13. SONIC-THROAT INLETS

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SUMMARY

An investigation of the sonic-throat inlet as a means of reducing the noise of turbofan-powered transport airplanes has been conducted. Of several concepts considered, the variable cowl inlet was selected for further evaluation in both model and full-scale boilerplate inlet configurations. Both model and full-scale test results of an eight-segment variable cowl inlet are presented. Substantial reduction of the forward-radiated discrete frequency fan noise has been achieved at inlet-center-line Mach numbers of 0.7 to 0.8 when operating at two simulated approach power conditions. A mechanized and controllable full-scale inlet configuration for future evaluation is also described.

INTRODUCTION

With the advent of turbofan-powered commercial airplanes, the exposure of communities surrounding major airports to aircraft noise has increased substantially. It has been found that the discrete frequencies associated with the fan are a major contribution to the noise particularly during landing approaches. The discrete frequencies are propagated forward through the inlet, as well as rearward through the fan discharge ducts. Thus, an effective noise reduction program must provide substantial attenuation of the noise propagating along each path.

If only noise propagating forward through the inlet is considered, two distinctly different solutions to the problem are available – namely, (1) insertion of acoustically absorbent panels in the path of propagation or (2) creation of a high velocity flow region to oppose the forward propagation of fan-generated noise within the inlet. If the velocity of the air entering the inlet becomes sonic, sound cannot pass forward through the inlet. Maximum attenuation is obtained when all the flow reaches sonic velocity; however, useful attenuation may still be obtained if the flow attains velocities near the sonic value.

In order to obtain these high velocities, it is necessary to reduce the flow area at some station within the inlet. The sonic or near-sonic velocities occur near the region of minimum area within the inlet; thus, an inlet of this type is designated a "sonic-throat inlet." Figure 1 illustrates the operation of a sonic-throat inlet as contrasted with that of a conventional inlet.

Tests conducted by The Boeing Company (and others) with both model-scale and full-scale inlets indicated that substantial reduction of forward propagating noise was attainable in practice with sonic-throat inlets. Accordingly, The Boeing Company (under NASA Contract NAS1-7129) is now engaged in an extensive program to evaluate and develop the sonic-throat inlet for possible application to large turbofan-powered airplanes. These efforts are described in this paper.

CONCEPTS

Although the sonic-throat inlet is not new, this program represents one of the first attempts to develop an inlet of this type within all the constraints of a practical and viable airplane application. Initial efforts were directed toward definition of the design constraints and selection of promising concepts to satisfy these constraints.

Design constraints established initially in the program included a target of a 15-PNdB reduction in noise during approach, no compromise of safety of flight, and no increase in crew workload. In addition, it was desired to maintain an economically viable airplane.

Other and more detailed design constraints became apparent as the design studies proceeded. Structural limitations associated with the engine were found which prevented use of an inlet longer than 50 inches. The constraint on inlet length was accompanied by a requirement to provide noise suppression at a minimum approach thrust of approximately 3000 pounds per engine. The minimum thrust value then dictated the minimum airflow at which sonic or near-sonic velocities must be attained in the throat region. The throat area which will provide these velocities at minimum approach thrust was found to be approximately 750 square inches, compared with a nominal throat area of 1570 square inches required for cruise operation. Thus, the inlet design problem became basically that of providing an inlet 50 inches long in which the throat area could be varied from 750 to 1570 square inches while providing flow of the quality demanded by the engine for satisfactory operation.

Consideration of the quality of flow required at the engine resulted in two additional constraints upon inlet design. First, the pressure recovery at the engine face must be sufficiently high and uniform to insure engine operation without surge. Second, the disturbances introduced into the flow by the inlet must be compatible with the fan blade vibrational characteristics.

Many sonic-throat-inlet concepts were considered, but all these concepts could be grouped into one of the three general types (or combinations thereof) shown in figure 2. Each concept appeared to offer certain advantages and disadvantages when compared on the basis of performance, weight, cost, controllability, safety, reliability, and maintainability. It was believed that, with sufficient development, each of the three inlet concepts (i.e., variable cowl, variable center body, and retractable vanes) could provide the desired noise attenuation and aerodynamic performance. However, the variable cowl inlet appeared to offer advantages with respect to the aerodynamic and mechanical design of a sonic-throat inlet, and it was selected for full-scale development.

Advantages found for the variable cowl inlet include an internal flow distribution with high velocities near the cowl wall, least disturbance of the core flow entering the gas generator portion of the engine, adaptability to boundary-layer control, and a geometric arrangement favorable for the mechanical actuation and sealing of the variable geometry components. Experience gained in other full-scale inlet tests prior to the concept selection date also weighed heavily in favor of the variable cowl inlet. Inlet models illustrating the selected concept are shown in figure 3.

SMALL-SCALE MODEL PROGRAM

Tests of a number of sonic-throat-inlet models were conducted by The Boeing Company prior to entering into contract with NASA. These models were

8.50, 14°, 20°, and 29° non-BLC diffusers
29° diffuser with one BLC blowing slot
22° diffuser with two BLC blowing slots
Peripheral choking
Radial vanes (8, 12, 16, 48, and 96)
11° diffuser (long five-door)

Very encouraging results (fig. 4) were obtained with one of the early models tested. This inlet model was characterized by a maximum diffuser angle of 8.50, measured between the diffuser wall and the longitudinal axis of the inlet. Significant and encouraging results were obtained also with boundary-layer control (BLC) applied to inlets with short, high-angle diffusers.

Additional model tests to assist in the definition and evaluation of inlet configurations suitable for full-scale development were conducted during the present program. The small-scale inlet models were evaluated by the use of one or more of the following facilities of The Boeing Company:

(1) Ejector Rig

(2) Powered Model Fan

(3) Low-Speed Wind Tunnels

(4) High-speed Wind Tunnels

(5) Water Table

The ejector rig facility provided a means of inducing airflow through the static model, together with means for measuring static-pressure distributions along the cowl wall and inlet total pressure recoveries at the simulated engine face. The powered model. fan used a single-stage inducer section from a Boeing T-50 gas turbine to simulate turbofan operation behind a sonic-throat inlet. The powered model fan and its air-driven turbine were enclosed within an anechoic chamber, and measurements of the noise emanating from the inlet were made with a boom-mounted microphone for a range of fan speeds and inlet-throat velocities. Tests in these facilities provided information on both noise attenuation and internal aerodynamic performance of inlet models.

Other tests were conducted with small-scale inlet models in both low-speed (up to 200 knots) wind tunnels and in high-speed subsonic wind tunnels (up to Mach number 0.9) both at Cornell Aeronautical Laboratories, Inc., and Boeing. Except for the high-speed wind-tunnel tests (which were 1/8 and 1/15 scale), all models tested were approximately 1/9 scale, based upon an engine face diameter corresponding to the JT3D-3B engine. Tests in the low-speed wind tunnels provided information with respect to internal performance of the inlets and effects of lip geometry upon inlet operation during take-off simulation. The high-speed wind-tunnel tests provided information with respect to the aerodynamic performance of external and internal cowl contours during simulated cruise conditions. All high-speed models utilized "flowthrough" nacelles in which the inlet airflow (and thus stream tube capture area) was varied by means of a movable plug at the discharge nozzle of the nacelle model.

Also, tests of two-dimensional inlet models were conducted on a large water table. These tests permitted observation of the general flow characteristics of several inlet configurations. The water-table tests were also used to supplement analytical studies of suction and blowing boundary-layer control as applied to the diffuser of the inlet.

The various types of small-scale inlet models evaluated in the present program are as follows:

24 retracting vanes
Variable center body
Eight-segment variable cowl:
  Non-BLC (750 sq in. throat area, full scale)
  BLC (750, 900, and 1370 sq in. throat area, full scale)
  Take-off
  Simulated cruise (internal only)
Cruise cowl (flow nacelle)

Following selection of the variable cowl inlet concept for full-scale boilerplate development, 1/9-scale inlet models simulating the take-off, cruise, and approach modes of operation were evaluated. Photographs of these models are shown as figures 5, 6, and 7. Boundary-layer-control blowing slots were incorporated in the models intended for use in the acoustic evaluations.

Noise reduction obtained with the eight-segment variable cowl inlet model simulating an approach configuration with a minimum throat area of 750 square inches is shown in figure 8. Results indicate that substantial noise reduction and high inlet recoveries were attained with boundary-layer-control blowing flow approximating 4 percent of inlet airflow. Also, low internal losses were measured with the inlet during cruise simulation. The low-speed wind-tunnel tests indicated that an extended inlet lip would improve inlet performance during static and low-speed take-off operation. Other results obtained in the high-speed wind tunnels indicated that the NACA 1-series external cowl contours would provide low drag during cruise.

Comparison of results from small-scale model and full-scale inlet tests shows excellent agreement. The model inlets have reproduced nearly all important aerodynamic and acoustic characteristics of the full-scale inlets.

BOILERPLATE/PROTOTYPE INLET TESTS

Although some experience with sonic-throat inlets had been acquired by The Boeing Company (and others) prior to the current program, nearly all this experience was related to operation with turbojet engines as opposed to turbofan engines. Because it was suspected that turbofan engines may be more critical with respect to inlet losses and distortion, it was desired to acquire experience with a turbofan engine operating behind a sonic-throat inlet early in the program. Tests were first conducted with a variable cowl inlet configuration installed on a JT3D-1 prototype engine. These initial tests verified that operation was indeed critical with the JT3D-1 engine, with surge encountered near throat Mach numbers of 1.0.

The inlet tested initially was approximately 70 inches long, with a distance between the throat and engine face of 57 inches. Minimum geometric throat area was 928 square inches. This inlet, which was designated the "five-door inlet," consisted of five movable doors separated and supported by five V-shaped longitudinal struts or "prongs." (See fig. 9.) The diffuser was designed with a maximum angle of 11° between the cowl wall and the longitudinal axis of the inlet; the equivalent conical diffuser angle (based upon inlet and exit area and diffuser length) was 6.7°.

As originally designed, the five-door inlet had no provision for boundary-layer control of the diffuser. Following engine surge difficulties encountered in the initial tests, a series of modifications were made in order to improve the flow entering the engine. The modifications included installation of vortex generators at various locations in the inlet, installation of an improved entrance lip, careful sealing of various joints, and installation of a T-shaped angle on the ground in front of the inlet to destroy or reduce the ground vortex which was formed at the higher airflows. Of these items tested, use of vortex generators at strategic locations within the inlet proved most effective; however, none of these modifications would permit operation at a fully sonic condition.

The inlet was subsequently modified for suction boundary-layer control, then later modified again for blowing boundary-layer control. Suction boundary-layer control proved to be ineffective, but blowing boundary-layer control proved to be particularly effective and fully sonic operation was achieved. The reduction of fan noise obtained during these tests is presented in figure 10.

In the interval following design of the five-door inlet, analyses of the structural limitations of the engine had proceeded sufficiently to establish a maximum length of 50 inches as an acceptable value for the inlet. Also, further consideration of the blade vibratory stresses indicated that eight excitations per revolution were preferable to the five excitations of the five-door inlet. These new design criteria were then integrated with the design experience obtained with the five-door inlet, and a completely new inlet design resulted which was designated the "eight-segment inlet." The eight-segment inlet was characterized by a diffuser 28 inches long, revised contours of the fixed supports, and two boundary-layer-control blowing slots installed downstream of the throat. The diffuser had a maximum angle of 21° between the cowl wall and the longitudinal axis of the inlet and an equivalent conical diffusion angle of 17°, based upon diffuser inlet and exit areas and diffuser length. Minimum throat area attainable with this inlet was 750 square inches.

Two configurations of the eight-segment inlet have been evaluated. In the first configuration (fig. 11), the inlet was constructed of fiber glass with steel inserts for the boundary-layer-control slots and other fittings, The throat area was fixed at 750 square inches, the segments were straight-line elements which formed an octagon-shaped passage through the inlet, and the boundary-layer-control slots were continuous in a circumferential direction. The slots were designed with removable plates that permitted variation of the slot openings from 0.114 to 0.25 inch in height for the front slot and 0.09 to 0.20 inch in height for the aft slot. This configuration served to verify the feasibility of the design concept and to investigate the boundary-layer-control blowing requirements for maintaining attached flow.

Tests of the fiber-glass fixed-throat inlet were quite encouraging, with best results obtained by the use of the larger boundary-layer-control slot sizes. It was also determined that a single boundary-layer slot was sufficient for controlling flow in the diffuser. Limited acoustic measurements obtained with this inlet were also encouraging, and it was decided to proceed with a complete evaluation of an adjustable boilerplate inlet on a specifically prepared acoustic test facility.

Cross sections of the boilerplate inlet with eight manually adjustable segments are shown in the minimum area approach (fig. 12) and take-off (fig. 13) configurations, while corresponding views of the inlet installed on a JT3D-3B engine are shown in figures 14 and 15. Results were again encouraging, with the fan noise reduced by approximately 17 to 20 decibels for Mach numbers of 0.7 or greater, as measured on the center line of the inlet.

As shown in figure 16, the results indicate that the noise levels decreased rapidly with inlet-center-line Mach numbers up to 0.8. Operations at higher Mach numbers did not result in significantly greater attenuation because of the presence of a noise floor due to other sources. Similar results were obtained with inlet throat areas of 750 and 900 square inches, and it is believed that a family of similar curves will exist for the range of throat areas likely to be used during approach flight. Based upon these results, it is believed that noise reductions in excess of the program goal can be achieved with the eight-segment inlet controlled to maintain center-line Mach numbers between 0.7 and 0.8.

Internal flow characteristics near the inlet throat were surveyed by means of a static-pressure probe (visible in fig. 14) which could be translated radially across the inlet. Figure 17 shows the local Mach number distribution within the inlet when operating with a minimum throat area at a nominal center-line Mach number of 0.8. Highest Mach numbers were present near the cowl wall, with the Mach numbers decreasing progressively as the inlet center line was approached. For this condition, a region of supersonic flow existed near the cowl wall. It is believed that the large values of attenuation achieved with this inlet configuration (for subsonic center-line Mach numbers) is attributable in large measure to the high velocities near the periphery of the inlet throat. With this configuration, the highest velocities occur where the flow area comprises a large percentage of the total flow area and sound pressure levels are likely to be highest.

Measurements of the total pressure recovery at the engine face were obtained for various values of inlet-center-fine Mach number; these results are shown in figure 18. The influence of boundary-layer-control blowing is evident from the total pressure recovery values greater than 1.0 near the fan tips. At the higher center-line Mach numbers, losses associated with the high velocities near the cowl wall are reflected in reduced values of pressure recovery at the engine face.

Boundary-layer-control blowing quantities of approximately 4 percent of inlet-throat mass flow provided satisfactory engine operation during these tests. Boundary-layer-control blowing air for these tests was supplied from four bleed ports on the high pressure compressor of the engine. As in the previous tests with the fiber-glass fixed-throat inlet, one boundary-layer-control blowing slot was found to be nearly as effective as two blowing slots. However, it is believed that further improvement in the flow from the blowing slots may be obtained with an improved plenum chamber and the boundary-layer-control distribution system.

Performance of the eight-segment inlet in the take-off configuration was found to be satisfactory, although cross-wind effects were not evaluated. Internal losses were found to be quite low and in excellent agreement with those previously measured in 1/9-scale-model tests.

Following completion of these tests, conversion of the manually adjustable eight-segment inlet to a mechanized and controllable configuration was undertaken. This work is presently in progress, with tests of the modified configuration scheduled before the end of 1968. The mechanized inlet will include eight hydraulically actuated segments, a boundary-layer-control blowing system, and an analog computer programed to control the inlet throat area as a function of engine speed and power lever position. A functional schematic of the control and actuation system is shown in figure 19.

The command signals generated within the computer were fed to eight independent servo amplifiers and hydraulic servo-control valves. These servo valves regulate the flow of hydraulic fluid to each actuator as required to increase or decrease inlet throat area in response to the command signal from the computer. The position of each segment (and thus throat area) is sensed by a potentiometer which provides feedback to the corresponding servo amplifier and control valve. Movement of the segment continues until a null is reached between the command signal and the position feedback signal. Response rates of the control and actuation system have been selected to be compatible with the acceleration and deceleration characteristics of the engine. It should be noted that synchronization of the position of the eight movable segments is thus maintained electrically rather than mechanically.

It is anticipated that the forthcoming tests of the mechanized and controllable inlet will provide verification of the inlet and control system compatibility with the engine during dynamic operation. Operation at inlet-center-line Mach numbers of 0.7 to 0.8 is anticipated, but the control system is sufficiently flexible to permit operation at other center-line Mach numbers if desired.

CONCLUDING REMARKS

Tests of the variable cowl sonic-throat inlet show reductions of 17 decibels or more in discrete fan noise during operation at inlet-center-line Mach numbers of 0.7 or greater. The tests also indicate that substantially greater attenuation of inlet noise can be achieved with the sonic-throat inlet but other noise sources associated with current JT3D-3B-powered airplanes (primary jet, turbine, fan discharge) establish noise levels below which further reduction of inlet noise is not advantageous.

Because of structural limitations on inlet length, boundary-layer control of the flow in the inlet has been found necessary to achieve satisfactory diffusion and surge-free engine operation. High pressure compressor bleed air has been successfully used for this purpose.

Tests to date have been conducted only for selected steady-state operating conditions, hence additional testing is necessary to verify that operation of the inlet and control system will be compatible with that of the engine in a dynamic flight environment. These additional tests with a mechanized and controllable inlet configuration are planned to begin in the immediate future.

The sonic-throat inlet is of necessity more complex than a conventional or non-articulated inlet. Variable geometry, boundary-layer control, and a computer are additional elements which will increase the complexity, weight, cost, and development time of the sonic-throat inlet. It is to be emphasized, however, that the sonic-throat inlet provides a demonstrated capability for further substantial reduction of inlet noise, if required. The added complexity thus may be justified for those applications where the full attenuation potential of the sonic-throat inlet can be utilized effectively.

NOISE PROPAGATION THROUGH CONVENTIONAL AND SONIC-THROAT INLETS

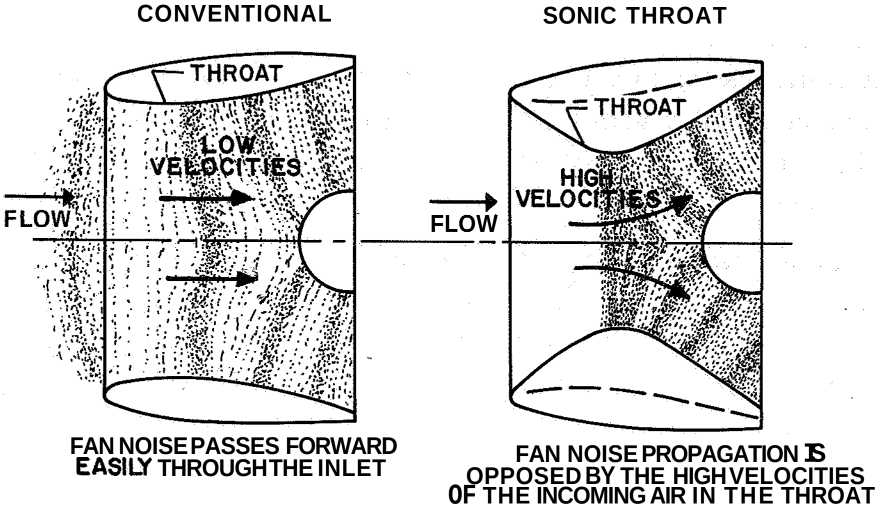


Figure 1

SONIC-THROAT INLET CONCEPTS

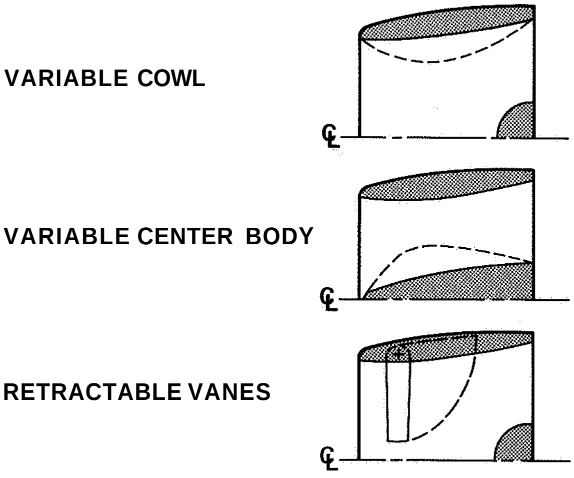
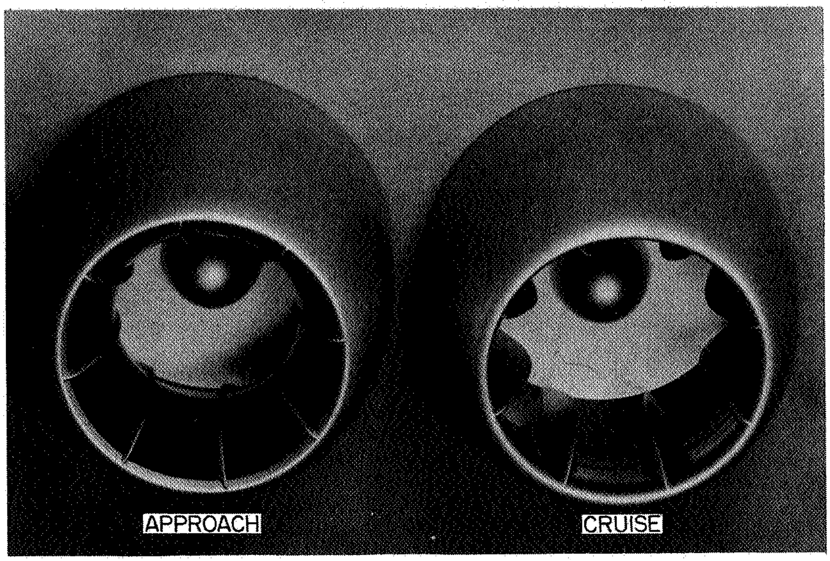
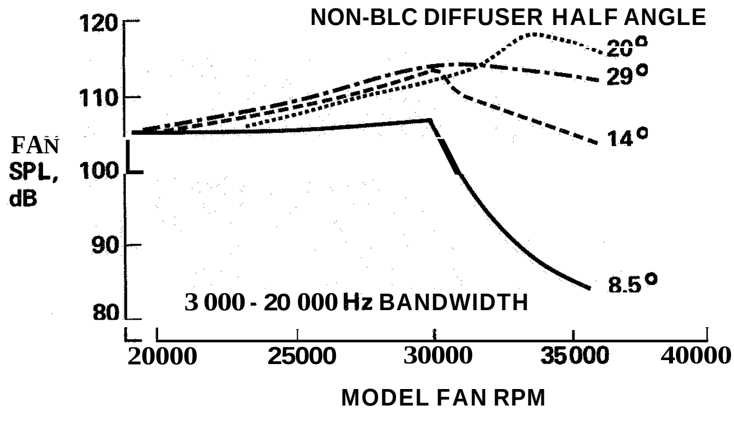


Figure 2



MODELS OF VARIABLE COWL INLET

Figure 3 L-68-8565



FAN NOISE ATTENUATION FOR VARIOUS DIFFUSER ANGLES

SONIC-THROAT INLET MODELTESTS PRIOR TO NASA CONTRACT

Figure 4

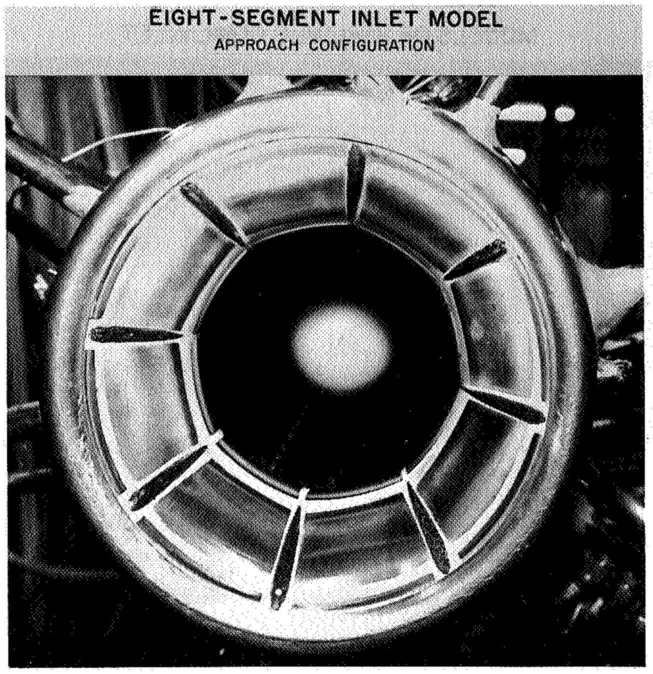


Figure 5 L-68-8568

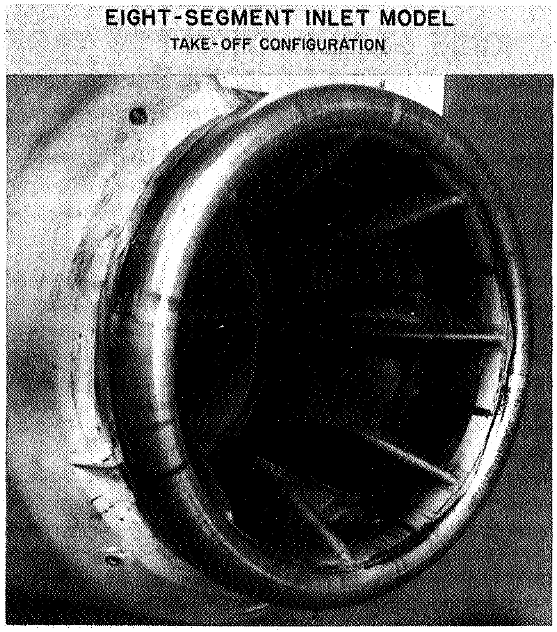


Figure 6 L-68-8569

Figure 7 L-68-8570

EFFECT OF BLC UPON FAN NOISE OF EIGHT-SEGMENT MODEL INLET

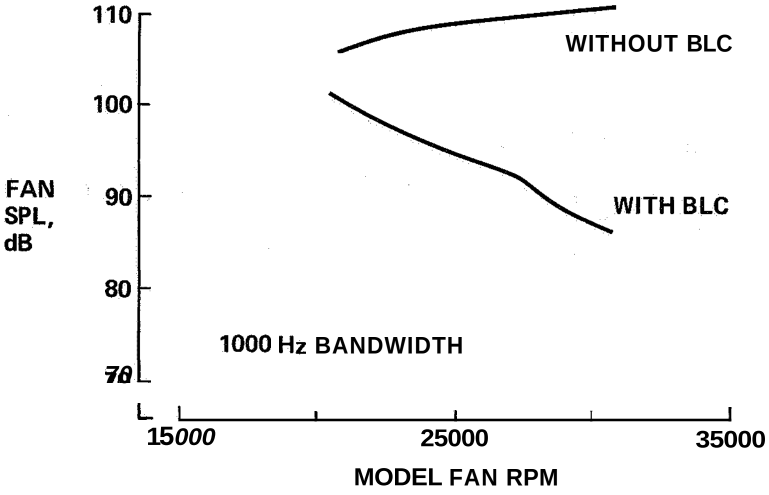


Figure 8

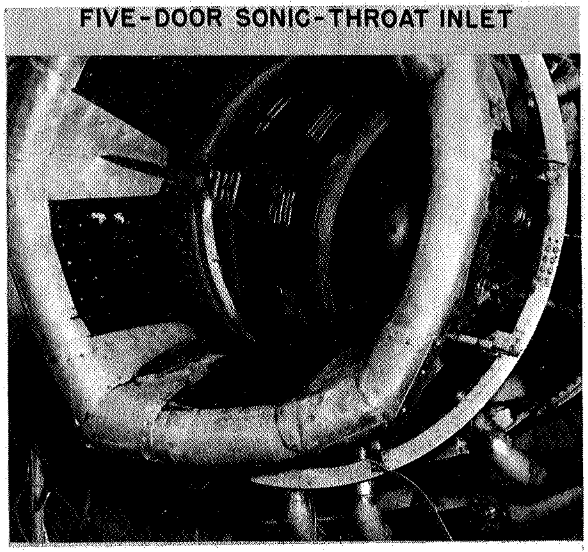

FIVE-DOOR SONIC-THROAT INLET

Figure 9 L-68-8571

FAN NOISE OF FIVE-DOOR SONIC-THROAT INLET

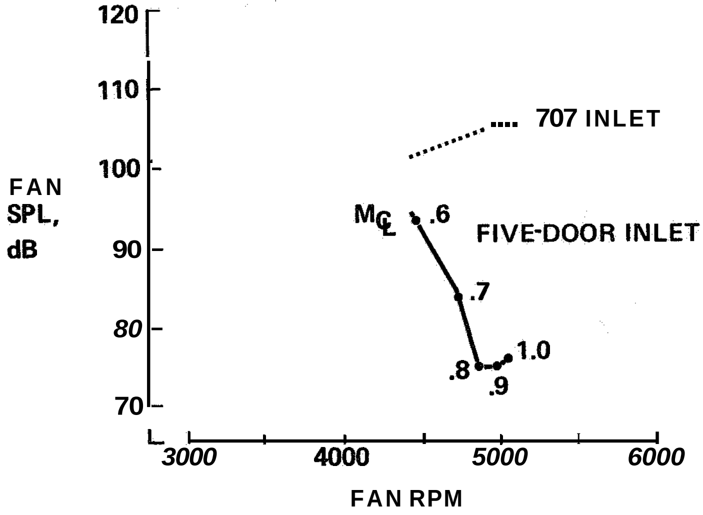


Figure 10

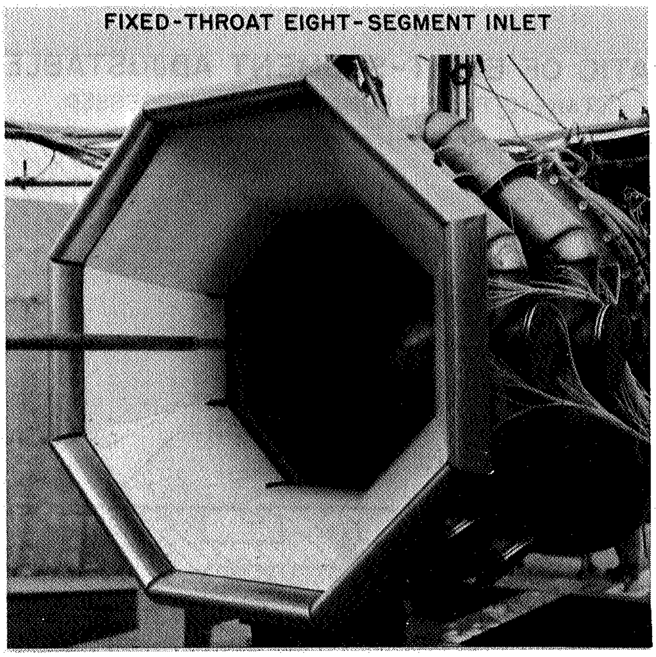
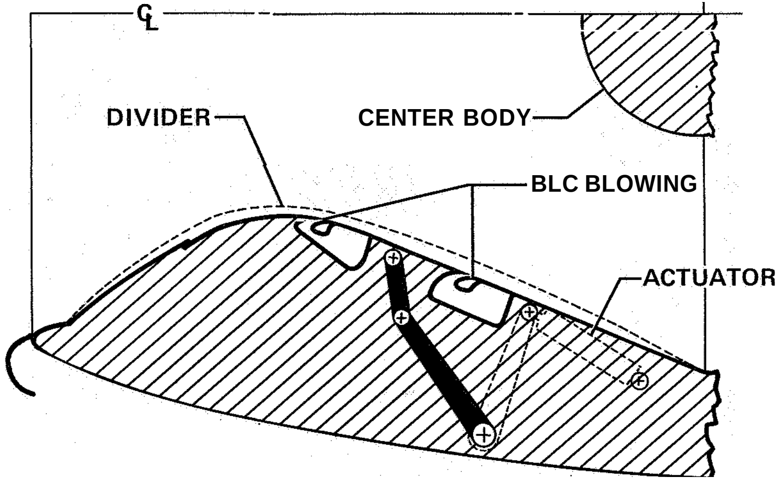


Figure 11 L-68-8572



SCHEMATIC OF EIGHT-SEGMENT ADJUSTABLE INLET

APPROACH CONFIGURATION

Figure 12

SCHEMATIC OF EIGHT-SEGMENT ADJUSTABLE INLET

TAKE-OFF CONFIGURATION; UNSUPPRESSED

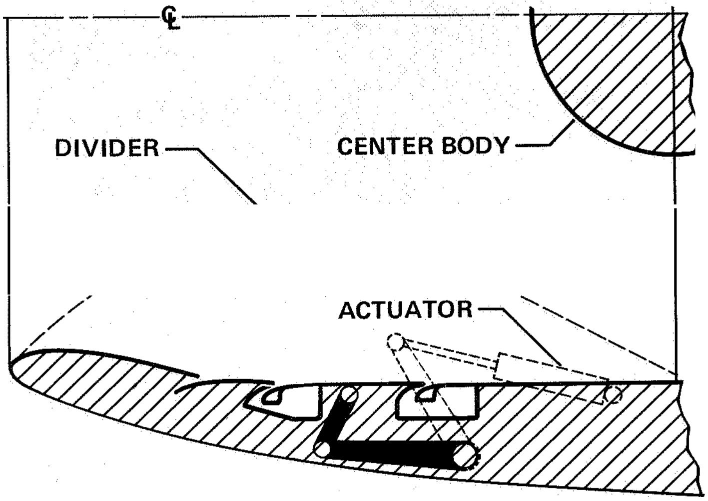


Figure 13

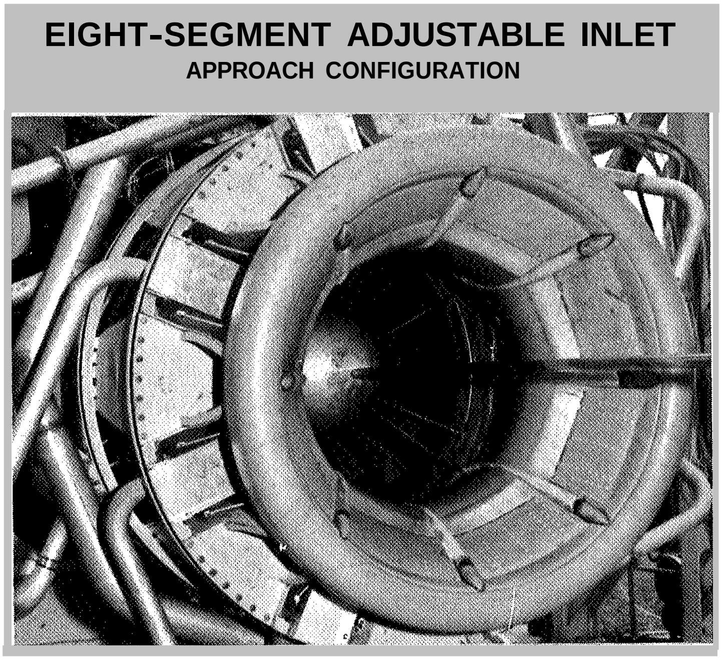


Figure 1

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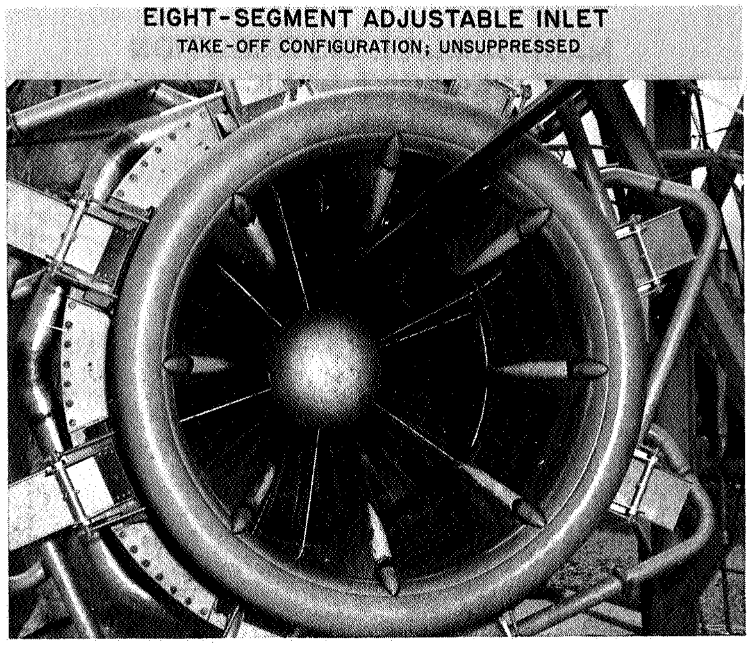

Figure 15

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FAN NOISE ATTENUATION OF EIGHT-SEGMENT SONIC-THROAT INLET

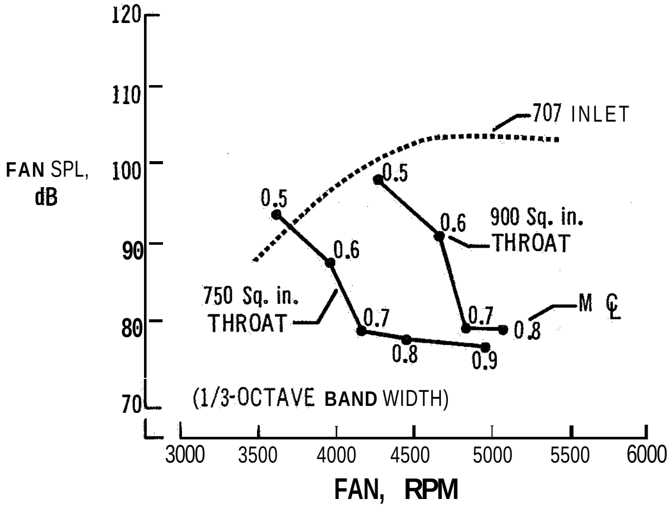

Figure 16

MACH NUMBER DISTRIBUTION IN THE EIGHT-SEGMENT SONIC-THROAT INLET

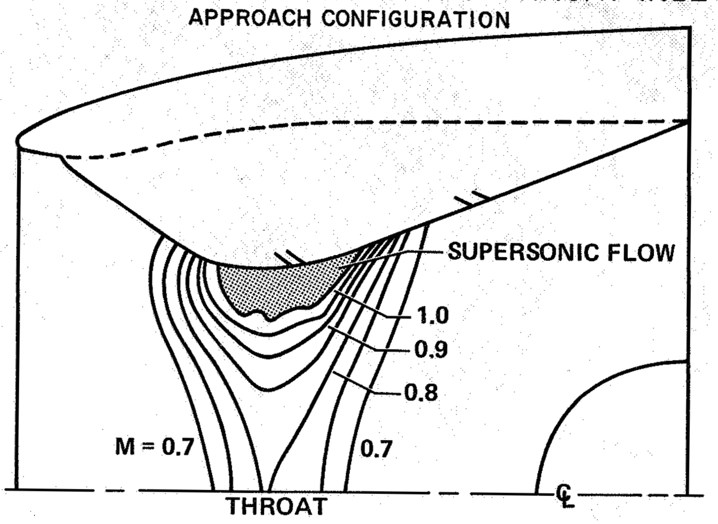

Figure 17

TOTAL PRESSURE RECOVERY AT FAN FOR VARIOUS INLET-CENTER-LINE MACH NUMBERS

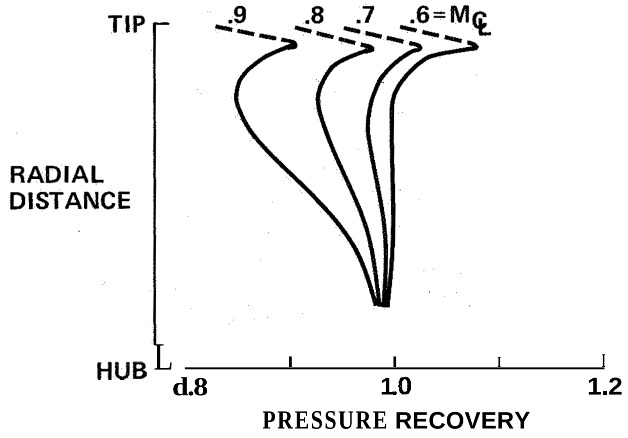

Figure 18

SIMPLIFIED SCHEMATIC OF INLET CONTROL SYSTEM FOR EIGHT-SEGMENT SONIC-THROAT INLET

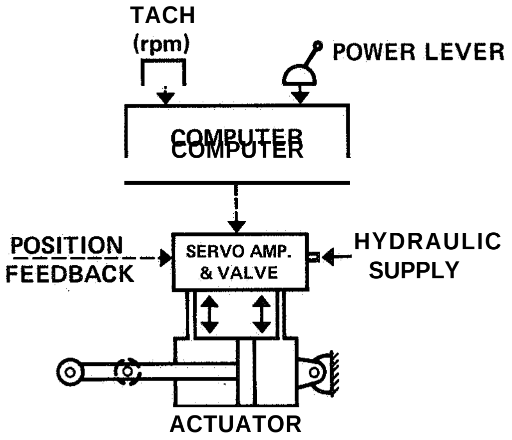

Figure 19