SUPERSONIC CRUISE INLETS FOR VARIABLE-CYCLE ENGINES

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SUMMARY

Variable-cycle engines have the potential to operate very efficiently over the wide speed range of a supersonic cruise aircraft. However, to choose the optimum installed variable-cycle engine, it is necessary to determine its performance when matched to a specific inlet. The performance of candidate supersonic cruise inlets is reviewed and the aerodynamic installation penalties for each type are defined. The main characteristics that affect the airflow schedules of variable-cycle engines are defined. These schedules are compared with the airflow schedules of the candidate inlets, and appropriate inlets are matched to the variable-cycle engine characteristics. Auxiliary inlets are also considered.

INTRODUCTION

Variable-cycle engines (VCE's) have the potential ability to operate more efficiently over the wide speed range of a supersonic cruise aircraft. In their various forms, they also have the ability to improve the matching of airflow schedules between the inlet and the engine and thereby to reduce the penalties normally associated with airframe installation. Since the characteristics of the available inlet and VCE types differ significantly, it is necessary to consider how the inlet and engine cycle characteristics complement each other before an optimum propulsion system can be defined. Prior to variable-cycle engines, the engine airflow schedule was presented to the inlet designer, who did his best to match it with an inlet that would incur the lowest performance penalties. More recently, the engine companies have been matching their engines to the characteristics of particular inlets. Neither approach is likely to lead to an optimum propulsion system. As a start in the search for the optimum, the characteristics of the existing supersonic cruise inlet types are reviewed and matched with the major cycle characteristics of the most promising variable-cycle engines.

INLET CHARACTERISTICS

Inlets whose characteristics are representative of those currently being considered for supersonic cruise applications are shown in figure 1. They are either axisymmetric or two dimensional with collapsing or translating centerbodies to provide throat area variation with Mach number. Conceptually, the collapsing axisymmetric inlet would have a centerbody that collapses from the beginning of the second cone to a station near the engine face inside the subsonic diffuser. This would require the circular centerbody to be constructed of overlapping leaves and seals, which would be mechanically complex but potentially feasible. In the collapsing double-wedge inlet, the centerbody consists of ramps. These can be more easily sealed and actuated but tend to be heavier because of the less desirable structural characteristics of flat cowling. Potentially the simplest mechanically is the axisymmetric inlet with a translating centerbody to provide throat area variation. This inlet should be lightweight because of its simple variable-geometry system and its structurally efficient circular shape.

Some of the characteristic aerodynamic properties of the different inlet types are associated with their percentages of internal compression (fig. 2). This term is defined as that portion (in percent) of the total supersonic area contraction from the free stream to the inlet throat that occurs inside the cowl lip at the design Mach number. Therefore, if the cowl-lip circular area is taken as the free-stream flow area, the percentage of internal contraction is 100 times the difference in the annular flow area between the cowl lip and the throat, divided by the difference between the cowl-lip circular area and the throat area.

With zero internal compression (or all external compression) the inlet throat is at the cowl lip. To achieve supersonic compression, the centerbody must turn the flow to high angles relative to the inlet axis in order to achieve a low throat Mach number. The high cowl-lip angle necessary to capture that flow incurs a large cowl drag. Therefore, to reduce the cowl drag to an acceptable level for supersonic cruise, the external compression or turning is reduced so that a relatively flat cowl can capture the flow and turn it efficiently back toward the inlet axis. With about 45-percent internal compression, the flow will be turned back to a throat with its cowl radius about equal to the cowl-lip radius. This is the location desired for a collapsing-centerbody inlet so that maximum throat area can be obtained in the collapsed position. However, for a translating-centerbody inlet, the cowl-throat radius must be significantly smaller than the cowl-lip radius so that the resulting smaller centerbody will provide an increased throat area when it is translated out to the cowl lip. Internal compression of the order of 80 percent is required to obtain the maximum off-design throat area for a translating-centerbody inlet.

At 45 percent internal compression, the flow is still turned to a relatively high angle by the centerbody. With an axial or cylindrical cowl, a relatively strong oblique shock forms at the cowl lip to turn the flow back axially. There is an associated loss in total-pressure recovery. If the cowl angle is increased to reduce the recovery loss, cowl-lip wave drag is also increased. There is a cowl-lip angle that provides an optimum trade-off between recovery and drag at each value of internal compression. Figure 3 shows the effect of internal compression on total-pressure recovery and cowl drag for the optimum cowl-lip angle at Mach 2.4. The ideal total-pressure recovery includes only the losses associated with the inlet shock structure. The cowl-lip wave drag considered here is only that associated with the immediate lip region before the external angle can be reduced to some nominal value required to reach the maximum nacelle diameter. Cowl-lip wave drag downstream of this point is assumed to be offset by favorable interference with the wing. For the variable-cycle engine used in the study, the optimum internal cowl angle was the minimum angle of 0° for internal compression greater than 45 percent. The resulting low external cowl angle is close enough to the nominal nacelle angle that any cowl-lip wave drag can be recovered through favorable interference. Therefore, only cowl-lip wave drag in excess of 0.0075 is considered a penalty for installed performance. Below 45-percent internal compression the internal cowl angle had to be increased to the minimum value required to prevent subsonic flow upstream of the throat. The higher cowl angles resulted in increased drag.

High inlet total-pressure recovery and low cowl-lip wave drag favor high internal compression, where the cowl-lip angle can be low and the cowl-lip oblique shock weak. However, the bleed flow for the inlet has not yet been considered. The inlet bleed correlation of reference 1 has shown that, for previously tested inlets, the bleed flow can be related only to the ratio of inlet internal wetted area to throat area. Also, the correlation shows that inlet wetted area increased with increasing internal compression. The effect of inlet recovery, cowl-lip wave drag, and bleed on installed cruise specific fuel consumption (sfc) is presented in figure 4. The cruise sfc increase is based on the cowl-lip wave drag of figure 3, the bleed flow predicted by the correlation of reference 1, and the ideal total-pressure recovery of figure 3, reduced by 0.04 to account for viscous losses. The total increase of 10 to 15 percent is based on a Lewis version of the variable-stream-control engine. This large increase in sfc is due to the specific thrust of this type of engine being about half that of the turbojets considered before FAR 36 noise constraints were imposed. As can be seen from the variation of sfc with percentage of internal compression for axisymmetric inlets, the increased bleed at high internal compression partially offsets the better total-pressure recovery. Therefore, an axisymmetric collapsing-centerbody inlet at 45-percent internal compression would provide an installed sfc about 0.013 higher than that provided by a translating-centerbody inlet at 80-percent internal compression. Some other features of low-internal-compression inlets that tend to offset this modest penalty are better angle of attack tolerance and a smaller unstart transient.

The correlation of inlet wetted area in reference 1 also showed that previously designed two-dimensional inlets had considerably more wetted area than equivalent axisymmetric inlets. In figure 4, the increase in bleed due to added wetted area penalized the two-dimensional inlet about 0.025 in installed sfc. The level presented assumes similar pressure recovery and no cowl-lip wave drag that cannot be recovered through favorable interference with the wing.

INLET/ENGINE AIRFLOW MATCHING

To understand the airflow matching of the inlet and the engine, it is first necessary to look at the airflow characteristics produced by the major VCE features. These are constant-speed and inverse throttle schedules and the double-bypass mode of operation for takeoff. The airflow characteristics are presented in figure 5, along with the engine mechanical and corrected speeds, as a function of Mach number. The values are presented as a fraction of their value at Mach 1. For the constant-speed throttle schedule, the engine mechanical speed is constant over the Mach number range, except at takeoff where the speed is increased about 5 percent. The corrected speed varies a little subsonically as the temperature changes with aircraft acceleration and climb. However, as the aircraft accelerates supersonically to the supersonic cruise Mach number of 2.32, the increased temperature reduces the corrected speed to about 0.8 of the value at Mach 1. The airflow at constant speed remains essentially constant subsonically but drops to about 0.62 of its Mach 1 value at the cruise Mach number of 2.32. With the inverse throttle schedule, mechanical speed is varied subsonically to retain constant corrected speed. During supersonic acceleration the low rotor speed is increased with Mach number until a 10-percent increase is provided at supersonic cruise. This still allows the corrected speed and airflow to decrease but increases the flow at cruise significantly over the constant-speed throttle schedule. This increased flow will require a larger inlet. The third characteristic, double bypass, changes the engine cycle at takeoff to pump more airflow to alleviate jet noise. The flow increase in this case is 15 percent, but other values have also been considered.

To determine the effect of these airflow schedules on inlet airflow matching, the matching of a constant-speed throttle schedule to a translating-centerbody inlet is considered in figure 6. The inlet area is presented as a portion of the engine-face annular flow area. The upper curve presents the capture area for an inlet designed to just provide the engine airflow at each Mach number. The lower curve presents the maximum throat area obtainable with that translating-centerbody inlet. This maximum throat area is obtained by sizing the centerbody so that, when it is translated forward, the flow area between the cowl lip and centerbody is just equal to the flow area between the cowl and the centerbody support tube. The required inlet capture area varies from 0.73 of the engine-face area at Mach 1 to 1.38 at Mach 3. Comparing the maximum throat area at each Mach number with the required area of 0.73 at Mach 1 shows that a translating-centerbody inlet will provide adequate throat area for design Mach numbers of 2.7 and above. However, for the cruise Mach numbers of current interest, between Mach 2.0 and 2.5, inadequate throat area is available. Therefore, such an inlet/engine combination would require auxiliary inlets in the transonic speed regime.

In figure 7, the capture and throat areas required for matching an inverse throttle schedule engine are added to figure 6. The increased airflow demand of the inverse throttle schedule requires a larger inlet capture area at the cruise Mach number. This increased inlet size increases the throat area enough to provide adequate transonic flow for engine matching. Therefore, the translating-centerbody inlet provides a good airflow match for the inverse throttle schedule engine.

To look at the airflow matching in more detail, figure 8 compares the variation of airflow with Mach number for inlets with collapsing and translating centerbodies. The design Mach number for the inlets is 2.32. When operating with supersonic internal flow at Mach numbers below the design value, the translating centerbody moves forward relative to the cowl lip. More flow is spilled than by an inlet with a centerbody that collapses in place. Therefore, because of its larger spillage, the translating-centerbody inlet provides less flow for the engine than the collapsing-centerbody inlet. Both axisymmetric and two-dimensional collapsing-centerbody inlets provide similar airflow schedules. The inlets cannot operate with internal supersonic flow at Mach numbers below 1.5, and below this Mach number the flow is governed by the maximum inlet throat size. Here again, the collapsing-centerbody inlet can provide more flow than the translating-centerbody inlet because of its larger throat area.

Figure 9 superimposes the engine flow requirements on the inlet airflow schedules. Again comparing the constant-speed throttle schedule with the translating-centerbody inlet, it is apparent that the inlet would need auxiliary inlets not only for extra flow at transonic speeds but also for speeds up to about Mach 2. A much better match for the constant-speed throttle schedule appears to be provided by the collapsing-centerbody inlet. Therefore, this conventional engine speed schedule appears to require a collapsing-centerbody inlet for design Mach numbers in the 2.0 to 2.5 range. A comparison of the inverse throttle airflow schedule with the translating-centerbody airflow schedule also shows a good match. Therefore, these two throttle schedules require different inlet types.

Another airflow matching problem occurs during takeoff, where the inlet must collect flow from a wide area. Normally either a bellmouth or the blunt lips of a subsonic inlet are available to collect the necessary flow and turn it toward the engine. However, the sharp inlet lips necessary for low drag at supersonic cruise conditions can only collect a portion of the flow required by the engine during static operation and takeoff. This problem is illustrated in figure 10. The critical parameter for this condition, the inlet mass flow divided by the mass flow necessary to choke the inlet throat at ambient total pressure and temperature, is plotted on the ordinate. Both the inverse and constant-speed throttle schedules require 0.9 of the choked flow of the translating- and collapsing-centerbody inlets, respectively. The double-bypass cycle requires 1.05 of the choked flow. Also plotted on the figure are lines of constant total-pressure recovery obtained from reference 2. As the inlet gains forward speed, the momentum of the captured flow is more alined with the inlet axis, allowing more flow to be collected by the sharp-lip inlet at a given total-pressure recovery. At Mach 0.1 for takeoff, the propulsion system should provide maximum thrust so that a high total-pressure recovery is required to minimize engine weight. If a total-pressure recovery of about 0.98 is assumed, the mass flow ratio cannot be greater than 0.45. Therefore, half of the conventional engine airflow requirement at takeoff has to be provided by an auxiliary inlet system. To provide the extra flow required by the double-bypass engine, the auxiliary inlet system will have to provide 57 percent of the engine airflow, or 132 percent of the main inlet flow.

At Mach 0.3 to 0.4, the fan noise will probably have to be suppressed to meet the flyover noise requirements. This can be accomplished with the conventional cycles by choking the main inlet, which can provide high recovery at that Mach number without auxiliary inlets. However, the increased flow requirement of the double-bypass engine would require choking the auxiliary and main inlet systems, which would incur added complexity. An alternative solution would be to reduce the engine airflow to the normal level before the flyover point is reached.

CONCLUSIONS

The characteristics of axisymmetric and two-dimensional inlets with collapsing or translating centerbodies have been compared with the requirements of variable-cycle engines with constant-speed or inverse throttle schedules and/or double-bypass features. The following conclusions were reached:

1. An engine with a constant-speed throttle schedule will require a collapsing-centerbody inlet for cruise Mach numbers between 2.0 and 2.5.

2. An engine with an inverse throttle schedule matches a mechanically simpler translating-centerbody inlet.

3. If a total-pressure recovery of 0.98 is assumed at takeoff, the larger airflow of the double-bypass engine requires the airflow of the auxiliary inlet system to be increased from 100 percent to 132 percent of the main inlet airflow.

4. At the flyover condition, fan noise suppression for the double-bypass engine will require choking both the main and auxiliary inlet systems or reducing the double-bypass engine airflow to the conventional engine airflow that can be supplied by the main inlet.

REFERENCES

1. Bowditch, D. N.: Some Design Considerations for Supersonic Cruise Mixed-Compression Inlets. AIAA Paper 73-1269, Nov. 1973.

2. Fradenburgh, Evan A.; and Wyatt, DeMarquis D.: Theoretical Performance Characteristics of Sharp-Lip Inlets at Subsonic Speeds. NACA TN 3004, 1953.

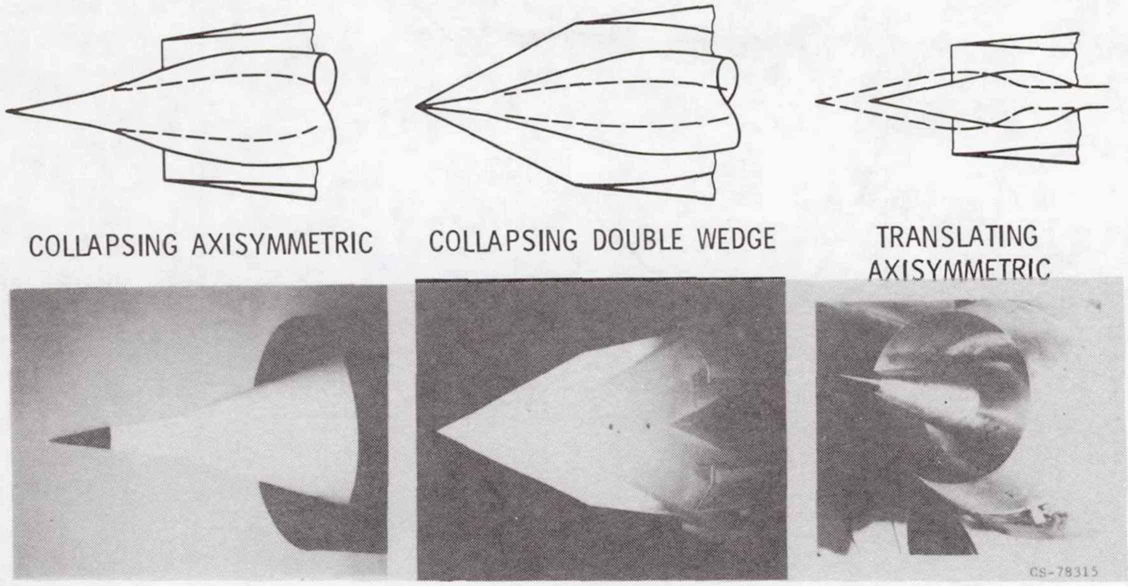
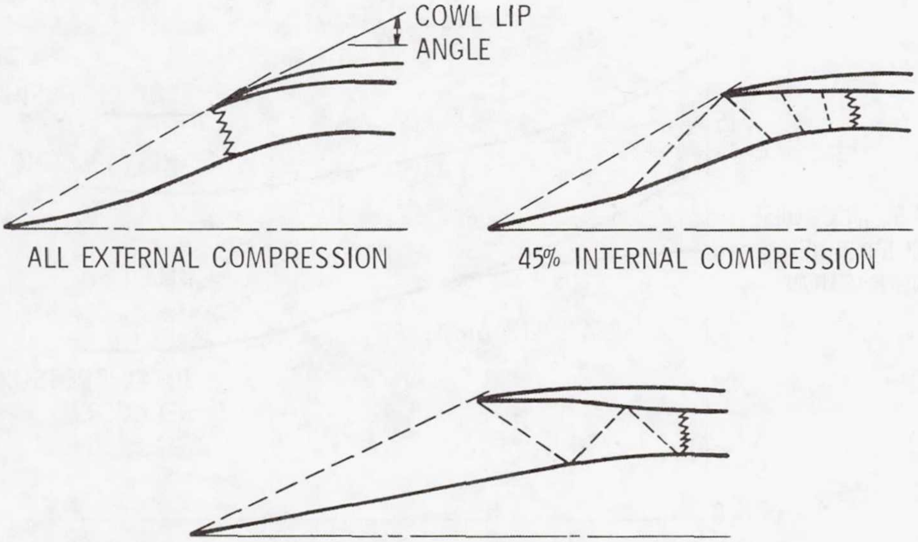
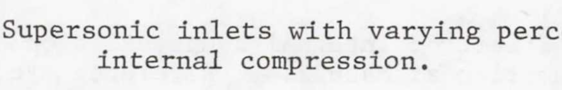


Figure 1.- Inlet concepts for use on supersonic cruise aircraft.



ALL EXTERNAL COMPRESSION

45% INTERNAL COMPRESSION



80% INTERNAL COMPRESSION

Figure 2.- Supersonic inlets with varying percentages of internal compression.

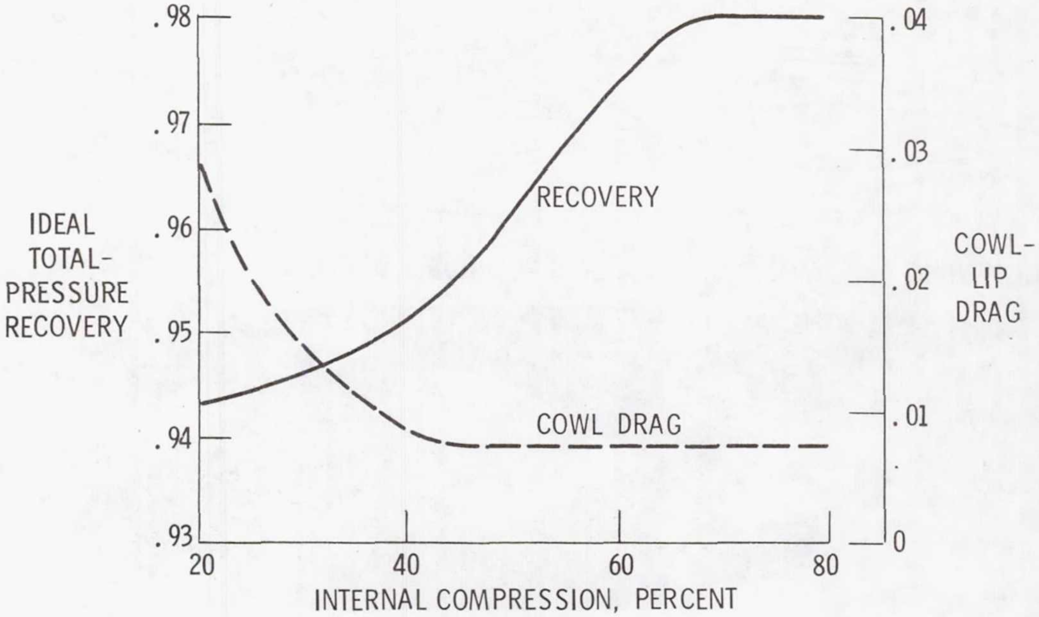


Figure 3.- Effect of internal compression on total-pressure recovery and cowl-lip wave drag at Mach 2.4.

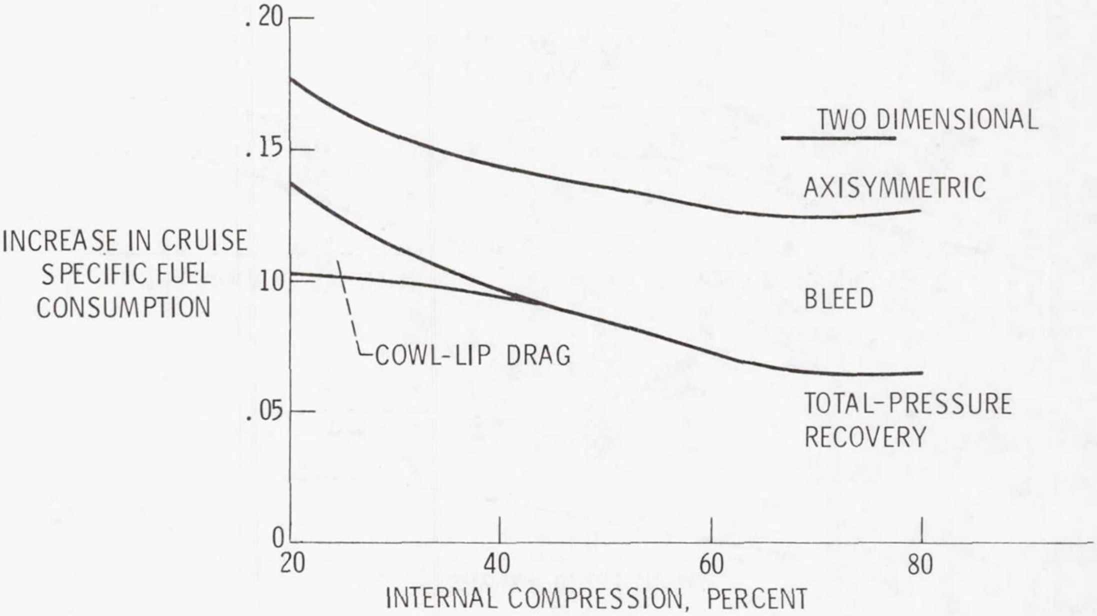


Figure 4.- Effect of internal compression on specific fuel consumption at Mach 2.4. Reference sfc, 1.19.

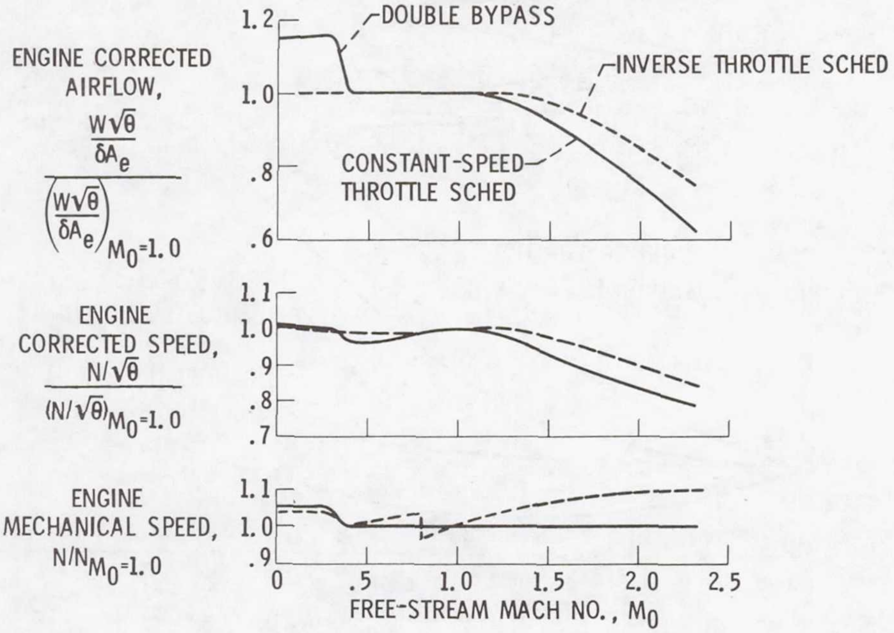


Figure 5.- Airflow characteristics of variable-cycle engines.

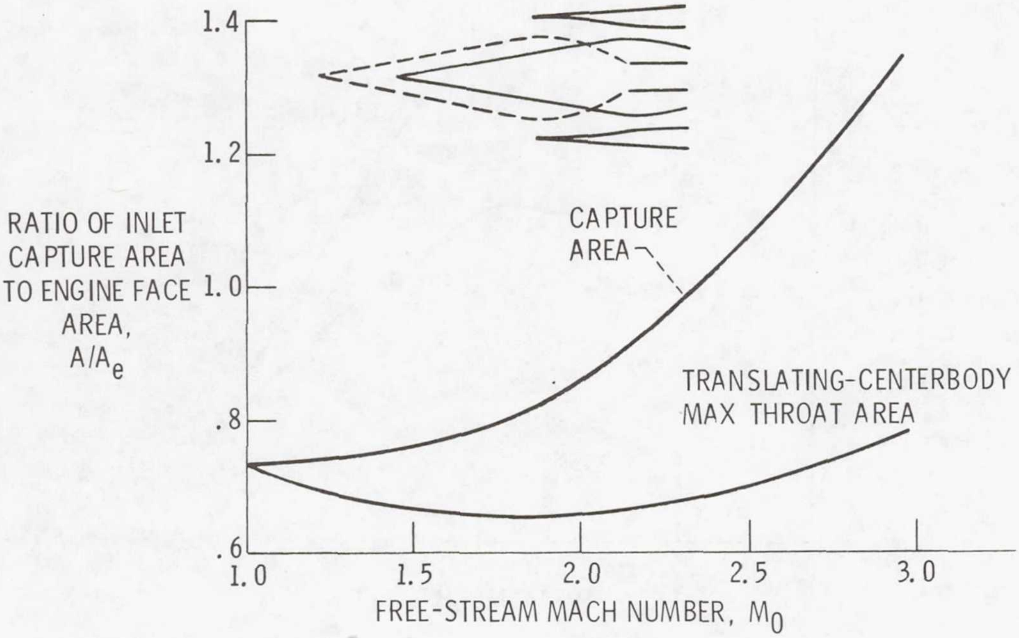


Figure 6.- Transonic airflow matching of constant-speed throttle schedule and translating-centerbody inlet.

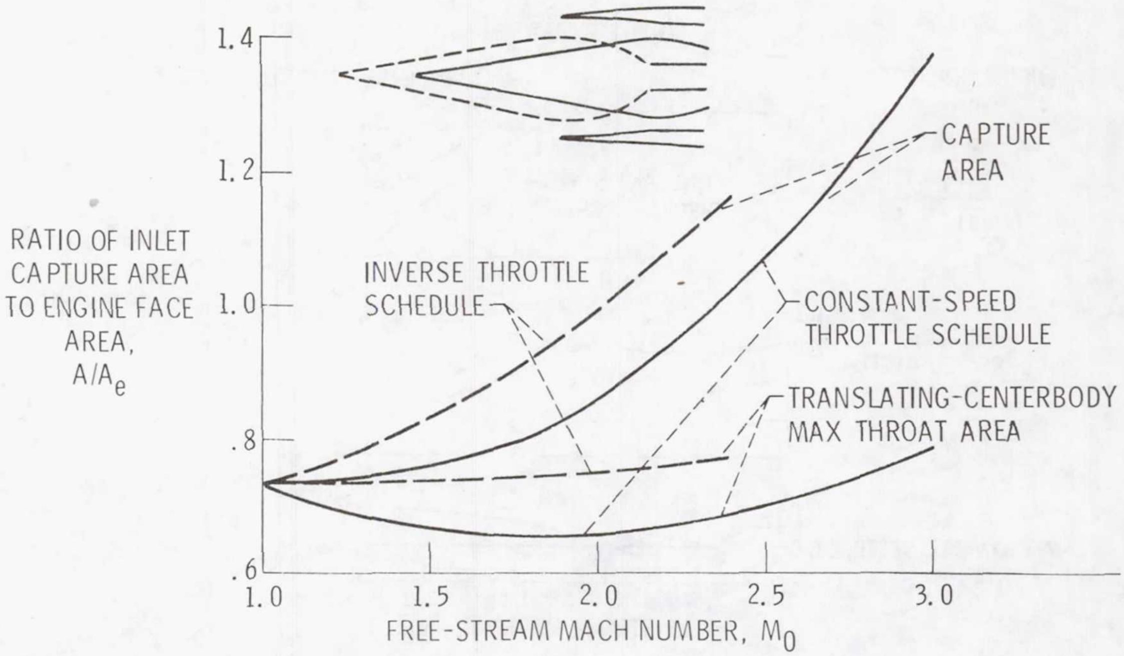


Figure 7.- Transonic airflow matching of inverse throttle schedule and translating-centerbody inlet.

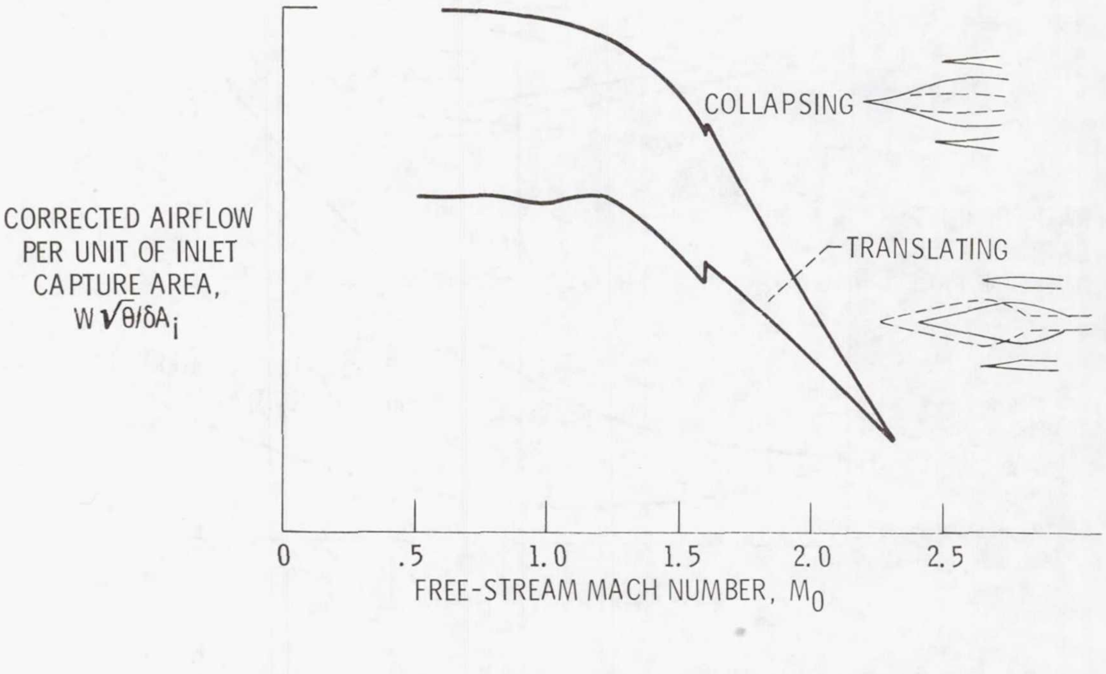


Figure 8.- Variation of airflow with Mach number for translating- and collapsing-centerbody inlets.

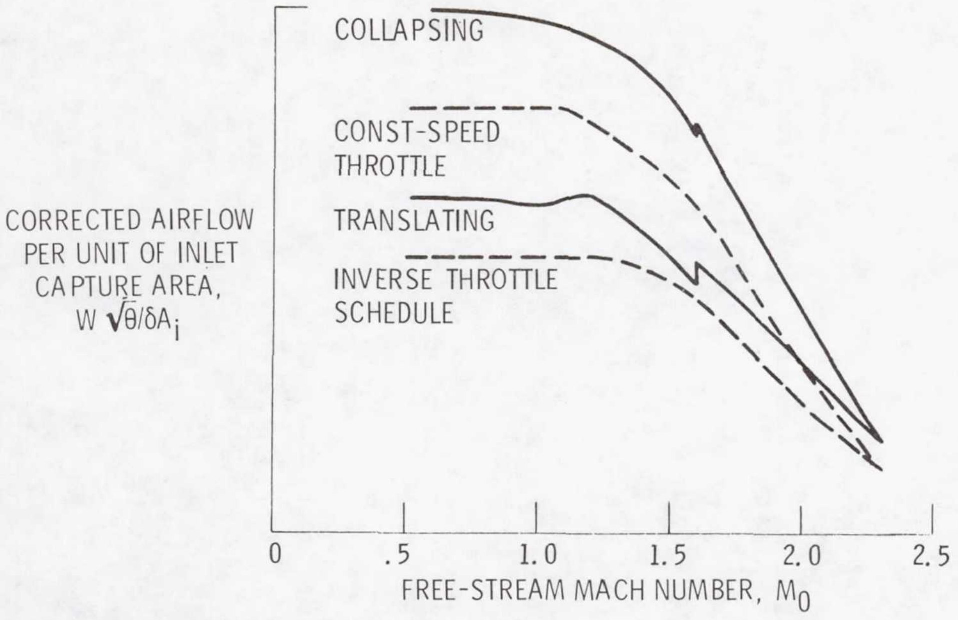


Figure 9.- Inlet/engine matching.

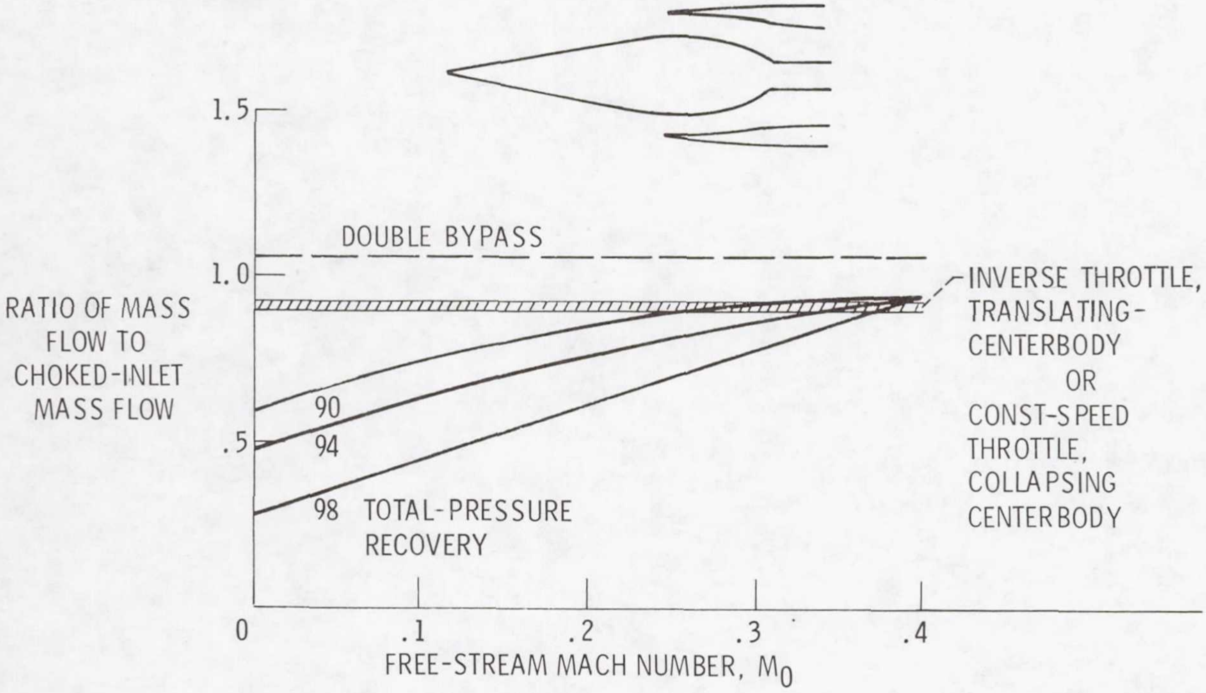


Figure 10.- Low-speed airflow matching.