitch continues to increase, the fan eventually stalls and the thrust falls to zero. This stalled condition unloads the blades to some degree, causing the fan speed to increase. Shortly after the blades reach their reverse position, the flow reattaches and reverse thrust is obtained. During the transient the core compressor must tolerate variations in pressure and speed (figs. 10(f), (g), and (h)). The compressor inlet pressure rises somewhat with increasing fan blade angle and then falls suddenly as the fan stalls while, in response to the change in fuel flow, the compressor speed and discharge pressure both increase. No problems with the core compressor were evident due to these variations.

Before attempting to analyze the through-feather-pitch transient operation, it is desirable to define several descriptive terms, as shown in figure 11. The primary means of reviewing specific transient sequences is by the thrust response time, which is defined as the time from the request to change the engine thrust level until 95 percent of the final thrust is achieved. Cutback position is a temporary level to which the power lever on the fuel controller is initially moved before the power lever is set to its final reverse-thrust position. Blade travel time is the time it takes the fan blade pitch to change from the initial forward-thrust angle to the reverse-thrust angle. Flow reattachment time is the time it takes the air to reattach to the fan blade after the fan blade has reached the reverse-thrust angle. Flow reattachment was assumed to occur when there was a rapid decrease in blade vibratory stress level. This assumption was supported when the rapid decrease in blade stress level was compared with other measured engine parameters, such as presented in figure 10. Flow reattachment was determined in this manner because, during the transient, oscillatory motion of the engine support structure precluded accurate measurement of engine thrust. If the fan speed is insufficient to generate the required reverse thrust when the flow reattaches to the fan blade (point A), a delay time occurs while the fan accelerates.

The thrust response time for thrust reversal through feather pitch is a summation of the blade travel time, the flow reattachment time, and the delay time, as shown in figure 11. The effect of blade travel time on thrust response time is presented in figure 12. Specifically, thrust response time varies directly with blade travel time, and blade travel time has no significant effect on flow reattachment time. Figure 13 presents the possible delay time that should be added if the fan speed at flow reattachment is not sufficient to generate the required reverse thrust. In general, the fan speed at flow reattachment is reduced by greater amounts of cutback for longer durations. Figure 14 presents flow reattachment time, which is the final controlling item of thrust response time, as a function of reverse fan blade angle. Flow reattachment appears to be significantly affected only by the reverse fan blade angle and the fan duct geometry. Flow reattachment time decreases as the reverse fan blade angle of attack is reduced (i. e., $\Delta\beta$ decreases). Flow reattachment time is also reduced by shortening the overall length of the fan inlet and exhaust ducts.

When considering figure 14, note that transient operation with blades moving directly to the selected steady-state relative reverse fan blade angle ($\Delta\beta = -90^{\circ}$) could not be performed because the air would not reattach to the fan blade. A method called "overshooting" was conceived that allowed transient operation to the selected fan blade angle. With *this technique, the fan blades are moved beyond the selected reverse fan blade angle,* held there for a short period of time (dwell time), and then returned to the selected fan blade angle. This overshoot temporarily reduces the angle of attack on the blades, allowing the separated airflow to reattach and reverse flow to be established. Figure 15 illustrates this operational technique. The dashed line shows that no reverse thrust, A, is generated if the fan blade angle is rotated directly to the selected reverse-thrust angle. If the fan blade angle is rotated directly to some angle beyond "optimum" so that reverse thrust is achieved, the level of reverse thrust, B, is less than desired, as shown by the dot-dashed line. The solid line shows how the "overshoot" technique is performed such that flow reattachment occurs and the required reverse thrust, C, is generated.

The results of using the overshoot technique are shown in figure 16. Presented is a plot of flow reattachment time as a function of degrees of fan blade angle overshoot. The thrust response time for these transients varied only with flow reattachment time since the delay time was zero and the blade travel time was approximately constant (1.09±0.05 sec). For a constant dwell time the flow reattachment time can be significantly reduced, approximately 0.5 second, by increasing the degrees of overshoot. Increasing the dwell time for a constant degree of overshoot will also reduce the flow reattachment time but only by approximately 0.2 second.

Reversal through feather pitch - flight inlet. - Testing with the flight inlet in contrast to the bellmouth inlet showed that with the fan stalled, the inlet can produce backpressure on the fan, which tends to prevent flow reattachment to the stalled fan blades and hence the establishment of reverse thrust. This can occur when the fan is started from rest with the blades initially in a reverse position or, more importantly, during a forward-to-reverse-thrust transient through feather pitch. This effect can be observed with the aid of tufts, as shown in figure 17. When the fan is in stall, the flow is primarily tangential, tending to rotate with the fan. When the fan is unstalled and producing reverse thrust, the flow is nearly axial.

For the swirling flow in the stalled condition to be exhausted out the smaller diameter throat of the flight inlet, the tangential components of velocity of the swirling flow must increase to conserve angular momentum. Since the static pressure at the front of the inlet is ambient, a higher than ambient pressure at the fan is implied. This higher pressure (called backpressure) at the fan tends to prevent flow reattachment. The magnitude of the backpressure will depend on the inlet geometry and the forward velocity (ram pressure).

Test data showing this effect are presented in figure 18. Ratios of wall static pressure to ambient pressure are compared for the extended bellmouth and the flight inlet for both stalled and unstalled conditions at the same fan speed (76 percent) and comparable fan blade angles (6° from the reverse fan blade stall angle). Of primary interest is the static pressure at the fan face. As can be seen from figure 18, in a stalled condition a higher pressure does exist with the flight inlet.

Successful forward-to-reverse-thrust transients through feather pitch were performed with the flight inlet by using the technique of fan blade overshoot. In this case, the fan blade overshoot angle was necessary to unstall the fan and to establish reverse flow, and the final reverse fan blade angle was necessary to obtain the required reverse thrust. The transients were performed with the maximum overshoot mechanical capability of the equipment. But this by itself was not large enough to consistently establish reverse flow, and augmentation from three air jets was also used. The purpose of the air jets was to help promote flow reattachment to the fan blades by blowing into the blade channels in the reverse flow direction. Even though the engine customer bleed would have been sufficient for the air jets, a facility air supply was used to simplify the test setup. The three air jets were installed approximately 6.35 centimeters behind the fan rotor and positioned 1/2 blade spacing apart, as shown in figure 19. The fan blades are shown at a forward-thrust pitch angle. A survey was performed to determine the best radial position and jet flow angle for the air jets. They were finally located 5.08 centimeters into the stream with the 2.54-centimeter by 0.64-centimeter slots oriented 68° in the feather-pitch direction from the fan blade design angle. The total air jet mass flow rate was 0.59 kilogram per second. If more overshoot capability could be made available by modifying the pitch change mechanism, the air jets would probably not be needed. Table II presents results of the fastest successful forward-to-reverse-thrust transient with the flight inlet. This thrust response time of 1.84 seconds is not optimum since the thrust response can be improved by decreasing the blade travel time by increasing the fan blade pitch change rate. Also the excessive flow reattachment time could have been reduced by a minor mechanical redesign to increase the fan blade overshoot capability.

Reversal through flat pitch. - For reverse-thrust applications where approximately 20 percent of takeoff thrust is adequate, operation through flat pitch can be considered. Through-flat-pitch operation is significantly noisier than through-feather-pitch operation (ref. 4). A typical time history for through-flat-pitch operation is presented in figure 20. All the data points are shown, and a curve was faired through them. In this transient, the blade pitch (fig. 20(a)) was changed at a rate of approximately 100 degrees per second, with the power lever and hence the fuel flow (fig. 20(b)) held constant.

Thrust (fig. 20(c)), presented as a percentage of measured takeoff thrust, responded to the blade angle change and fell off smoothly. The final reverse-thrust level was reached in somewhat less than 1 second. The fan during this time accelerated quickly (fig. 20(e)) as the load on the fan blades was reduced. As the blade loading increased again in reverse thrust, the fan speed peaked and then converged on the final reverse-thrust value. During this same time period, there occurred a slight dip in torque (fig. 20(d)). Torque started to decrease due to the reduction in the fan blade loading, which was followed by an increase as the blade loading increased in reverse thrust. Core compressor speed (fig. 20(f)) and compressor discharge static pressure ratio (fig. 20(h)) remained practically constant since there was no change in fuel flow. The compressor inlet total pressure ratio (fig. 20(g)) fell off to a level slightly higher than a similar through-feather-pitch transient.

As with the through-feather-pitch transients, it is desirable to define several terms, which are illustrated by figure 21. Cutback position and blade travel time maintain the same definitions as previously described. Duration is the time that the power lever is maintained at the cutback position. If the initial fan speed is too great for the power lever angle selected, the fan will overspeed as demonstrated in the illustration by comparing the solid and short-dashed lines. If the higher initial fan speed is required, careful selection of power lever cutback position and duration are required to prevent a fan overspeed from occurring.

The thrust response time for thrust reversal through flat pitch is a function of the fan acceleration time and the blade travel time. Fan acceleration time is a function of the cutback position and the initial fan speed. For a reduced initial fan speed (76 percent), the effect of cutback position and duration are shown in figure 22. The fan acceleration time varies directly with duration and inversely with cutback position.

When starting from a higher initial fan speed, the fuel flow can initially be cut back to reduce the available engine power during the transient such that when the reverse blade position is reached the fan speed is at the desired level and no overspeed occurs. Figure 23 presents test data that show the effect of initial fan speed on forward- to reverse-thrust through-flat-pitch operation. When a high initial fan speed was used, the fuel flow and fan blade pitch change rate needed to be coordinated to prevent a fan overspeed condition, which limits further reductions in thrust response time (see fan speed versus time, long-dashed curve in fig. 21). However, with a reduced initial fan speed and proper coordination of fuel flow and fan blade pitch change rate, the thrust response time could be reduced to the blade travel time without a fan overspeed.

Fan blade stress. - Of significant interest is the structural response of the fan blades during the forward- to reverse-thrust transition. Figure 24 presents real-time traces of the fan blade vibratory stress. The transient was initiated at time zero. For through-flat-pitch transitions (fig. 24(a)), the vibratory stress gradually increased throughout the transient, leveling off at approximately twice its initial value. The through-feather-pitch transition (fig. 24(b)) was significantly different. During the transient, the fan blade stresses built up and peaked as the blade stalled. A second peak, generally somewhat higher than the first, occurred as flow reattached to the blades in the reverse direction. These stress peaks, while high relative to forward-thrust levels, did not limit the transient tests.

The peak vibratory stress is important, but it alone does not present the entire picture. The time duration of the high vibratory stress is also important, and together they affect the fatigue life of the fan blade if the high stress exceeds the infinite life allowable stress of the fan blade material. The effect of flow reattachment time on the fan blade relative fatigue life is presented in figure 25. The absolute value of fatigue life used per transient is primarily a function of fan blade material selection and is not important for this discussion. Reducing the flow reattachment time provides for an increase in fatigue life by reducing the time period of high vibratory stress.

Aborted-Takeoff Transient Performance

Also of significant interest is the aborted-takeoff emergency operation in which the propulsion system must generate the required reverse thrust with the engine initially at takeoff power. Figure 26 presents the results of the aborted-takeoff transient operation through feather pitch. The results are consistent with the approach power transients, in which the thrust response time is a function of blade travel time and flow reattachment time. As a result of the high initial power lever position, the delay time is zero.

For aborted-takeoff transient operation through flat pitch, only a few transients were conducted, but this mode of operation was satisfactorily demonstrated. For example, the thrust response time was 1. 3 seconds for a transient in which fan speed started and finished at 100 percent and the fan blade pitch change rate was 110 degrees per second. To avoid fan overspeed, the fuel flow must be cut back and hence, in this case, the power lever was cut back to idle for 0. 5 second.

SUMMARY OF RESULTS

This test program, conducted to develop the technology necessary for a Quiet, Clean, Short-Haul Experimental Engine (QCSEE) type of propulsion system, has shown that variable-pitch fans offer a potentially attractive means of providing rapid reverse-thrust capability for future short-haul aircraft. More specifically, these tests have shown the following:

1. Approach power forward-to-reverse-thrust response times of approximately 1. 0 second can be achieved either through feather pitch or through flat pitch without any significant engine operational limitations.
2. The thrust response time for reversal through feather pitch can be described as the summation of blade travel time, flow reattachment time, and delay time; while the thrust response time for through flat pitch is a function of blade travel time and fan acceleration time.
3. For through-feather-pitch transient operation, the flow reattachment time is significantly affected by the reverse fan blade angle and fan duct geometry. Decreasing the angle of attack of the fan blade at flow reattachment reduces the flow reattachment time.
4. Forward-to-reverse-thrust, through-feather-pitch transients with the flight inlet identified fan blade "stall" problems. Using the maximum "overshoot" capability and air jet assistance provided a means for unstalling the fan blades and generating the required reverse thrust. If more overshoot capability were available, the air jets would probably not be needed; however, the stall problem needs further exploration to determine possible forward flight velocity effects.

5. For through-feather-pitch operation, high fan blade vibratory stress levels can occur during the transient but should not be a limiting factor in considering this operational mode with proper fan blade material selection. Reducing flow reattachment time increases fatigue life by shortening time period of high vibratory stress.

6. There is a tendency during through-flat-pitch thrust reversals for the fan to overspeed. The amount of overspeed can be reduced by initiating the transient at a lower fan speed or by carefully coordinating the fuel flow and the fan blade pitch change rate during the transient.

7. Satisfactory aborted-takeoff thrust reversals have been demonstrated without any engine operational problems.

Lewis Research Center,
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APPENDIX - SYMBOLS

D_{HL}	inlet highlight diameter
D_{max}	inlet maximum external diameter
D_T	inlet throat diameter
D_t	inlet diameter at diffuser exit
F	engine net thrust
L	inlet length from highlight to diffuser exit
N	fan speed, rpm
NC	engine speed, rpm
P_S	local static pressure
P_T	local total pressure
P_0	ambient pressure
$\mathscr{T}$	engine torque
T_0	ambient temperature
WF	engine fuel flow
β	fan blade angle
$\Delta\beta$	relative fan blade angle
δ	ratio of total pressure to standard sea-level pressure
θ	ratio of total temperature to standard sea-level temperature

Subscripts:

2	compressor inlet
3	compressor outlet
5	low-pressure-turbine inlet

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11. Study of Quiet Turbofan STOL Aircraft for Short-Haul Transportation. Volume 2: Aircraft. (MDC-J4371-Vol-2, Douglas Aircraft; NAS2-6994) NASA CR-114607, 1973.

11. Howard, D. F.; et al.: Quiet Clean Short-Haul Experimental Engine Preliminary Under the Wing Flight Propulsion System Analysis Report. (R75AEG349, General Electric Co.; NAS3-18021) NASA CR-134868, 1976. (Available from NASA Regional Dissemination Centers only to U. S. requesters.)

TABLE I. - FAN AND ENGINE CHARACTERISTICS

Fan design pressure ratio	1.18
Fan design specific flow, kg/(sec)(m^2)	194
Fan tip diameter, m	1.4
Number of fan blades	13
Fan design blade angle, β, deg	52
Fan tip diameter (based on chord angle at 75-percent blade height), m	1.40
Fan rotor solidity (hub/tip)	1.0/0.67
Fan rotor hub-tip diameter ratio	0.46
Fan design tip speed, m/sec	247
Number of fan stator vanes	7
Bypass ratio	18
Compressor pressure ratio	8
Measured corrected thrust (bellmouth inlet), N	31 900

TABLE II. - RESULTS OF AIR-JET-ASSISTED REVERSE TRANSIENT WITH FLIGHT INLET

Thrust response time, sec	1.82
Flow reattachment time, sec	0.62
Percentage of structural life used	1×10^{-3}
Relative reverse fan blade angle, $\Delta\beta$, deg	-90
Fan blade travel time, sec	1.19
Degrees of overshoot	14
Overshoot dwell time, sec	0.74
Delay time, sec	0
Reverse-thrust level, percent of takeoff thrust	~35

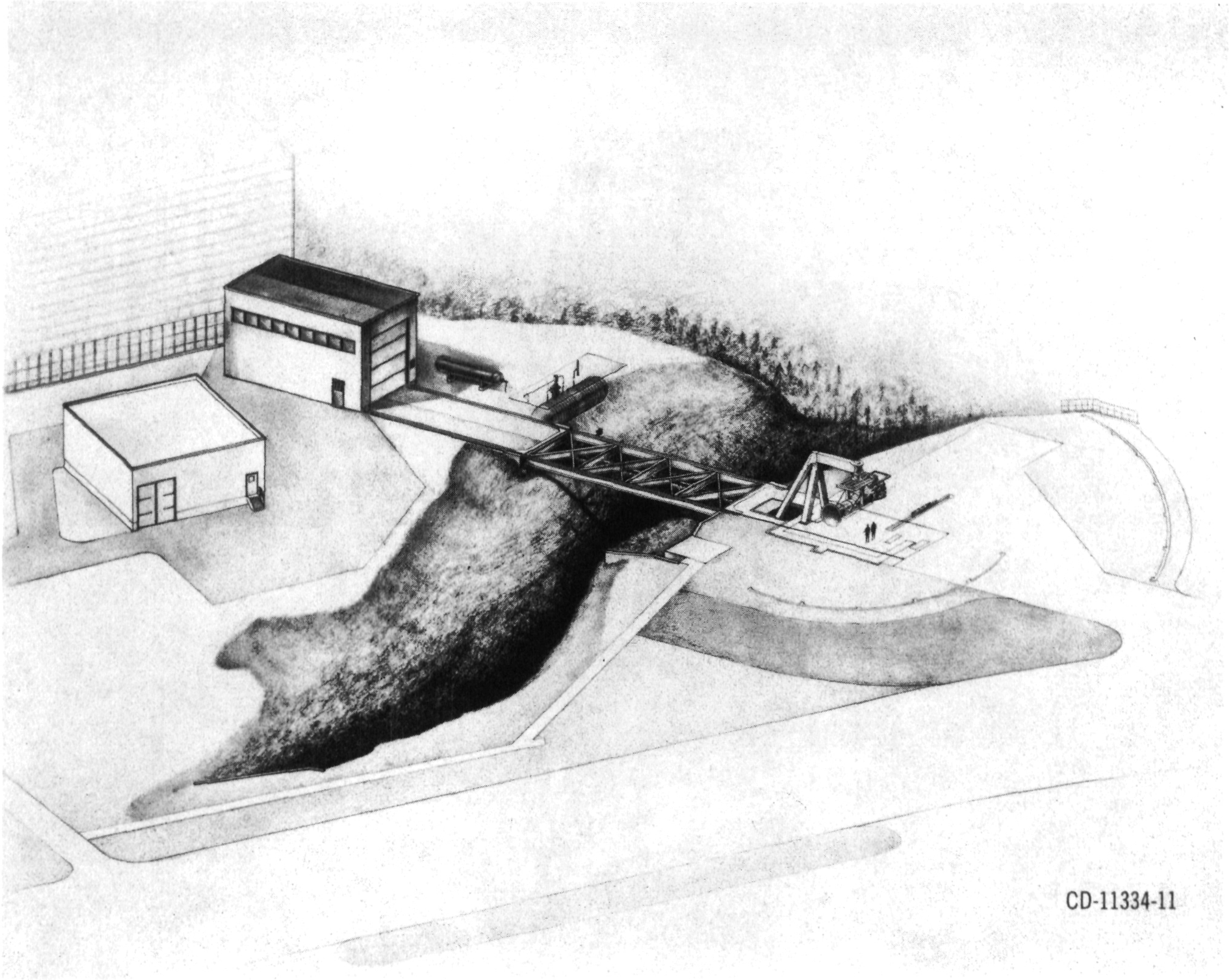


Figure 1. - Perspective view of NASA Lewis test facility.

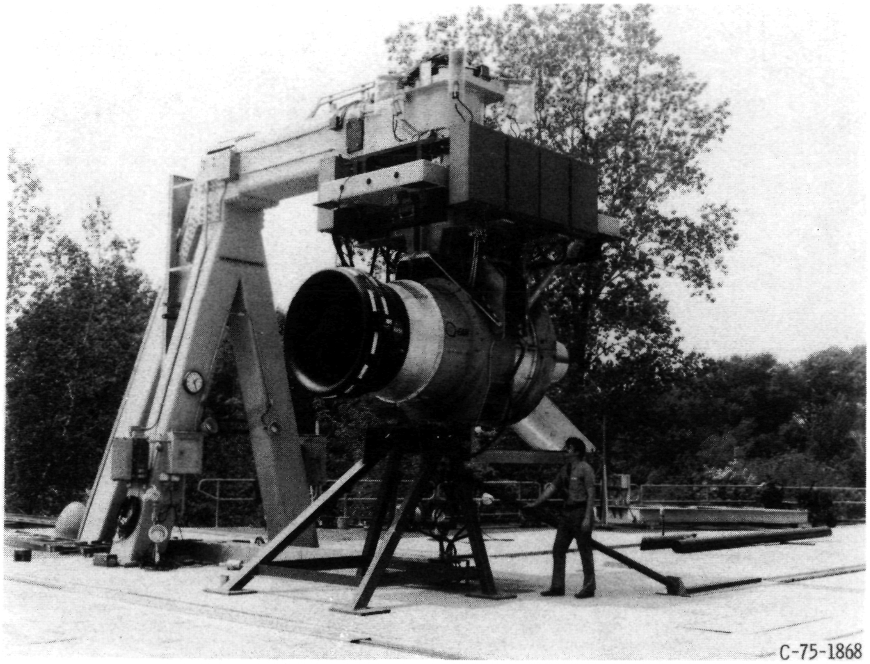
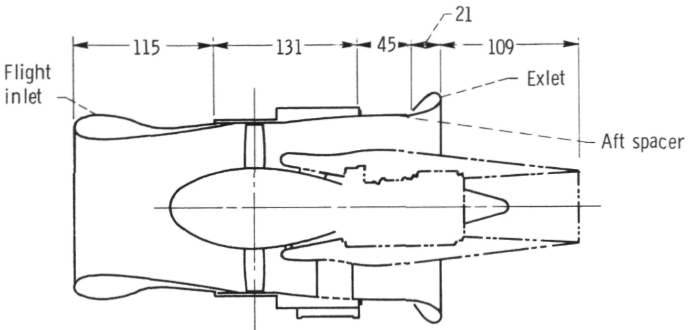
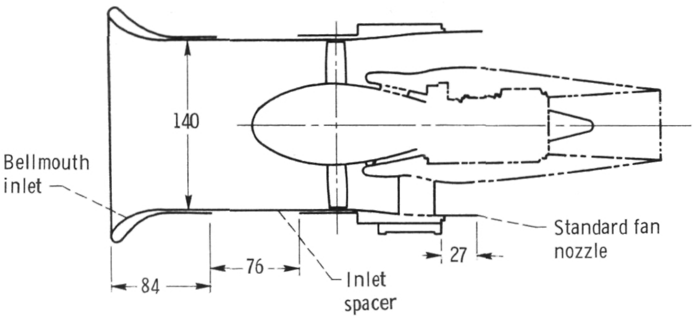


Figure 2. - High-bypass ratio, variable-pitch-fan engine with flight inlet installed at NASA Lewis test facility.



(a) Flight inlet.



(b) Extended bellmouth inlet.

Figure 3. - Cross-sectional views of engine and inlet hardware. (Dimensions are in centimeters.)

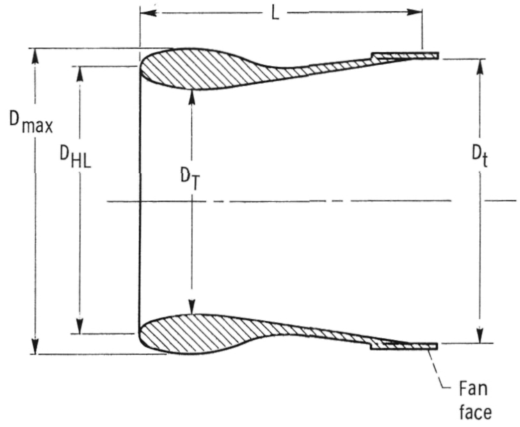
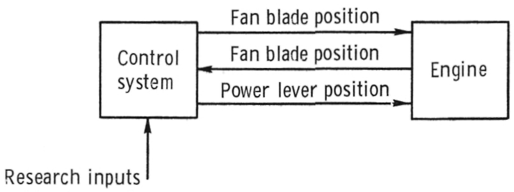
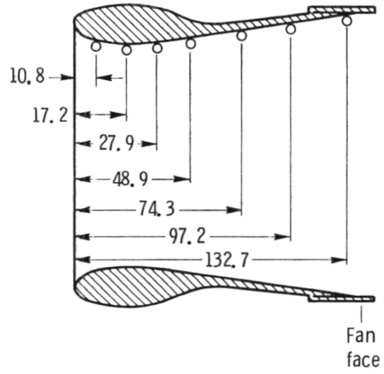


Figure 4. - Cross-sectional view of flight inlet. Ratio of inlet length to inlet diameter at diffuser exit, L/D_t, 1.0; ratio of inlet highlight diameter to inlet throat diameter, D_{HL}/D_T, 1.21; ratio of inlet highlight diameter to inlet maximum external diameter, D_{HL}/D_{max}, 0.909; ratio of throat diameter to diffuser exit diameter, D_T/D_t, 0.80; equivalent conical diffusion half-angle, 6.9°.

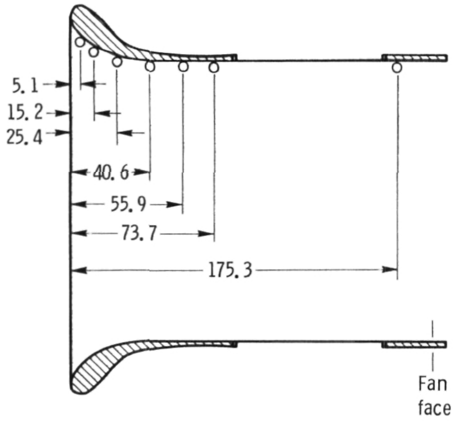


Starting fan blade position
Ending fan blade position
Fan blade pitch change rate
Fan blade dwell time
Starting power lever position
Ending power lever position
Power lever cutback position
Power lever cutback duration

Figure 5. - Schematic of computer control system.



(a) Flight inlet.



(b) Extended bellmouth inlet.

Figure 6. - Inlet wall static pressure locations. (Dimensions are in centimeters.)

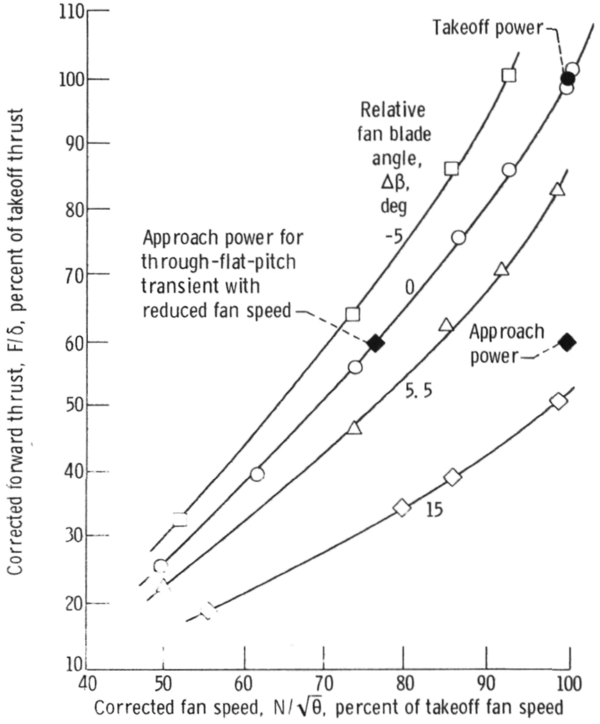
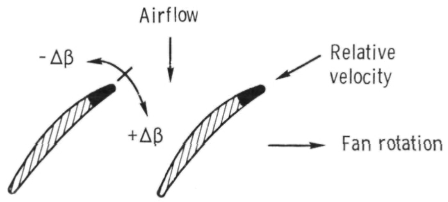
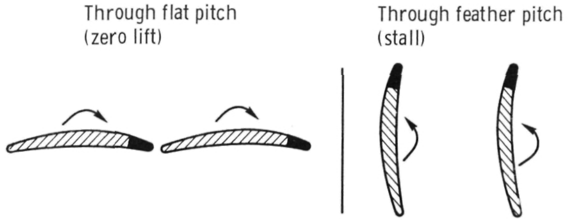


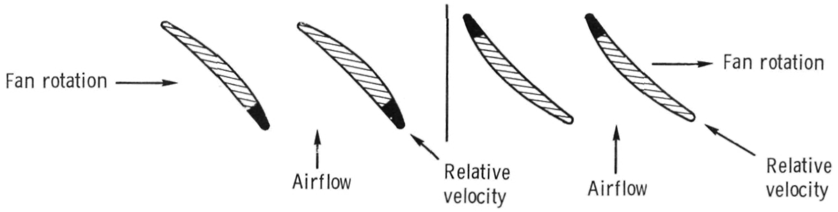
Figure 7. - Corrected forward thrust as function of corrected fan speed with the flight inlet and the standard fan nozzle.



(a) Forward thrust.



(b) Transition.



(c) Reverse thrust.

Figure 8. - Fan blade pitch alternatives for reverse thrust.

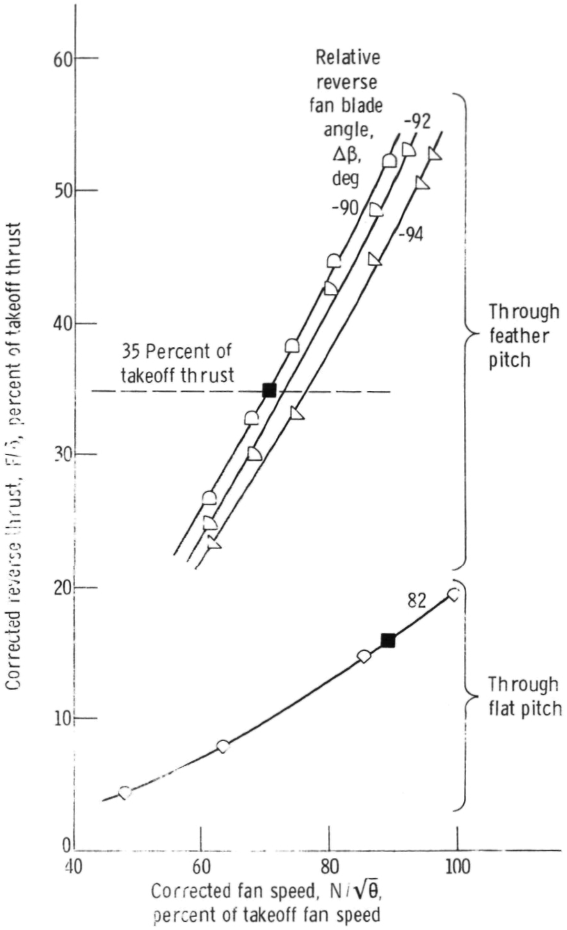
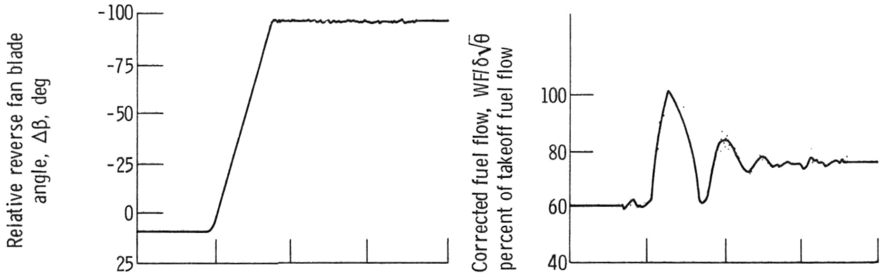
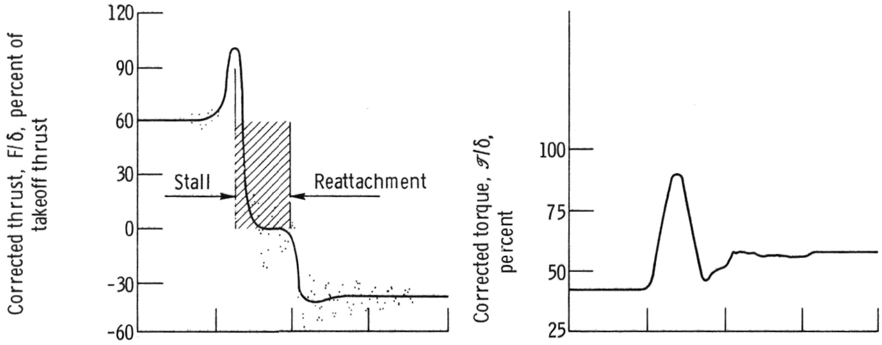


Figure 9. - Corrected reverse thrust as function of corrected fan speed with the flight inlet and the fan exlet.



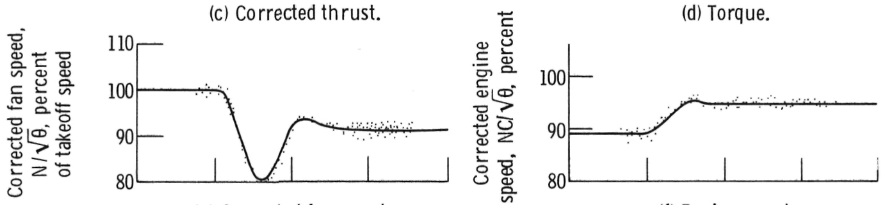
(a) Relative reverse fan blade setting angle.

(b) Fuel flow.



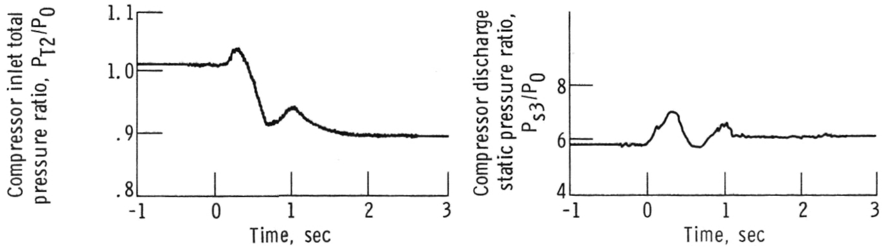
(c) Corrected thrust.

(d) Torque.



(e) Corrected fan speed.

(f) Engine speed.



(g) Compressor inlet total pressure ratio.

(h) Compressor discharge static pressure ratio.

Figure 10. - Real-time traces of selected engine parameters for a through-feather-pitch transient.

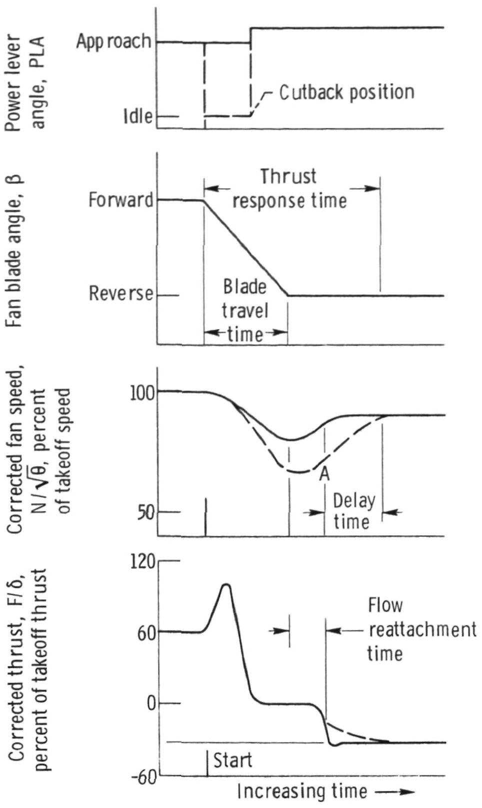


Figure 11. - Illustration of through-feather-pitch transient operation.

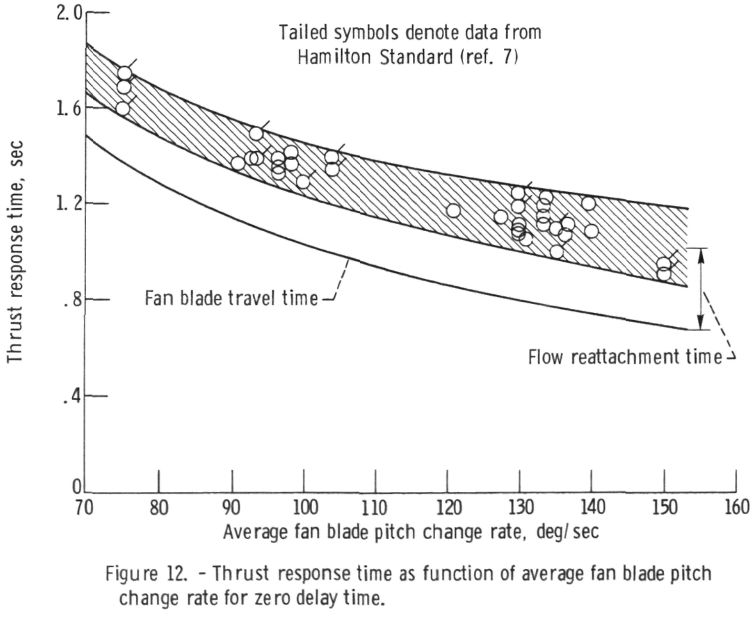


Figure 12. - Thrust response time as function of average fan blade pitch change rate for zero delay time.

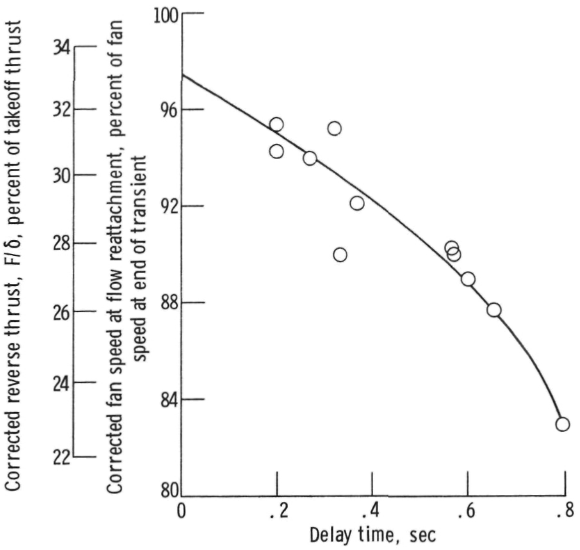


Figure 13. - Delay time as function of fan speed at flow reattachment.

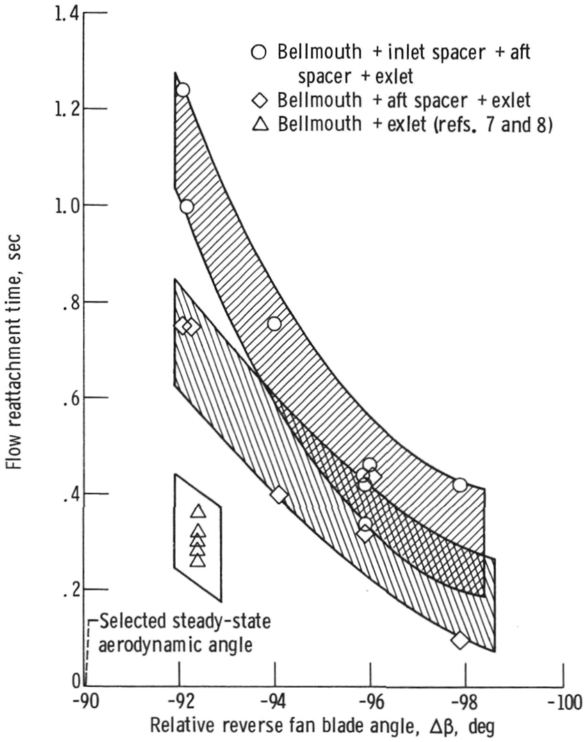


Figure 14. - Flow reattachment time as function of reverse fan blade angle.

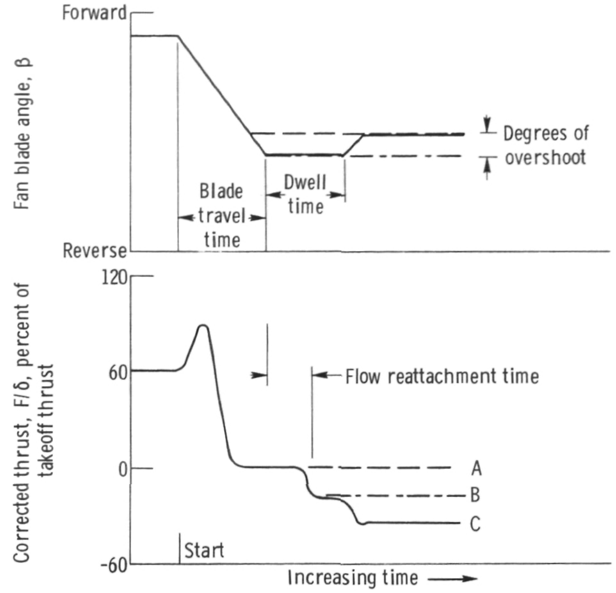


Figure 15. - Illustration of overshoot transient operation.

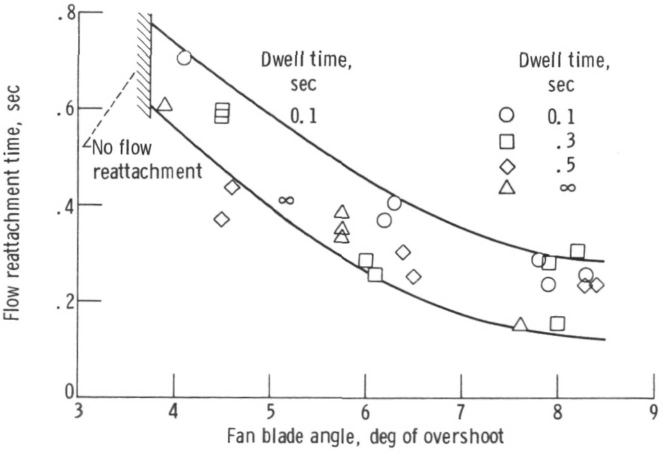
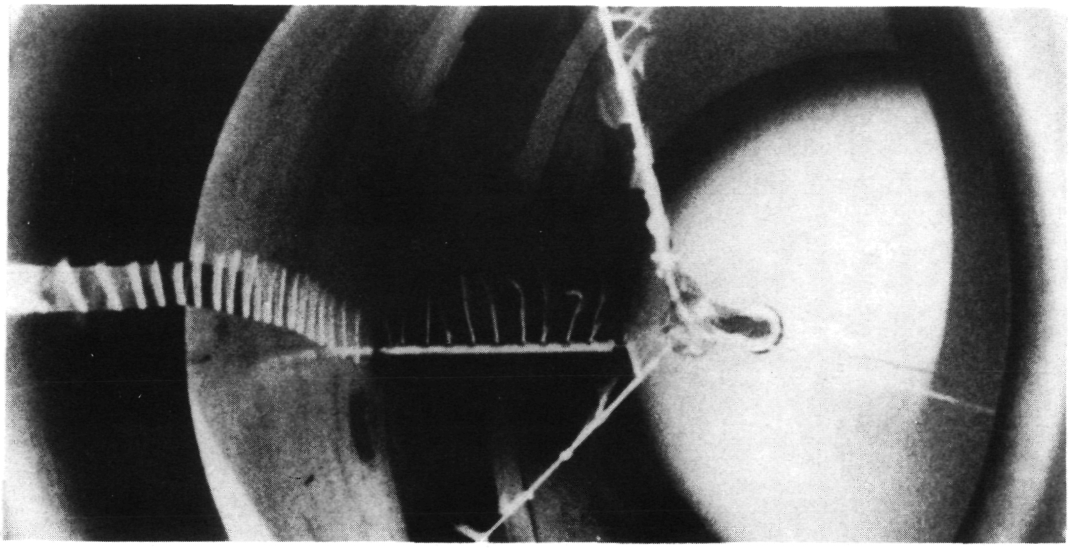
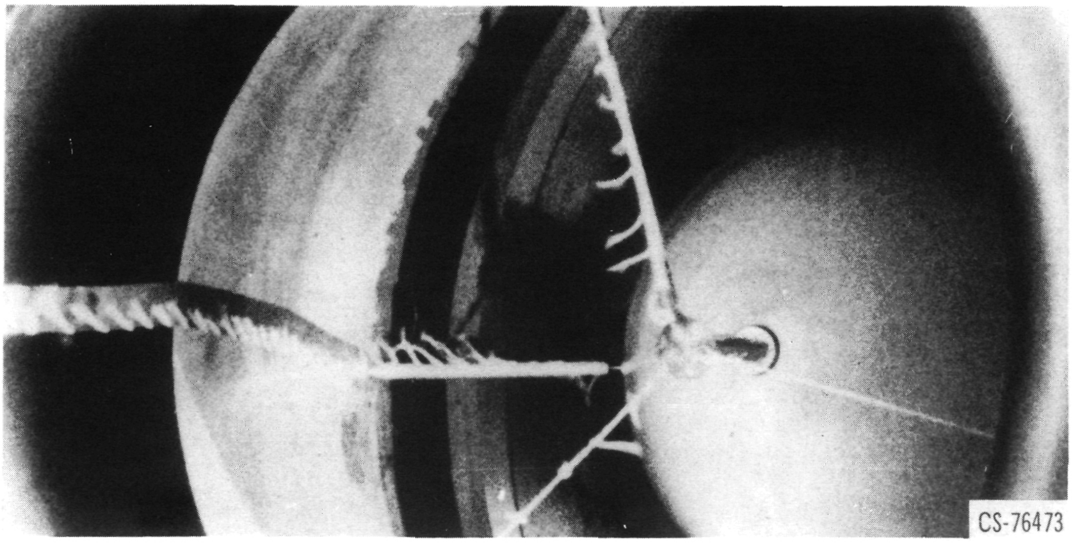


Figure 16. - Flow reattachment time as function of fan blade overshoot.



(a) Stalled.



(b) Unstalled.

Figure 17. - Reverse flow field in flight inlet.

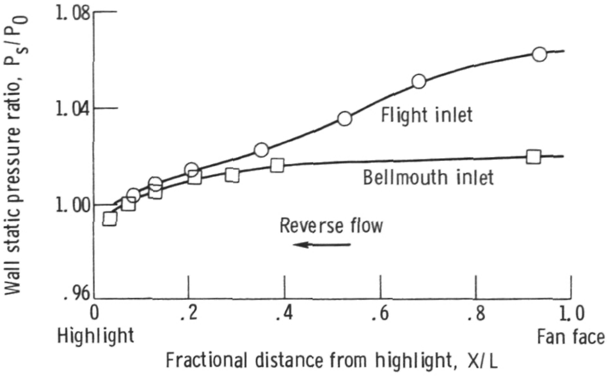


Figure 18. - Inlet backpressure effect during stall. Fan speed, 76 percent of takeoff speed.

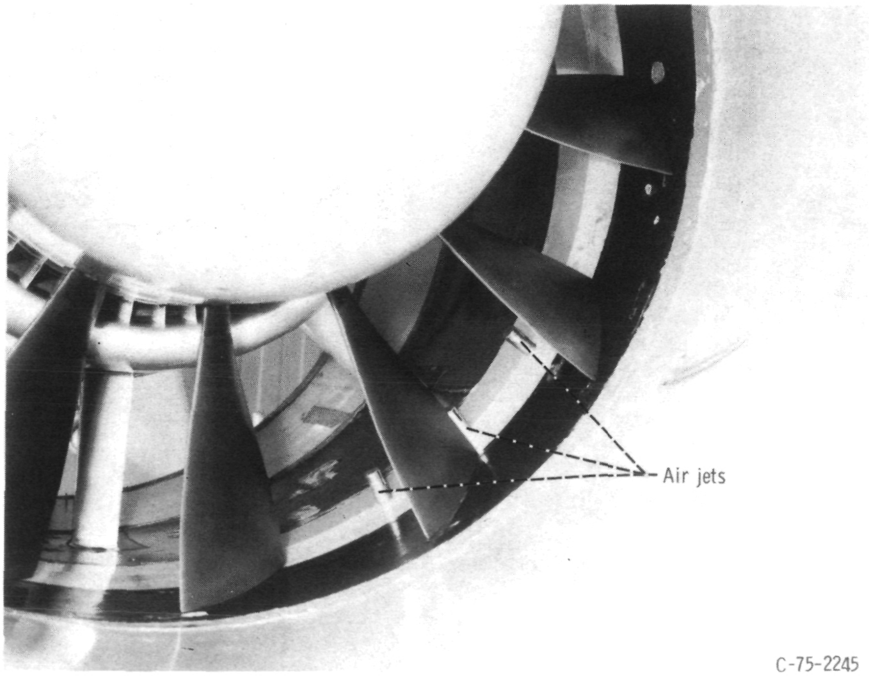
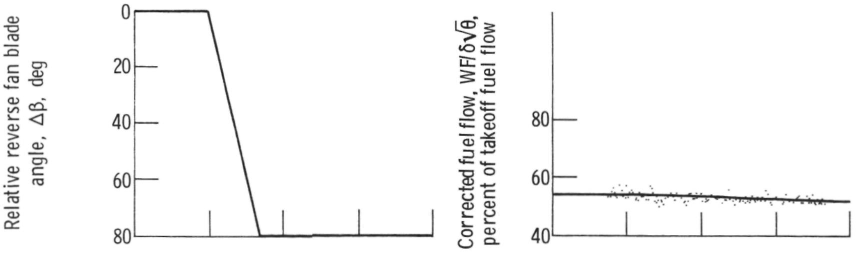
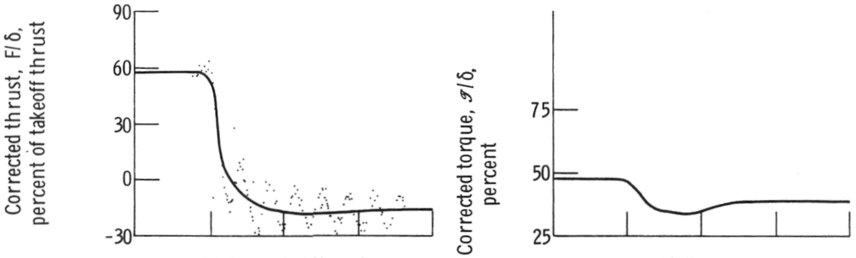


Figure 19. - Optimum air jet slot orientation shown in position behind fan (view aft with fan blades in forward-thrust pitch).



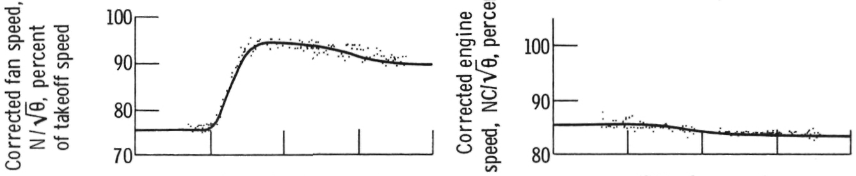
(a) Relative reverse fan blade setting angle.

(b) Fuel flow.



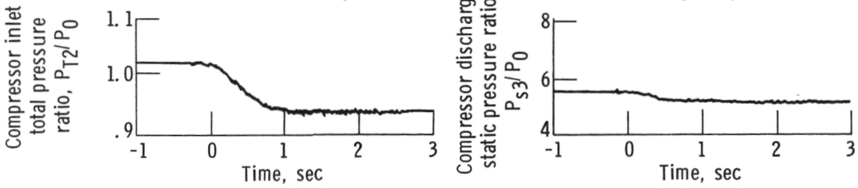
(c) Corrected thrust.

(d) Torque.



(e) Corrected fan speed.

(f) Engine speed.



(g) Compressor inlet total pressure ratio.

(h) Compressor discharge static pressure ratio.

Figure 20. - Real-time traces of selected engine parameters for a through-flat-pitch transient.

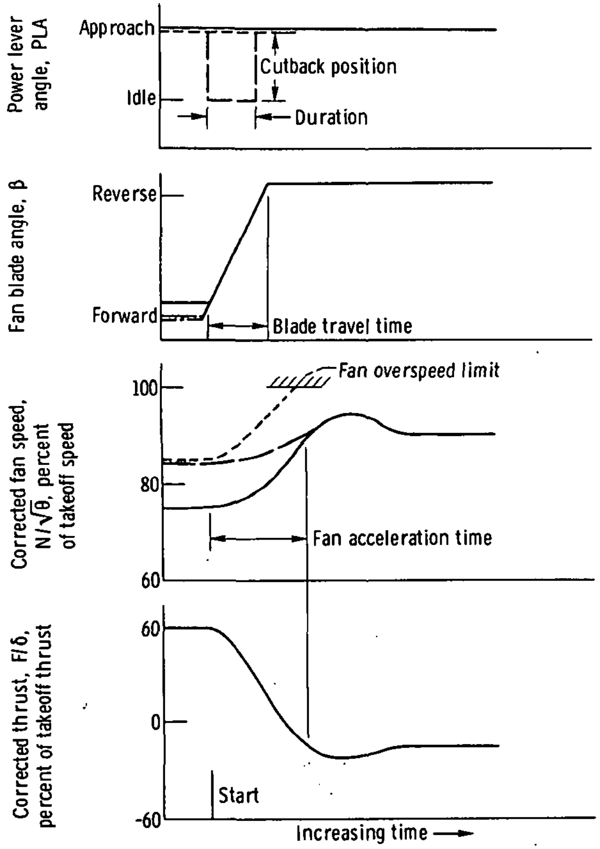


Figure 21. - Illustration of through-flat-pitch transient operation.

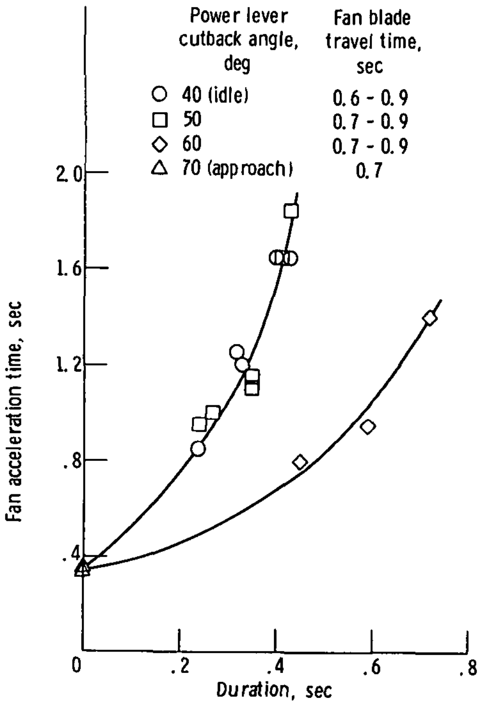


Figure 22. - Results of approach power, reverse through-flat-pitch operation. Initial fan speed, 76 percent; final fan speed, 90 percent.

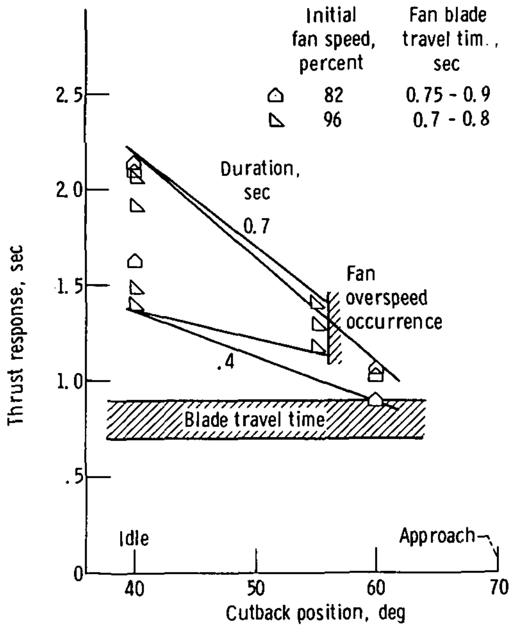
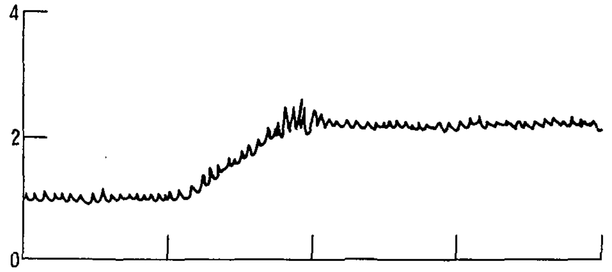
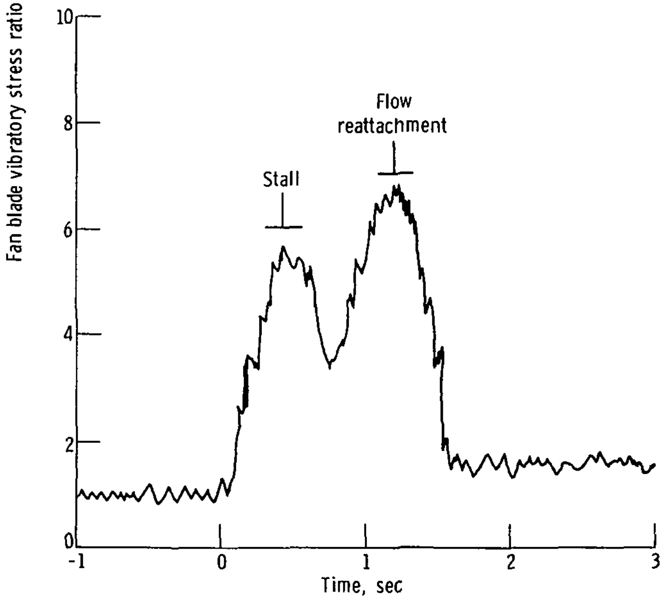


Figure 23. - Thrust response time as function of cutback position and initial fan speed for through-flat-pitch transient operation. Fan speed at transient completion, 100 percent; data source, Hamilton Standard (ref. 7).



(a) Through flat pitch.



(b) Through feather pitch.

Figure 24. - Typical traces of fan blade vibratory stress for forward- to reverse-thrust transients.

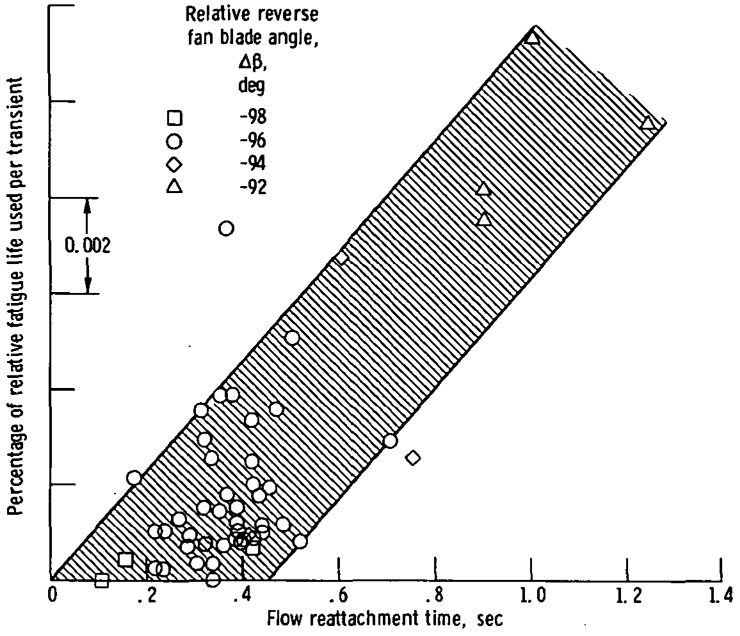


Figure 25. - Fan blade relative fatigue life as function of flow reattachment time.

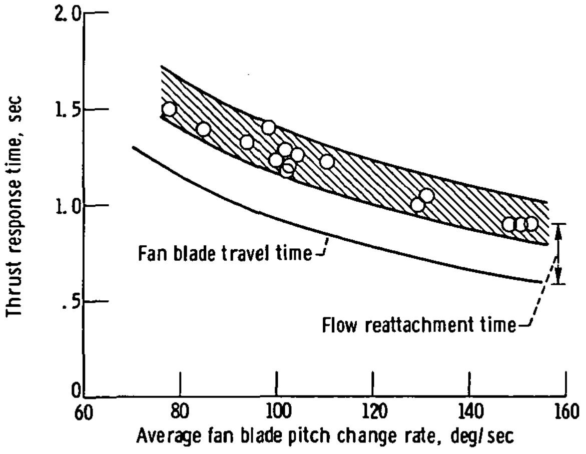


Figure 26. - Thrust response time as function of fan blade pitch change rate for aborted-takeoff transient (through-feather-pitch operation with zero delay time). Data source, Hamilton Standard (ref. 7).

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