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THRUST MODULATION METHODS FOR A SUBSONIC V/STOL AIRCRAFT

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INTRODUCTION

The military services are actively interested in the development of V/STOL aircraft. The Navy interest is centered around aircraft operations from smaller destroyer-sized ships and Air Force interest lies in operation from airfields with bombed or otherwise damaged airfields. There are also civilian applications for V/STOL aircraft including rescue missions, transportation into undeveloped areas and into city centers.

Three types of V/STOL aircraft can be identified; rotorcraft, subsonic cruise, and supersonic cruise. Each type of aircraft requires a propulsion system that can provide the thrust and the control of thrust needed for; (1) vertical takeoff and landing, (2) the transition from engine supported to wing supported flight, and (3) conventional cruise. Many V/STOL airplane and propulsion concepts have been proposed. One example of a subsonic cruise V/STOL aircraft is the tilt-nacelle concept shown in figure 1. As illustrated, during the approach and landing the inlet angle of attack may range from 0° to as high as 120°. For all operating conditions the inlet must provide air to the engine which is steady enough and of a high enough total pressure in order to avoid both an unacceptable thrust loss that could occur discontinuously and high fan blade vibratory stresses. This usually means that the inlet internal flow must remain attached in order to avoid the total pressure loss and distortion that accompany flow separation. However, as will be shown by results presented in this paper, it may also be possible to attain the required thrust levels within acceptable blade stress limits even with the inlet internal flow separated.

As shown in figure 2, during the approach from 64 m/sec (125 knots) to a landing, the engine nominal thrust may vary from 50 percent to 100 percent. To maintain airplane attitude and altitude control in large magnitude air turbulence, an additional variation of ± 25 percent about the nominal thrust may be required, as indicated by the band. The overall range of thrust modulation required is thus from 25 to 125 percent of the design value.

There are numerous techniques available for attaining this thrust modulation; each has its advantages and disadvantages. These techniques are depicted in figure 3. First, the engine rotational speed may be varied. Varying the engine speed is the simplest technique and it requires no additional engine modification. The second technique that could be used is to vary the fan nozzle exit area. This technique would, of course, require the design and control of a variable area nozzle. The last two techniques involve changing the thrust of the propulsion system by using either a variable pitch rotor (VPR) or variable inlet guide vanes (VIGV).

The purpose of this paper is to examine the thrust modulation range, thrust level and blade stresses for each of the thrust modulation systems. Results will be shown at the high angles of attack associated with tilt-nacelle V/STOL aircraft. Finally, the interrelationship between the inlet and the thrust modulation system will be illustrated for two inlet types.

EXPERIMENTAL MODEL

In order to evaluate the performance of the various thrust modulation systems, a series of experiments were conducted in the Lewis Research Center's 9x15 foot Low Speed Wind Tunnel. The installation of the test model in the wind tunnel test section is shown in figure 4. The model fan is 0.508 meter in diameter and represents roughly a 0.3 scale model for a two engine 40,000 pound gross weight airplane. The fan has 15 blades, a hub-to-tip ratio of 0.46 and was designed at 2.3 m/sec (700 ft./sec.) tip speed and 1.20 pressure ratio. In this particular photograph the model is shown with a double slotted inlet which will be described in more detail shortly.

Thrust modulation from variation in fan speed was attained by varying the flow rate of the pressurized, heated air supplied to the fan drive-turbine. Thrust modulation from variation in fan exit area was attained by running the fan with three different sized fan nozzles.

The fan stage was designed to provide for variable pitch rotor (VPR) blade capability in order to vary thrust by this method. A photograph of the VPR configuration is shown in figure 5. (Note the instrumentation section consisting of total and static pressure probes installed in front of the fan.) The insert on the photograph shows how the angle of the rotor blade change from design   was measured. A positive angle indicates a decrease in the pitch of the rotor blade as measured from the incoming air flow.

The second variable fan stage geometry for attaining thrust modulation was constructed by fixing the blade angle of the fan rotor blades at their design setting and installing a set of variable inlet guide vanes (VIGV) located 0.24 fan diameters ahead of the fan consisting of 20 full span NACA 63-series vanes with a thickness to chord ratio of .09. A photograph of these vanes mounted in front of the fan is shown in figure 6. The insert on the photograph is a schematic of the VIGV's and shows how the vane deflection angle is measured. The training edge flap chord varied from 60% of the total chord at the hub to 65% at the tip. In their design position, the vanes are aligned to the axial direction. The vane angle varied from -10° to +40°. In this particular photograph the model is shown with a thick lip inlet which is described below.

The interaction between the thrust modulators and the inlet was examined with two different inlets. The inlets used are shown in figure 7. (Photographs with the two inlets in place were shown in figures 4 and 6.) One inlet was a short slotted design with a leading edge slat, the details of which, are shown in figure 7(a). This inlet will be referred to as the double slotted inlet. It is axisymmetric and has its throat located at the total pressure rake measuring station that is upstream of the fan face of the VPR model by about 0.05 fan diameters. The downstream slot encompasses the entire circumference and about 10% of the fan flow passes through the slot. The open slot configuration represents an inlet with hinged blow-in doors in the open position. During the low speeds of landing or take-off, the aerodynamic forces on the inlet will be such that the blow-in doors would open automatically. At high flight speeds and cruise conditions, the aerodynamic forces will be such that these blow-in doors would close automatically. To form the second slot a 120° extent leading-edge slat was mounted about .01 meter ahead of and centered at the windward meridian of the inlet. Further details of this inlet design can be found in reference 1.

The other inlet tested is the thick lip inlet shown in figure 7(b). The inlet has a thick lower lip with a local contraction ration of roughly 1.69. The overall inlet length was 0.80 fan diameters. Further details of this inlet design can be found in reference 2.

RESULTS

Thrust Modulation Characteristics

By Fan Rotational Speed Variation: Gross thrust (calculated from fan pressure and temperature measurements) as a function of fan speed is presented in figure 8 for the double slotted inlet at a freestream velocity of 41m/sec(80 knots) and an angle of attack of 0°. (The fan blade angle was fixed at its design value.) The range of thrust modulation required for V/STOL operation (from figure 2) is presented as a bar on the ordinate on the figure. Comparing the measured thrust with this bar, it can be seen that the range of thrust modulation obtained is large enough for V/STOL application.

The fan blade stress associated with varying the fan speed is presented in figures 8(b) and (c) at angles of attack of 0° and 90° respectively. At an angle of attack of 90°, where the internal flow for this particular inlet design is separated at all fan speeds, the blade stress at fan speeds where resonant frequencies are excited are high, although still within the safe operating limit. Even at 0° angle of attack, figure 8(b), there are fan speeds at which fan blade resonance occurs. Hence, as the fan speed is varied in order to obtain the required range of thrust, the fan would necessarily pass through these resonances. In addition, a specific thrust demand might require the fan to remain at a frequency equal to a resonant frequency. These are of course, undesirable operating conditions because if the level of the stress at these resonant frequencies gets high enough, then fan blade life may be shortened.

It should also be noted at this point that even though the inlet's internal flow separates and the fan blade stresses get higher, they do not, at least in this case, get high enough to preclude safe operation at these conditions. Hence, at least in terms of fan blade stresses, operating with an inlet having separated flow is not necessarily to be avoided. (These blade stress results would also hold for a full size version of the same fan design.) There are other factors, however, such as whether the required level of thrust is being attained or whether the flow separation is ingested by the engine core which must also be considered when the determining the adviseability of operating an engine with separated inlet flow. The question of whether or not the required thrust level can be attained with separated flow will be addressed later in this paper. The question of whether or not the separated region will be ingested by the core engine is beyond the scope of this paper.

Another disadvantage of varying the fan speed to obtain the required thrust variation is the time it takes to change the fan speed. It can take as much as 10 seconds to "rev up" the engine of large fans from idle to full speed. Even though it would not be required to make excursions in thrust of this magnitude (unless there was an engine out situation), the $\pm 25\%$ variation in thrust about any nominal value must take place on the order of 0.2 seconds, far exceeding the capability of a large fan.

By Fan Nozzle Area Variation: The range of thrust obtainable from variation in nozzle exit area is shown in figure 9. As indicated, the thrust range obtained with this fan stage for the fan nozzle exit area variation considered is significantly less than that required for V/STOL operation. Larger variations in nozzle exit area would, of course, provide a larger variation in thrust, however, the gradient of thrust change with exit area is low, and fan stall and stator choking impose constraints on just how much area change can be accommodated.

The range in thrust variation obtained for a given change in nozzle exit area is a function of fan pressure ratio and for higher pressure ratio fans, the thrust variation that accompanies a given area variation is generally larger. There is also the possibility of utilizing changes in nozzle exit area in combination with other variable geometry features to extend the range of thrust modulation.

By Variable Pitch Rotor (VPR): The thrust variation obtained by varying fan blade pitch angle, β , is shown in figure 10 for a freestream velocity of

80 knots and a fan rotational speed of 110 percent of design with the double slotted inlet. Operation at a constant high fan speed and achieving thrust modulation by blade angle change yields a fast rate of thrust change and hence is desirable. The circular symbols and the corresponding solid line on the figure represent the thrust variation obtained at 0° angle of attack. The thrust level decreases almost linearly with increasing blade angle, β. The dashed line is an extrapolation of the data to a blade angle of -10°. As indicated, the required thrust modulation range is readily achievable with a blade pitch angle change from about 0° to +40°.

The square symbols and the corresponding solid line on the figure are data at a freestream velocity of 41m/sec (80 knots) and a 90° angle of attack. There are several important points to be made. First, the fact that the thrust values at 0° and 90° angle of attack are nearly coincident means that the inlet and fan are both operating satisfactorilly aerodynamically at a 90° angle of attack. There are no significant losses due to operating at these conditions. Secondly, the fact that the data could be taken means that the blade stress levels were acceptable.

By Variable Inlet Guide Vanes (VIGV): Data similar to that for the variable pitch rotor are presented in figure 11 for the variable inlet guide vane system with blade trailing edge angle, β, varying from -10° to +40°. In general the conclusions from the data are the same as those for the VPR. The required thrust modulation range is achievable with blade angle variation from -10° to +38°.

The shape of the curve of thrust variation with VIGV trailing edge angle is a little different from that for the VPR. The VIGV appears to be more effective in decreasing the thrust by going to positive blade angles than in increasing the thrust by going to negative blade angles.

In summary of the discussion thus far, of the four thrust modulation schemes considered, both the VPR and the VIGV systems with a double slotted inlet give the desired thrust modulation range at a freestream velocity of 41 m/sec (80 knots) and an angle of attack as high as 90°. The interaction of the inlet and the thrust modulation system is a remaining point of considerable interest and importance which will be discussed next.

Interaction Between Thrust Modulation System and Inlet

Double Slotted Inlet with VPR and VIGV: The variation in thrust with blade angle change is shown in figure 12 for both the VPR and the VIGV operating with the double slotted inlet at a freestream velocity of 41 m/sec (80 knots), an angle of attack of 90° and a fan speed of 110 percent of design (the curves are repeated from figures 10 and 11). The blade angle below which the inlet internal flow separates is shown on the curves. The inlet flow reaches a separation point with decreasing blade angle because a reduction in blade angle represents an increase in inlet weight flow which at some point can cause the inlet flow to separate (reference 3). The important point to be made from this figure is that even though the inlet flow is separated at low blade deflection angles for both the VPR and the VIGV systems, the thrust continues to increase with decreasing blade angle to a value which meets the requirement. Also, as was pointed out earlier, the fan blade stresses which were monitored during the course of the test were also within safe operating limits at the conditions where the inlet flow was separated. Hence, at least in the case of the double slotted inlet, operating with the inlet flow separated did not adverseiy affect either the achievement of the required thrust range or the fan blade stresses.

The aerodynamic performance of the double slotted inlet with both the VPR and VIGV thrust modulation systems is shown in figure 13 in terms of the separation-free angle of attack capability of the inlet. Results are again shown at a freestream velocity of 41m/sec (80 knots) and a fan speed of 110 percent. Blocked on the figure is the propulsion system operating requirement for the tilt nacelle V/STOL aircraft. This requirement is the most severe of the major types of subsonic V/STOL aircraft under consideration. The upper boundary of the blocked region is determined from the 87° inlet angle of attack requirement for the aircraft at a freestream velocity of 41m/sec (80 knots). The side boundaries of the blocked region are determined from figures 10 and 11 and correspond to the VIGV and VPR blade angles needed to obtain the required thrust range; that on the right for maximum thrust and that on the left for minimum thrust. The separation boundary for the inlet with VPR and VIGV is shown by the solid curves on the figure. The area of the figure that lies below these curves represents conditions where the inlet internal flow is attached; the area above the curves represents conditions where the flow is separated. The dashed portion of the bound indicates that up to that angle of attack (which was the maximum tested to) the inlet flow remained attached and the actual flow separation angle was something greater than that indicated.

It can be seen from the figure that the short slotted inlet with the VIGV thrust modulation system meets the aircraft requirements over a large portion of the operating envelope with the exception of a region at high angle of attack and high thrust conditions, i.e. at small β . With the same inlet but with the VPR thrust modulation system, however, the region over which the requirements are met is further reduced. Hence, the same inlet has considerably different angle of attack capability depending on whether the VIGV or the VPR thrust modulation system is used. In fact, the difference in angle of attack capability of the two systems is as great as 35° at a blade angle of 0°.

There are two geometric differences between the VIGV abd VPR configurations that may contribute to this difference in angle of attack capability. One difference is that the radius of the centerbody of the VIGV system was smaller than that of the centerbody of the VPR system. This results in an increase of inlet flow area of approximately 7% for the VIGV system which in turn tends to decrease the Mach numbers on the inlet surface. Since the flow separation in the short slotted inlet is a result of a shock-boundary layer interaction occuring in the supersonic flow region near the inlet highlight (references 3 and 4), the reduction in surface Mach number that results from the smaller radius centerbody would permit attainment of a higher angle of attack before the surface Mach numbers become high enough to cause the flow to separate. The other difference in geometry between the VIGV and VPR configurations is that with the VIGV's installed, the fan is moved further away from the inlet and further away from the high radial velocity gradients present within the short inlet that result from turning the flow through the angle of attack. Hence, if the operating characteristics of the fan itself contribute to the onset of inlet flow separation, then this difference between the fan inflow field that occurs for the VIGV and VPR systems (and perhaps the presence of the VIGV's themselves) may also be a contributing factor to the difference in angle of attack capability shown in figure 13.

In summary, the angle of attack capability of the double slotted inlet is dependent on whether the VPR or VIGV thrust modulation system is utilized. In both cases the inlet does not completely meet the angle of attack requirements for the tilt-nacelle V/STOL aircraft when attached inlet flow is used as the criteria for meeting the requirement. However, in terms of achieving the required thrust variation and operating with acceptance fan blade stresses, the double slotted inlet with both VPR and VIGV thrust modulation systems does meet the requirements in spite of operating with the separated inlet flow that occurs at high angles of attack and low blade angle settings.

VIGV With Double Slotted And Thick Lip Inlet: The variation in thrust with VIGV blade angle change is shown in figure 14 for both the double slotted inlet and the thick lip inlet at an angle of attack of 90°, a fan speed of 110 percent of design and freestream velocities of 31 and 41 m/sec (60 and 80 knots) for the thick lip and double slotted lip respectively. The VIGV blade angle at which inlet flow separation occured is again indicated on the curves for both inlets. As before with the double slotted inlet, decreasing the VIGV blade deflection angle has the effect of causing the inlet flow to separate at some point but the thrust continues to increase and meets the thrust requirements. With the thick lip inlet, however, increasing the VIGV blade angle has the effect of causing the inlet flow to separate at some point and the range of thrust variation required is still achieved. (Data was not obtained at the highest blade deflection angle with the thick lip inlet, however, the trend of the data suggests the required level of low thrust would likely be met.) Hence, with both inlets the VIGV system provides the required range of thrust variation at an angle of attack of 90° (the blade stresses are also again at acceptable levels) even with the inlet flow separated at some blade deflection angles, but the interesting point here is that with the double slotted inlet, decreasing blade deflection angle leads to flow separation and with the thick lip inlet, increasing blade deflection angle leads to flow separation. This point is further illustrated by the inlet flow separation bound curves shown in figure 15.

The opposite effect of changing VIGV blade deflection angle on the separation characteristics of the two inlets is a result of the difference in slope of the two separation bound curves shown in figure 15. As indicated, decreasing VIGV blade angle results in a lower separation angle of attack for the double slotted inlet and a higher separation angle for the thick lip inlet which in turn explains the opposite effects of blade angle changes indicated in figure 14. The reason for this completely different behavior of the VIGV system with the two different inlets is that the flow separation mechanism for the two inlets is completely different. As already discussed, flow separation with the double slotted inlet results from the formation of shocks in the supersonic flow region in the vicinity of the inlet highlight. Increasing VIGV blade angle has the effect of decreasing inlet weight flow which then reduces the inlet surface Mach numbers which in turn means a higher angle of attack can be reached before the flow will separate. Hence, as VIGV blade angle is increased, the flow separation angle of the double slotted inlet increases as indicated in figure 14.

Flow separation in the thick lip inlet, however, is not caused by shock formation on the inlet lip but rather by reaching a limit on the amount of diffusion from the maximum inlet surface velocity on the lip to the minimum surface velocity at the inlet diffuser exit. This type of inlet flow separation is also discussed in references 3 and 4. In this case, as the VIGV blade angle is increased (weight flow decreased) the ratio of maximum inlet surface velocity to minimum inlet surface velocity actually increases and, therefore, the angle of attack where flow separation occurs decreases. Hence, as VIGV blade angle is increased, the flow separation angle of the thick lip inlet decreases as indicated in figure 14.

In summary, again the VIGV thrust modulation system with either the double slotted inlet or with the thick lip inlet provides the needed variation in thrust, with acceptable blade stresses, even with the inlet internal flow separated. The behavior of a given inlet design that results from changes in VIGV blade setting angle can be considerably different, however, depending on the nature of the inlet flow separation mechanism, i.e., whether the separation is induced by high surface velocities (shocks) or by an excessive amount of diffusion from the maximum surface velocity on the lip to the minimum surface velocity at the inlet's diffuser exit.

SUMMARY OF RESULTS

Low speed wind tunnel tests were conducted to assess the capability of four different methods for attaining the thrust modulation required for V/STOL aircraft. The four methods were; (1) fan speed change, (2) fan nozzle exit area change (3) variable pitch rotor (VPR) fan, and (4) variable inlet guide vanes (VIGV). In addition, the interrelationship between the inlet and the thrust modulation system was investigated using a double slotted inlet and a thick lip inlet. The results can be summarized as follows:

(1) The VPR and VIGV thrust modulation systems were the two most promising concepts investigated. They both provided the required range of thrust modulation for V/STOL aircraft.

(2) The VPR and VIGV thrust modulation systems tested here obtained the required levels of thrust with acceptable levels of fan blade stress even at conditions where the inlet flow was separated. The feasibility of operating a propulsion system during flight with the inlet flow separated would, of course, be expected to depend on details of the fan, thrust modulation, engine core and inlet design and in any event, is an area where further research is required.

(3) Changing VIGV (and also VPR) blade angle to obtain changes in fan thrust can have significant implications for the inlet. Depending on the mechanism responsible for inlet flow separation, the inlet flow may be more likely to separate or more likely to remain attached with a given change in VIGV or VPR blade angle.

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4. Luidens, R. W., Stockman, N. O., and Diedrich, J., "Optimum Subsonic, High-Angle-of-Attack Nacelles", International Council of the Aeronautical Sciences, Congress, 12th, Munich, West Germany, October 12-17, 1980, Proceedings, AIAA, pp. 530-541.

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Figure 1. - Tilt-nacelle subsonic V/STOL landing sequence.

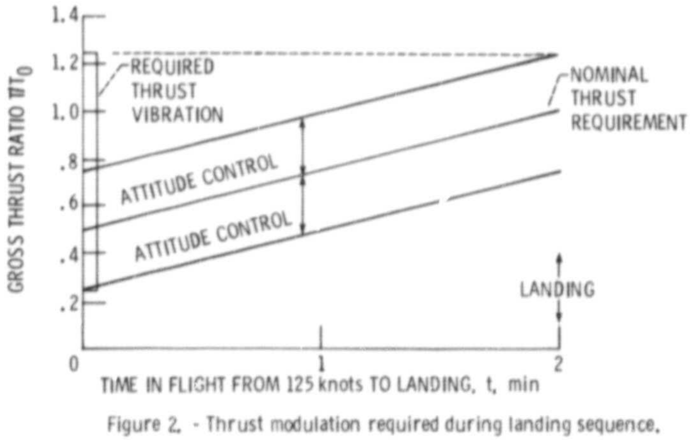


Figure 2. - Thrust modulation required during landing sequence.

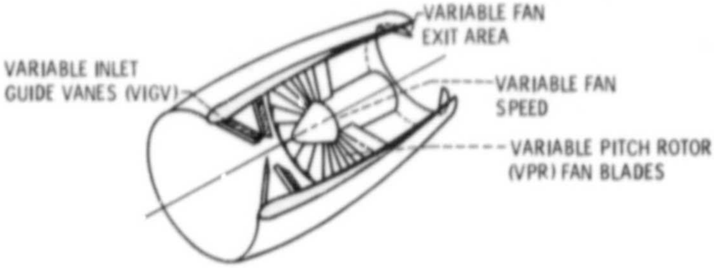


Figure 3. - Methods for attaining thrust modulation.

Figure 4. - Test installation in 9x15-foot low speed wind tunnel. Variable pitch rotor fan with double slotted inlet.

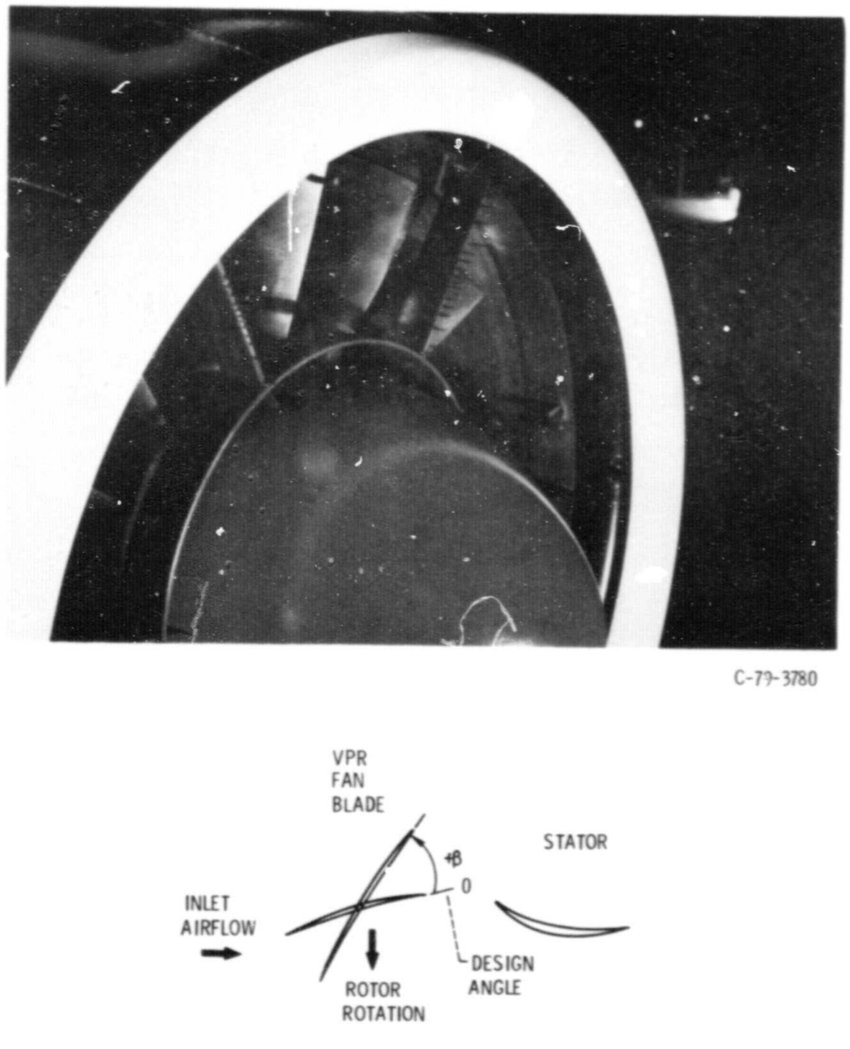
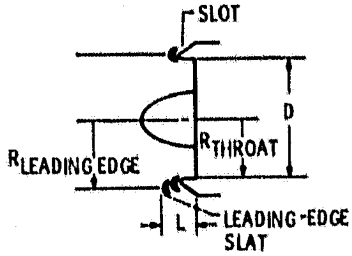


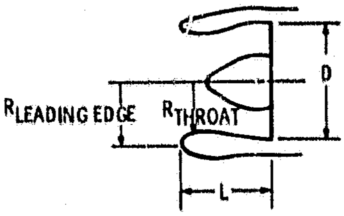
Figure 5. - Variable pitch fan blades on model 0.508-meter-diameter turbofan.

Figure 6. - Variable inlet guide vanes on model 0.508-meter-diameter turbofan; thick lip inlet.



L/D	LIP LOCAL CONTRACTION RATIO, $(R_{LEADING\ EDGE}/R_{THROAT})^2$
0.31	1.30

(a) DOUBLE SLOTTED INLET.



L/D	LIP LOCAL CONTRACTION RATIO, $(R_{LEADING\ EDGE}/R_{THROAT})^2$
0.80	1.69

(b) THICK LIP INLET.

Figure 7. - Inlet designs.

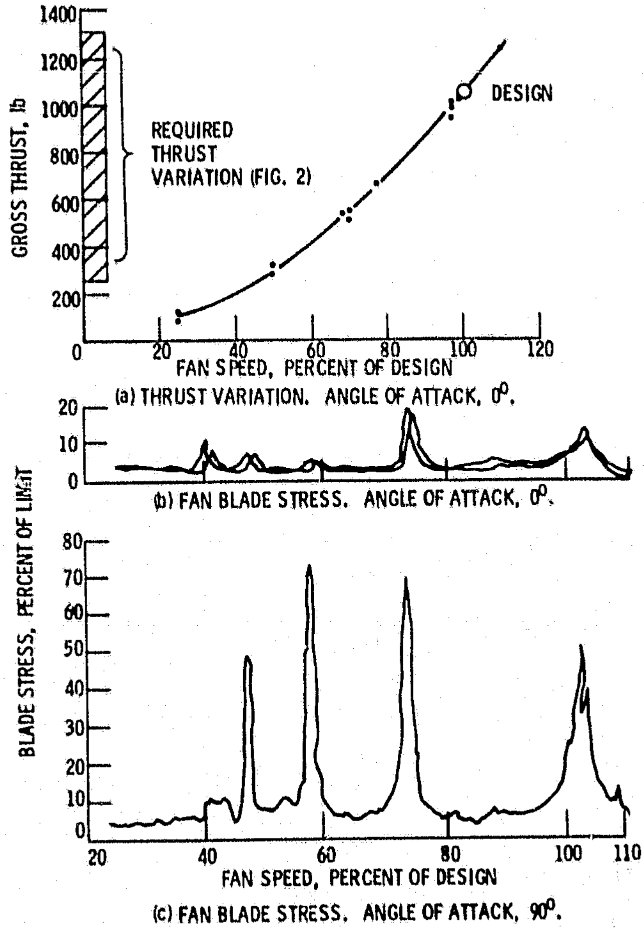


Figure 8. - Thrust modulation and fan blade stress obtained by varying fan speed. Free-stream velocity, 80 knots; double slotted inlet.

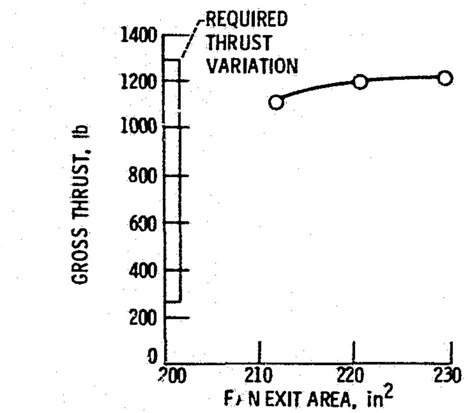


Figure 9. - Thrust modulation obtained by varying fan exit area. Free-stream velocity, 0 knots; fan speed, 110 percent of design.

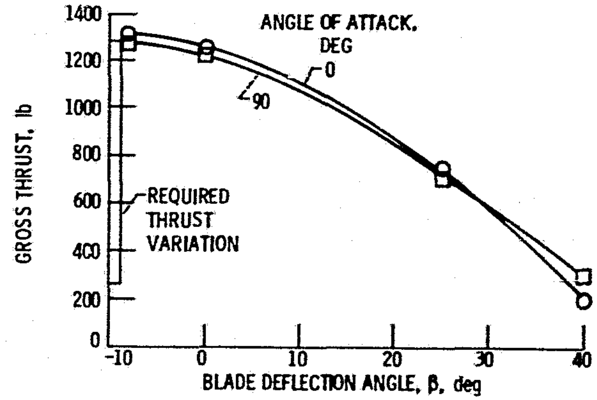


Figure 11. - Thrust modulation obtained using variable inlet guide vanes. Double slotted inlet; free-stream velocity, 80 knots; fan speed, 110 percent of design.

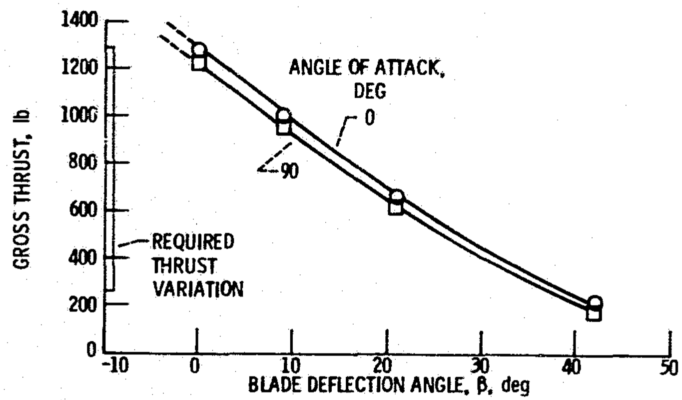


Figure 10. - Thrust modulation obtained using variable pitch fan. Double slotted inlet; free-stream velocity, 80 knots; fan speed, 110 percent of design.

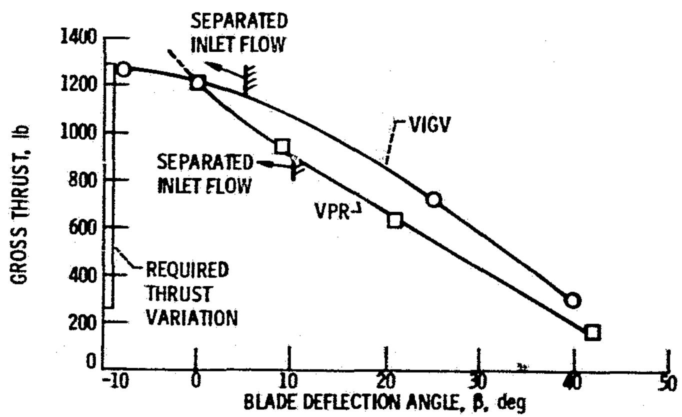


Figure 12. - Effect of inlet separation on thrust variation obtained from variable pitch rotor (VPR) fan and variable inlet guide vanes (VIGV). Double slotted inlet; free-stream velocity, 80 knots; angle of attack, 90°; fan speed, 110 percent of design.

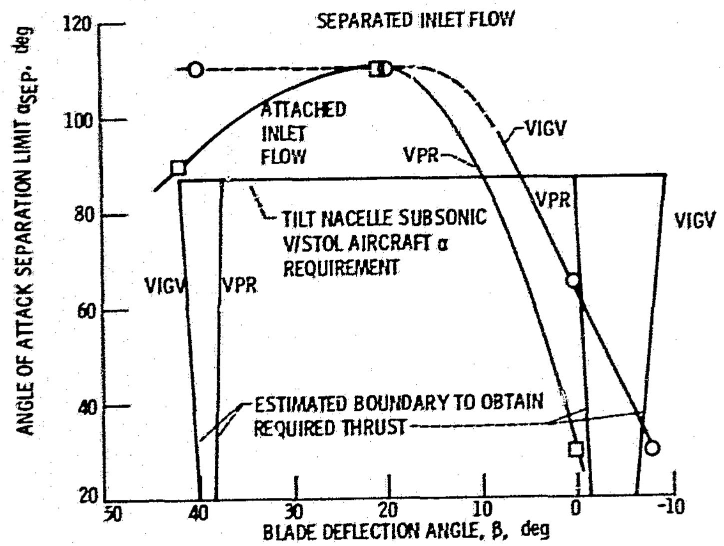


Figure 13. - Double slotted inlet separation characteristics for VPR and VIGV thrust modulation systems. Free-stream velocity, 80 knots; fan speed, 110 percent of design.

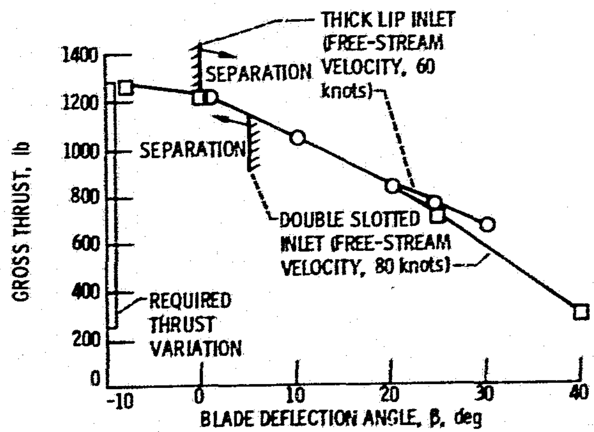


Figure 14. - Effect of inlet separation on thrust variation from VIGV system for two inlet types. Angle of attack, 90°; fan speed, 110 percent of design.

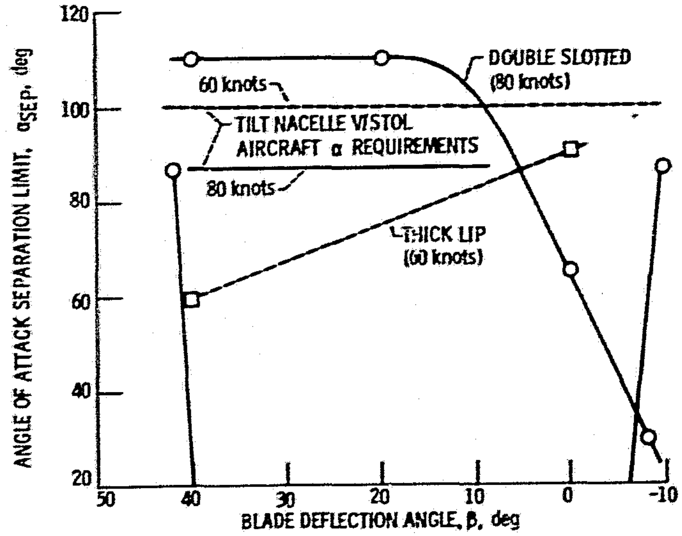


Figure 15. - Separation characteristics of two inlets with VIGV thrust modulation system. Free-stream velocity as indicated; fan speed, 110 percent of design.