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Flight and Wind-Tunnel Test Results of a Mechanical Jet Noise Suppressor Nozzle

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This paper presents, for the first time, comprehensive acoustics and propulsion data from tests of a mechanical jet noise suppressor designed to the requirements of a future supersonic transport. Details from static, wind tunnel, and flight tests (British Hawker Siddeley HS-125 aircraft) are presented illustrating forward-flight effects for correcting static acoustics and propulsion results. Flight test results are presented for a large scale mechanical suppressor/ejector model. The flight program was a joint effort by McDonnell Douglas, Rolls-Royce, Ltd., and the British Aerospace Corporation. The test aircraft had an uprated Viper engine providing pressure ratios approaching advanced supersonic transport engine designs. The Royal Aircraft Establishment provided the airplane. Results show the suppressor/treated ejector configuration provides a potential noise reduction at large scale of 16 EPNdB from that of the conventional conical nozzle at the highest pressure ratio tested (approximately 2.5). The nacelle, engine, and nozzle configurations from the HS-125 were tested with NASA's cooperation in its Ames Research Center 40- by 80- Foot Wind Tunnel for propulsion performance. The nozzle efficiencies derived from preliminary wind-tunnel data are compared with previous data obtained in the McDonnell Douglas static test facility.

Nomenclature

a_0 = ambient speed of sound, ft/s
C_V = nozzle velocity coefficient (net measured thrust/measured weight flow times ideal jet velocity/gravitational correction constant)
V_A = airplane velocity, ft/s
V_J = ideal, fully expanded jet velocity, ft/s

Introduction

THE McDonnell Douglas Corporation (MDC) conducted system studies of potential advanced supersonic transport (AST) designs under NASA sponsorship augmented by company funding.[1,2] The need for advanced suppressor technology was identified early in the present overall program.[3] In associated programs by the engine manufacturers (General Electric and Pratt & Whitney Aircraft), NASA sponsored studies of advanced engines for application to future AST aircraft and identified several potential engine cycles as candidates.[4-7] The low bypass ratio turbofan engines require significant jet noise reductions to meet anticipated noise-level requirements for a typical four engine transport configuration. The variable cycle engines employ inverted velocity profiles (coannular suppression) to reduce jet noise, but were found to require additional jet noise suppression to meet similar noise-level requirements. Another engine manufacturer, Rolls-Royce (RR), has been studying advanced engine concepts.[8,9] References 10 and 11 present results of MDC studies of the advanced technology engines integrated into a conceptual AST baseline design.

Designers of jet noise suppressor nozzles attempt to achieve significant noise reductions at minimum in-flight thrust losses. In the past, mechanical jet noise suppressors that have been designed and built have demonstrated significant levels of noise reduction statically but have suffered dramatic losses in forward velocity effectiveness.[12] Others have shown large thrust losses in achieving significant noise reductions.[13]

The ICAO Working Group E Jet Suppressor Subgroup, after a careful examination of the then available test data worldwide, recommended that a 12 PNdB jet noise reduction for 10% thrust loss be used for mechanical suppressor parametric studies.[14] Previous model scale results indicated that an MDC mechanical suppressor/ejector configuration had the potential for achieving a level of greater than 11 PNdB jet noise reduction for 5.5% thrust loss at AST engine design nozzle pressure ratios. This performance level was based on acoustic test results from the RR spin rig at Aston Down, England[15] and unpublished thrust performance results from tests at an MDC facility. Measured noise levels in the NASA Ames 40- by 80-Foot Wind Tunnel[16] were significantly different from the measured spin rig noise reductions. To resolve the discrepancy, flight test results were required to verify the actual noise levels.

Accordingly, a joint flight test program was defined by MDC, RR, and British Aerospace (BAe). A Royal Aircraft Establishment (RAE) HS-125 aircraft was modified by BAe to accept an uprated RR Viper 601 engine with conical reference and mechanical suppressor nozzles and an acoustically treated ejector. With NASA support, the uprated Viper 601 engine, the flight nacelle, and the test nozzles subsequently were mounted on a simulated fuselage in the Ames wind tunnel to obtain both thrust performance at forward velocity and acoustic data. This paper presents the pertinent acoustic results from the flight test program for the AST applicable nozzles and preliminary thrust performance results from the Ames wind-tunnel tests.

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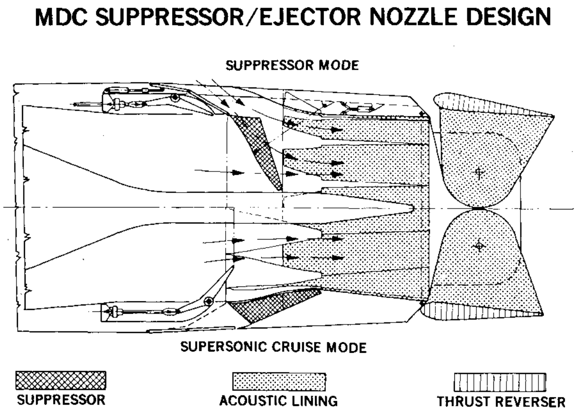

Fig. 1 MDC AST exhaust system.

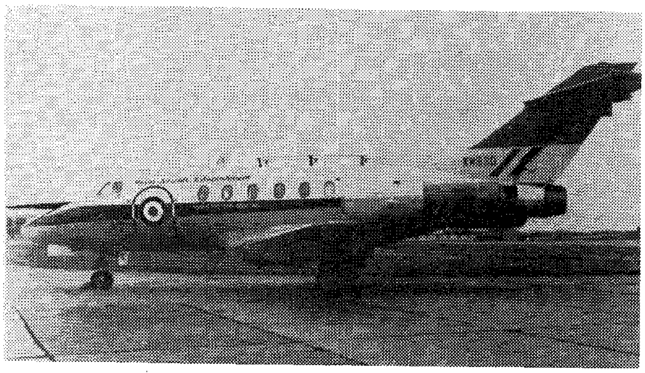

Fig. 2 HS-125 test aircraft with DAC-4 configuration.

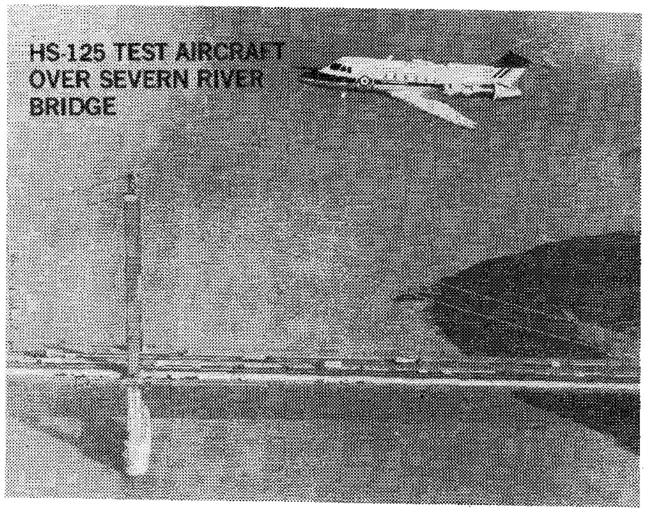

Fig. 3 HS-125 test aircraft over Severn River Bridge with DAC-3 configuration.

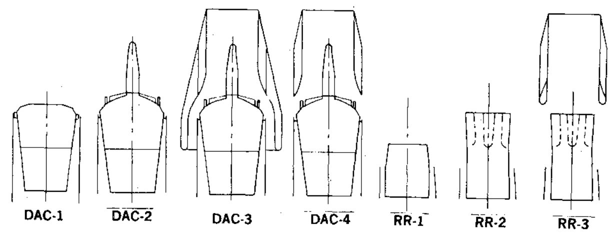

Fig. 4 HS-125 flight-test configuration summary.

Background

Development of an integrated engine/exhaust system meeting airport noise requirements is one of the pacing items for a new supersonic transport. Therefore, it is most important to define jet noise suppression potential at the earliest possible date. To expedite this activity MDC, under NASA sponsorship and with company funds, has from 1973 used a baseline configuration as the vehicle for detail integration studies of the advanced technology engines and noise suppression schemes being derived by the major U.S. engine manufacturers under NASA contract. In these studies, noise suppression schemes and suppression data provided by the engine companies have been used. These studies led directly to the work described in this paper, which was needed to provide data for the mechanical suppressor program.

As part of its technology updating effort, MDC reviewed the results of the previous mechanical suppressor testing programs conducted prior to the design of an efficient nozzle suppressor/ejector/reverser configuration for the conceptual MDC baseline 2.2 Mach cruise vehicle. The design requirement was for the nozzle to be integrated with the airplane without any cruise performance penalty. The MDC exhaust system schematic is shown in Fig. 1. The design for the HS-125 test is based on the schematic shown in the figure.

Flight Tests

The flight test program described in Ref. 17 was instituted jointly to obtain in-flight acoustic data on two conical reference nozzles and two mechanical jet noise suppressor nozzles with and without a treated ejector. In any flight research program, two major steps are the selection of the test aircraft and the test engine.

Aircraft/Engine Selections

In the choice of an aircraft/engine combination, it was desired to choose an engine with the highest possible jet velocity to simulate as closely as possible the jet velocities projected for low bypass ratio AST engines at takeoff and cutback.

RR identified an uprated Viper 601 engine as an excellent test engine (due to its high nozzle pressure ratio) and the HS-125 aircraft as an attractive test vehicle. The test engine provided ideal jet velocities up to 2360 ft/s which compares favorably with the anticipated maximum jet velocity of 2500 ft/s for a projected low bypass ratio AST engine. RR had available a lined tailpipe, tuned to minimize core noise, from a previous test program.[18] This tailpipe was installed on the test engine for all flights in the program. RAE provided an HS-125 research aircraft, Fig. 2, from the Bedford Systems Group and BAe agreed to modify the aircraft as needed for instrumentation, nozzle mounting, and ejector attachment.

Test Site

RR proposed use of a tower on the Severn River Bridge as the microphone location based on their successful use of this location previously.[19] Figure 3 shows the test aircraft flying past the test site.

Nozzle Configurations

The seven nozzle configurations tested are illustrated schematically in Fig. 4. Two conical reference nozzles are included as are two mechanical jet noise suppressor nozzles, one intended for subsonic aircraft research (RR-2) and the other for the AST (DAC-2). The suppressor nozzles can be fitted with a treated ejector to increase the noise reduction.

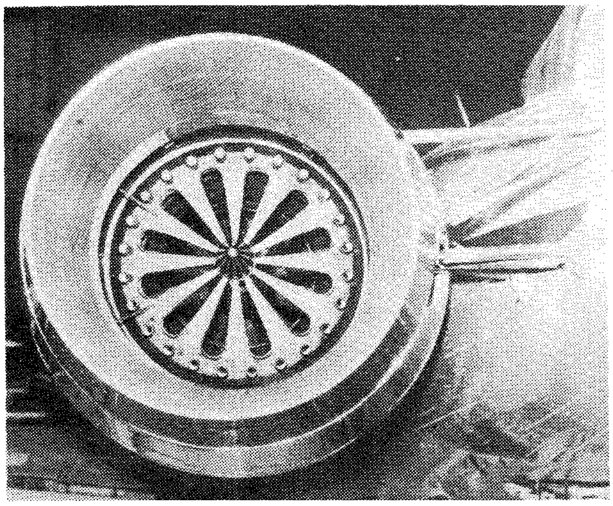

Fig. 5 MDC suppressor/treated ejector (DAC-4) installed on the HS-125 airplane.

Figure 2 shows the test aircraft with the uprated Viper engine and the DAC-4 nozzle configuration installed, and Fig. 5 is an end view of this configuration.

Instrumentation

Two acoustic recording systems are employed to provide redundancy. In each system, two B&K ½-in.-diam type 4133 microphones are pointed upward and mounted vertically on poles about 20 ft above the tower roof and 450 ft above the water. Wind screens are used. Acoustic data are recorded on Nagra IV SJ portable tape recorders. The center track (FM) is used to record voice information between flights and IRIG B time code data during the flight recording.

The aircraft flight path is tracked by an RR photographic system comparable to a minikinetheodolite system. A camera is used to take numerous photographs of the test aircraft as it flies past the test site. Camera elevation and tilt angles are encoded on one channel of a Nagra IV SJ tape recorder, camera shutter contact pulses on the second channel, and voice and time code (IRIG B) data on the FM center track. A second photographic method is employed as a backup for estimating the aircraft position and altitude.

Wet and dry bulb air temperatures, wind velocity, and direction data are obtained at the tower test site. The air pressure is derived from measurements at Filton Airfield nearby. Surveys of the air conditions are made in a Tiger Moth aircraft and are conducted before and after each test flight.

The aircraft flight recorder is programmed to record engine parameters, ambient air, airplane and test identification data. Synchronization of the data from the aircraft flight recorder, the aircraft tracking system, and the acoustic data acquisition system is done by the IRIG B time code.

Procedure

Prior to each flight test, the test aircraft is ferried from Bedford to Filton Airfield. At the test site, a pink noise signal (200 mV) from a pseudorandom noise generator is recorded on each tape for each microphone installation. Pistonphone calibrations are conducted at the beginning and end of each test. Ambient noise is recorded prior to the test and at selected intervals during the test. The test aircraft is flown over the test site with a minimum of three passes for each test point. Test conditions included nominal nozzle pressure ratios of 1.6, 1.8, 2.0, 2.2, and maximum. All configurations were flown at 172 knots nominal airspeed. In addition, the RR-1 nozzle was flown at 140 and 250 knots, and the DAC-4 configuration at 250 knots. The majority of the flights are performed with the nontest engine operating at idle power. A limited number of "control" flights are performed with the test engine at idle power and the nontest engine at takeoff power. The test passes are flown at constant airspeed and attitude to achieve a desired attitude over the test site of 500 ft.

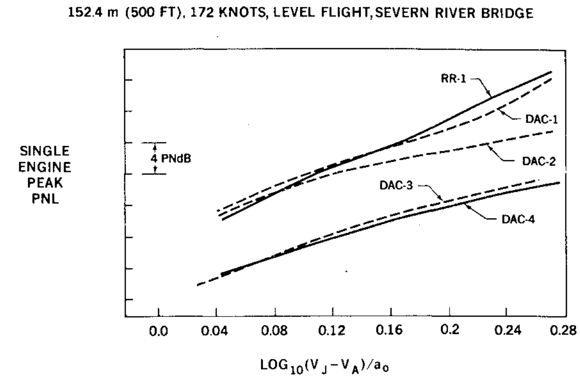

Fig. 6 Variation of peak PNL with relative jet velocity.

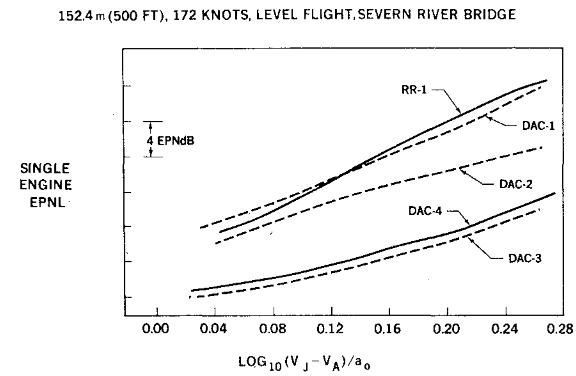

Fig. 7 Variation of EPNL with relative jet velocity.

Limitations

The tests are conducted with the following weather limitations: 1) precipitation – none; 2) wind speed – not more than 10 knots (initial goal, subsequently modified to 15 knots); and 3) humidity – not less than 50% nor greater than 90%.

Acoustic Results and Discussion

The acoustic results for the two reference nozzles (RR-1, DAC-1), the MDC suppressor nozzle (DAC-2), and the MDC suppressor nozzles with ram (DAC-3) and flight type (DAC-4) ejectors are presented here. They are given in terms of the variation of peak perceived noise levels (PNL) and effective perceived noise levels (EPNL) with ideal jet velocity, PNL directivity, and ⅓ octave band sound pressure level (⅓ OBSPL) spectra at the peak noise angle and at selected angles of 90 and 150 deg to the inlet. All noise levels are adjusted to level flight.

The variation of peak PNL with relative jet velocity is shown in Fig. 6. The noise levels produced by the two reference conical nozzles (RR-1 and DAC-1) are substantially the same; therefore, RR-1 is used as the reference nozzle for subsequent comparisons. The noise reductions provided by the mechanical jet noise suppressor (DAC-2) are clearly evident at high engine powers, but they decrease to zero at the low end of the engine power range tested. It can be observed that the treated ejector is effective in providing additional noise reduction throughout the power range tested. Also, the suppressor/ejector configuration with the ram scoop inlet

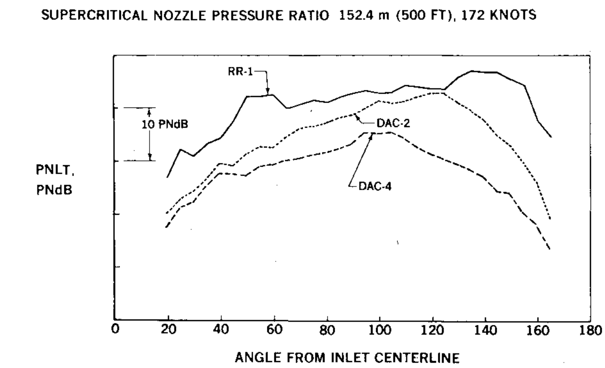

Fig. 8 PNLT directivity patterns at a typical supercritical nozzle pressure ratio.

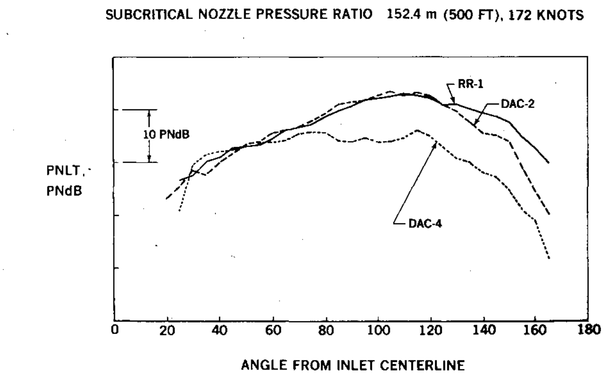

Fig. 9 PNLT directivity patterns at a typical subcritical nozzle pressure ratio.

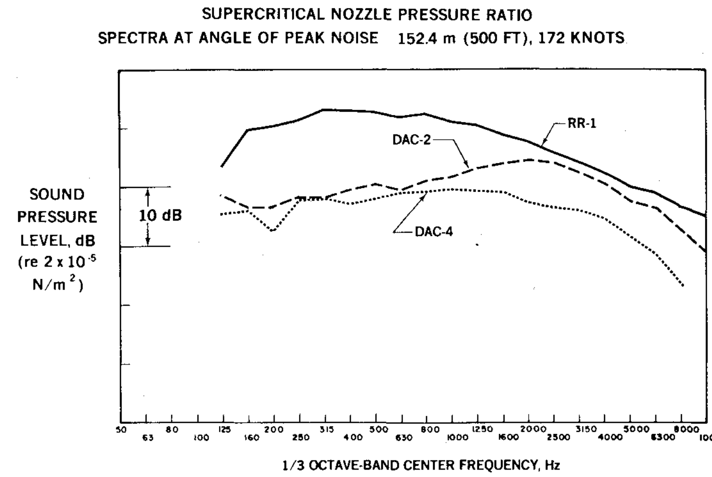

Fig. 10 Peak noise angle SPL spectra at a typical supercritical nozzle pressure ratio.

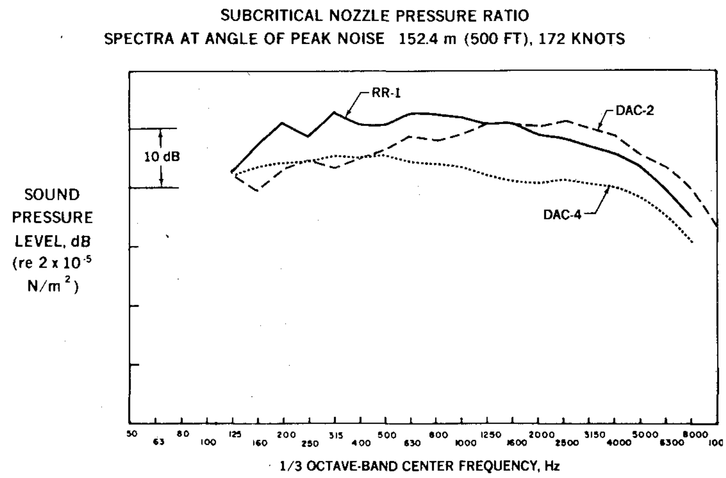

Fig. 11 Peak noise angle SPL spectra at a typical subcritical nozzle pressure ratio.

(DAC-3) produced noise levels similar to those of the flight type inlet configuration (DAC-4). Both configurations produced measured noise reductions of approximately 14 EPNdB. Thus, previous questions of differences between the two configurations were answered. The ram scoop inlet configuration was included in the test program because all model scale tests had included the ram scoop inlet but not the flush inlet.

The corresponding variation of EPNL with relative jet velocity is shown in Fig. 7. It can be observed that the pattern of variation for the nozzles with EPNL is substantially the same as for peak PNL, which means that the mechanical suppressors and the treated ejector did not change the duration correction factor component of EPNL. The beneficial effects of the treated ejector in providing additional noise reduction over the entire engine power range tested are apparent. Again, DAC-3 noise levels are not substantially different from DAC-4 noise levels. The PNL and EPNL data are shown at equal jet velocities, not at equal thrust levels. At the highest jet velocity the measured noise reduction is 14 EPNdB.

In the analysis that follows, two cases are considered; one at a supercritical nozzle pressure ratio (2.2 NPR nominal), and one at a subcritical nozzle pressure ratio (1.6 NPR nominal). All data presented are corrected to level flight 500 ft above the microphone, reference weather conditions, and 172 knots airspeed. The tone corrected PNL (PNLT) directivity patterns are illustrated for the supercritical case in Fig. 8 and for the subcritical case in Fig. 9. For the sake of clarity, data are shown only for the conventional reference and the AST applicable nozzles. Since DAC-3 results are substantially the same as DAC-4, only DAC-4 results are shown. In Fig. 8, the hump in the noise levels of the reference nozzle in the region of 40-70 deg is attributed to shock cell associated noise and the hump in the rear arc is jet noise. In Fig. 8, the anticipated trend of the suppressor to move the angle of peak noise more forward is apparent. This trend is continued with the treated ejector attached.

It can be observed from Fig. 9 that the MDC suppressor alone is ineffective in reducing the noise level below that of the reference nozzle at 1.6 NPR. However, the addition of the treated ejector with its broadband bulk treatment does provide noise reductions, particularly aft of 80 deg. No definite change in the peak noise angle with the ejector fitted is apparent.

⅓ OBSPL spectra are presented in Fig. 10 for the 2.2 NPR case at selected angles of peak noise. Similar data for the 1.6 NPR case are given in Fig. 11.

From Fig. 10, the reference nozzle (RR-1) spectral shape for 2.2 NPR at the peak noise angle (approximately 135 deg) appears to be primarily due to jet noise. It can be observed that the MDC suppressor (DAC-2) reduces the low-frequency noise levels. The treated ejector with the flush inlet (DAC-4) reduced the low-frequency noise levels a little more, but reduced the high-frequency noise levels significantly. At 1.6 NPR (Fig. 11), the MDC suppressor reduced the low-frequency noise levels but increased the high-frequency noise levels compared to the reference nozzle. Such behavior has been demonstrated by previous mechanical suppressors. When the treated ejector with the flush inlet is added to the mechanical suppressor, noise reductions relative to the reference nozzle are provided throughout the spectrum. The beneficial effect of the treated ejector is again apparent.

The noise reduction provided by the DAC-4 configuration relative to the conventional reference nozzle at equal jet

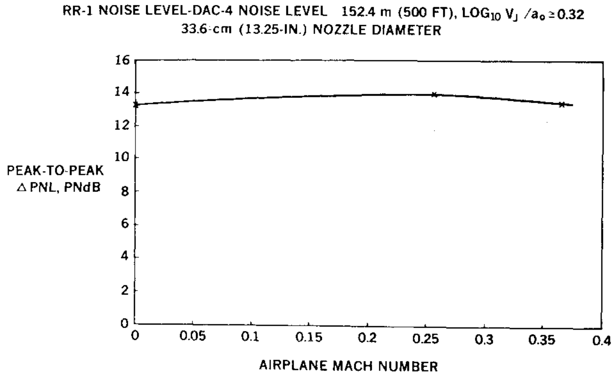

Fig. 12 Variation of noise suppression with airplane speed.

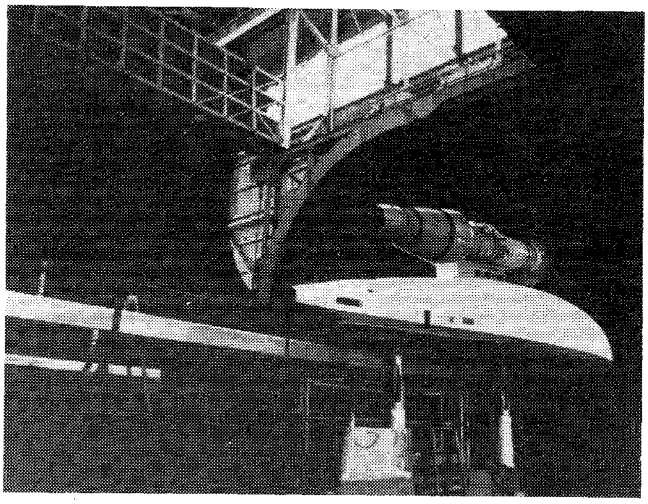

Fig. 13 Viper 601 engine and simulated HS-125 fuselage in NASA Ames 40- by 80-Foot Wind Tunnel.

velocities was independent of aircraft speed, as shown in Fig. 12. These results illustrate clearly that carefully designed mechanical jet noise suppressor exhaust systems do not lose appreciable noise reduction capability in flight.

Wind-Tunnel Tests

The purpose of the wind-tunnel tests is to determine propulsion performance and obtain acoustic data for correlation of the configurations tested in flight on the HS-125 airplane. Since this HS-125 test aircraft is not instrumented to determine engine thrust, net thrust measurements of each configuration at forward speed are particularly important. These data will allow the deduction of net thrust in flight based on engine pressure ratio. Near field acoustic measurements (in conjunction with outdoor static acoustic data) will allow actual flight to be predicted and compared.

Configurations

Upon conclusion of the flight testing, the engine, inlet, nacelle, and nozzle test parts were removed from the HS-125 airplane and shipped to the NASA Ames Research Center, Moffett Field, Calif. The installation in the NASA Ames 40- by 80-Foot Wind Tunnel is shown in Fig. 13. A portion of the HS-125 fuselage was simulated in order to provide as close a representation of the flight configuration as possible. Since all of the acoustic measurements in flight were taken below the aircraft, it was decided to rotate the engine and simulated fuselage 90-deg clockwise (looking forward) for the tunnel tests. In addition, the vertical and horizontal tail surfaces were simulated for test purposes.

Two of the configurations utilized inlet and exit fairings in order to determine the drag tare. The seven configurations

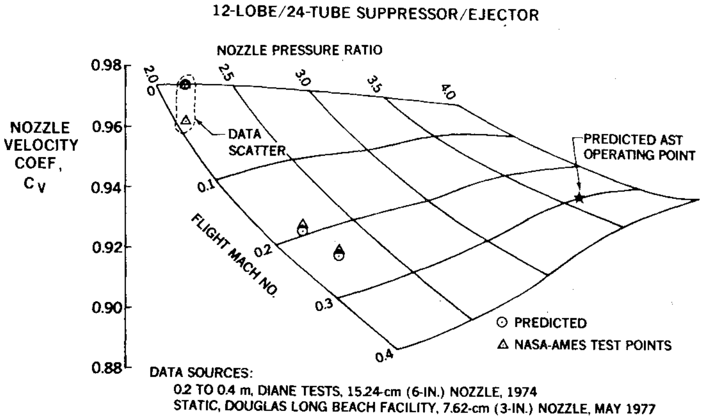

Fig. 14 MDC 12 lobe-24 tube suppressor/treated ejector nozzle performance.

flown on the test aircraft were run statically and at 0.20 and 0.26 Mach in the wind tunnel.

The acoustic array consisted of two microphones (at a lateral distance of 8 and 12 nozzle diameters) on a linear traverse from 27 to 166 deg and four fixed microphones 20 ft to the side. In order to decrease the reverberant characteristics of the 40- × 80-ft test section, acoustic foam was installed on the floor and part way up to the side nearest the fixed microphones.

Instrumentation

In addition to the microphone array and thrust system described earlier, instrumentation was utilized on the engine and within the test section.

Test Procedure

After calibration of the acoustic system, the engine was started and stabilized at 40% rpm. The wind tunnel was started and stabilized at the desired speed. The engine was then set at various speeds between 80 and 100% rpm. At each speed, a microphone traverse was made from front to back and data were recorded from both the traverse and fixed microphones. Propulsion data and thrust/drag measurements were taken at the start, middle, and end of the traverse cycle. After the engine and wind tunnel were shut down, the acoustic system was calibrated.

Results

The data from the wind-tunnel tests presently are being reduced and analyzed. Initial and final engine calibration, utilizing an instrumented bellmouth inlet and conical nozzle, have been checked and agree with the calibration data run by RR.

Figure 14 presents the results of previous MDC tests with a 6-in. model of the 12 lobe/24 tube suppressor/treated ejector over a wide range of nozzle pressure ratios and simulated flight Mach numbers. Predicted propulsion results for the DAC-4 configuration in the NASA Ames Viper 601 engine test are shown and preliminary test results are indicated. The agreement between the predicted and the measured test results at NASA Ames is very close at forward speeds (C_V within 0.2%). Statically, however, the agreement between predicted and measured test results is 0-1.2% lower than the previous data.

The results of the combined flight and wind-tunnel tests should have significant implications for future advanced supersonic transports. They demonstrate that a mechanical jet noise suppressor/treated ejector nozzle exhaust system can be designed to provide large noise reductions with acceptable thrust losses. The two results—noise reduction and thrust performance—are discussed in order.

The 500 ft level-flight data at Viper 601 engine test conditions were scaled to a nozzle size of 37.5-in. equivalent diameter and projected to typical AST anticipated

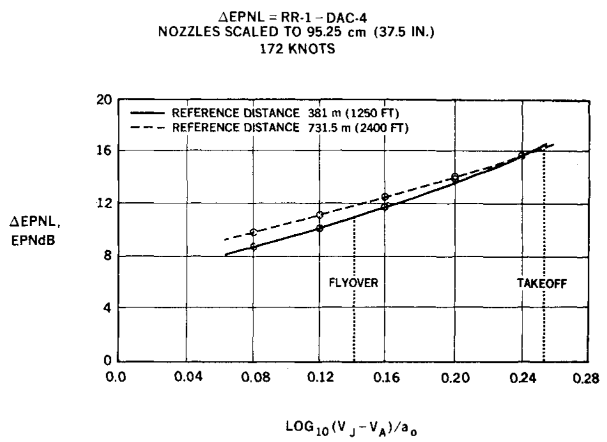

Fig. 15 Variation of noise suppression scaled to AST engine size with relative jet velocity.

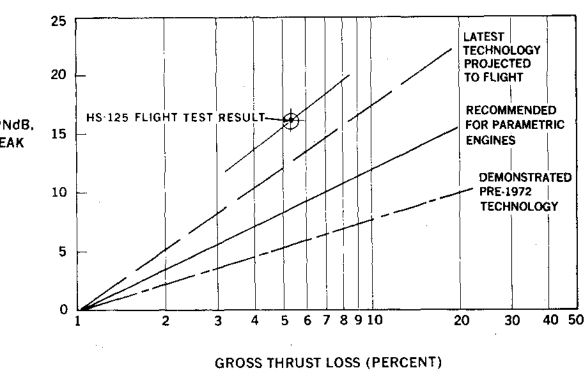

Fig. 16 Working Group E jet suppressor subgroup recommendation for tradeoffs of noise suppression and thrust loss.

flyover/cutback altitude and sideline slant range distance of 1250 and 2400 ft, respectively (corresponding to the FAR Part 36 Stage 2 takeoff and sideline measuring conditions for 4 engine aircraft). The results are presented in Fig. 15, and indicate a noise level reduction of 16 EPNdB at the takeoff power setting. These results are for equal jet velocities, not for equal thrust levels. The increments will be adjusted to equal thrust levels when the thrust data are available.

Based on the excellent results of 6-in. equivalent diameter nozzle tests in an MDC facility and the preliminary Ames propulsion data, it is estimated that the in-flight thrust loss for a typical AST suppressor/ejector nozzle configuration (37.5-in. equivalent diameter) would be 5.4% at takeoff power settings and 6.6% at cutback power settings.

The recommendation made by the ICAO Working Group E Jet Suppressor Subgroup, taken from Ref. 7, is presented in Fig. 16. The subgroup's recommendation of the variation of noise reduction in PNdB with percent gross thrust loss is represented by the center line. This variation was recommended for the Working Group E parametric studies. Also shown on Fig. 16 is the estimate for the MDC mechanical suppressor/treated ejector configuration at a typical takeoff power setting applicable to the sideline noise measuring condition.

Conclusions

An extremely successful cooperative flight and wind-tunnel acoustic/propulsion test program has been completed. The acoustic flight-test data, when scaled to an AST engine nozzle size and projected to a typical sideline distance, indicate a noise reduction of 16 EPNdB is possible for the mechanical jet noise suppressor/treated ejector nozzle.

The current test program has demonstrated that mechanical suppressor/ejector systems can be designed for AST application that have both efficient sound suppression and propulsion performance characteristics. A major conclusion from the testing is that carefully tailored propulsion system designs can result in negligible acoustic performance degradation in flight.

Acknowledgments

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