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Zero-Length Slotted-Lip Inlet for Subsonic Military Aircraft

E. R. Glasgow* and W. E. Beck†
Lockheed-California Company, Burbank, Calif.
and
R. R. Woollett‡
NASA Lewis Research Center, Cleveland, Ohio

Zero-length, slotted-lip inlet performance and associated fan-blade stresses were determined during model tests using a 20-in.-diam fan simulator in the NASA-LeRC 9- × 15-ft low-speed wind tunnel. The model configuration variables consisted of inlet contraction ratio, slot width, circumferential extent of slot fillers, and length of a constant area section between the inlet throat and fan face. Inlet configurations having contraction ratios of 1.2 and 1.3 satisfied all critical low-speed inlet operating requirements for a fixed horizontal nacelle and tilt-nacelle-type subsonic V/STOL aircraft, respectively. Relative to a conventional axisymmetric tilt-nacelle inlet, the zero-length, slotted-lip inlet has a 27% smaller inlet lip contraction ratio, an 83% shorter total length, and a 5% smaller maximum cowl diameter.

Nomenclature

CR = inlet lip area contraction ratio, $(R_{HL}/R_T)^2$
L_D = inlet diffuser axial length
L_{FB} = inlet external forebody axial length
L_L = inlet lip axial length
L_T = inlet total axial length, $L_L + L_D$
M_F = fan face Mach number
M_0 = freestream Mach number
M_T = inlet throat Mach number
N = fan speed
$N/\sqrt{\theta}$ = corrected fan speed, $N/\sqrt{T_{T_F}/518.69}$
NDI = fan flow distortion index
P = static pressure
P_T = total pressure
P_{T_F} = fan face total pressure
P_{T_0} = freestream total pressure
R = radius
R_F = fan tip radius
R_{FC} = fan case radius
R_H = fan face hub radius
R_{HL} = inlet highlight radius
R_{MX} = maximum cowl radius
R_T = inlet throat radius
T_{T_F} = fan face total temperature
X = inlet axial coordinate
α = angle of attack
θ = circumferential position from windward meridian
θ_W = inlet diffuser half-wall angle
σ = fan-blade vibratory stress

Subscripts

max = maximum
min = minimum

Conversion Factors

in. = 0.0254 m
kT = 667 M_0
m/s = 1.9439 kT

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*Department Manager. Member AIAA.
†Group Engineer.
‡Aerospace Engineer.

Introduction

It is necessary to design subsonic engine air inlets to have low cruise drag and to provide flow with low total pressure loss and low distortion. For many advanced aircraft concepts, such as a subsonic V/STOL aircraft, this task is more complex and significant than it has been for previous aircraft since the inlet must perform efficiently over a wider range of operating conditions. For a subsonic V/STOL aircraft, for example, the inlet must be capable of operating 1) in high crosswinds during hover and very low forward speeds; 2) at relatively high angles of attack during transition from vertical to horizontal flight and vice versa, especially for tilt-nacelle concepts; 3) with large upwash from the forebody/wing flowfield during aircraft high-lift operation; and 4) with low drag during high-speed cruise where the mass flow ratio is relatively low since the thrust required by the aircraft is approximately half that available from the engines.

The task of designing a subsonic inlet for advanced aircraft concepts is particularly challenging since it is also desirable that the inlet be of minimum length. Decreasing the inlet length has the beneficial effect of reducing inlet weight, decreasing the moment arm associated with the inlet ram force during crosswind conditions, and of improving pilot visibility in the side/aft directions for fixed-nacelle applications. These first two benefits are particularly significant for a V/STOL aircraft since they directly affect the size of the propulsion system.

If a conventional subsonic inlet design approach is employed, a relatively long diffuser (inlet section from throat to fan face) is required to prevent internal flow separation. This length of diffuser is a function of the throat-to-engine-face-area ratio and the maximum internal wall angle for which the flow will remain attached (with some margin). Increasing the throat area allows a reduction in diffuser length; however, if the inlet lip contraction ratio (highlight-to-throat area) is reduced to compensate for this area, the tolerance of the inlet to static-crosswind and low-speed angle-of-attack conditions will be degraded. Also, the favorable forebody lip suction force at cruise conditions will decrease if the maximum-to-highlight-area ratio is reduced, and the nacelle friction and aftbody boattail drag will increase if the maximum diameter is increased. The challenge thus becomes that of designing short, thin inlets without sacrificing overall inlet performance.

Several approaches to designing short, thin inlets for separation-free operation at low speeds have appeared in recent years, including V/STOL inlets with and without boundary layer control. Of all the inlets tested, only the slotted-lip inlet has provided any significant reduction in inlet length relative to that of a conventional axisymmetric inlet. In fact, the slotted-lip inlet has no diffuser, and thus is identified as having "zero length."

The purpose of this paper is to present experimental results for a zero-length, slotted-lip inlet, as determined during model tests using a 20-in.-diam fan simulator in the NASA LeRC 9- × 15-ft low-speed wind tunnel. This test, which is described in greater detail in Ref. 1, was initiated to determine the suitability of such an inlet for advanced subsonic aircraft, especially military aircraft where the minimum inlet length is not constrained by acoustic treatment considerations. Only inlet models having contraction ratios suitable for V/STOL applications were tested. Model and flight test data already exist for transport applications since zero-length, slotted-lip inlets are installed on the Lockheed C-141, as described in Ref. 2.

Concept Description and Application

The zero-length, slotted-lip inlet concept and associated overall geometric design parameters are illustrated in Fig. 1. Also shown for comparison is a schematic of a conventional axisymmetric inlet. Both inlets have been designed to satisfy the operating requirements for a subsonic tilt-nacelle-type V/STOL aircraft. Relative to the conventional inlet, the zero-length, slotted-lip inlet has a 27% smaller inlet lip contraction ratio, an 83% shorter total length (inlet lip plus diffuser) and a 5% smaller maximum cowl diameter.

The zero-length, slotted-lip inlet is axisymmetric, has the throat located at the fan face and consists of a single cowl lip, single slat which encompasses the entire circumference, slat support struts, and a series of spring loaded blow-in doors. The struts support the slat in a fixed position ahead of the cowl lip such that a slot forms between the two components. The blow-in doors, which are hinge mounted to the cowl, expose the slot when opened inward and seal the slot when closed. Also, when closed, the external surface of the blow-in doors serves as a part of the inlet forebody. The aerodynamic forces on the inlet are such that the blow-in doors open automatically at static and low forward speeds and close automatically at high speeds.

The surface loading required to turn the flow into the inlet is reduced when using a slotted-lip approach. This approach results in lower peak surface Mach numbers and a corresponding decrease in the probability of boundary layer separation. The reduction in loading and separation probability is due primarily to having increased cowl-lip surface area, three thin boundary layers (cowl lip and inner and outer slat) rather than one relatively thick (cowl) boundary layer, and the following beneficial flow interaction effects. The flow passing through the slot and entering the main inlet stream just ahead of the inlet throat will effectively increase the inlet slat contraction ratio. Also, the external flow around the slat will help the flow through the slot turn towards the fan. Furthermore, the fan enhances the overall flow-turning process owing to its pumping characteristics and location near the cowl lip.

The inlet lip contraction ratios for the slat and cowl must be designed to be sufficiently large so that flow separation does not occur at the most critical low-speed operating condition. The effect of inlet lip contraction ratio on the maximum angle of attack for separation-free flow is shown in Fig. 2 for several different types of inlets.

For a conventional axisymmetric inlet, the limit line shown in Fig. 2 identifies the angle-of-attack conditions where separation just starts in the diffuser near the fan face. By increasing the angle of attack beyond the limit, the separation location moves forward in the inlet and the fan-blade stresses become progressively larger. Generally, the growth of the separated region within the diffuser is such that a significant portion of the fan is affected when the separation location reaches the vicinity of the inlet lip. For this situation, the movement of the separation location is often uncontrolled and the fan-blade stresses are unacceptably large.

For zero-length, unslotted-lip inlets, the limit line corresponds to angle-of-attack conditions where the flow just separates from the cowl lip. Unlike the conventional inlet, the separated region has little length in which to grow, and thus has little initial effect on fan blade stresses. The limit line for the zero-length, unslotted-lip inlet is higher than that for the conventional inlet, as shown in Fig. 2, since the flow separation is lip induced for the former and diffuser induced for the latter.

A further increase in separation angle of attack can be achieved by inserting a slot in the zero-length inlet cowl, as indicated in Fig. 2. The data shown for the zero-length, slotted-lip inlet were obtained only from those configurations for which the separation limits had been fully explored during the Ref. 1 test. Actually, these data are conservative since configurations having more optimum slot gap heights were tested which still were not separated at angles of attack higher than those associated with the limit line. Data for these more optimum configurations will be presented later in this paper.

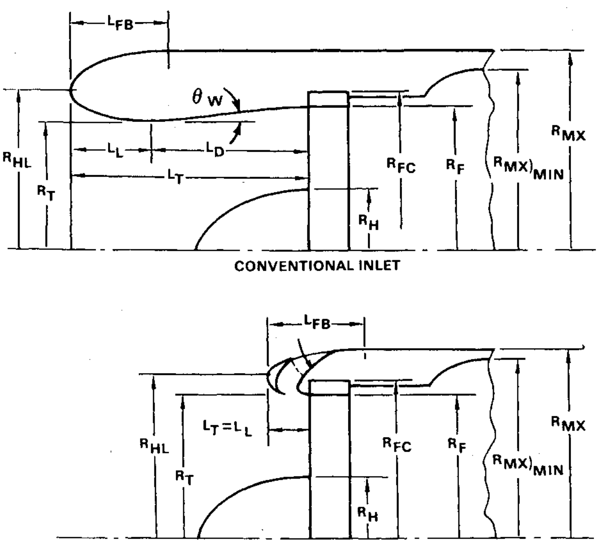

Fig. 1 Zero-length slotted-lip inlet concept.

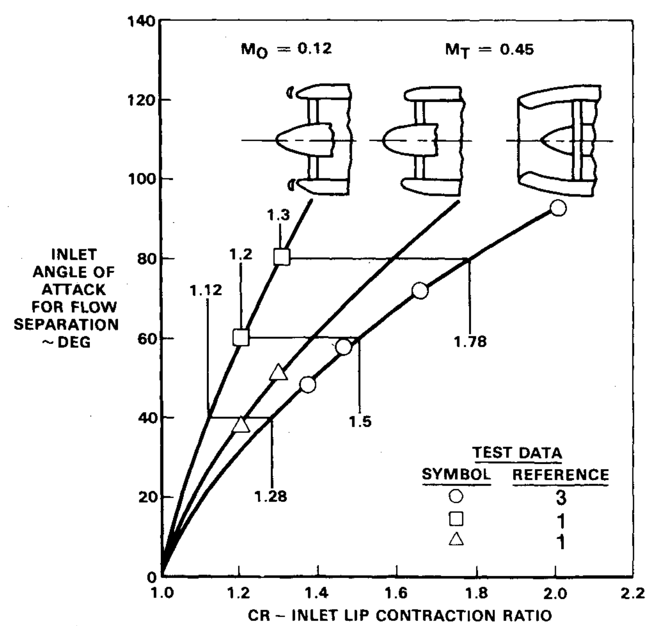

Fig. 2 Effect of slot and diffuser length on inlet lip contraction ratio.

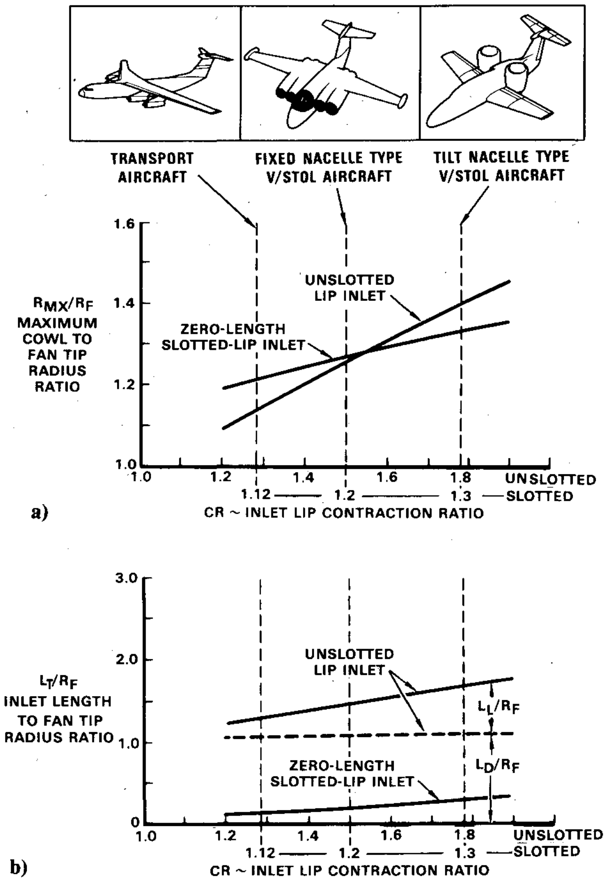

Fig. 3 Zero-length slotted-lip inlet applications. a) Maximum cowl radius effects. b) Inlet length effects.

It is evident from Fig. 2 that the inlet lip contraction ratio required for a given separation angle of attack becomes progressively smaller in going from a conventional inlet to a zero-length, unslotted-lip inlet and then to a zero-length, slotted-lip inlet. Also, the percentage reduction in inlet lip contraction ratio increases with increasing contraction ratio. The suitability of the zero-length, slotted-lip inlet over a more conventional inlet depends to a large extent on the degree by which the contraction ratio reduction compensates for the required throat-area increase, as reflected by the maximum cowl diameter differential.

Zero-length, slotted-lip inlets are suitable for most subsonic military aircraft applications, especially those where large inlet lip contraction ratios are required. This is illustrated in Fig. 3 by comparing at various inlet lip contraction ratios the maximum cowl radius and inlet length (referenced to the fan tip radius) of zero-length, slotted-lip inlets with the corresponding values for conventional axisymmetric inlets. For a tilt-nacelle-type V/STOL aircraft, such as that described in Ref. 4, significant benefits in both maximum cowl radius and inlet length are obtained when using a zero-length, slotted-lip inlet. Also, for a fixed-nacelle-type V/STOL aircraft, such as that described in Ref. 5, a sizable reduction in inlet length can be obtained without adversely affecting the maximum cowl radius.

For a transport aircraft, the percent reduction in contraction ratio in going from a conventional inlet to a zero-length, slotted-lip inlet is not sufficient to compensate for the required increase in throat area. As a result, a penalty in maximum cowl radius exists which must be weighed against the benefit in inlet length reduction. This penalty did not materialize for the C-141 transport, however, since the maximum cowl radius required to accommodate the engine envelope was very nearly the same as that needed to satisfy the aerodynamic requirements for the zero-length, slotted-lip inlet. Thus, by deciding to install zero-length slotted-lip inlets on the C-141, a reduction in inlet length and weight was achieved without having to compromise the maximum cowl radius.

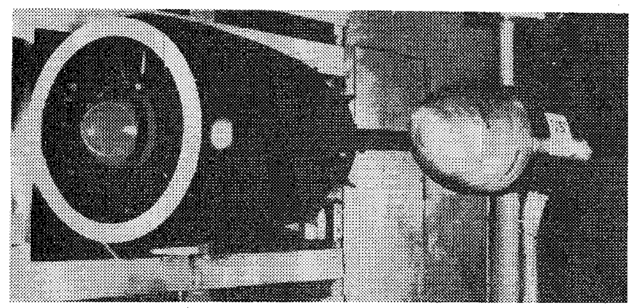

Fig. 4 Inlet/fan installation in NASA LeRC 9- × 15-ft low-speed wind tunnel.

Test Apparatus and Procedure

Facility Apparatus

The inlet test discussed herein was conducted in the NASA LeRC 9- × 15-ft low-speed wind tunnel. This facility operates at atmospheric total pressure and has a freestream Mach number range of 0-0.22. A 20-in.-diam, turbine driven, single-stage fan was used to simulate the inlet mass flow.

A photograph of the inlet/fan installation in the test section is shown in Fig. 4. The model rotates in a horizontal plane about a vertical support post which also provides a passage for the heated, high-pressure, turbine driven air. A portion of the wind tunnel vertical wall adjacent to the model was removed to allow the fan and turbine exhaust flows to pass through the wind tunnel during high angle-of-attack conditions.

The turbine-driven fan was designed to simulate the relatively low pressure ratios representative of subsonic V/STOL aircraft having shaft coupled engines. At the maximum tested fan speed of 7800 rpm, the fan pressure ratio is approximately 1.15 and the fan face Mach number is 0.52. The fan has 15 rotor blades and 25 stator blades with a rotor-stator spacing of approximately one rotor tip chord length. The rotor blades have circular arc airfoil sections with no midspan dampers and were tested with the blade pitch set at the design angle. The rotor blades were fabricated from a titanium alloy.

Detailed information regarding the aerodynamic characteristics of the fan can be found in Ref. 6.

Wind Tunnel Model

The wind tunnel model was designed to represent a zero-length, slotted-lip inlet with the cowl blow-in doors in the open position. The model scale of approximately one-half for a four-engine fixed-nacelle type V/STOL aircraft and one-third for a two-engine tilt-nacelle-type V/STOL aircraft was dictated by the size and airflow of the NASA LeRC 20-in.-diam fan simulator. The basic model is axisymmetric and has a full circumferential slat which is attached to the cowl lip through use of six slat support struts.

The model configuration variables are identified in Fig. 5. Two interchangeable slats were tested using a single cowl lip which had a highlight-to-throat-area contraction ratio of 1.12. The attachment of the slat support struts to the cowl lip is adjustable so that the desired slot gap widths can be easily and accurately set. Spacer rings were used to locate the cowl lip at various distances forward of the fan face. Removable filler blocks were also provided to simulate a conventional unslotted-lip inlet (360-deg filler) and the effect of an adjacent nacelle at high angles of attack (45-135-deg filler) and during high crosswinds (135-225-deg filler). All blocks were designed to fill the 0.51-in.-wide slot gap passage.

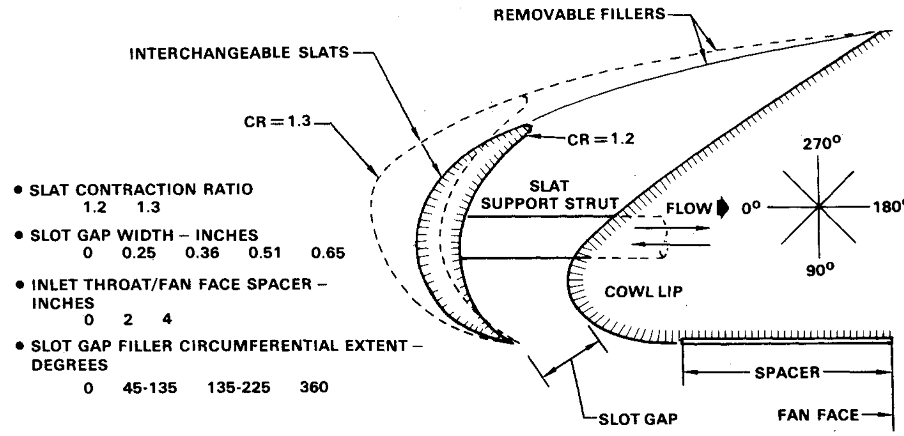

Fig. 5 Model configuration variables.

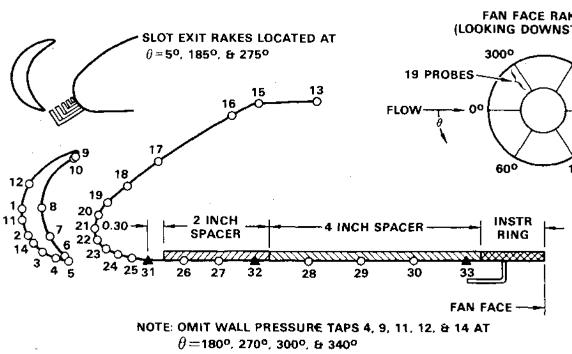

Fig. 6 Model instrumentation.

The two slats were designed to have the same trailing-edge angle and accommodate the same blow-in door installation. For the 1.3 contraction ratio slat, the maximum angle of the blow-in door in the closed position was allowed to be larger than that for the 1.2 contraction ratio slat, so that a reasonable external slat forebody shape could be obtained. Even then, the 1.3 contraction ratio slat has higher external surface angles near the highlight region than does the 1.2 contraction ratio slat. Increasing the slat contraction ratio from 1.2 to 1.3 also results in an increase in inlet length of 0.45 in., enough increase in slot entrance area to reduce the entrance Mach number by 20%, and an increase in average slot exit flow angle.

Instrumentation

The model instrumentation is shown in Fig. 6. The inlet slats, cowl lip, and spacers have axial rows of static pressures located at five circumferential angles. These angles were selected so that the circumferential extent of adverse crosswind and high angle-of-attack effects could be determined. Three removable five-tube total pressure rakes were located at the slot exit. Also, six equally spaced rakes, each containing 19 total pressure probes and two static pressure taps, were located at the fan face. The total pressure probe closest to the outer wall was located 0.6% of the duct height away from the wall.

To detect the onset of internal flow separation within the inlet, the fan-blade stresses, two fan face total pressure probes (referenced to duct static pressure), and a slat-surface static pressure were continuously recorded and visually monitored during the test. The total pressure probes were located 0.6% and 7% of the duct height away from the wall at the 0-deg circumferential station. The slat pressure was located in the region below the highlight where the maximum surface Mach number was expected to occur (pressure tap number 11 in Fig. 6).

The fan-blade vibratory stresses were measured using strain gages located at the root of the suction side and the tip of the pressure side of three chosen blades. Each strain gage was calibrated in terms of the maximum stress for each blade vibrational mode. Since all three gages for a given blade location (i.e., root or tip) indicated essentially identical readings and the blade stresses at the root were greater than those at the tip, only one of the root gages was monitored continuously during the test. The maximum allowable vibratory stress, as determined by a combined analytical/experimental procedure, was 3.5×10^4 lb/in.^{2} peak-to-peak (2.4×10^8 N/m^2 peak-to-peak). Below this stress level the fan can be operated indefinitely.

Test Procedure

Initially, the freestream Mach number/angle-of-attack matrix representative of V/STOL aircraft operation was examined. For each test point the fan speed was increased from approximately 2000 rpm to a maximum of 7800 rpm and then returned to approximately 2000 rpm before proceeding to the next test point. Static conditions were examined first. Then an angle-of-attack sweep from low to high was made for each progressively higher freestream Mach number. This procedure was repeated for all model configurations.

Since the fan-blade stresses never exceeded 10-15% of the maximum stress limit for the initial test matrix, the test matrix was expanded for selected configurations to investigate the inlet angle of attack corresponding to the onset of flow separation. This condition was defined to exist when the total pressure measured by any probe on the fan face rake was equal to the associated wall static pressure.

Test Results

The model test results indicate that zero-length, slotted-lip inlets having 1.2 and 1.3 contraction ratio slats satisfy all critical low-speed inlet operating requirements for a fixed-nacelle and tilt-nacelle-type V/STOL aircraft, respectively. The results obtained for the 1.2 contraction ratio inlet configurations are summarized herein. A detailed discussion of these results as well as those obtained for the 1.3 contraction ratio inlet configurations is provided in Ref. 1.

Basic Performance Characteristics

The fan face area weighted average total pressure recovery characteristics for the baseline 1.2 contraction ratio inlet are shown in Fig. 7. This inlet has a 0.36-in. slot gap width and no spacer or filler. Extremely high recoveries were obtained for all conditions tested. In fact, in order to illustrate in Fig. 7 the effect on recovery of freestream Mach number, angle of attack, and fan face Mach number, it was necessary to use a very expanded scale since the maximum recovery loss encountered was less than 1.2%.

In general, the total pressure recovery decreases with increasing freestream Mach number for a fixed angle of attack. At low forward speeds, where a conventional inlet generally has internal flow separation, the zero-length, slotted-lip inlet, having no diffuser, exhibits high recovery. Also, the flow

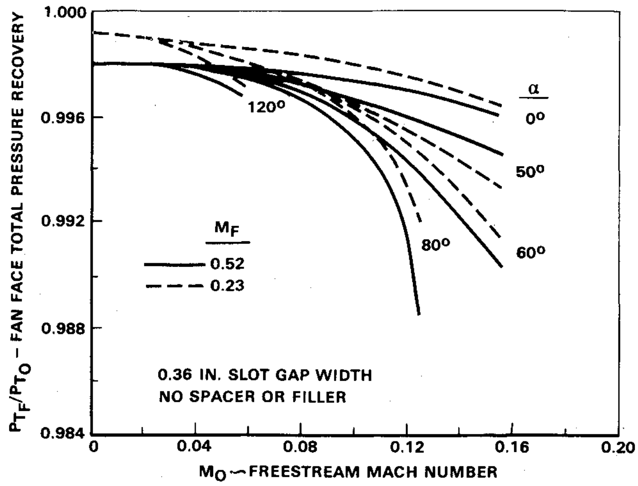

Fig. 7 Fan face total pressure recovery characteristics for $CR = 1.20$; zero-length slotted-lip inlet.

enters the slot from the rear with very little flow turning required. As the freestream Mach number is increased, the stagnation point on the cowl moves forward. As a result, the flow must approach the slot from a forward direction and turn to enter the slot. The flow turning around the inner portion of the slat upper lip separates locally, thus causing a loss in total pressure recovery.

Increasing the angle of attack for a fixed freestream Mach number results in a reduction in total pressure recovery. This reduction increases with increasing freestream Mach number. As the inlet angle of attack is increased, the amount of flow around the slat and through the slot increases on the windward side and decreases on the leeward side. Since an adverse pressure gradient exists on the internal lip of the cowl and on the external portion of the slat lower lip, flow separation is likely to occur on these surfaces and grow as the surface Mach number increases. This will happen when the angle of attack is increased, thus resulting in a lower total pressure recovery.

Figure 7 shows the total pressure recovery at a fan face Mach number of 0.52, which is the largest value tested, and at a fan face Mach number of 0.23, which is the lowest value of interest for a V/STOL aircraft application. At low angles of attack, the turning losses associated with the flow entering the slot cause the total pressure recovery to decrease with increasing fan face Mach number. At high angles of attack, where such slot entrance turning losses are less significant, the total pressure recovery actually increases with increasing fan face Mach number until an angle is reached where the peak surface Mach numbers on the slat and cowl lip become so high that flow separation occurs. When this happens, the recovery at the high fan face Mach number of 0.52 is less than that at the low fan face Mach number of 0.23.

At the low fan speed range (idle, ground operation, etc.), which is not of particular interest for performance evaluation, separation did occur on the cowl lip and slat. No appreciable fan-blade stress was measured. When the fan speed was increased, the separation was eliminated. Furthermore, when the fan speed was reduced to the low values from the high values, the flow separation generally did not return.

Design Point Performance

A typical operating envelope during takeoff for a fixed-nacelle-type V/STOL aircraft, such as that described in Ref. 5, is shown in Fig. 8. Also shown are the freestream Mach number/angle-of-attack conditions for which test data were obtained. As indicated by the open symbols, the inlet flow remained attached for all operating conditions within the envelope. Furthermore, the lines of constant fan-face total pressure recovery shown in Fig. 8 indicate that the maximum recovery loss within the envelope was only 0.5%.

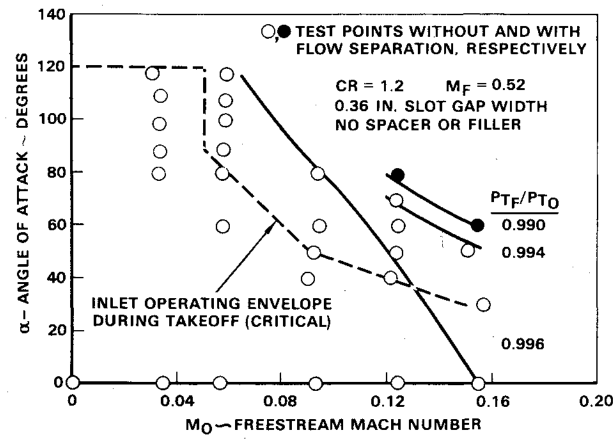

Fig. 8 Operating envelope for fixed-nacelle-type V/STOL aircraft application.

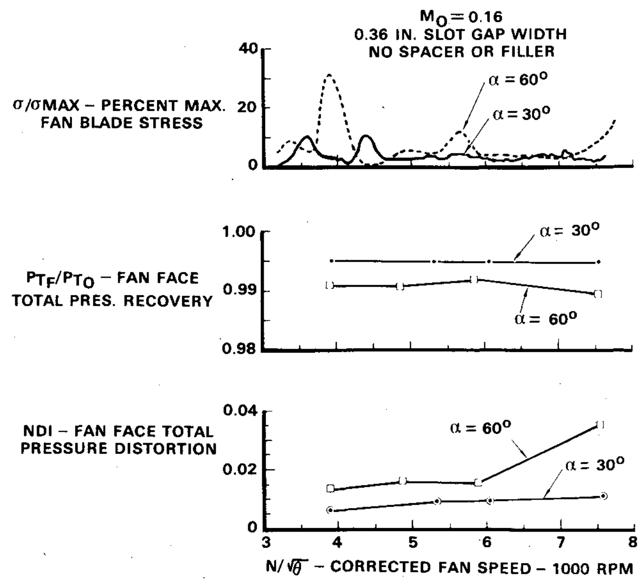

Fig. 9 Inlet aerodynamic performance and fan-blade vibratory stress characteristics—$CR = 1.2$.

Inlet internal flow separation at the maximum fan face Mach number of 0.52 was identified at freestream Mach numbers of 0.16 and 0.12 and angles of attack of 60 and 80 deg, respectively, as shown by the solid symbols in Fig. 8. The former condition is considered more critical than the latter because the angle-of-attack margin relative to the operating envelope is 30 rather than 40 deg. No other margin would be smaller since the envelopes for takeoff and landing are approximately the same and flow separation is most likely to occur at the maximum fan face Mach number. Even then, a 30-deg angle-of-attack margin is considerably greater than required. Thus an inlet having a slat contraction ratio less than 1.2 would be better suited for this particular application, provided the engine geometric envelope could still be accommodated with a cowl having a smaller maximum radius.

Detailed data at the critical condition ($M_0 = 0.16$ and $\alpha = 60$ deg) are presented for the baseline inlet in Figs. 9-11. For comparison, data are presented at 0- and/or 30-deg angle-of-attack conditions. The latter condition exists at the boundary of the operating envelope.

Figure 9 relates the fan face total pressure recovery and distortion to the fan-blade vibratory stress characteristics over the range of corrected fan speeds expected for a V/STOL aircraft application. The distortion index being used is defined in Ref. 7. For the TF34-GE-2 engine, the maximum allowable stress corresponds to a *NDI* of 0.2, with performance losses occurring within an *NDI* range of 0.1-0.2. At

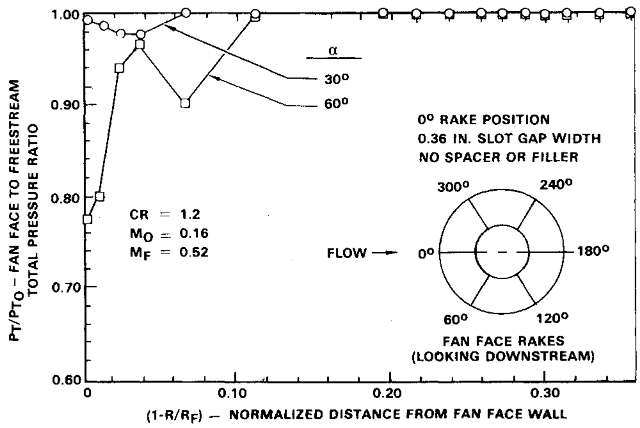

Fig. 10 Fan face total pressure profiles.

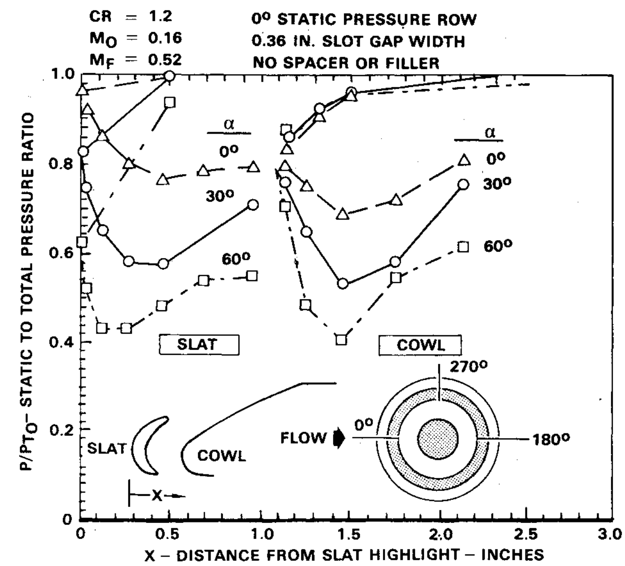

Fig. 11 Slat/cowl surface static pressure distributions.

30-deg angle of attack, the fan-blade stresses are less than 10% of the limit, and the fan face recovery and distortion data indicate that the inlet is free of flow separation. At a 60-deg angle of attack, the fan-blade stress levels become more significant (30% of limit), especially where the bending mode frequency is in resonance with an integer of the fan speed. At the maximum fan speed tested the inlet flow is separated, as indicated by the fan face recovery and distortion data, causing the fan-blade stresses to increase just prior to the next higher resonance frequency. A more significant fan-blade stress would be expected at this frequency.

The flow separation at a 60-deg angle of attack occurs on the internal lip of the cowl and on the external portion of the slat lower lip, as indicated by the fan face total pressure profiles in Fig. 10 and the slat/cowl surface static pressure distributions in Fig. 11. The separated flow regions are located on the windward side of the inlet where peak Mach numbers are much greater than those on the leeward side.

Even though the total pressure distortion at a 60-deg angle of attack is relatively low, a significant velocity gradient exists across the fan face. This potential flow type distortion results in a circumferential variation in incidence angle on the rotor blade. Whether or not this produces significant fan-blade stresses depends on the type of fan employed.

A fan having a map with a shallow constant speed line slope (i.e., variable corrected airflow with changing fan pressure ratio) will be unable to equalize the crossflow velocities, and thus must accept a mass flow gradient across the fan. This will result in fan performance loss and high fan-blade stresses, as encountered during the V/STOL lift fan model test reported

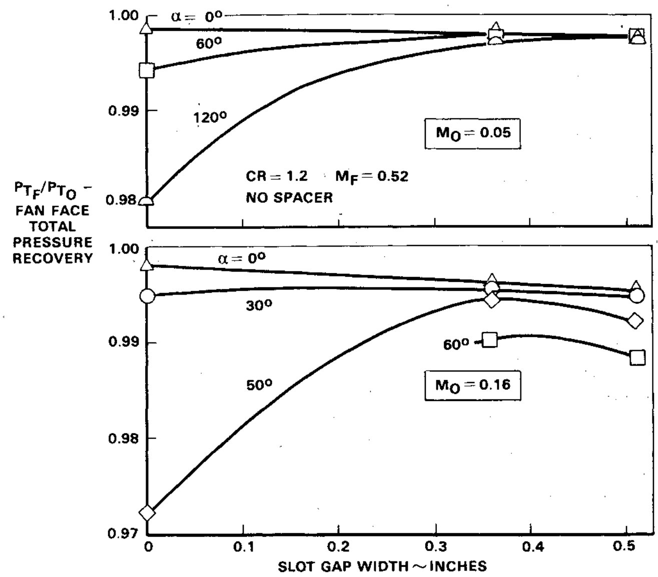

Fig. 12 Effect of slot gap width on fan face total pressure recovery.

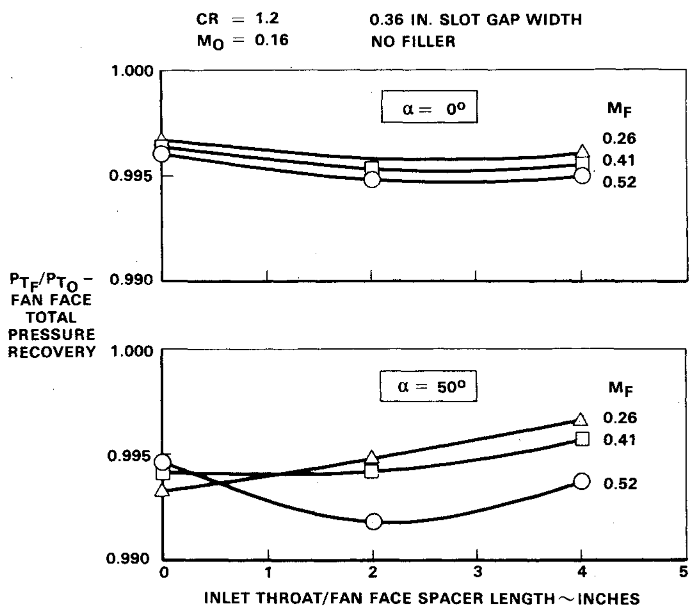

Fig. 13 Effect of inlet throat/fan face spacer on fan face total pressure recovery.

in Ref. 8. The fan used for the zero-length, slotted-lip inlet test had a moderately shallow constant speed line slope and yet the fan-blade stresses were relatively low. Also, the average total pressure ratio across the fan was found to be independent of angle of attack.

The nongeared, high-pressure ratio fans now being considered for V/STOL aircraft applications have a relatively steep constant speed line slope (i.e., fixed corrected airflow with changing fan pressure ratio). Such fans will be better able to adjust the crossflow velocities so that no mass flow gradient will exist across the fan. As a result, zero-length, slotted-lip inlets can be installed, as was done on the C-141, without producing high fan-blade stress levels.

Effect of Slot Gap Width

Flow separation on the outer portion of the slat lower lip and on the internal cowl lip at low and high slot gap widths, respectively, results in optimum performance being obtained at an intermediate slot gap width of 0.36 in. This is illustrated in Fig. 12 for a fan face Mach number of 0.52. Similar trends were obtained for all other fan speed conditions tested.

For a zero slot gap width, all of the inlet flow must be turned by the slat lip. Such a configuration was simulated by installing full circumferential filler blocks in the slot gap passage. At high angles of attack, the peak surface Mach numbers become sufficiently high for the flow to separate. This is evident from the low fan face total pressure recovery shown in Fig. 12 and from the large deficit in total pressure existing near the fan face wall.

As the slot gap width is increased, more flow enters the slot and less flow is turned by the slat lip. At a slot gap width of 0.36 in., both the slat lip and cowl lip have a minimum amount of flow separation. This results in a high fan face total pressure recovery and reasonably flat total pressure profile. At higher slot gap widths, the peak surface Mach numbers become sufficiently high for the flow to separate from the cowl lip, especially for high freestream Mach number/angle-of-attack conditions. When cowl lip separation occurs, both total pressure recovery losses and profile deficits reappear.

Effect of Throat/Fan Face Spacer

Installing a spacer between the inlet throat and fan face is an effective way of reducing the velocity gradients across the fan face. As discussed previously, this potential flow-type distortion may produce significant performance losses and fan-blade stresses, especially for those fans having a map with a shallow, constant-speed-line slope. However, separating the throat from the fan face reduces the beneficial effect of fan-pumping on the overall flow-turning process and of the spinner on the slat/cowl lip pressure gradients.

As shown in Fig. 13 the inlet throat/fan face spacer has relatively little effect on the fan face total pressure recovery of the baseline configuration, especially at low angles of attack. At high angles of attack, where the inlet flow is more likely to separate, the fan face total pressure recovery increases slightly with increasing spacer length at low fan speeds, where the fan-pumping effect is small. Evidently, adding length between the throat and fan face allows the flow to reattach ahead of the fan face, which more than compensates for any recovery reduction associated with spinner location. At high fan speeds, the recovery decreases initially because of the reduced fan-pumping effect, and then increases slightly because of the flow reattachment effect with increasing spacer length.

Effect of 90-deg Slot Fillers

Installing a 90-deg slot filler to simulate an adjacent nacelle at high angles of attack (45-135-deg filler) and during high crosswinds (135-225-deg filler) had essentially no effect on fan face total pressure recovery and only a slight effect on fan face total pressure distortion. Since most of the slot flow occurs on the windward side, the filler blocks displace only a small amount of slot flow. This results in higher slot flow per unit area and lower recoveries on the windward side. These recovery losses, however, are compensated by higher recoveries in the vicinity of the fillers. Such a redistribution in recovery results in higher fan face distortion. The 45-135-deg filler being located closest to the windward side displaces the most slot flow and, thus has the highest fan face distortion.

Summary

Zero-length, slotted-lip inlets are suitable for most subsonic military aircraft where the minimum inlet length is not constrained by acoustic treatment considerations. The inlet is particularly well suited for V/STOL aircraft where large inlet lip contraction ratios are required. For a tilt-nacelle-type V/STOL aircraft, the reduction in inlet lip contraction ratio in going from a long, conventional axisymmetric inlet to a zero-length, slotted-lip inlet is sufficient not only to compensate for an increase in throat area but also to allow for a reduction in maximum cowl radius. Even for a fixed-nacelle-type V/STOL aircraft, a sizable reduction in inlet length can be obtained without adversely affecting the maximum cowl radius.

Model tests using a 20-in.-diam fan in the NASA LeRC 9- × 15-ft low-speed wind tunnel indicate that zero-length, slotted-lip inlets having 1.2 and 1.3 contraction ratio slats satisfy all critical low-speed inlet operating requirements for a fixed-nacelle and tilt-nacelle-type V/STOL aircraft, respectively. The fan face total pressure distortions and fan-blade vibratory stresses were extremely low for both types of V/STOL aircraft, and the maximum total pressure recovery loss for all conditions within the operating envelopes was less than 1%.

The inlet performance measured during the test was dependent on slot gap width and relatively independent of inlet throat/fan spacer length and slot flow blockage created by 90-deg slot fillers. Optimum performance was obtained at a slot gap width of 0.36 in. The spacers were effective in reducing potential flow distortion, although this type of distortion did not have an adverse effect on the fan. The negligible effect of the slot fillers on inlet performance indicates that good inlet performance could also be obtained for a Siamese inlet arrangement.

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References

[1] Beck, W.E., Glasgow, E.R., and Woollett, R.R., "Wind Tunnel Tests of a Zero-Length, Slotted-Lip Engine Air Inlet for a Fixed Nacelle V/STOL Aircraft," Lockheed Report 29526 (to be published as NASA Technical Paper).

[2] Saylor, J.M. and Smith, R.E. Jr., "Internal and External Aerodynamics of the C-141 Nacelle," AIAA Paper 65-604, June 1965.

[3] Burley, R.R., Johns, A.L., and Diedrich, J.H., "Subsonic VTOL Inlet Experimental Results," *Proceeding of V/STOL Aircraft Aerodynamics,* Naval Postgraduate School, Monterey, Calif., May 1979, Vol. II, pp. 648-664. Sponsored by Naval Air Development Center.

[4] Shaw, R.J., Williams, R.C., and Koncsek, J.L., "Tilt Nacelle Aerodynamics and Its Application to Fan Blade Stresses," *Journal of Aircraft,* Vol. 16, No. 9, Sept. 1979, pp. 591-598.

[5] Glasgow, E.R. and Skarshaug, R.E., "Type A V/STOL Propulsion System Development," *Journal of Aircraft,* Vol. 17, No. 10, Oct. 1980, pp. 741-748.

[6] Lewis, G.W. Jr. and Tysl, E.R., "Overall and Blade-Element Performance of a 1.20-Pressure Ratio Fan Stage at Design Blade Angle Setting," NASA TMX-3101, Sept. 1974.

[7] General Electric Co., "TF34-GE-2 Engine Model Specification E1130C," Amendment 1, May 1973.

[8] Lidblein, S., Yuska, J.A., and Diedrich, J.H., "Performance Characteristics of a Model VTOL Lift Fan in Crossflow," *Journal of Aircraft,* Vol. 10, No. 3, March 1973, pp. 131-136.