# Q-Fan Demonstrator Engine

R. M. Levintan*

*Hamilton Standard/United Technologies, Inc., Windsor Locks, Conn.*

**Design criteria as well as a general description are provided for the first full-scale variable pitch fan engine tested in this country. The test facility for this 6700 lb thrust engine is defined, and a summary of the test program is presented. Aerodynamic, acoustic, and structural data from the initial test phase are discussed. A ground adjustable mechanism was used to set fan blade angle for the first series of tests. A second test phase was conducted with a dynamic pitch change capability incorporated in the engine; the significance of reverse transient results are examined.**

A CONCENTRATED technology program was implemented by Hamilton Standard during the period 1969-1971. This activity focused on high by-pass, variable pitch fan engines. Acoustic and aerodynamic model testing formed the backbone of this program, complemented by the creation of new analytical methodology in these two basic disciplines. Installation studies, conceptual mechanical design, fan blade development, and control system synthesis received significant attention in this time period, as did evaluation of the potential benefits of the variable pitch fan engine for various vehicle applications.

A focal point for the technology base thus created was established in mid 1971. A definitive plan was formulated, having as its objective the design, fabrication, and test of a full-scale variable pitch fan engine. A key element of the plan was a wind-tunnel test of a one-third scale (18 in. diam) model of the engine. The model was configured with a dual flow path. Design of the model and full-scale system were initiated in June 1971. The model shown in Fig. 1 was tested in November of that year and provided experimental validation of critical design parameters for the full-scale design. Approximately 130 hours of wind-tunnel testing in both the positive and negative thrust regimes yielded the following results: a) verification of low-speed performance predictions; b) measurement of low-core flow distortion in positive and negative thrust; c) record of reverse "through feather" thrust values, more than double the levels obtained by reversing through "flat pitch"; and d) establishment of the feasibility of reverse through feather operation, made possible by aero/structural results.

Subsequent to completion of the model program, the design and fabrication of the full-scale unit was completed. Test stand and engine shake down was accomplished in September 1972, 15 months from inception. The effort up to that point had been a company funded enterprise; under a contract from NASA-Lewis, a formal test program was initiated in September and was completed in February 1973. During that period the fan blade angle was resettable, that is operation of the engine was conducted at a series of fixed blade angles covering a spectrum of both positive and negative thrust settings. A brief, but extremely significant period of transient testing was accomplished in the first half of 1973 following the incorporation of a dynamic pitch change system into the engine.

## Design Criteria

Two factors influenced the selection of the engine's design parameters: the first was availability from government inventory of a suitable shaft engine. This criteria resulted in a choice of the Lycoming T-55-L11 engine, rated at 3750 hp. The second factor was the establishment of a thrust rating that would be potentially applicable to the NASA Questol aircraft, under consideration at the time. The growth projection of the T-55 engine to 4600 hp was judged to be adequate to fulfill this objective. The fan system; i.e., fan stage, flow path, gearbox, etc. were sized to the parameters listed in Table 1 under the "Design" column. The maximusm test values achieved during the test program using the T-55-L11 engine obtained from the Army are also listed in Table 1.

Presented as Paper 73-1215 at the AIAA/SAE 9th Propulsion Conference, Las Vegas, Nevada, November 5-7, 1973; submitted December 20, 1973; revision received December 23, 1974.

Index category: Airbreathing Engine Testing.

*Chief of Preliminary Design.

## Engine Description

Figure 2 depicts the basic configuration of the engine as well as identifying its key elements. Fan diameter is 4.6 ft and the hub-to-tip ratio is 0.46. The fan stage consists of thirteen solid aluminum spar-fiberglass shell blades retained in a one-piece steel disk which incorporates the circular ball race blade retentions required for variable pitch. The disk, like the fan blade, was designed to flight weight criteria to facilitate a meaningful assessment of operating stresses and structural dynamics. The mechanical, ground adjustable pitch change mechanism provides simultaneous angle setting of all 13 fan blades by use of a single point adjustment and suitably located index markings; adjustment over a range of blade angles from

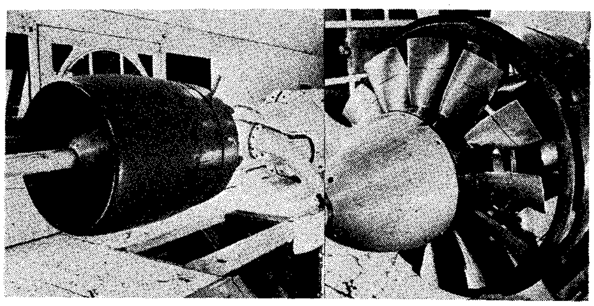

**Fig. 1 1/3-scale model (18 in. diam) fan.**

**Table 1 Engine parameters**

| | Design | Max. test value |
|---|---|---|
| Fan pressure ratio | 1.18 | 1.14 |
| Core engine SHP | 4600 | 3750 |
| Tip speed (fps) | 810 | 810 |
| Thrust (lb) | 8300 | 6700 |
| By-pass ratio | 17:1 | 15:1 |

−50° to +160° was possible with this system. The details of the fan blade/stator aerodynamic design are provided in Table 2. The fan stage was designed for a solidity of less than unity to permit reverse operation in both the "through feather" and "through flat pitch" modes.

A single stage star gear train having a 4.75:1 reduction ratio was used. The 100% output speed of the T-55 power turbine (16,000 rps) produces 3120 rpm at the fan. The gearing was taken from an existing gearbox and packaged in a new housing. The T55-L-11 engine is attached to the inner mounting ring by four solid mounts. A sheet metal cowling completely encloses the core engine to provide the proper aerodynamic contour. A dummy pylon simulates a normal installation as well as providing a path for routing services and instrumentation into the nacelle. Acoustic treatment is used in the core engine inlet to reduce compressor noise. The engine does not incorporate any acoustic treatment for suppression of fan noise. The engine installed on the test stand is shown in Fig. 3.

## Test Facility

The engine was mounted on a test stand designed and fabricated specifically for this program. The total engine package was mounted on a column which in turn was mounted atop a platform, resulting in the thrust axis being 20 ft from the ground. Trees and shrubs were removed to a radius of 200 ft to prevent undesirable acoustic reflections. Careful planning of the total installation produced an ideal acoustic test setup as well as one that was aerodynamically clean.

A 50 ft traveling boom was used to mount microphones and provided coverage from directly in front of the fan to 140° in the aft quadrant; sixteen automatic measuring stations were positioned within the arc. An anechoic platform was attached to the boom to eliminate acoustic ground reflections at the two microphones located at the 25 ft radius position on the boom. A microphone was also located at the 50 ft radius position on the boom. Both the 25 and 50 ft radius microphones were positioned 20 ft from the ground level with the engine thrust axis. There were a number of static microphones placed at various ground levels and at 20 ft vertical positions as well as several that were flush mounted in the outer fan duct wall. The test setup is displayed in Fig. 4. The control room is located 30 ft from the stand on the opposite side from the area of acoustic measurements; it is constructed below ground with only 5 ft protruding above ground level.

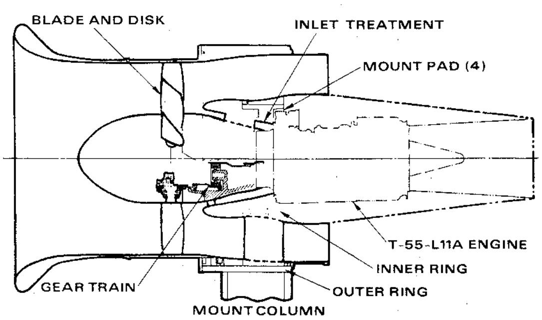


**Fig. 2 Engine configuration.**

**Table 2 Rotor/Stator aerodynamic definition**

| | Fan blades | Stators |
|---|---|---|
| No. blades/stators | 13 | 7 |
| Root aspect ratio | 2.23 | 2.11 |
| Airfoil | 65 series | 400 series |
| Root solidity | 0.85 | 0.76 |
| Taper ratio | 1.46 | 1.0 |

## Test Summary

The phase one test program is summarized in Table 3. The negative blade angle range tested corresponds to the "through feather" mode of reversing and was selected because of the high levels of reverse thrust measured in the scale model wind tunnel test. It was originally planned to acquire performance and noise data at fan blade angle settings representative of reversing through flat pitch as well; however, the added scope did not fit within program constraints. This area remains of interest and is planned for inclusion in a future effort.

A single test point is defined as operation of the engine at a specific combination of fan blade angle setting and rpm. A total of 125 data points were recorded. Identical test sequences were used for both the positive and reverse thrust portions of the program. Structural, performance, and core engine compatibility parameters were first evaluated for the planned test envelope in order to assure satisfactory operation as well as to establish engine performance. Once operational clearance was obtained, any instrumentation that might contribute to the noise signature was removed and the acoustic portion of the plan was executed.

## Instrumentation

Instrumentation was employed to monitor five basic areas of interest, acoustic signature, fan duct airflow, core engine airflow, blade, disk and stator stresses, and normal engine and gearbox operational parameters.

The aerodynamic instrumentation is shown in Figs. 5 and 6 for positive and reverse thrust testing, respectively. In addition, the location of strain gages on the blade, disk, and

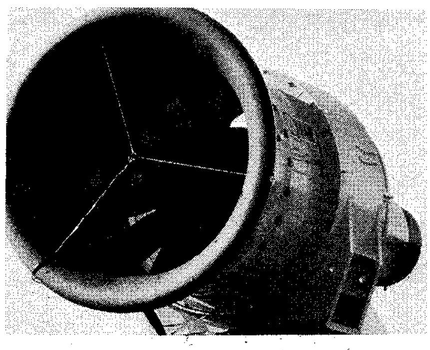

**Fig. 3 Q-Fan demonstrator engine.**

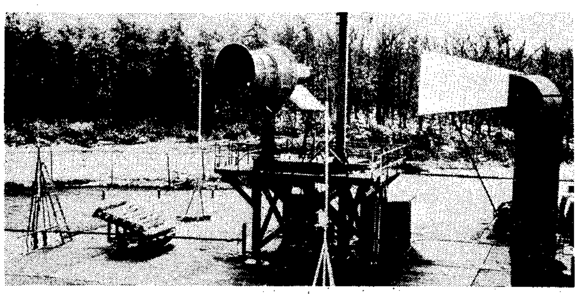

**Fig. 4 Test facility.**

**Table 3 Test summary**

| Scope | Variables | |
|---|---|---|
| 53 hr | Blade angle | |
| 125 Data points | Positive thrust | 33° → 60° |
| 99 Positive thrust | Reverse thrust | 138° → 150° |
| 26 Reverse thrust | Tip speed | 400°-810 fps |
| | Thrust | 1000-6700 lb |
| | Fan pressure ratio | 1.01 → 1.14 |

stators is depicted. Since the test stand did not incorporate a thrust meter, engine performance was computed from the probe measurements which were displayed on a manometer board and photographically recorded. The acoustic instrumentation was previously defined under the description of the test facility. One special provision made was the imbedding of four high frequency pressure transducers in the surface of two fan blades, as shown in Fig. 6. The purpose of this diagnostic instrumentation was to measure pressure fluctuations on the fan blade surface for correlation with acoustic measurements. Conventional instrumentation was used to monitor gas generator and gearbox operation.

## Test Results

Before discussing the more salient test results of the subject program it is appropriate to list the basic objectives that were established at the outset of the program: a) to establish a full-scale acoustic signature and compare it with predictions; b) to measure reverse noise levels; c) to verify favorable compressor face distortion characteristics projected from the scale model test, with emphasis on the reverse operation; d) to evaluate structural dynamics and stress levels of fan blades and disk; and e) compare aerodynamic data with the results of the 1/3-scale model test.

The emphasis was on obtaining basic powerplant operational characteristics in *full scale* with a "real" core engine. The use of fixed pitch fan blade angle settings permitted the systematic, carefully monitored exploration of the operational envelope without the influence of fan blade dynamic pitch change.

### Acoustic

A significant portion of the testing under NASA sponsorship was devoted to acoustics, the full details of which are covered in Ref. 1. In addition, a complete overview of Hamilton Standard's progress in acoustic technology is presented in Ref. 2. This discussion will be limited to a few of the more significant test results.

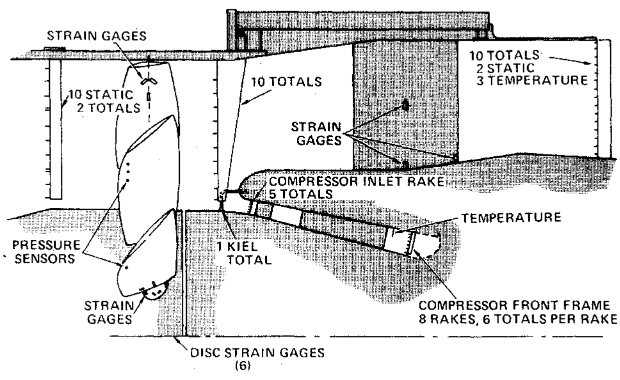


**Fig. 5 Forward thrust configuration.**

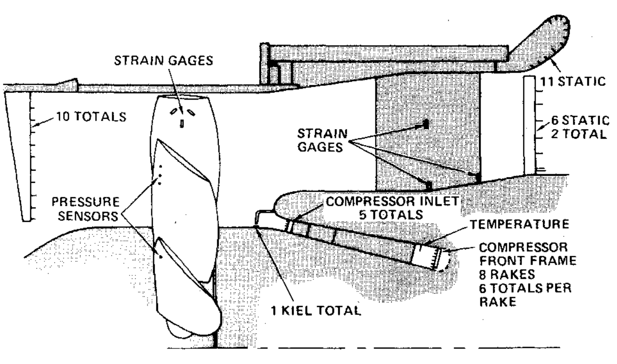


**Fig. 6 Reverse thrust configuration.**

Figure 7 is a plot of noise (PNdB @ 500 ft sideline) vs thrust over the range of tip speed and fan blade angles tested. It is apparent that blade angle and tip speed can be combined to produce minimum noise at a given thrust level. The potential, therefore, exists for selecting minimum noise points consistent with performance requirements for each portion of an aircraft operating envelope. This flexibility is one advantage of the variable pitch fan concept. Another characteristic of the data is that the minimum noise at a specific thrust value can be achieved over a rather wide range of tip speeds. In supersonic tip speed turbofans, sideline noise has been found to be front quadrant dominated. In the Q-Fan demonstrator engine, as in all of the Q-Fan's tested to date, an aft domination has been found. Noise peaks at about 120° from the inlet axis and typically exceeds inlet noise by 4 PNdB.

As expected, there is a significant shift in directivity as the Q-Fan moves from the forward to the reverse thrust mode. In reverse thrust, the noise is highest in the forward quadrant. Figure 8 is a comparison of reverse thrust noise with forward thrust noise. This figure shows the reverse thrust noise levels for a blade angle of 142° compared to the forward thrust noise levels for a blade angle of 56.8°. The variation in noise with tip speed is nearly equal for both forward and reverse thrust operation. The reverse thrust noise levels are, however, approximately 5 PNdb higher than those for forward thrust at the same tip speed and power. Percentages of maximum positive thrust are superimposed on both curves. The level of reverse thrust normally considered to be adequate is approximately 40% of maximum positive thrust; the reverse noise at that value would be approximately 2 PNdb below the maximum positive thrust noise level, indicating that variable pitch fans may produce a lower reverse noise signature than conventional turbofan thrust reversers.

Unlike the turbofan reverser, which places noise generating deflectors or spoilers in the fan and/or core engine flow path,

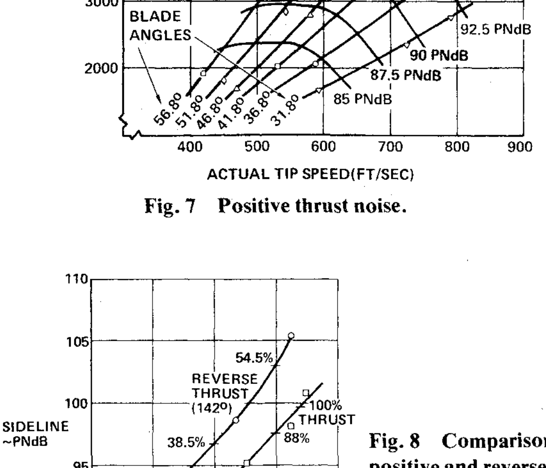


**Fig. 7 Positive thrust noise.**

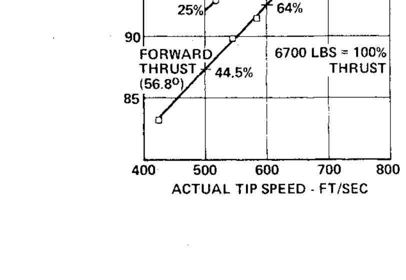


**Fig. 8 Comparison of positive and reverse thrust noise.**

a variable pitch fan simply reverses the airflow through the fan duct. As a consequence, the reverse thrust noise is similar in character to that of forward thrust noise; i.e., tones superimposed on a broad-band floor noise.

The noise values from Figs. 7 and 8 are generally 2 PNdb higher than free-field values due to the effects of ground reflection and engine core noise. With corrections to free field, the predicted overall noise was 97.9 PNdb while the measured value was 96-97 PNdb at 500 ft.

### Aerodynamics

For clarity of presentation the performance data will be subdivided and discussed in two parts, positive and reverse thrust.

#### Positive Thrust

As noted earlier, the engine test facility did not incorporate a thrust measuring system, therefore, the performance was established using the 98 total and static pressure measurements in conjunction with gas generator readout and calibration data. Very early in the test program it was established that the total pressure readings from the rake directly aft of the fan were incorrect. The pressures recorded at this rake were lower than the fan duct exit values; moreover, the readings at the rake station closest to the spinner were lower than the single kiel probe installed on the spinner afterbody immediately downstream of the fan. The disparity was attributed to the inflow angle to the rake exceeding its angular tolerance limit. The data from this rake was, therefore, not used in computing positive thrust performance.

Normal procedures were followed to insure consistent, accurate, and repeatable data. Repeatability of test points showed a variation of pressure readings of less than 1% on an absolute basis. All values of fan/duct thrust displayed in this paper do not include primary core thrust which was 260 lb at the maximum thrust setting.

The variation of fan duct thrust with corrected tip speed and blade angle is shown in Fig. 9. The thrust values were derived from the fan duct exit pressure measurements. The data follows well ordered trends with blade angle and corrected speed. Figure 9 highlights one of the basic advantages of the variable pitch fan. There are many combinations of fan blade angle and speed which can be selected to produce a desired thrust level; the selection can be used to optimize thrust specific fuel consumption or as noted above to minimize noise, or to insure rapid thrust response as in the case of approach. The thrust varies as approximately the 2.28 power of the corrected speed. Total measured engine airflow is shown in Fig. 10 based on both inlet and exit rake measurements; the exit rake values include core engine flow. The comparison with the predicted flow shows excellent agreement.

The distortion at the compressor face is shown in Fig. 11. The distortion plotted is defined as the maximum minus the minimum total pressure over the average total pressure at the compressor face. The maximum and minimum total pressure do not necessarily occur at the same azimuthal location. Therefore, the distortion shown in this plot is more severe than that which could be considered for pure radial distortion. All of the measured values are well below the distortion limit of 0.07 defined by Lycoming. The maximum and minimum total pressure did not occur at the same azimuthal station. In general, there is no set pattern to the pressure variation; i.e., the minimums do not correspond to the locations of support struts or other disturbances in the stream. In general, the measured performance agreed very closely with predicted levels as well as agreeing with the data from the 1/3-scale model test. An example of the agreement with prediction is shown in Fig. 12.

#### Reverse Thrust

There were two basic performance questions to be answered for reverse operation; what level of reverse thrust was achievable and what were the distortion levels at the core engine inlet. The reverse thrust performance testing was con-

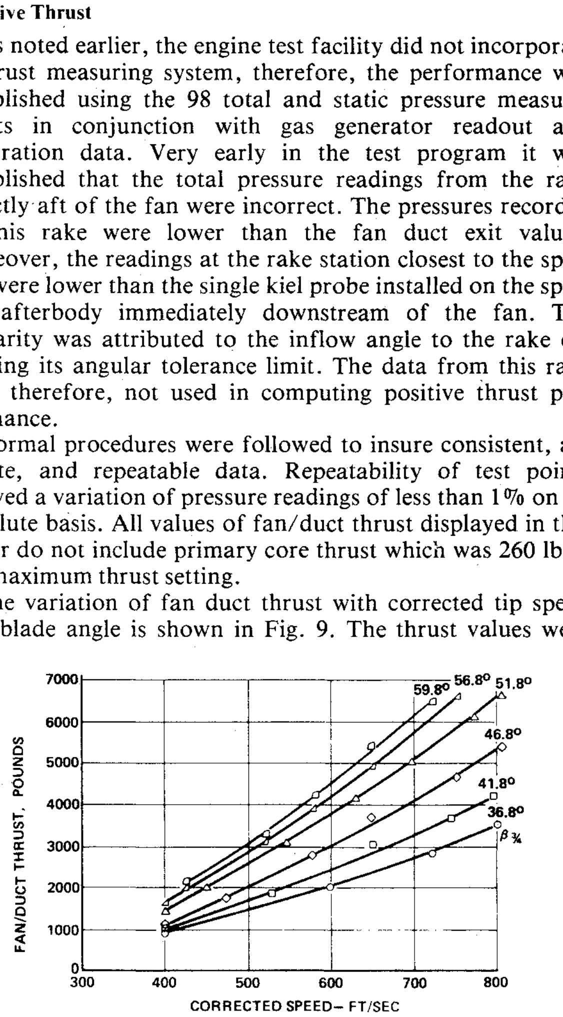


**Fig. 9 Variation of positive thrust with blade angle and tip speed.**

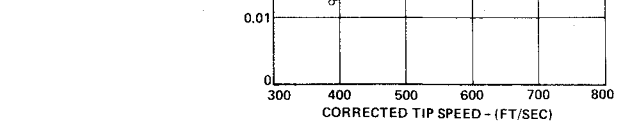


**Fig. 11 Compressor face distortion—positive thrust.**

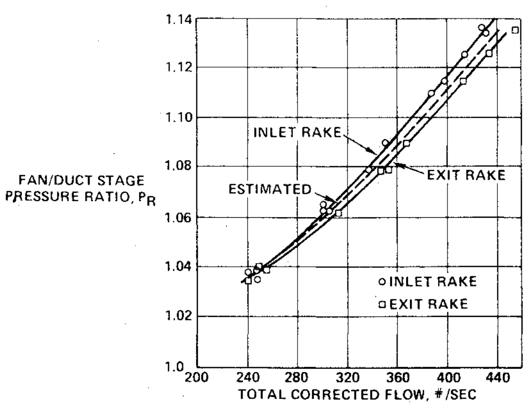


**Fig. 10 Static load line.**

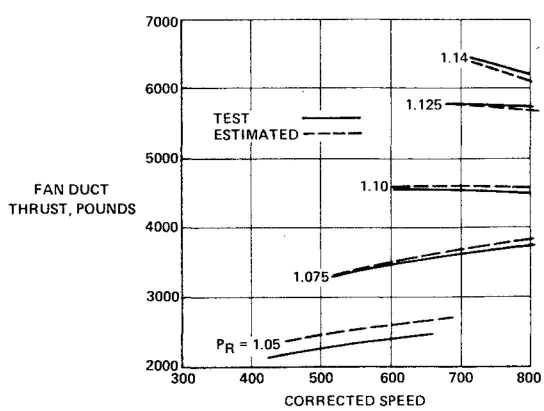


**Fig. 12 Comparison of calculated and measured performance.**

ducted using fixed rake instrumentation to measure the flow ahead of and behind the rotor. Since the flow must pass through the duct stators before it reaches the rotor, it is difficult to accurately define the magnitude and direction of the flow through the rotor and it was necessary to position the fan exit rake based on an estimated flow direction. Based on these airflow measurements, reverse thrust was estimated to be 63%. By comparison the 1/3-scale model yielded a 65% level of reverse thrust for reverse through feather operation, (140-150° fan blade angle range).

A bellmouth nozzle, as depicted in Fig. 6, was used for this initial demonstration of reverse operation as a cautious entry into this portion of the test envelope. It is significant that testing of the 1/3-scale model demonstrated essentially no difference in thrust levels or in compressor face distortion levels in reverse with either a bellmouth or a sharp edged nozzle. The reverse thrust test envelope is shown in Fig. 13. The thrust curve for the positive angle of 56.8° is displayed for reference purposes. As in the case of forward thrust, power absorbed varied as the cube of corrected speed.

Compressor face distortion measured during reverse testing is shown in Fig. 14. As in the case of forward thrust testing, the distortion presented is the maximum minus the minimum divided by the average total pressure at the compressor face, regardless of the azimuthal angle at which the maximum and minimum total pressures occur. The distortion patterns in reverse were similar to the patterns measured for positive thrust blade angles. The distortion levels are low, no more severe than those measured during the forward thrust testing, as indicated by the dash line on Fig. 14. The distortion measurements shown on Figs. 11 and 14, for positive and reverse thrust, are well within the maximum value of 0.07 defined by Lycoming. The average total pressure at the compressor face was below the ambient total pressure. This was true for all test points where high reverse thrust was indicated, resulting from the engine requirement to draw air from the rear of the duct through the stators and into the engine inlet flow path with accompanying high losses. However, this lower than ambient pressure had no effect on engine operation, except to reduce available power.

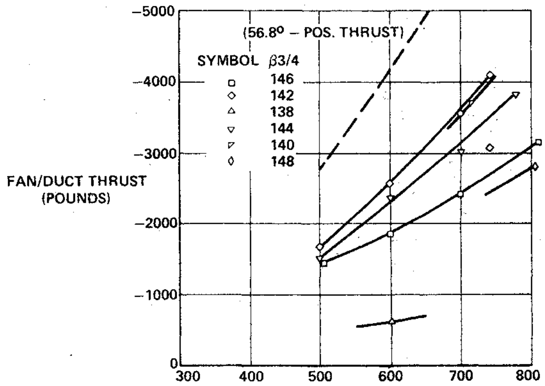


**Fig. 13 Variation of fan/duct reverse thrust with corrected tip speed.**

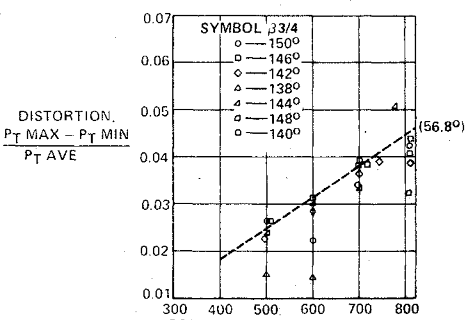


**Fig. 14 Compressor face distortion—reverse thrust.**

#### Structural

One of the purposes of the demonstrator test program was to provide stress data for key structural parts of a full-scale Q-Fan. As described above, the instrumentation for this testing included strain gages on the blades, barrel, and exit guide vanes, plus vibratory motion pickups at various locations on the nonrotating structure. Of the data obtained with this instrumentation, the most significant is that from the blade strain gages.

For all conditions, in both the positive and reverse blade angle range (testing was not conducted at intermediate angles), all stresses were well within predetermined allowable levels and there was no evidence of any flutter. The general character of the blade vibratory stress data was normal.

#### Transient Testing

The initial test program described above, conducted under NASA sponsorship, evaluated two blade angle ranges; positive thrust angles between 35° and 60° as well as the reverse range of 138-150° associated with reverse "through feather." Intermediate angles were not investigated.

Subsequent to this work and prior to incorporation of a pitch change mechanism, a series of test runs were made to assess fan blade stressing at the intermediate angles. The test procedure employed was to set a blade angle and increase power and consequently rotational speed in small step increments while monitoring fan blade stress levels. It was recognized that the resultant steady-state flowfield was not representative of the transient condition wherein the blades would pass rapidly through this intermediate blade angle range in traversing from the positive to negative thrust positions. However, it was thought that the results would provide an indication of fan blade structural dynamics particularly in the vicinity of stall. Test results, in fact, indicated that vibratory stresses were higher than the endurance limit of the blade at certain blade angles and rpm values. The higher levels were due to the appearance of bending flutter over a small portion of the test spectrum near stall.

At this juncture in the program, a pitch change mechanism

**Table 4 Transient test summary**

| | |
|---|---|
| No. of data points | 45 hr |
| Test time | 5 hr |
| Maximum pitch change rate | 170°/sec |
| Maximum initial condition | |
| Fan RPM | 92% |
| Engine thrust | 60% |

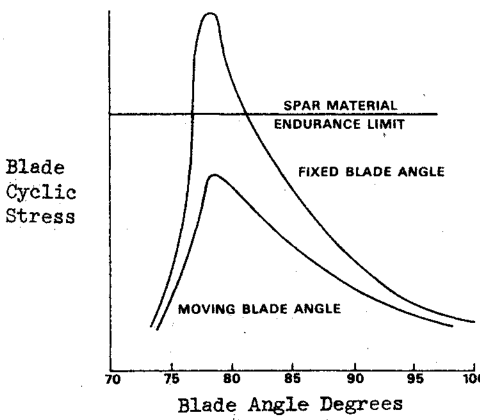


**Fig. 15 Reverse transient blade stresses.**

was added to the engine in order to conduct reverse transients representative of an operational variable pitch fan engine. An existing propeller hydraulic pitch change mechanism was utilized and was powered from a remote hydraulic source. A maximum pitch capability of 200° /sec was built into the system. Blade pitch change is accomplished by an electrical signal, which will permit its tie-in to a digital control system at a later date. Testing was conducted using the same instrumentation as during the earlier fixed blade angle investigations with the added provisions required to record transient values of fan blade angle, fan speed, and engine torque.

The test procedure employed was based on a noncoordinated pitch change and power level schedule; i.e., these two basic parameters were independently variable. A low-power thrust setting was initially set with a blade angle corresponding to a low rpm value. The fan blade angle was then commanded to rotate to full reverse, fuel flow being maintained constant throughout the blade angle excursion. The initial rpm and power settings were then incrementally raised. The test effort is summarized in Table 4.

The results of this initial exploration were rather remarkable. Fan blade stresses during the reversing transient were significantly reduced from steady-state values as shown in Fig. 15 and there was no indication of any flutter. At the maximum pitch change rates tested, the complete reverse transient was accomplished in 1 sec. That was the time required for transition from the steady state positive thrust setting to a fully stabilized reverse thrust condition. Operation of the engine was entirely normal throughout the test period. Tufts on both the fan inlet and nozzle provided visual evidence of the almost instantaneous flow reversal that occurred during the transient.

## Summary

Almost 80 hr of engine test time have yielded significant results, the more significant of which are: 1) Core engine inlet distortion was found to be well within allowable limits throughout the test envelope. Of particular significance was the very low distortion levels in reverse operation. 2) Overall engine performance was "as predicted"; in addition, test data confirmed the results of the 1/3-scale model test. 3) Reversing "through feather" yielded a reverse thrust level equivalent to 63% of maximum positive thrust. By comparison, the 1/3 scale model yielded a 65% value. 4) One second reversals were demonstrated. 5) All positive and reverse thrust operation and reverse thrust transient operation yielded low vibratory stresses in the fan blade and disk, well within endurance limits. 6) The overall fan PNL was 1-2 PN-db less than predicted. 7) A comparison of positive and reverse thrust noise indicates that it may be possible to provide adequate reverse thrust with a variable pitch fan at a noise level that is less than takeoff noise.

Although the technical progress reflected in this paper is an impressive beginning, much remains to be done. It is true, however, that the progress being made in this country as well as overseas bodes well for the future of the concept. Plans for the Q-Fan demonstrator engine call for its further use to significantly expand the technology base.

## References

[1]Demers, W.J., Metzger, F.B., Smith, L.W., and Wainauski, H.S., "Testing of the Hamilton Standard Q-Fan™ Demonstrator," CR-121265, March 1973, NASA.

[2]Metzger, F.B., "Progress in Source Noise Suppression of Subsonic Tip Speed Fans," AIAA Paper 73-1032, Seattle, Wash., 1973.