Variable Geometry for Supersonic Mixed-Compression Inlets

Norman E. Sorensen,* Eldon A. Latham,† and Donald B. Smeltzer†
NASA Ames Research Center, Moffett Field, Calif.

Study of two-dimensional and axisymmetric supersonic mixed-compression inlet systems has shown that the geometry of both systems can be varied to provide adequate transonic airflow to satisfy the airflow demand of most jet engines. Collapsing geometry systems for both types of inlet systems provide a generous amount of transonic airflow for any design Mach number inlet system. However, the mechnaical practicality of collapsing centerbodies for axisymmetric inlet systems is doubtful. Therefore, translating centerbody axisymmetric inlets with auxiliary airflow systems to augment the transonic airflow capability are an attractive alternative. Estimates show that the capture mass-flow ratio at Mach number 1.0 can be increased approximately 0.20 for a very short axisymmetric inlet system designed for Mach number 2.37. With this increase in mass-flow ratio, even variable-cycle engine transonic airflow demand can be matched without oversizing the inlet at the design Mach number.

Nomenclature

A_c = capture area
A_0 = freestream tube area entering the inlet
D = inlet capture diameter
M_{des} = design Mach number
M_L = local freestream Mach number
M_{th} = throat Mach number
m_{bl} = bleed mass flow
m_∞ = capture mass flow
p_{t_2} = engine-face total pressure
$\bar{p}_{t_2}$ = area-weighted average engine-face total pressure
p_{t_∞} = freestream total pressure
Δp = engine-face total-pressure distortion, $(p_{t_{2_{max}}} - p_{t_{2_{min}}}/\bar{p}_{t_2}$

Subscripts

max = maximum
min = minimum

Introduction

THE design of mixed-compression supersonic inlet systems for long-range supersonic cruise aircraft has centered mainly about the design Mach number requirements. Off-design requirements, generally, have taken secondary roles in establishing final designs. As a result, the off-design engine matching and performance requirements have been satisfied by complex variable geometry systems, which, in some cases, may not assure inlet-engine matching compatability. Moreover, innovative variable geometry alternatives that have less complex design features for mixed-compression supersonic inlet systems have not been available, especially for axisymmetric inlets. Consequently, the main objectives of this paper are to 1) describe the effects of new, as well as established, variable geometry alternatives on inlet design and complexity, and then 2) compare the estimated engine matching characteristics of each alternative.

Collapsing Geometry Inlets

Both two-dimensional and axisymmetric inlet systems have used collapsing geometry to attain needed off-design performance and airflow to satisfy jet engine demands. Examples of each type of inlet designed for Mach number 2.65 are shown in Fig. 1; both inlets have been tested.[1,2] The two-dimensional inlet,[1] inlet *A*, uses conventional collapsing ramps. Even though the ramp system is complex, the mechanical design allows little leakage or disturbance of the local boundary layer, and the movable leaves that support the ramps are suited for compartmentalizing the required boundary-layer bleed regions (not shown) on the ramp. (It is important to compartmentalize the bleed to prevent recirculation of bleed airflow and minimize the bleed drag.[3]).

The axisymmetric inlet,[2] inlet *B*, since it is circular in shape, uses multiple, longitudinal centerbody segments that collapse radially for off-design operation. This multiple-segmented system in mechanically more complex than the two-dimensional ramp system, and its design is such that preventing leakage and compartmentalizing the boundary-layer bleed regions are more difficult. In fact, the limited practicality of compartmentalizing for several bleed regions may, of itself, restrict the usefulness of this concept to Mach numbers below 3.0.

Both inlets *A* and *B* can provide high transonic airflow and can match the airflow demand of most jet engines. Figure 2 shows the capture mass-flow ratio A_0/A_c supplied by each inlet and the capture mass-flow ratio demanded‡ by a typical study engine, the P&W 5A dry turbojet, as a function of the local freestream Mach number M_L up to the inlet starting§ Mach number, $M_L = 1.6$. With an assumed inlet throat Mach number of 0.85, inlet *A* can supply $A_0/A_c = 0.686$ at $M_L = 1.0$, and inlet *B* can provide substantially more, $A_0/A_c = 0.781$. However, in principle, it is possible mechanically to collapse the two-dimensional ramp system so that the transonic mass-flow ratio could be made approximately equal to that of the axisymmetric inlet system. Still, both inlets easily match the demand of the study engine.

Translating Centerbody Inlets

Since two-dimensional inlet systems are relatively easy to adapt to collapsing geometry, consideration of other variable geometry alternatives, such as translation, is academic for this type of inlet. However, for axisymmetric inlets, translating the centerbody for off-design operation has proven to be aerodynamically efficient and mechanically practical. But axisymmetric inlets with translating centerbodies suffer from relatively low transonic airflow capability. One way to overcome this transonic deficiency is to design an inlet system, which, in the transonic geometry, has an upsteam throat (formed by the cowl and centerbody) that is greater than the

Submitted Oct. 18, 1974; presented as Paper 74-1172 at the AIAA/SAE 10th Propulsion Conference, San Diego, Calif. Oct. 21-23, 1974; revision received April 16, 1975.

Index category: Airbreathing Propulsion, Subsonic and Supersonic.

*Research Scientist. Member AIAA.

†Research Scientist.

‡ In this paper, engine demand is calculated by using a typical supersonic transport engine-face total-pressure recovery schedule.[4] Data for the tested inlets[1-7] show that the schedule can be approximated (at $M_L = 1.0$, $\bar{p}_{t_2}/p_{t_\infty} = 0.94$ to 0.98 and, at cruise, $\bar{p}_{t_2}/p_{t_\infty} = 0.90$ to 0.94) with acceptably low engine-face distortion (transonically, $\Delta p < 0.15$ and, at cruise, $\Delta p < 0.10$) and reasonably low boundary-layer bleed flow (transonically, $m_{bl}/m_\infty \cong 0$ to 0.02 and, at cruise, $m_{bl}/m_\infty = 0.05$ to 0.07).

§"Starting" refers to the process by which the internal flow in the supersonic diffuser is changed from subsonic to supersonic.

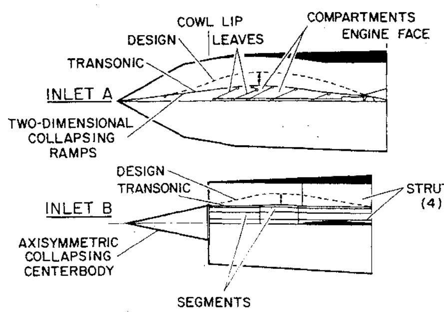

Fig. 1 Collapsing geometry inlets, $M_{des} = 2.65$.

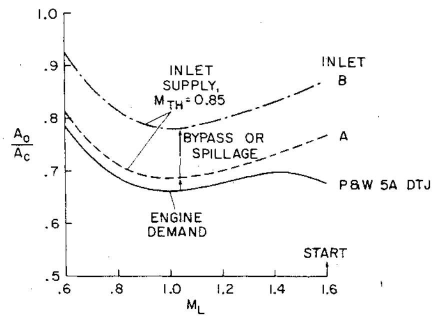

Fig. 2 Transonic engine matching for collapsing geometry inlets, $M_{des} = 2.65$.

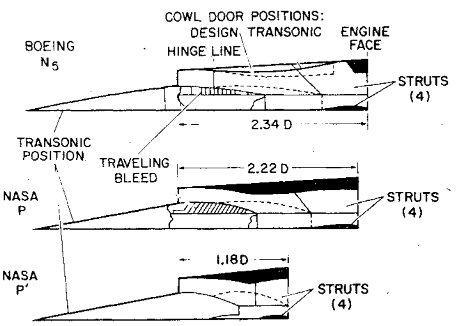

Fig. 3 Translating centerbody inlets, $M_{des} = 2.65$.

downstream throat (formed by the cowl and the centerbody support tube). The downstream throat then is enlarged by using cowl doors. A tested inlet that uses cowl doors, designated Boeing N_5[4,5] is shown in Fig. 3. The throat doors (hinged upstream in the supersonic diffuser) extend downstream just ahead of the engine face, and open outwardly to create a downstream throat area that is greater than the upstream throat area (near the cowl lip). This system is not only complex but accounts for approximately 23% of the inlet weight.[3] A further complexity is added to this system in the form of a traveling bleed system. The multiple compartments of the traveling bleed system are required to maintain throat bleed opposite the stationary cowl bleed—an inherent requirement for axisymmetric inlets with relatively small-diameter translating centerbodies. If cowl doors are eliminated, somewhat less transonic airflow must be accepted, since now the centerbody diameter must be increased just enough to avoid a downstream throat. The tested NASA P inlet[3,6,7] shown in Fig. 3 is such an inlet. For this inlet system the complexity of the traveling bleed system must be retained if a reasonably low rate of subsonic diffusion is to be maintained with the centerbody at the design Mach number position. If it becomes possible to control boundary-layer separation in a very rapidly expanding subsonic diffuser, an inlet such as the NASA P' would be practical. Although this inlet (Fig.3) has the same supersonic diffuser as the NASA P inlet, it has a much more rapidly expanding subsonic diffuser. The throat now remains fixed on the centerbody instead of on the cowl, thereby eliminating the need for a traveling centerbody bleed system. This shortens, by 47%, the inlet from $2.22D$ to $1.18D$. However, the transonic airflow capability remains the same as for the NASA P inlet.

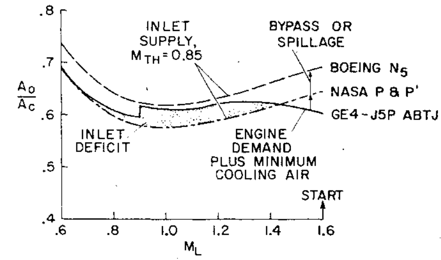

Fig. 4 Transonic engine matching for translating centerbody inlets, $M_{des} = 2.65$.

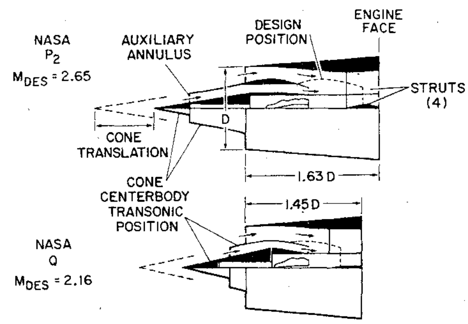

Fig. 5 Auxiliary airflow inlets with translating centerbodies.

The transonic matching characteristics of the three inlets are shown in Fig. 4. Once again, capture mass-flow ratio A_0/A_c is plotted as a function of local Mach number M_L. The Boeing N_5 inlet just can match the GE4-J5P afterburning turbojet, whereas the NASA P and P' inlets show a deficit, up to $M_L = 1.43$, where the inlet presssure recovery is reduced enough (because of normal shock losses) to reduce the engine demand to equal the inlet supply. To supply the engine demand (plus minimum cooling air), the NASA P and P' inlets would have to be oversized by 7% at cruise,[4] thereby creating an undesirable increase in inlet drag and weight. However, oversizing may not be necessary for a dry turbojet if the engine rotational speed, at the transonic Mach number, can be reduced enough to lower the engine demand to match the inlet supply.

Auxiliary Airflow Inlets

A new but untested alternative to using throat doors (for increasing transonic airflow of axisymmetric inlets) is that of using a centerbody auxiliary airflow system. Such systems are shown in Fig. 5 for inlet systems that are designed for Mach numbers 2.65 (NASA P_2) and 2.16 (NASA Q). In these systems, the forward section of the centerbody cone is translated aft, creating an annular auxiliary opening whose area is approximately 11% of the capture area.¶ In this configuration, the auxiliary airflow can pass through the centerbody and mix with the main duct airflow on its way aft to the engine face. The inlet systems shown do not require centerbody traveling bleed systems, because the centerbody maximum diameter is large enough to maintain the throat on the centerbody as the centerbody translates for off-design operation. In fact, the centerbody maximum diameter of the NASA P_2 inlet[3] is larger than the NASA P inlet, and, consequently, the main-duct transonic mass-flow ratio is 0.066 lower. An auxiliary airflow system is required if the transonic mass-flow ratios of these two systems are to be comparable.

¶Since all supersonic mixed-compression inlet systems require boundary-layer bleed systems (not shown) to prevent boundary-layer separation in the supersonic diffuser during started operation, a rather complex cross-passageway system is required between the auxiliary airflow passageway and the bleed airflow passageway. This complexity limits the auxiliary airflow area to a maximum of approximately 10 to 12% of the capture area.

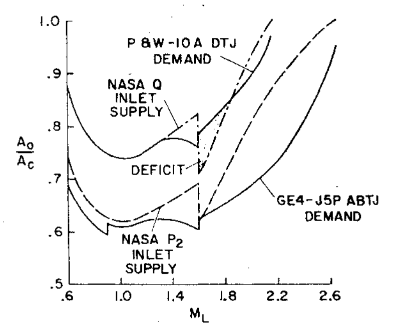

Fig. 6 Engine matching for auxiliary airflow inlets, $M_{des} = 2.16$ and 2.65.

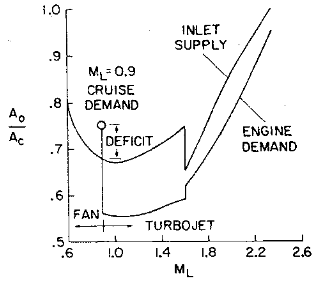

Fig. 7 Variable-cycle engine matching for centerbody auxiliary airflow, $M_{des} = 2.37$.

But since the NASA P_2 inlet does not need a traveling bleed system, the centerbody support struts can penetrate the aft skirt of the centerbody subsonic diffuser, allowing a shortening of the inlet length, as measured from the cowl lip to the engine face, by approximately 27% (2.22D to 1.63D) of the NASA P inlet. The NASA Q inlet is even shorter – only 1.45D long.

The estimated engine matching characteristics of these two inlets up to the design Mach numbers are shown in Fig. 6. The NASA P_2 inlet centerbody auxiliary airflow now can match** the transonic demand of the GE4-J5P engine. However, there is a slight inlet airflow deficit at the starting Mach number of 1.6. This can be overcome easily by starting the inlet at a slightly higher Mach number ($M_L = 1.75$). For the lower design Mach number NASA Q inlet, the transonic mass-flow ratio is considerably higher than for the NASA P_2 inlet, because of the larger main-duct throat area (lower contraction ratio) that is required for the lower design Mach number. The NASA Q inlet just can match the demand of a typical study engine, the P&W 10A dry turbojet, up to the starting Mach number. However, a large deficit beyond a Mach number of 1.6 is shown. Therefore, starting should be delayed to Mach number 1.9 for this inlet system.

Variable-Cycle Engine Matching

With the advent of variable-cycle engines (VCE), which promise greater efficiency and range for supersonic cruise vehicles,[8] new inlet-engine matching problems arise. Figure 7 shows the engine demand curve of a typical VCE and the inlet supply curve for an inlet that has a centerbody auxiliary airflow system that is similar to those shown in Fig. 5 but that is designed for Mach number 2.37. The VCE at Mach number 0.9 cruise operates as a high airflow-demand turbofan engine. Once acceleration to supersonic speeds is initiated, the cycle can be varied to the low-demand turbojet mode. In the turbojet mode, the inlet supply can be reduced to match the engine demand by partially or completely closing the auxiliary airflow system. But in the turbofan mode, even with an auxiliary centerbody airflow system, there is a deficit. The deficit may be overcome simply 1) by increasing the size of the inlet, thereby oversizing the inlet at the design Mach number, with the attendent weight and drag penalties for bypassing the extra airflow around the engine, or 2) by high-flowing the engine (i.e., increasing the rotational speed of the compressor) to accept the higher inlet airflow. Another new but untested alternative to oversizing the inlet is to admit additional auxiliary airflow through the cowl, as shown in Fig. 8. In this example, outside cowl doors are opened to allow transonic ram airflow to diffuse through the bypass takeoff screens to the engine face. In this design, a subsonic diffuser is used to prevent sudden expansion total-pressure losses in the bypass plenum chamber which would tend to prevent induction of the cowl airflow into the high-pressure main-duct engine-face airflow.

**For the untested auxiliary airflow inlets, the transonic performance with $M_{th} = 0.85$ will probably be lower than that of the tested inlets,[4,6] because of the more complex passageways that the auxiliary airflow must navigate. However, with the greater flow area available, transonic engine matching may be possible with lower M_{th}, resulting in lower losses in the airflow passageways and thus allowing performance levels comparable to the tested inlets. At cruise, engine-face performance should be comparable to the tested inlets,[4,6] because the supersonic diffusers are similar and the subsonic diffusion rates are about the same.

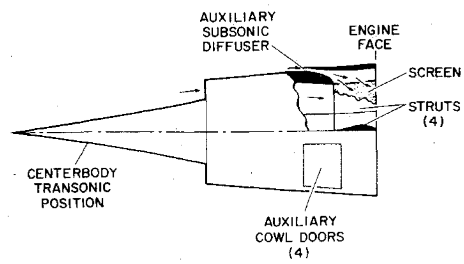

Fig. 8 Cowl auxiliary airflow.

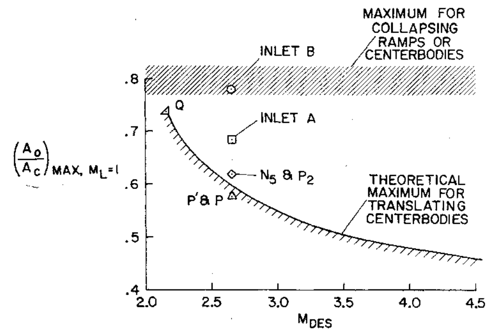

Fig. 9 Transonic airflow characteristics.

Transonic Airflow Characteristics

Only the transonic airflow characteristics of selected inlets up to Mach number 2.65 have been presented. To provide a greater perspective, the transonic airflow prospects for inlets designed for high Mach numbers are shown in Fig. 9. The estimated trend of the maximum capture mass-flow ratio at Mach number 1.0 for the types of inlets discussed is plotted as a function of design Mach number. The maximum capture mass-flow ratio for each of the inlets discussed also is shown. The trend for axisymmetric inlets is the theoretical maximum[7] without auxiliary airflow systems. Although the two-dimensional inlet A shows only 0.685 mass-flow ratio, whereas the axisymmetric inlet B showns a considerably higher mass-flow ratio of 0.780, the collapsing ramp and centerbody systems, as mentioned before, still can offer comparable airflow capability. Furthermore, high mass-flow ratio throughout the design Mach number range shown is a characteristic of collapsing systems.

For axisymmetric inlets with translating centerbodies, capture mass-flow ratio tends to decrease with increasing design Mach number. However, this characteristic is not necessarily a detriment to engine matching, since inlet capture areas tend to become larger in diameter than the engine-face diameter, and the transonic engine demand decreases in terms of capture mass-flow ratio, partially or entirely compensating for the relatively low transonic mass-flow capability of axisymmetric inlet systems.

Concluding Remarks

We have seen that two-dimensional and axisymmetric inlet systems with collapsing geometry can match the transonic demands of most jet engines. However, the practicality of collapsing geometry for axisymmetric inlets is presently doubtful. Therefore, translating centerbody axisymmetric inlet systems with auxiliary airflow systems may be considered as likely alternatives if high transonic airflow capability is required. Both centerbody and cowl auxiliary airflow systems seem to be reasonable means for increasing transonic airflow, and both means may be needed for matching variable-cycle jet engines.

References

[1] "Supersonic Transport Development Program, Phase III Proposal," Lockheed-California Co., Burbank, Calif., Vol. II-E Propulsion Rept. Book 1 of 3, Rept. 19841, Sept. 1966.

[2] "Commercial Supersonic Transport Proposal," Propulsion A-VI, The Boeing Company, Seattle, Wash., Rept. D6-2400-12, Jan. 15, 1964.

[3] Sorensen, N.E. and Bencze, D.P., "Possibilities for Improved Supersonic Inlet Performance," *Journal of Aircraft*, Vol. 11, May 1974, pp. 288-293.

[4] Syberg, J. and Koncsek, J.L., "Transonic and Supersonic Test of the SST Prototype Air Intake," Federal Aviation Agency, Washington, D.C., FAA-55-72-50, April 1972.

[5] Tjonneland, E., "The Design, Development and Testing of a Supersonic Transport Inlet System," *NATO/AGARD 38th Meeting of Propulsion and Energetics Panel*, Paper 18, Sept. 1971, Sandefjord, Norway.

[6] Koncsek, J.L. and Syberg, J., "Transonic and Supersonic Test of a Mach 2.65 Mixed-Compression Axisymmetric Intake," NASA CR-1977, March 1972.

[7] Smeltzer, D.B. and Sorensen, N.E., "Analytic and Experimental Performance of Two Isentropic Mixed Compression Axisymmetric Inlets at Mach Number 0.8 to 2.65," NASA TN D-7320, June 1973.

[8] Driver, C. "Advanced Supersonic Transport Design Developments," AIAA Paper 74-987, Los Angeles, Calif., 1974.