Investigation of Very High Bypass Ratio Engines for Subsonic Transports

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A study of propulsion system performance for a family of high bypass ratio turbofan engines is presented. The bypass ratio range is from 6 to 17.5, and both bare engine performance and nacelle installation performance have been considered. Geared, variable pitch/variable nozzle engines with bypass ratios of 10.6, 14, and 17.5 have been studied parametrically, and the performance of a fixed pitch, gearless engine of bypass ratio 9.6 has been estimated to represent an advanced engine with conventional mechanical complexity. Nacelle performance data for a bypass 5 engine have also been included as a baseline. Thrust reverser design for these engines is also considered. Results of this study indicate that conventional nacelle installation losses do not reverse the trend of improving engine fuel efficiency with bypass ratio out to at least bypass ratio 17.5. If innovative concepts are used, such as reverse thrust from a reverse fan pitch and a short fan cowl, the installed fuel efficiency for high-bypass-ratio engines looks even better. The bypass 9.6 engine shows a lower fuel burn benefit than the bypass 17.5 engine, but it offers the potential of reduced mechanical complexity and lower maintenance cost.

Introduction

An important factor in the optimization of engine installations for commercial transports has always been the engine bypass ratio (BPR). From the earliest jet-powered aircraft with turbojet engines to current turbofan power aircraft with BPRs of 5 to 6, the trend has been consistently toward increasing bypass ratio. The motivating factors have been improved fuel consumption and reduced noise made possible by improved core technology. Turboprop propulsion systems, which are at the high end of the bypass ratio range (BPR > 30), are standard for most smaller transport aircraft, and efforts are underway in many segments of the aircraft industry and NASA to extend the application of turboprops to larger and faster transport aircraft.[1,2]

In this study the intermediate range of bypass ratios will be examined; for example, turbofan engines with BPRs in the range of 5 to 17.5. Cycle characteristics for hypothetical advanced engines in this bypass ratio range will be presented for geared, variable pitch fans and for a fixed pitch gearless engine with BPR 9.6. Analytical results for nacelle components such as inlets, nozzles, and thrust reversers will then be discussed with emphasis on using engine cycle characteristics to the best possible advantage in the choice of nacelle configuration.

Since analytical methods have been relied upon heavily in this study, a discussion will also be included in which gaps in the available data base are identified, and the types of experimental programs needed to verify the study results will be outlined.

Engine Cycle Analysis

Improved engine specific fuel consumption can be achieved via two fundamental approaches; namely, improved thermal efficiency and improved propulsive efficiency. Improved thermal efficiency requires increases in overall pressure ratio, turbine inlet temperatures, and component efficiency levels. Improved propulsive efficiency can be obtained through increased engine bypass ratio with a corresponding reduction in fan pressure ratio (low specific thrust). This paper addresses the latter approach. The engines discussed include BPR 17.5 and 14 configurations with geared, variable pitch fan blades that might be usable for producing reverse thrust; a BPR 10.6 configuration with a geared fixed pitch fan but variable fan nozzle provisions for stability; and a fixed geometry, nongeared BPR 9.6 design. The specific fuel consumption improvements relative to a conventional turbofan range from approximately 12% for the BPR 17.5 to approximately 8% for the BPR 9.6.

Figure 1 shows the effect of BPR on thrust specific fuel consumption (TSFC) for a hypothetical family of engines. The study assumed a core technology consistent with the early 1990s time period. A turbine rotor inlet temperature of 2500°R at typical maximum cruise operating conditions was assumed along with an overall pressure ratio (OPR) of 40/1. The core high pressure compressor ratio was fixed at 20/1.

Increasing the BPR from today's typical turbofan of approximately 5 to 70 or more, as might be obtainable with advanced unducted propeller configurations, reduces TSFC by

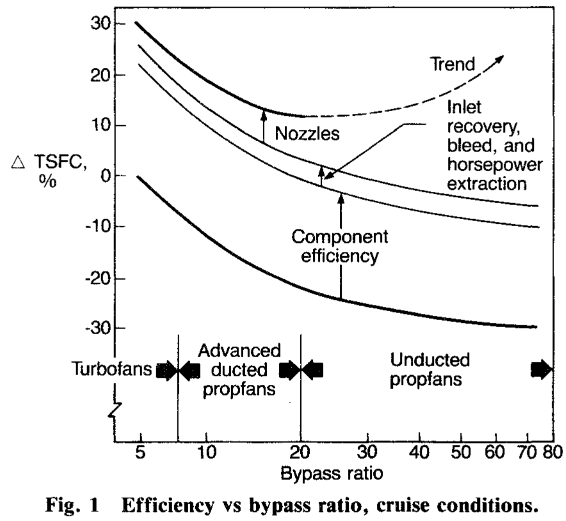

Fig. 1 Efficiency vs bypass ratio, cruise conditions.

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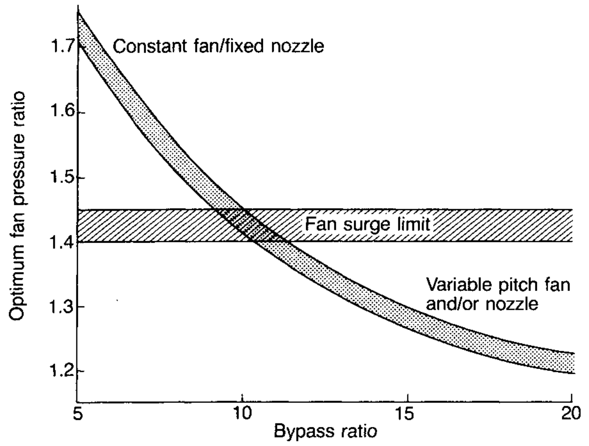

Fig. 2 Optimum fan pressure ratio as a function of bypass ratio.

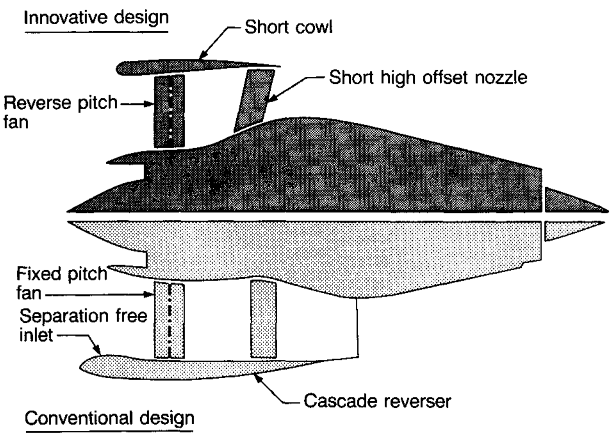

Fig. 3 Innovative nacelle design.

more than 25% for the ideal case, 100% efficient components. When realistic levels of component efficiency are considered, the absolute level of TSFC at all BPRs is significantly degraded, but the favorable trend with increasing BPR remains. It should be noted that the significant loss in TSFC, due to inefficiencies, points out the need to continue research and development of improved turbomachinery components. Installation effects such as air conditioning bleed air and horsepower extraction also have a detrimental effect on TSFC but do not reverse the trend.

The trend of improving TSFC with increasing BPR requires that the fan pressure ratio be optimized for each BPR. The variation of optimum fan pressure ratio with BPR from 5 to 20 is shown in Fig. 2. For low pressure ratios, the nozzle will be operating unchoked, and large excursions of the fan operating line between cruise and sea level static operation will occur. Adequate engine stability and fan surge margin for fan pressure ratios less than 1.40 to 1.45 will require variable pitch fan blades and/or a variable area fan nozzle. Although verification testing would ultimately be required, it is believed that a fixed geometry fan of 1.45 pressure ratio would have adequate stall margin. This pressure ratio limit then sets the maximum BPR achievable without variable geometry to approximately 10 or less.

Referring back to Fig. 1, it is noted that the trend in improving TSFC is adversely affected when nacelle installation (nozzle) losses are considered. If the total pressure loss associated with conventional fan duct and nozzle designs is applied to higher BPR engines, there is little improvement beyond BPR 20 and, in fact, the TSFC gets worse beyond BPR 30. External fan cowl drag and weight further deteriorate the performance.

For BPR > 30, a solution to the problem is to eliminate the fan cowling altogether and use a turboprop configuration. For the intermediate BPRs of 10 to 20, innovative nacelle design approaches must be used to minimize installation penalties and maintain the improved TSFC due to increased BPR.

Fan/Nacelle Integration

It is evident that the nacelle designs will require shorter than conventional inlets and nozzles if drag and weight penalties are to be minimized. This, in turn, requires a closer integration of the fan stage and cowling design than for previous configurations. Figure 3 shows an aggressive cowl design based only on aerodynamic requirements, for a flight Mach number of 0.80, as will be discussed in the following sections. Later designs will be compromised to meet the requirements of acoustic lining and a thrust reverser. Because of the close coupled effects, the inlet and nozzle design have on fan performance, a study was conducted to determine the effects of the inlet fan face Mach number and fan stage exit Mach number on fan stage efficiency so that the interaction between nacelle and fan design can be better understood. Both single-rotation and counter-rotation fan designs were considered as well as two different fan pressure ratios: 1.24 and 1.45. Fan efficiency is based on the rotor and structural fan exit guide vane performance for the single-rotation design and on the two fan rotors and structural fan case exit struts for the counter-rotation designs. Figure 4 shows the results for the 1.24 pressure ratio case. Considering the base case of a single-rotation design with a fan face Mach number of 0.65 (typical of top-of-climb operation) and a stage exit Mach number of 0.55, it is seen that increasing inlet Mach number decreases fan efficiency due to increased rotor relative Mach number. It is also noted that an increased stage exit Mach number can significantly improve efficiency. High stage exit Mach numbers are possible with short nozzles because the flow accelerates directly to the nozzle and does not flow through a fan duct as is the case in conventional designs. This points out the importance of integrating the fan exit guide vane design with the nozzle design. The high exit Mach number is obtained by convergence across the rotor and stator thereby reducing diffusion in the blading. If convergence is allowed only across the stator, as may be the case with variable pitch blades, only one-third to one-half the improvement will be realized.

Also noted in Fig. 4 is that the counter-rotation design clearly shows an improvement at all fan face Mach numbers. The counter-rotation design can tolerate higher Mach numbers because of reduced hub solidity (fewer blades per row) than the single rotation, which will choke earlier. The counter-rotation design does not significantly benefit from an increased exit Mach number, however, because the two rotors have low diffusion losses to begin with, and the structural struts have little or no aerodynamic loading.

Similar trends in fan efficiency variation were found for the 1.45 pressure ratio design.

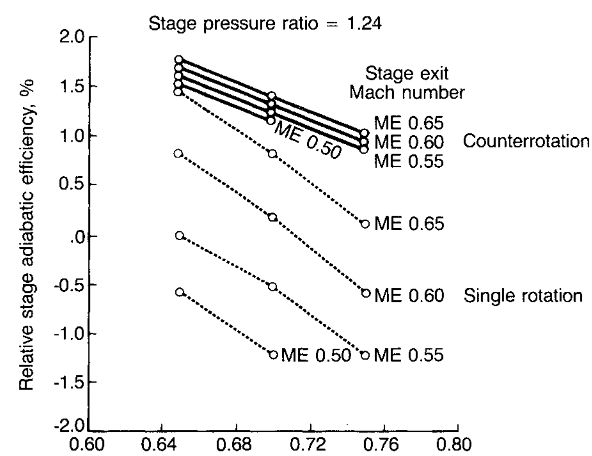

Fig. 4 Relative fan stage efficiency as function of inlet and exit mach number.

Geared vs Gearless Fan Design

As BPR increases, the mismatch between fan speed and low pressure turbine (LPT) speed required for optimum efficiency becomes significant. Generally, the fan requires relatively lower tip speeds at a given pressure ratio to reduce the relative blade Mach number, whereas the LPT requires higher speeds to reduce the loading for a given number of stages. For BPR > 10, a gearbox would be used to provide optimum speeds for both the fan and LPT and would reduce the number of turbine stages required. For BPR < 10, a study was conducted to determine the optimum speed required for six LPT stages and no gearbox. A six-stage LPT was assumed to be a practical limit from a mechanical complexity and cost standpoint. Figure 5 shows that for an engine designed for a fan pressure ratio of 1.45 and six LPT stages, the optimum fan tip speed for best TSFC is approximately 1300 ft/s. Reducing the number of turbine stages results in increased loading and a loss in efficiency and TSFC. The use of a gearbox for this design results in a 1% TSFC improvement (and a reduced number of turbine stages) because the increased fan efficiency and turbine efficiency due to the use of optimum speeds for both components offsets the gearbox efficiency loss. The use of more turbine stages for the gearless design would result in TSFCs as good as the geared design, but this was not considered because of the previously mentioned cost and complexity assumption. The same is true for the consideration of additional stages for the geared design.

Nacelle Design

As shown in the previous discussion, significant TSFC benefits are available from higher BPR engine cycles. Whether these benefits can actually translate into an efficient installation depends on developing nacelle configurations that minimize weight and drag penalties. In addition, it is likely that a thrust reverser will have to be included in any design for a transport aircraft and an innovative concept will probably be necessary to avoid prohibitive weight for this item. In the following discussion, study results for each nacelle component will be presented along with comments regarding the impact of component integration into a complete system. The studies were done for a flight Mach number of 0.80. The impact of higher cruise Mach numbers on nacelle design has been considered in a related study.[3]

Inlet

As is the case for any subsonic inlet design, the primary function of the inlet is to insure acceptable fan face pressure distortion at all required flight and ground operation conditions. The first step in this process is to determine the engine airflow requirements over the range of operating conditions and to allow for growth, if desired. For this study, it has been assumed that the limiting fan airflow condition is a fan face average Mach number of 0.70. This Mach number is generally higher than the design point for the hypothetical engines studied, but it is close to the fan face limit for most modern engines. It is assumed that the design cycle flow rates can be extrapolated to the growth airflow cases in a linear fashion.

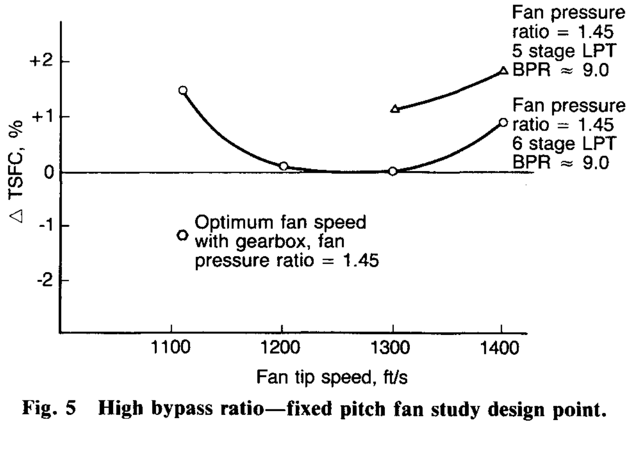

Fig. 5 High bypass ratio—fixed pitch fan study design point.

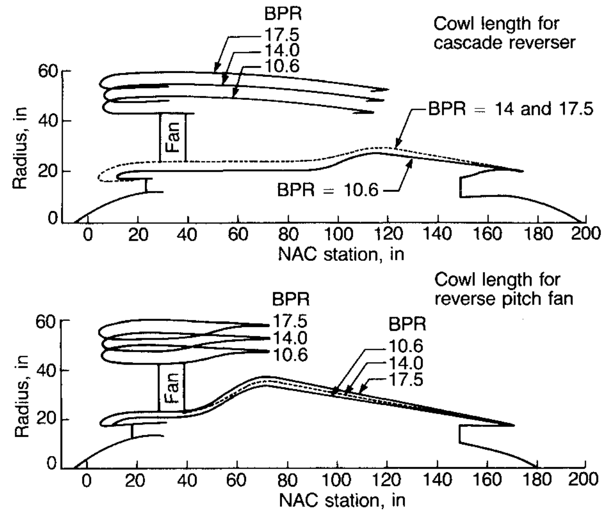

Fig. 6 Nacelle geometry comparison for geared fan study, inlet separation angle = 24 deg.

Fan cowl length is assumed to be the parameter that will contribute most directly to fan cowl weight as well as drag; therefore a natural objective of this study was to design for the minimum possible length. Acoustic lining requirements, which may set inlet length for lower BPR engines, have not been considered as constraints for the geared fan studies. Although this assumption may be optimistic, it may be possible that the higher BPR will require less acoustically treated area because of the lower fan tip speed. For the BPR 9.6 study, provision for acoustic lining has been made.

Inlet lip design depends heavily on the operational angle-of-attack requirements that are needed for a given application. Since this parameter has a significant effect on inlet length (and therefore drag and weight), a range of inlet boundary-layer separation angle-of-attack limits were analyzed to establish the sensitivity of this parameter. These limits were 8, 16, and 24 deg. It is assumed that 24 deg represents a conventional inlet requirement, 16 deg would be an aggressive design that would require increased engine tolerance to distortion, and 8 deg would represent a very aggressive design that could require an active stability augmentation system.

The analytical tools used for inlet studies consist of a three-dimensional transonic potential flow method[4] and a three-dimensional boundary-layer code.[5] The potential flow code uses Cartesian mesh for geometric flexibility and multigrid for computational efficiency. The finite difference boundary-layer method computes both laminar and turbulent flow and allows for various means for locating transition points.

Using the above tools and assumptions, inlets were designed for geared, variable pitch fans of BPR 14 and 17.5 and a geared fan of BPR 10.6. It was found that the inlets could be very short indeed if nonaerodynamic length constraints were ignored. Figure 6 shows a comparison of inlets for engines with the above BPRs that meet the 24-deg inlet separation angle-of-attack requirement discussed above. The upper portion of Fig. 6 shows cowls that were designed to accommodate a cascade thrust reverser, whereas the lower portion of the figure shows cowls designed for engines that achieve reverse thrust from reverse fan pitch. For these engines, inlet length-to-diameter ratio ranged from about 0.1 to 0.25 compared to 0.4 to 0.6 for conventional inlet designs, and contraction ratios ranged from 1.1 to 1.15 compared to 1.25 to 1.3 for a conventional inlet. Several engine characteristics have been exploited in the design of these inlets. The most important consideration is that the high BPR engines tend to have higher thrust lapse rates than conventional engines. Assuming the engine is sized for an altitude climb condition, thrust available at

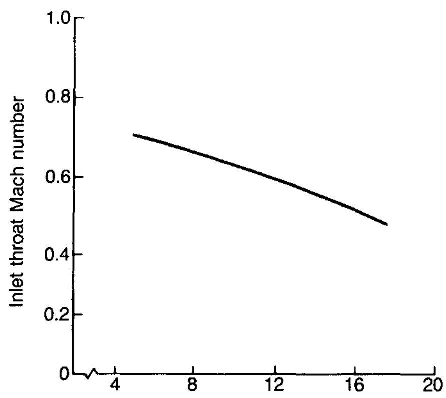

Fig. 7 Inlet throat Mach number variation with bypass ratio for a typical transport application, takeoff conditions.

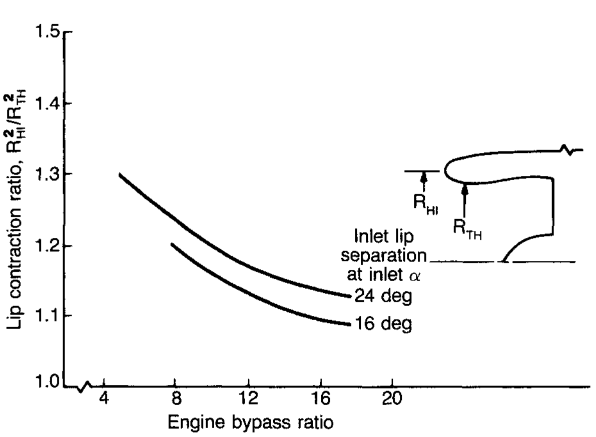

Fig. 8 Required inlet lip contraction ratio as a function of engine bypass ratio.

takeoff is considerably greater than needed to meet the conventional airplane performance requirement. Thus, satisfactory low-speed airplane performance can be obtained from a high bypass engine that is effectively derated at takeoff. This, in turn, lowers takeoff airflows and throat Mach numbers, which makes an inlet with a given contraction ratio much more tolerant to angle of attack. Figure 7 shows the variation in inlet throat Mach number with BPR that resulted from the engine cycles studied. It was found that design takeoff throat Mach number could be reduced from about 0.7 for a conventional inlet to less than 0.5 at BPR 17.5. This reduction in throat Mach number has a strong effect on the contraction ratio required to meet a given separation angle-of-attack requirement, as shown in Fig. 8. For a lip separation angle of attack of 24 deg, it was found that contraction ratio could be reduced from 1.3 to about 1.15, and even thinner lips could be used if lower separation angles were acceptable.

External Cowl Contour

Once inlet lip contraction ratio and throat diameter have been established, the external cowl shape needed to minimize external drag must be determined. This is a critical step for this high BPR engine study because one of the primary goals is to minimize cowl length while avoiding high cowl drag penalties. The design objective was to develop cowl external contours that avoided boundary layer separation and had little or no wave drag (drag due to transonic shock losses). Controlling wave drag became the primary issue. As in past studies, it was found that the critical shape parameter was the ratio of maximum diameter to highlight diameter (forward projected area). For a very short cowl, increasing forward projected area requires an increase in the fan cowl trailing edge radius since length available for fan cowl boattail is limited. An example of the effect of fan cowl trailing edge radius on cowl wave drag is shown on Fig. 9. It was found, for this case, that fan cowl trailing edge radius equal to (or greater than) the highlight radius would result in negligible external wave drag. The trend shown on this figure is typical for all of the short cowl designs. Long duct cowls were also considered to evaluate the effect of this parameter on the overall installation. As would be expected, external cowl wave drag was also negligible for these designs.

A favorable engine characteristic also can be exploited in the choice of an external contour, namely the variation of engine airflow with power setting at an altitude and a speed which is less than for lower BPR engines. This gives idle and windmilling airflows that are a higher fraction of cruise airflow. Thus, the inlet spillage drag at reduced power settings will be less for a given forebody contour, and the cowl forward projected area needed to control spillage drag will be reduced. Figure 10 illustrates this engine airflow characteristic for the study engines. The effect of capture area ratio on nacelle drag for the BPR 10.6 engine is shown in Fig. 11. Although this is the worst case for the geared engines, no external cowl separation is predicted. Windmilling airflow could not be estimated by the analytical methods used, although it would undoubtedly be somewhat lower than at idle conditions. It is possible that increased cowl forebody projected area would be needed if windmilling drag was found to be excessive.

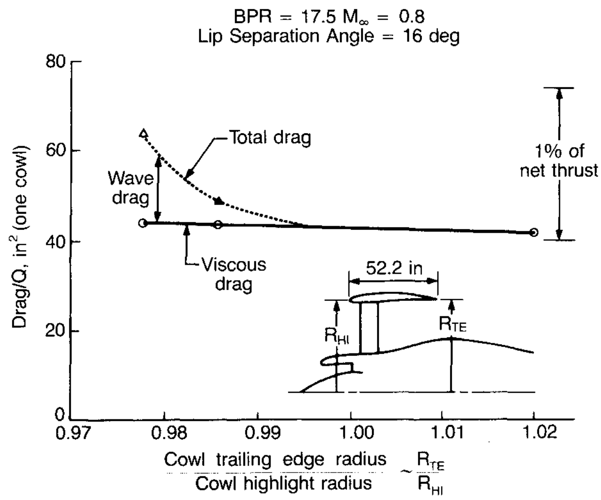

Fig. 9 Cowl drag vs fan cowl trailing edge radius.

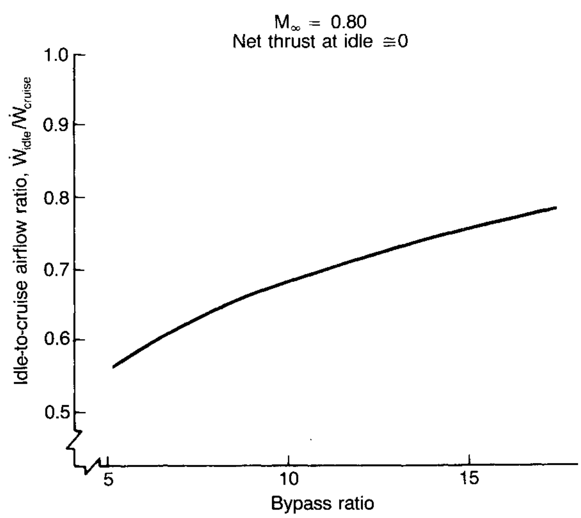

Fig. 10 Variation of engine airflow from idle to cruise power.

Nozzle

The nozzle designs have been chosen to match the estimated fan module length, the required flow area, and the minimum length cowl trailing edge location. The result is a short, high-offset nozzle with a relatively long fan nozzle afterbody surface. Because of the short fan cowl and the long fan nozzle afterbody, the high offset nozzle does not lead to excessive fan afterbody angles. Computed fan nozzle velocity coefficient (*Cv*) includes internal losses and fan nozzle afterbody scrubbing. Figure 12 shows the computed variation in fan nozzle *Cv* for the study engines. Values are somewhat higher than for conventional engines, primarily because of reduced length. Certain aspects of the fan duct flow could not be estimated with the available analysis tools. The primary item is the extent to which secondary flows contribute to nozzle flow stream losses. If data were available to assess this loss, it might be possible to reduce it with internal contour modifications. For instance, fan duct contours from the fan station aft could be tailored to match the required fan nozzle location instead of starting downstream of the fan exit guide vanes, as is done on many current engines.

Thrust Reverser

Thrust reverser designs for very high bypass engines will be a challenging task. For the long fan duct nacelle designs, it would be possible to use a conventional cascade thrust reverser. However, weight could be very high, and the use of a long duct design would also result in increased drag. To explore some alternative concepts for reversing thrust, an analytical study was carried out of the internal nacelle flowfield assuming a reverse pitch fan was used to obtain reverse thrust.

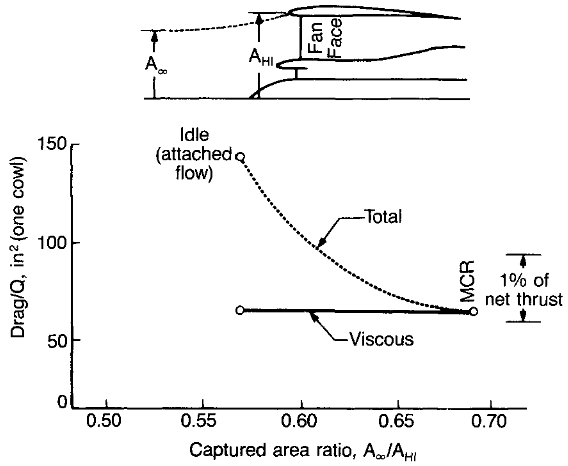

Fig. 11 Cowl drag vs inlet capture ratio.

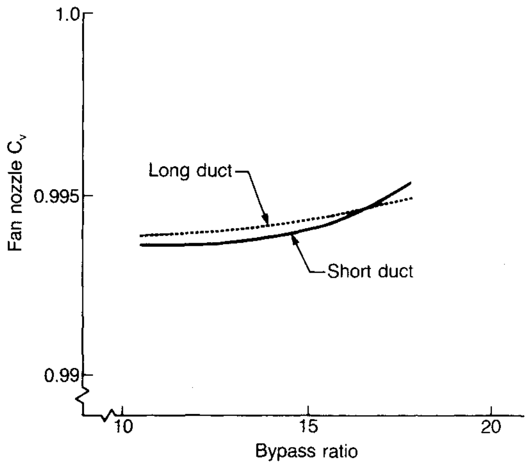

Fig. 12 Fan nozzle velocity coefficient variation with bypass ratio.

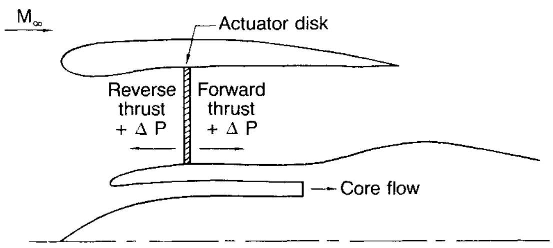

Fig. 13 Flowfield used in reverse pitch fan flow analysis.

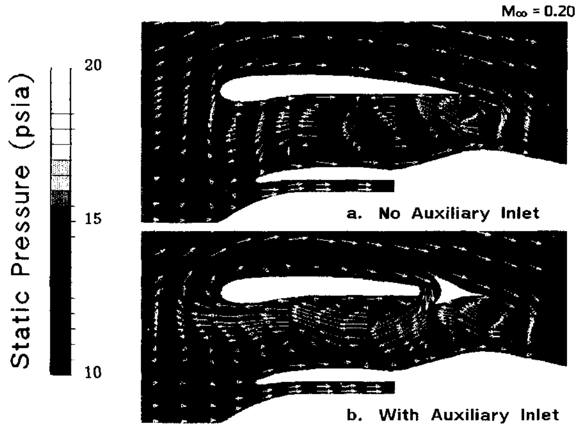

Fig. 14 Computational fluid dynamics analysis of a very high bypass engine, reversed pitch fan flowfield.

An axisymmetric Navier-Stokes method[6] was used to analyze the configuration shown in Fig. 13. The fan was simulated by use of an actuator disk at which the pressure rise characteristic could be reversed to represent forward or reverse thrust. Previous experimental studies[7,8] have shown that high levels of reverse thrust could be obtained at static or low forward speed, but that, at higher speed, much lower levels of thrust were obtained. To investigate the characteristics at higher speeds, the configuration shown in Fig. 13 was studied at a forward speed of about 125 kt with the fan in the reverse pitch mode. Analysis results, shown in Fig. 14a, tend to support the experimental results in that little or no flow reversal is apparent using the unmodified cowl contour. If an auxiliary flow path is provided, however, a much improved pattern appears to develop as shown in Fig. 14b. The above experimental results were all obtained with some fan nozzle modification, but no forward speed data has been found for an auxiliary scoop. It is possible that variable pitch fans could provide very effective reverse thrust with this type of configuration. It should be noted that three-dimensional effects are very important in the external flowfield for the reverse pitch case and, thus, considerably more analysis and testing would be needed to verify this concept. Reingestion of the external flow could not be studied because of the axisymmetric flow assumption.

Reingestion of internal reverse flow into the core stream did occur in the analytical studies and it is an area of concern. Core reingestion was also present in the experimental programs cited above,[7,8] and it was not reported to have caused core instabilities.

The configuration shown should be compatible with the short cowls discussed above. The weight penalty for this concept would be limited to translating mechanisms or movable doors, but no cascades would be needed.

Geared Fan Nacelle Performance

By combining the bare engine TSFC performance, nacelle drag, and nozzle performance from the previous sections, the overall propulsion system performance can be assessed. The primary variables are engine BPR, inlet separation angle, and fan duct length. Figure 15 presents a summary of this data referenced to the bare engine TSFC prediction for the BPR 10.6 cycle. The bare engine performance improvement between BPR 10.6 and 17.5 is about 5%. A relatively conventional nacelle for these engines would result in about a 5% penalty in TSFC at BPR 10. 6 and about 6% at BPR 17.5. Although this is a substantial penalty, Fig. 15 shows that the predicted changes in performance level do not cancel out cycle benefits for these engines. Using short nacelle designs for these engines results in a reduction in nacelle losses for all BPRs with a net benefit at 17.5 of 2.5% for the short nacelle relative to a conventional nacelle. It is also clear from Fig. 15 that the very aggressive inlet lip (separation at 8 deg) does not yield a very large payoff in terms of overall propulsion system performance. The intermediate risk lip would appear to warrant further consideration.

Bypass 9.6 Engine Design

As just discussed, the engines and nacelles designed for BPR 10 to 17.5 require gearboxes and variable geometry fans and nozzles to achieve TSFC improvements and maintain engine stability. In an attempt to eliminate the complexity and cost associated with variable geometry, a study was conducted to determine the maximum BPR feasible without these features. The minimum fan pressure ratio for a fixed pitch fan was set at 1.45 for fan-engine stability reasons. Cycle analysis indicates that the optimum BPR is 9.6 for this design. The number of LP turbine stages was limited to six. A cross section of the engine is shown in Fig. 16, and it is noted that acoustic lining and a translating cascade thrust reverser have been provided. The fan flow path shown is preliminary, and subsequent studies have shown that a constant fan tip diameter and a more uniformly convergent inner duct wall will provide a more favorable Mach number distribution through the flow path.

While this configuration does not offer the same TSFC benefits as the higher BPR engines, it does provide for modest improvements with minimum cost impact. The use of this concept with an existing core warrants further attention because of its potential for improved TSFC, increased thrust, reduced maintenance cost, and improved service entry reliability relative to the other designs.

Bypass 9.6 Nacelle

Development of a nacelle configuration for the BPR 9.6 engine follows closely the philosophy used in development of the geared fan engine nacelles. Primary differences are that the cruise to takeoff airflow variation is somewhat smaller, and cruise-to-idle airflow variation may be somewhat larger resulting in higher spillage drag risk. Figure 16 shows a nacelle cross section for this engine. Contraction ratio is 1.22 and inlet L/D is 0.34. Nacelle weight will also be impacted by the thrust reverser concept. The configuration shown in Fig. 16 incorporates a translating cascade arrangement because it is felt that this would give the shortest cowl and could permit a light weight axisymmetric fan cowl structure. Adequate access to engine accessories should be possible through core cowl doors with out the need for a heavier D-duct design.

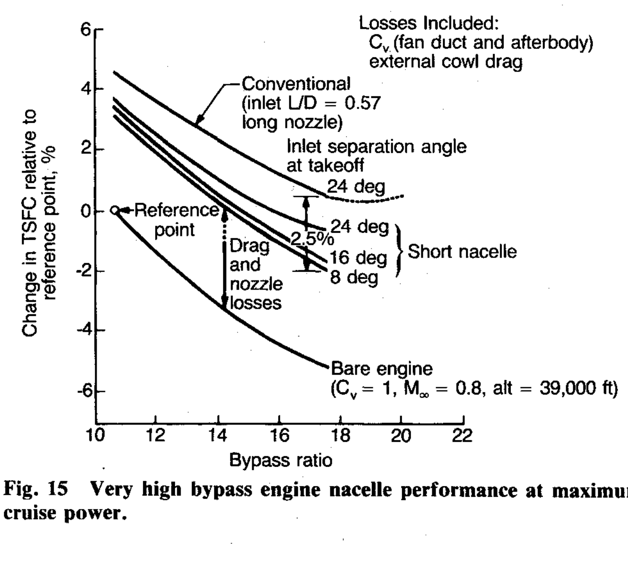

Fig. 15 Very high bypass engine nacelle performance at maximum cruise power.

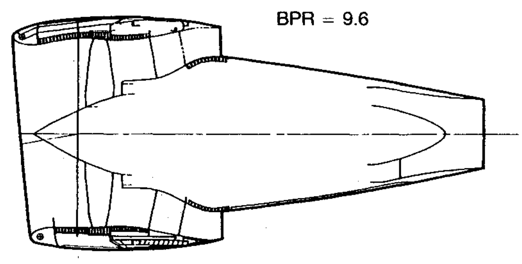

Fig. 16 Very high bypass ratio gearless engine.

Nacelle performance penalty on TSFC relative to the bare engine is 5.7% for this nacelle.

Limitations of Analytical Methods

Limitations in the analytical methods available for this study leave some nacelle design areas with a higher risk. Experimental programs are needed in several areas to supplement and confirm analytical studies.

The high-offset nozzle, long-afterbody combination should be tested with modeling of candidate duct bifurcations. For the short duct nacelle, integration of nozzle lines into the engine fan case geometry may be necessary and, thus, modeling of engine features such as fan exit guide vanes and swirl may also be needed. Initial testing could probably be done on a conventional nozzle test rig, but ultimately powered testing may be necessary.

Inlet-fan interaction is also a question that needs to be addressed experimentally. Short inlets will probably have higher levels of residual swirl at the fan face than is found in current inlets. Thus, the fan blades will be subjected to greater variation in incidence angle during one fan revolution. This effect would be most pronounced at a high angle of attack.

Lower pressure ratio fan tolerance to inlet total pressure distortion is another area that needs to be investigated, especially for inlet lips that may have boundary layer separation at lower angle of attack than current inlets. Short inlets may have total pressure distortion patterns that have a reduced radial extent relative to longer inlets which could have a favorable effect on engine distortion tolerance.

All of the above questions relating to distortion and swirl can only be studied through powered fan testing, which includes representative inlet and perhaps fan duct geometries.

Conclusions

It is concluded from this study that substantial benefits in thrust-specific fuel consumption are available from turbofan engines in the BPR range of 9 to 17.5. Relative to conventional BPR 5 engines, it may be necessary to consider several new fan design features such as variable pitch, geared fans, and variable area nozzles. Innovative nacelle design concepts will also be required to limit the impact that larger diameter fans have on nacelle weight and drag. The use of variable pitch fan blades to achieve reverse thrust appears to be a promising concept if an auxiliary inlet can be provided.

The alternative BPR 9.6 engine offers slightly reduced TSFC benefits when compared to the higher BPR engines but would be conventional in mechanical design and, thus, may be attractive when all operating costs are considered.

These engines and nacelles are more closely coupled in many ways than current engines and, therefore, test programs that study inlet-fan and fan-nozzle interactions are needed to provide the necessary data base to verify the predicted benefits.

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