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REVERSE-THRUST TECHNOLOGY FOR VARIABLE-PITCH FAN PROPULSION SYSTEMS

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SUMMARY

During the past several years, a number of tests have been conducted to develop the technology necessary to meet the unique reverse-thrust performance requirements of a variable-pitch fan propulsion system. Areas that have been investigated include the losses and distortion associated with the air entering the fan and core compressor from the rear of the engine, the direction of fan blade pitch rotation for best reverse-thrust aeroacoustic performance, and engine response and operating characteristics during forward- to reverse-thrust transients. The test results of several scale fan models as well as a full-size variable-pitch fan engine are summarized. More specifically, these tests have shown the following: A flared exhaust nozzle makes a good reverse-thrust inlet, acceptable core inlet duct recovery and distortion levels in reverse flow were demonstrated, adequate thrust levels were achieved, forward- to reverse-thrust response time achieved was better than the goal, thrust and noise levels strongly favor reverse through feather pitch, and finally, flight-type inlets make the establishment of reverse flow more difficult.

INTRODUCTION

The short field lengths envisioned for short-haul aircraft operation have made reverse-thrust performance a critical part of the propulsion system's design requirements. The conventional approach to providing reverse thrust in turbofan engines is to use target or cascade thrust reversers to redirect the engine exhaust flow in a forward direction. Considerable study in recent years has been directed toward an alternate approach to reverse thrust - the variable-pitch fan.

Noise requirements for short-haul aircraft dictate that a low pressure ratio, high bypass ratio fan be used especially for an under-the-wing engine installation. For such requirements, engines designed with variable-pitch fans for reverse thrust have been shown (refs. 1 and 2) to be superior to those with fixed pitch fans and conventional reversers. The primary advantage is lower propulsion system weight. An added benefit is faster response times in forward thrust which are important for approach waveoff maneuvers. The faster forward thrust response times are a result of a variable-pitch fan's ability to provide approach thrust at high fan speeds (ref. 1). Because of these advantages, a variable-pitch fan was incorporated in the under-the-wing engine of NASA's Quiet Clean Short-Haul Experimental Engine (QCSEE) Program.

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Obtaining reverse thrust with a variable-pitch fan engine involves a new mode of engine operation. In normal forward-thrust operation engine air enters the inlet, passes through the engine, and is exhausted out the rear as shown in the upper half of figure 1. In reverse thrust the fan blade pitch is changed so that the fan air flows in the opposite direction. Air must be drawn from the rear of the engine; the air is required to turn 180° from its original direction, as shown in the lower half of figure 1. Part of this air must turn nearly 180° again to supply the engine core. The rest of the air passes through the fan and is exhausted out the inlet. Requiring the air to follow this difficult path and operating the engine during the forward to reverse thrust transition raises a number of design questions:

(1) What nozzle shape is required to minimize the pressure losses and distortion in reverse thrust?

(2) Will pressure recovery and distortion levels into the core compressor be satisfactory?

(3) In which direction should the fan blade pitch be changed for adequate reverse-thrust levels?

(4) Can the forward to reverse-thrust transition be accomplished in the required time without engine operational problems?

(5) What effect will a flight-type inlet have on reverse-thrust operation?

A number of tests have been conducted over the past several years to answer these questions. The results of some of these investigations are discussed in this report to provide an overview of reverse-thrust technology for variable-pitch fan propulsion systems. To add perspective to the test results, the reverse-thrust requirements are discussed first.

REVERSE-THRUST REQUIREMENTS

Reverse-thrust regulations for short-haul aircraft have not been established. However, based on a number of aircraft systems studies, reverse-thrust objectives have been defined for QCSEE. They are compared to typical reverse thrust characteristics for conventional engines in table I. The reverse-thrust level for QCSEE, 35 percent of takeoff thrust, is required for landing on icy runways or in the event of brake failure (as described in ref. 3). Although the QCSEE objective falls on the low side of the range for conventional aircraft, the resulting aircraft deceleration is comparable to conventional aircraft because QCSEE is designed for an aircraft with a high thrust-weight ratio.

The forward- to reverse-response time objective, or time to reverse, for QCSEE is considerably more stringent than for conventional aircraft because of the short field operation. However, the time to reverse for conventional aircraft is longer mostly because of the time required to increase the engine speed from a near flight idle condition at the initiation of reverse thrust to the design reverse-thrust condition. Thus, some reverse thrust is being generated during most of that time.

Operating an engine in reverse thrust at low forward velocities can result in exhaust gas reingestion, foreign object damage from the reverse jet impinging on the ground, and the impingement of hot exhaust gases on aircraft structures. Because of this, reverse-thrust operation is usually prohibited below certain forward velocities. A comparison of the minimum forward-velocity limits (table I) shows that the QCSEE objective is more stringent than conventional aircraft, again because of the short field operation.

The importance of low noise in all phases of short-haul operation resulted in a reverse-thrust noise objective for QCSEE. For 108 400 newtons of reverse thrust a maximum noise level of 100 PNdB on a 152.4-meter sideline has been established.

AIR INTAKE CHARACTERISTICS

Exlet Performance

To assist the flow of air into the rear of the engine during reverse thrust, the fan nozzle can be opened to form a flared shape, called an "exlet," as shown in figure 1. A number of scale exlet models were tested (refs. 4 and 5) to determine what geometry results in the lowest total pressure loss and distortion level. The exlet configurations tested covered flare angles Θ from 0° to 60°, contraction ratios A_T/A_E from 1.4 to 2.8, and ducts with and without simulated acoustic splitters.

The results, along with geometric definitions, are summarized in figure 2 for freestream velocities V_∞ of 0 and 41.2 meters per second and a fan duct Mach number M_d of 0.4. The results indicate that a flare angle of 30° gave the highest pressure recovery. At flare angles other than 0°, the data fell in a relatively narrow band showing relative insensitivity to contraction ratio and the presence of an acoustic splitter. A flare angle of 0° represents a nozzle in a forward thrust position and would not normally be considered for reverse thrust operation except in the event of a nozzle actuator failure. In general, the exlet tests showed that the total pressure recovery was high when the sharp turn the flow must make around the exlet lip is considered. However, test data shown in figure 2 are for smooth axisymmetric exlets and constant fan duct Mach number. Therefore, the effects of differences in these characteristics should also be considered.

Exlet shapes with V notches which more accurately represent a variable area nozzle were also tested. These tests showed that for a configuration similar to the QCSEE nozzle the presence of notches would reduce recovery about 0.5 percent (ref. 5).

The fan duct Mach number has an effect on recovery, but to a lesser extent than the free-stream velocity (ref. 4). For example, changing the duct Mach number from 0.4 to 0.5 reduced recovery less than 0.5 percent.

Distortion levels in the fan duct were also measured. For the exlet geometries tested in reference 5 (except for the 0° flare), the distortion levels were less than 7 percent. Such levels were considered acceptable for an engine like QCSEE.

Core Inlet Duct Performance

Like the exlet, the core inlet duct offers a similar sharp turn for the air to negotiate. But in terms of pressure loss, this turn is more severe. The Mach number of the flow at the beginning of the turn is three or four times that for the exlet. Also, the flow must pass through the fan stators and, depending on the core inlet design, the core inlet guide vanes. The losses in the fan stators are expected to be low. However, these stators impart a swirl to the reverse flow which will result in an unfavorable incidence angle on the core inlet guide vanes. This in turn could result in more significant losses.

Core inlet recovery test data for two engine configurations are presented in figure 3 from tests described in reference 6 and from an unpublished investigation by J. W. Schaefer of Lewis Research Center. The first engine configuration shown in figure 3 is the full-size Q-fan T-55 engine and the second one shown is a scale model (50.8-cm fan diameter) of the QCSEE engine. Both sets of data show that core-inlet total pressure recovery is a function of fan duct Mach number.

The importance of core inlet recovery is shown by the core limit lines on this figure. These points are operating conditions where further increases in reverse thrust level cannot be achieved without exceeding a core operational limit. For the Q-fan T-55, the core operational limit is the compressor speed; for the QCSEE engine, the calculated core limit is the turbine inlet temperature.

The solid symbols in figure 3 show the point where the required reverse-thrust level is obtained. In both cases the core recovery is adequate to meet the required reverse-thrust level.

As can be seen from figure 3, both sets of data are adequately represented by the same loss coefficient line of 1.5, even though the core inlet duct configurations are different. The Q-fan T-55 splitter lip is more rounded than the sharp lip of the QCSEE model which would suggest higher losses for the QCSEE model. However, the core inlet guide vanes of the Q-fan T-55 are located in the core inlet duct and are subject to unfavorable incidence angles. The QCSEE core inlet guide vanes are external to the core duct which allows most of the core flow to bypass them in reverse thrust. Apparently, these configuration differences have offsetting effects which result in similar loss characteristics.

Distortion levels at the compressor face were also measured during the reverse-thrust tests of the Q-fan T-55 and QCSEE models (refs. 6 and 7). For the Q-fan T-55, the reverse-thrust distortion level (combined radial and circumferential) was about the same as for the forward-thrust level. This unexpected result may be partially attributed to the inlet guide vanes which are located in the core inlet duct. This location may help to make the core flow more uniform. Results of QCSEE scale model tests indicated the reverse-thrust distortion to be higher than in forward thrust but acceptable for full-scale engine operation.

FAN DESIGN AND OPERATION

A basic concern for 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 4. A cross section of two fan blades shown in their normal forward-thrust position is 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 of figure 4. 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 one at all radii. This 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 alternate approach is to turn the blades through feather pitch, passing through a stall condition. This is shown on the right side of figure 4. In this case, blade camber is correct in the reverse position, but the leading and trailing edges are reversed. During the transition the flow over the blades separates or stalls. The flow then reattaches in reverse thrust and moves in the opposite direction relative to the blade. With this approach the blade solidity may exceed one, although the blade twist and camber will still limit the hub solidity to some extent.

Thrust

To determine which approach is best, both steady-state reverse thrust performance and transient operating characteristics must be considered. A comparison of static reverse-thrust levels at nominal reverse-thrust blade angles is shown in figure 5. The data are from tests of the Q-fan T-55 and QCSEE scale model (unpublished Lewis data and ref. 6). Both tests were conducted with similar flight-type inlets. In all cases the reverse-thrust data are presented relative to the design takeoff thrust level. The design takeoff condition, however, was never achieved in tests of the Q-fan T-55 due to a core horsepower limitation. The fan was designed for a higher horsepower model of the T-55 than what was tested. This horsepower limited to some extent the maximum reverse thrust attained. Reverse-thrust levels for the Q-fan T-55 are direct force measurements while reverse-thrust levels for the QCSEE model are calculated from measured pressures and temperatures.

As shown in this figure, reverse-thrust levels exceeding the 35-percent goal can be achieved through feather pitch before reaching the core limiting conditions. By comparison, reverse-thrust levels through flat pitch are less than half of those through feather pitch and, even at the fan limits, are considerably less than the goal.

Noise

Noise is another factor to consider when deciding which way to change fan blade pitch for reverse thrust. Unsuppressed reverse-thrust noise level data (unpublished Lewis data) for the Q-fan T-55 are compared in figure 6. The noise data show that reverse through flat pitch is a considerably noisier way to achieve reverse thrust.

Transient Performance

The data that have been discussed so far have all been at steady-state conditions. Critical to which way blade pitch should be changed and to the whole issue of achieving reverse thrust with a variable-pitch fan engine is the performance of the engine during the forward- to reverse-thrust transition. Tests to determine transient performance have been conducted with the Q-fan T-55 both at Hamilton Standard and NASA Lewis test facilities (unpublished Lewis data and ref. 8). A photograph of this engine at NASA Lewis is shown in figure 7. The results of these tests are discussed by comparing a representative example of a through flat pitch and through feather pitch transient.

Considering first reverse through flat pitch transients, time histories for fan blade angle, thrust, fan speed, and fan blade stress are shown in figure 8 for a representative transition from a landing approach to a reverse-thrust condition, In this figure the transient is initiated at time equals zero. The blade pitch was changed at a rate of about 100° per second starting from the design angle in forward thrust and moving to the reverse angle, 80° in the flat pitch direction. The throttle was held constant in this transient. Thrust, presented as a percent of measured takeoff thrust, responds to the blade angle change and falls off smoothly. The final reverse-thrust level is reached in somewhat less than 1 second. The fan speed during this time accelerates quickly as the load in the fan blades is reduced. As the blade loading increases again in reverse thrust, the fan speed peaks and then converges on the final reverse-thrust value. Fan blade vibratory stresses gradually build up during the transient and reach a level slightly over twice that in forward thrust. This level is well within the limits of normal blade design.

The primary operational problem encountered in the reverse through flat pitch transients is that the fan tends to overspeed. There are two ways to help reduce this effect. First, the transient can be initiated at a reduced fan speed to allow more overspeed margin as was done in the example of figure This could reduce the engine's forward-thrust response time for waveoff manuevers. Second, starting from a higher initial fan speed, the fuel flow can initially be cut back in an attempt to reduce the available engine power while the fan blades pass through flat pitch. This requires careful control of the fan blade pitch and engine throttle during the transient to reach the reverse blade position with the fan speed at the desired level.

A somewhat different sequence of events occurs during a reverse through feather pitch transient which is shown in figure 9. The transient was initiated from the same approach thrust level as the transient in figure 8 but at a higher fan speed for better waveoff response capability. The fan blade pitch was changed, in the feather pitch direction, at about 130° per second. This change initially 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. The throttle in this case was immediately reset to the final reverse-thrust level. As the blade pitch continues to change, the fan eventually stalls and the thrust falls suddenly to zero. This unloads the blades to some degree and causes the fan speed to increase. Shortly after the blades reach their reverse position, the flow reattaches and reverse thrust is obtained. The final reverse-thrust level is reached about 1 second after the transient was initiated.

During the transient, the fan blade stresses build up and peak as the blade stalls. A second peak, generally somewhat higher than the first, occurs as flow reattaches to the blades in the reverse direction. These stress peaks, while high relative to forward-thrust levels, did not limit the transient tests of the Q-fan T-55. Even though these results are encouraging, further tests of higher pressure ratio variable-pitch fans, such as QCSEE, are needed before more general conclusions can be drawn.

INLET BACKPRESSURE

Tests of the Q-fan T-55, as well as the QCSEE scale model, showed that a flight-type inlet can produce a backpressure on the fan which tends to prevent the establishment of reverse flow. 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 transient through feather pitch. This effect can be explained by noting that when the fan is stalled, flow in the duct is primarily tangential and tends to rotate with the fan. When the fan is unstalled and producing reverse thrust, the flow is nearly axial. Photographs of tufts in the fan inlet in figure 10 show the stalled and unstalled flow fields.

In order for the swirling flow in the stalled condition to be exhausted out the smaller diameter throat of the inlet, the flow velocity 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 face is implied. The fan must, therefore, overcome this backpressure to clear stall. The magnitude of the backpressure will depend on the inlet geometry.

Test data showing this effect are presented in figure 11 for the Q-fan T-55 at a reverse through feather blade angle. Wall static pressures divided by ambient pressure are compared for a bellmouth and a flight-type inlet both in stalled and unstalled conditions for the same fan speed. Of primary interest is the static pressure at the fan face. As can be seen from figure 11, a higher pressure does exist with the flight-type inlet in a stalled condition. The nearly identical static pressures for the two configurations in the unstalled condition demonstrated that the inlet backpressure effect is due to more than just the one-dimensional difference in throat areas.

A technique to overcome the effect of inlet backpressure and promote quick establishment of reverse flow was demonstrated during reverse through feather transient tests of the Q-fan T-55 (unpublished Lewis data). With this technique, the fan blades are moved beyond the final reverse position, held there for a short period of time, and then returned. This temporarily reduces the angle of attack on the blades which allows reverse flow to be established. This technique was shown to be effective without increasing response time.

CONCLUDING REMARKS

The tests conducted to develop reverse-thrust technology for variable-pitch fan engines have done much to demonstrate the viability of this approach for powered-lift propulsion systems. More specifically, these tests have shown the following:

1. A flared exhaust nozzle is an acceptable reverse thrust inlet.
2. Acceptable core inlet duct recovery and distortion levels in reverse flow have been demonstrated.
3. Adequate reverse-thrust levels can be achieved.
4. Forward- to reverse-thrust response times better than the goal have been demonstrated without any significant operational problems.
5. Thrust and noise levels strongly favor reverse through feather pitch.
6. Flight-type inlets make the establishment of reverse flow more difficult, but moving the fan blades beyond their normal reverse thrust position for a short period of time was effective in overcoming inlet backpressure.

Areas where variable-pitch fan technology for reverse thrust needs to be expanded include the following:

1. Effect of forward velocity on the establishment of reverse flow especially with flight-type inlets
2. Fan blade stress levels for higher pressure fans during reverse through feather transients
3. Aircraft installation effects - flap-exlet interaction and reverse-jet ground impingement

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TABLE I. - REVERSE-THRUST REQUIREMENTS

	QCSEE objectives	Conventional engine characteristics
Reverse-thrust level, percent takeoff thrust	35	35 to 50
Time to reverse, sec	1.5	5 to 10
Minimum forward-velocity operating limit, m/sec	5.1	15 to 30
Noise (152.4 m sideline PNdB; reverse thrust, 108 400 N)	100	--------

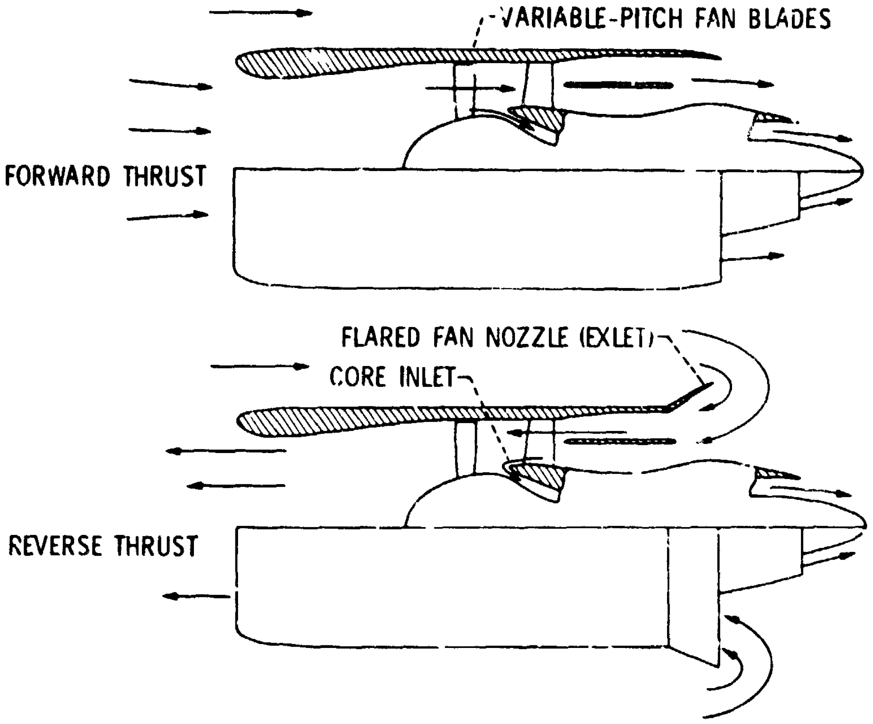

Figure 1.- Variable-pitch fan engine operation.

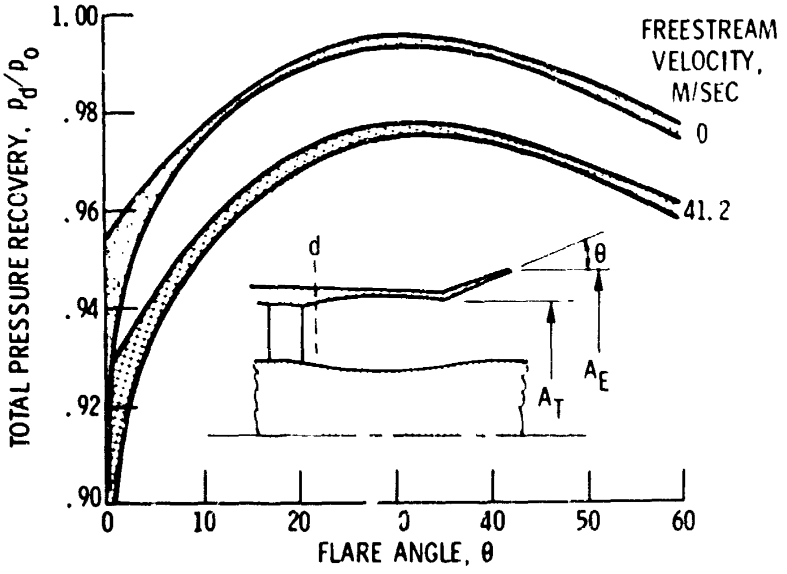

Figure 2.- Exlet performance. Fan duct Mach number, M_d, 0.4; contraction ratios, A_E/A_T, 1.4 to 2.8; p_d, duct total pressure; p_o, ambient pressure.

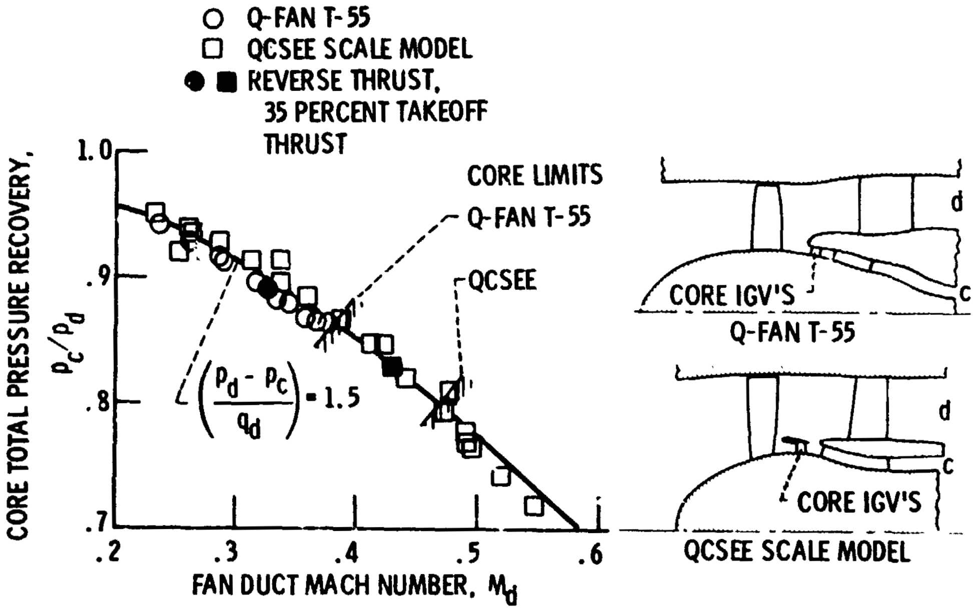

Figure 3.- Core inlet performance. p_c, core total pressure; p_d, duct total pressure; q_d, duct dynamic pressure.

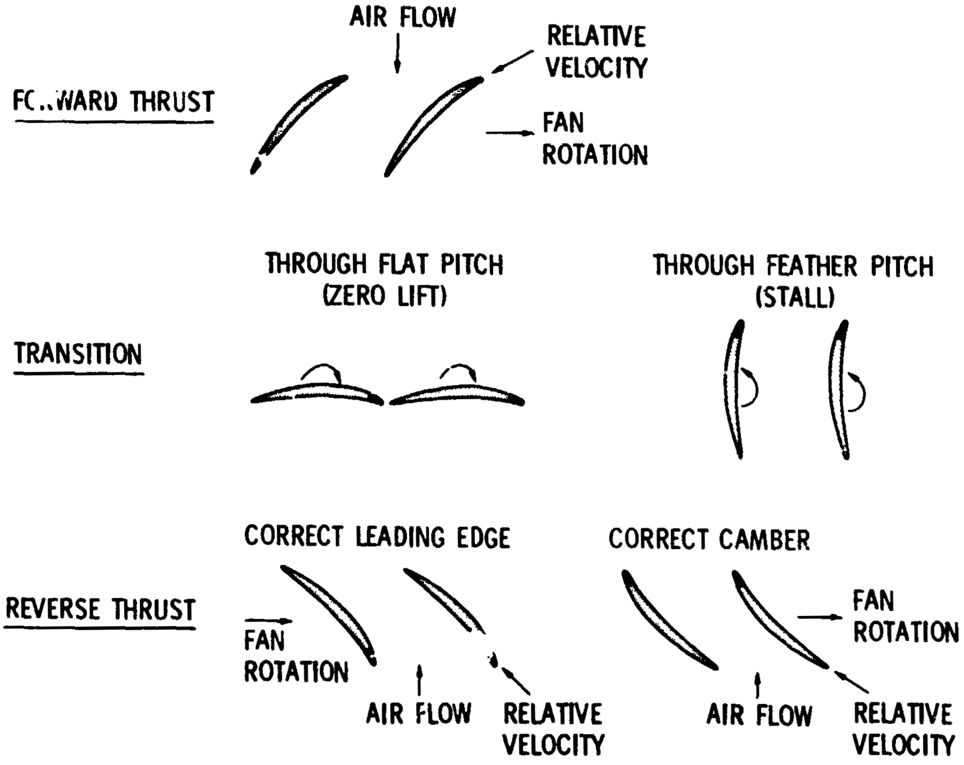

Figure 4.- Reverse pitch alternatives.

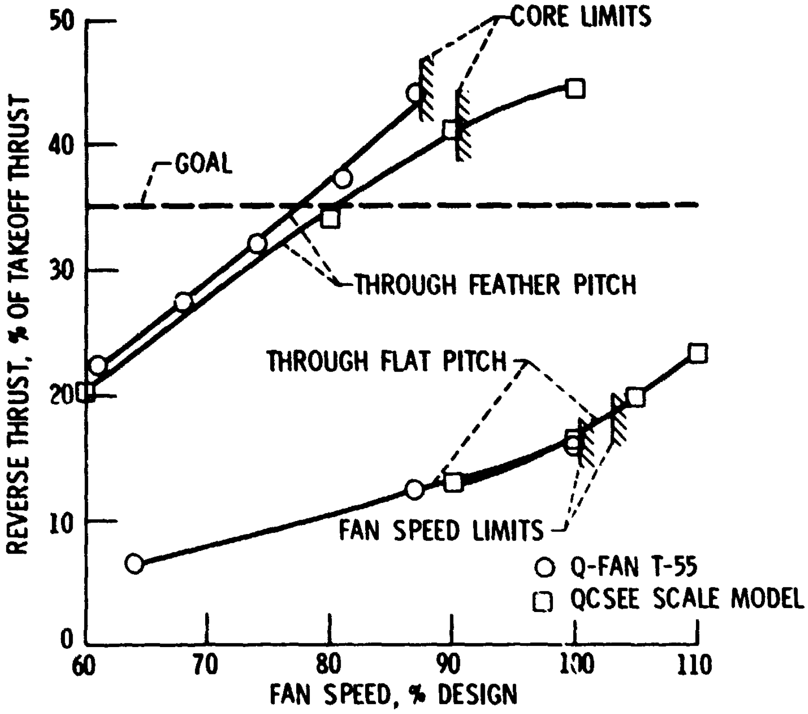

Figure 5.- Static reverse thrust.

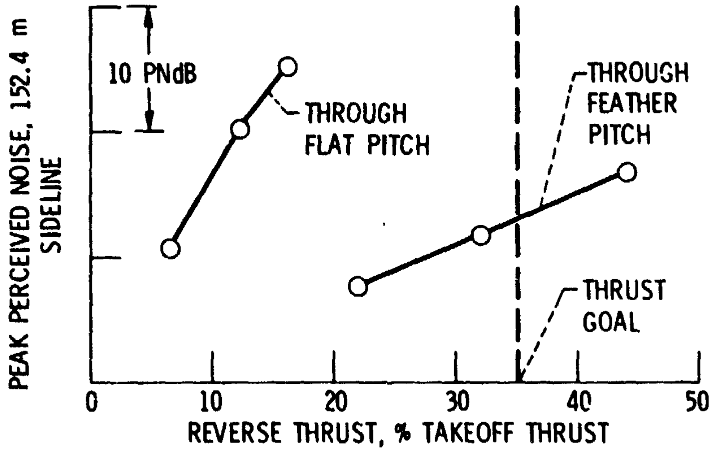

Figure 6.- Unsuppressed reverse-thrust noise for Q-fan T-55.

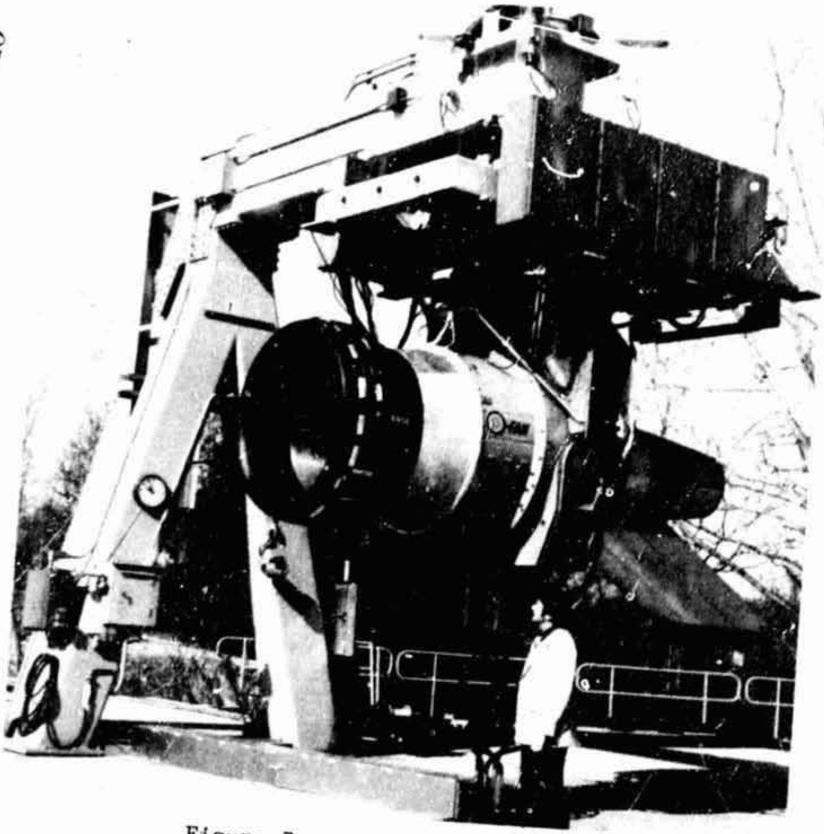

Figure 7.- Q-fan T-55 engine at NASA Lewis Research Center.

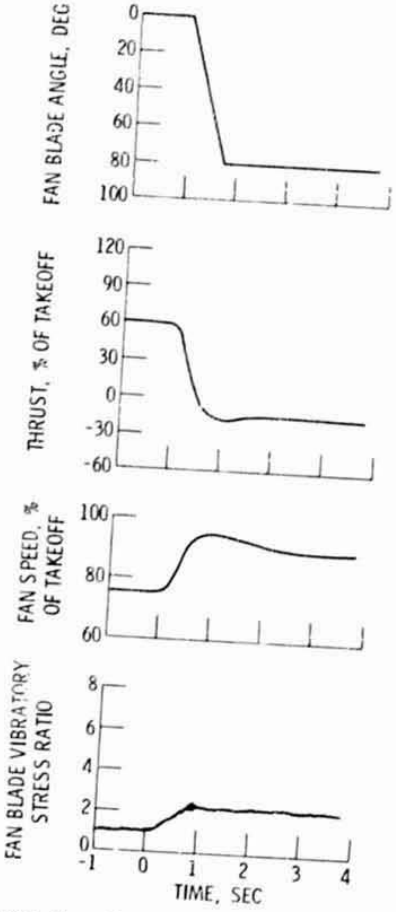

Figure 8.- Forward- to reverse-thrust transient through flat pitch.

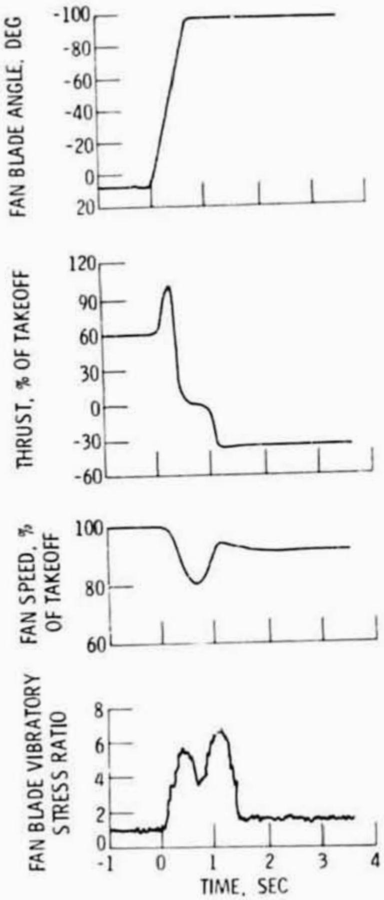

Figure 9.- Forward- to reverse-thrust transient through feather pitch.

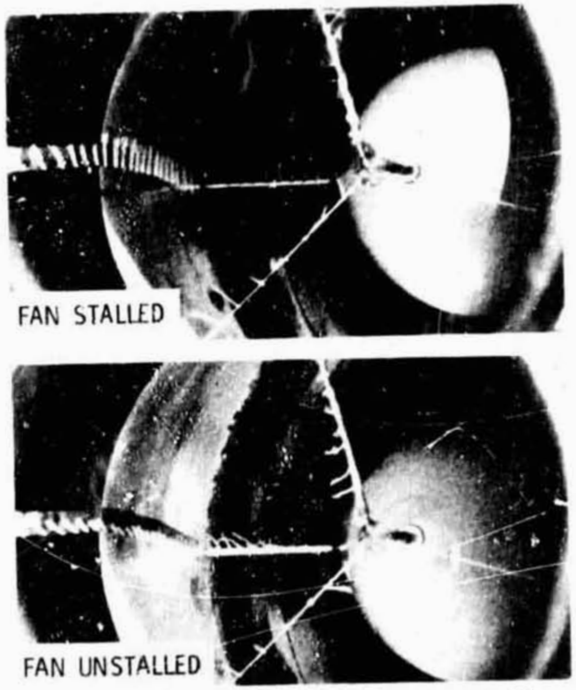

Figure 10.- Inlet reverse-thrust flow of Q-fan T-55 engine.

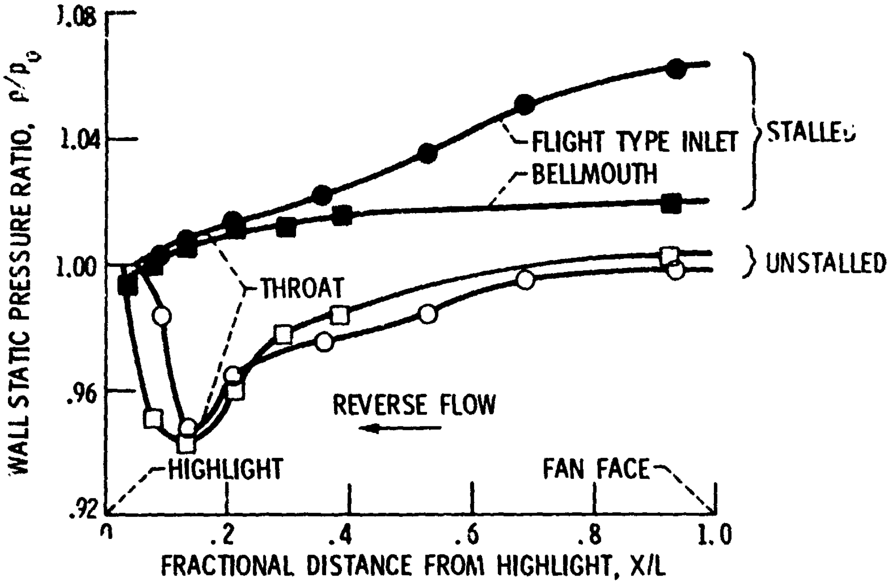

Figure 11.- Inlet backpressure of Q-fan T-55. Fan speed, 76 percent of takeoff; p, static pressure; p_0, ambient pressure; x, distance from inlet highlight; L, inlet length.