Development of a Technique for Inflight Jet Noise Simulation – Part I

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A study was conducted to identify and evaluate several inflight simulation techniques. These include closed-circuit wind tunnels, freejets, rocket sleds, and high-speed trains. The most promising technique was selected for demonstration and validation. The pertinent results from the evaluation phase and the rationale which led to the selection of the freejet simulation technique are discussed, including advantages and disadvantages. Acoustic results from the Learjet and NASA-Lewis F106 aircraft flyovers and the French Aerotrain tests, taken with a baseline, 8-lobe, and 104-tube nozzle, were used to formulate a data base for verification of the inflight simulation technique. The freejet scale model test results are discussed and compared to the full-scale flight tests which included the Learjet, F106, and Bertin Aerotrain.

Nomenclature

A_8 = exhaust nozzle area, in.^{2}
EGA = extra ground attenuation
r = source-to-observer distance, ft
T_{T8} = exhaust gas total temperature, °R
V_J = jet velocity, isentropic fully expanded, fps
V_o = freestream velocity, fps
θ_I = acoustic angle referenced to the nozzle inlet
ρ_{ISA} = ambient density, lbm/ft^3
ρ_j = fully expanded jet density, lbm/ft^3
ω = density ratio exponent

I. Introduction

DURING the past two decades, extensive static testing has been conducted to determine the mechanisms of jet noise generation for simple and complex exhaust nozzle systems. An experimental static and flight data base that assists the designer has resulted, but no reliable method to determine the inflight noise of jets from static measurements has been found. From a cost and convenience point of view, it would be desirable to find a static test procedure that could simulate as closely as possible actual flight test results. In addition, the static facility would permit the utilization of diagnostic techniques such as the laser velocimeter and ellipsoidal mirror.

Under flight conditions, the jet noise sources are modified due to the relative velocity between the jet and ambient; furthermore, a shift in frequency and pressure occurs due to the motion of the noise source. Therefore, as a minimum, the static facility must be able to duplicate the source modifications due to flight. This can be accomplished, for example, by the use of a freejet facility, where the microphone is placed outside a coannular flow enveloping the jet exhaust nozzle. Alternatively, a wind tunnel where the microphone is now placed within the stream can also be employed. Although both schemes yield the desired source alteration due to flight, significantly different analytical procedures must be applied to the measured far-field acoustic pressures in the two systems to relate them to flight noise signatures.

Because the jet noise sources are extended over a considerable distance, extremely large wind tunnels would be required to insure the location of the instream microphone in the geometric far-field. The freejet, on the other hand, which can be located in a reasonable size anechoic facility, allows for the microphone to be placed in the far-field. However, the freejet introduces an extra complexity in that the effects of an additional shear layer must now be accounted for. The analytical approach employed to achieve this is discussed in Ref. 3. Actual flight test results with Learjet, F106, and Bertin Aerotrain were obtained in order to compare with the data obtained in the freejet facility. These comparisons are also presented in Ref. 3. This paper discusses the evaluation that was conducted of the fixed- and moving-frame techniques, the Freejet Test Program, the Gates Learjet and F106 Flyover Test Programs, and the Bertin Aerotrain Test Program.

II. Evaluation of Fixed- and Moving-Frame Techniques¶

An obvious approach to evaluating the flight noise signature of any exhaust nozzle system is by actual flight testing. However, careful analysis of flight test procedure reveals the following limitations of this technique. Acoustic propagation path lengths are long, and atmospheric attenuations can have a significant effect. The determination of aircraft location with respect to the microphone is difficult. It is not currently considered feasible to use existing source location techniques to determine the changes in the mechanisms of jet noise due to inflight effects. Flight hardware is expensive, requires long lead time, and does not have the flexibility for parametric variation typical of scale model systems, with exception of a highly flexible sled concept. Test conditions are limited to the specific engine cycle, resulting in an inadequate vehicle for parametric testing. These

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¶"Fixed-frame" refers to an experimental system in which the source (jet nozzle) is stationary relative to the observer (microphone). "Moving-frame" refers to an experimental system in which the source is in motion relative to the observer as in actual flight test.

limitations provided the impetus to search for a more flexible and economical way to determine the flight noise signature.

In view of the disadvantages for flight testing listed in the foregoing, a fixed-frame facility would be desirable. Two types of facilities were considered – closed-circuit wind tunnels and freejets.

Closed-circuit wind tunnels have been used for many years for aerodynamic performance measurements. There would be a significant cost advantage if these same facilities could be used for acoustic measurements. Closed-circuit wind tunnels also have two inherent advantages over freejet-type facilities. The medium through which the sound is propagating is in the correct reference frame. Dynamic effect corrections are therefore unnecessary and only a Doppler shift correction must be applied. Also, shear layer corrections that are necessary in a freejet facility are not required in a wind tunnel, because the microphones are placed inside the flow stream.

The acceptability of a closed-circuit wind tunnel must be determined relative to two additional criteria.[1] These are that the impact of tunnel drive background noise, wind noise, and reverberation on the noise signature that is being measured must be assessed, and that measurements must be made in a region where extrapolations to representative distances may be accomplished using inverse square law and appropriate air attenuations.

Both freejets and wind tunnels have been used to obtain aerodynamic nozzle performance data.[2] The freejet facility is a viable and cost-effective system for aerodynamic and acoustic performance testing. Changes in the turbulent structure of a jet nozzle's plume due to external flow are simulated and, based on analytical and experimental results, are believed to be those experienced during flight. These attractive characteristics warranted that a freejet system be evaluated as a simulated inflight effects acoustic test facility.

The major disadvantage of a freejet facility is that the relative motion between the source and the medium of sound propagation is only partially simulated. Analytical and experimental studies were conducted[3] to determine: 1) the most acceptable freejet-to-nozzle area ratio, and 2) the effect of the noise produced by the simulated freestream. This test program, in addition to data from Ref. 4, provided the background data for evaluating the freejet technique.

Five typical fixed-frame facilities were chosen for detailed evaluation. These facilities and the results of the facility evaluation phase are summarized in Table 1. The goal requirements are defined to make a useful research facility for jet exhaust nozzle testing. The results of this evaluation led to the selection of the freejet as the fixed-frame facility which could meet the goal requirements. The moving-frame simulation systems considered were high-speed trains, rocket sleds, and spinning rigs. Two rocket sled facilities were evaluated. These were the test tracks at Holloman Air Force Base, Alamogordo, New Mexico, and Naval Weapons Center, China Lake, California. Results of this evaluation indicated that a functional system meeting goal objectives similar to those stated in Table 1 could be developed. However, the costs associated with development, plus the high operating costs once the system was functional, plus background noise restrictions, plus the limitation that source location techniques (such as laser-velocimeter and ellipsoidal mirror) could not be utilized led to the conclusion that this approach was too high-risk and uneconomical, so it was dropped.

Two high-speed train facilities met the requirements in terms of operational velocity capability. These were the Linear Induction Motor Research Vehicle at the DOT High Speed Ground Test Center located at Pueblo, Colorado, and the Bertin Aerotrain in Gometz, France. The Linear Induction Motor Research Vehicle (LIMRV) was developed as an experimental test vehicle at the DOT High Speed Ground Test Center. The LIMRV utilizes a T64 gas turbine as a main power source and can attain speeds of approximately 290 fps. In addition, boost power generated by two J52 engines allows the vehicle to attain a top speed of 360 fps. However, use of the J52 engines for the proposed acoustic testing was not considered viable because the noise they generate would mask the acoustic signals from any test nozzle. The added weight of the nozzle test module (estimated at 15,000 lbs), without the added power of the J52 engines, would limit the maximum attainable speed to an estimated 240 fps. Utilization of this high-speed train on this program was not pursued further because of its limited speed capability

The Bertin Aerotrain test facility is located at Gometz, France, and was specifically developed as a flight jet-noise test

Table 1 Evaluation of fixed-frame facilities

FACILITY REQUIREMENTS	OBJECTIVES	NASA/ LANGLEY	NASA/ LEWIS	NASA/AMES 7' X 10'	NASA/AMES 40' X 80'	GE OPEN THROAT ANECHOIC WIND TUNNEL
NOZZLE WEIGHT FLOW	25 LBM/SEC	17 LBM/SEC	25 LBM/SEC	25 LBM/SEC WITH MODIFICATION	25 LBM/SEC WITH MODIFICATIONS	42 LBM/SEC
NOZZLE SIZE	4" - 6"	?	4" - 6"	4"	6"	6"
EXHAUST GAS TOTAL TEMPERATURE RANGE	520°R-2500°R	BURNER NEEDS TO BE PROVIDED	AMBIENT	AMBIENT	AMBIENT - 1600°R	AMBIENT - 3000°R
NOZZLE PRESSURE RATIO	1.5 - 4.0	?	1.5 - 4.0	1.0 - 2.5	1.0 - 2.5	1.5 - 4.0
FREE STREAM VELOCITY RANGE	0-400 FT/SEC	0-400 FT/SEC	0-220 FT/SEC	0-400 FT/SEC	0-325 FT/SEC	0-330 FT/SEC
FACILITY WALL TYPE	ANECHOIC	ANECHOIC	HARDWALL	SCOTTFELT	PARTIALLY TREATED	ANECHOIC
PERFORMANCE MEASUREMENTS	PROVEN NOZZLE PERFORMANCE SYSTEM + 1/2% ACCURACY	EXTENSIVE MODIFICATIONS	WILL HAVE CAPABILITY BY DEC. 1974	EXTENSIVE MODIFICATIONS	EXTENSIVE MODIFICATIONS	FEASIBILITY TO BE STUDIED
FACILITY AVAILABILITY	1974, 1975, 1976	1974, 1975, 1976	1976	1974, 1975, 1976	9 WEEKS/YR	1975, 1976
DURATION OF OPERATION	CONTINUOUS	BLOWDOWN	CONTINUOUS	CONTINUOUS	CONTINUOUS	CONTINUOUS
CAPABLE OF PERFORMING LASER VELOCIMETER MEASUREMENTS	LARGE WINDOW HIGH QUALITY OPTICAL GLASS	MINOR MODIFICATIONS	WOULD REQUIRE MODIFICATIONS	YES	WOULD REQUIRE MODIFI-	DESIGNED TO ACCEPT LASER VELOCIMETER

Fig. 1 Aerotrain test facility.

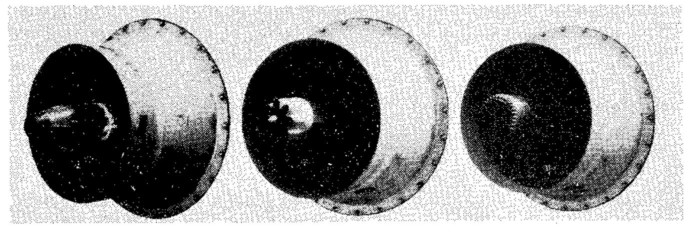

Fig. 2 Photographs of the conical, 8-lobe, and 104-tube nozzles used in the freejet test.

facility. The Aerotrain vehicle is supported by an air cushion provided by a Palouste engine and is propelled by a General Electric J85 engine over its 6-km track. A photograph of the Aerotrain with the 104-tube suppressor nozzle is presented in Fig. 1. The vehicle is capable of obtaining a speed of 275 fps. This vehicle was chosen for further demonstration testing because of its unique capability to provide high-quality moving frame data. A detailed description of the test results is presented in Sec. III along with a complete description of the vehicle's capabilities.[5]

III. Selection and Verification of the Inflight Simulation Technique

Section II identified the advantages and disadvantages of several fixed- and moving-frame facilities. Where possible, meaningful exploratory experimental work was performed to aid in the decision making. Several closed-circuit wind tunnels were evaluated. These facilities were rejected after being subjected to the acoustic and aerodynamic requirements (see Table 1). The Holloman Air Force Base and Naval Test Station rocket sled facilities were examined in depth. Developing these vehicles for moving frame acoustic testing represented a very high technical risk; therefore, they were eliminated as viable options. High-speed trains such as the DOT LIMRV and Bertin Aerotrain, except to verify specific nozzle characteristics, were also rejected because of their inherent inflexibility, remoteness of site, and expensive test costs for the sustained parametric investigations envisioned.

An analytical effort was initiated concurrently with the evaluation of fixed- and moving-frame facilities to evolve a theoretical technique to relate freejet data to flight conditions as discussed in Ref. 3. The combined use of freejet test data and the analytical transformation was dubbed the "hybrid" technique and was selected as the inflight simulation technique to be verified. This technique was validated by transforming the freejet data and then comparing it to the Aerotrain results. These comparisons are presented in Ref. 3. The freejet tests utilized exact, one-third-scale duplicates of the suppressor nozzles used on the Learjet, F106, and Aerotrain. These tests were formulated to provide a set of far-field acoustic data for scale models of a conical, 8-lobe, and 104-tube nozzle. The testing was conducted at the General Electric Jet Engine Noise Outdoor Test Site (JENOTS) using a freejet shroud of 25.6-in diameter, which permitted evaluating the nozzles at freejet-to-exhaust nozzle area ratio of nominally 40-50 to 1. The freejet incorporated a modest contraction ratio which resulted in measured turbulence levels of approximately 3-4% in the potential core of the freejet. Velocity uniformity across the freejet exit area was held to less than 4%. Figure 2 presents photographs of the three configurations evaluated. Acoustic measurements were made on a 40-ft arc using microphones 16-ft above the ground. All measurements were corrected to freefield and extrapolated to a 400-ft sideline distance assuming no extra ground attenuation (EGA). In all cases measurements were made with wind speeds less than 5 mph. A summary of the test variables is shown in Table 2.

Figures 3 and 4 present peak overall sound pressure level (OASPL) and OASPL directivity characteristics for the 3.56-in conical nozzle. Examination of Fig. 3 reveals that static and wind-on data exhibited previously observed power-law dependencies – at $V_o = 0$, $n \simeq 7.8$, and at $V_o \simeq 325$ fps, $n \simeq 10$. The directivity comparisons illustrated in Fig. 4 show that as jet velocity was increased the noise field became less directional, particularly in the forward arc. This characteristic of conical nozzles operating supercritically (underexpanded) was noted by Harper-Bourne and Fisher in their 1973 AGARD paper.[6] In contrast, the directivity plot at 1830 fps in Fig. 4 is representative of convergent nozzles operating at or below critical pressure ratios.

The maximum OASPL/jet velocity characteristics of the 8-lobe nozzle are shown in Fig. 5. The data exhibit the often-observed, multielement suppressor trends, namely, the relatively low slope of the noise level in the low velocity region (primarily attributed to the premerged portion of the jet) and the rather abrupt increase in slope at the higher velocities (usually associated with the coalesced region of the jet).

The 8-lobe nozzle $OASPL_{max}$ exhibits a noise reduction with increasing freejet velocity (as was the case for the conical nozzle); however, the noise reduction with primary velocity remains essentially invariant for velocities below 2200 fps. At higher velocities the reduction due to freejet velocity decreases with increasing jet velocity (as with the conical nozzle). The directivity characteristics of the 8-lobe nozzle tend to show the same insensitivity to angle from the inlet with increasing freestream velocity that was exhibited by the conical nozzle. The directivity pattern at $V_j \simeq 2400$ fps tends to be less directional. Shocks may be contaminating the forward arc (since the nozzle is operating supercritically). This speculation is reinforced by looking at the 50 deg spectra shown in Fig. 6. The just-choked, 1800 fps data at 50 deg exhibit essentially a broadband reduction in SPL, with some biasing of the benefit in the high-frequency portion of the double-humped spectrum. Data below 160 Hz are not presented because the freejet noise contaminated the jet noise.

The 1800 fps spectra at 50 deg have a marked reduction in forward flight benefit compared to the 2400 fps spectra. The 50 deg spectra at 2400 fps are definitely affected by the shock structure. The tone which corresponds to the high-frequency portion of the double-humped pure jet noise spectrum has the classic shock noise shape. The low-frequency region (corresponding to the coalesced region of the jet) benefits from the V_R effect, whereas the high-frequency region which appears to be infested with shocks is not affected by forward speed.

The peak OASPL/jet velocity trends for the 104-tube nozzle shown in Fig. 7 again exhibit noise level reduction with

Table 2 Range of test variables

Freestream velocity	0 → 350 fps
Primary jet velocity	800 → 2600 fps
Primary nozzle pressure ratio	1.2 → 3.75
Exhaust gas stagnation temperature	1000 → 1800°R

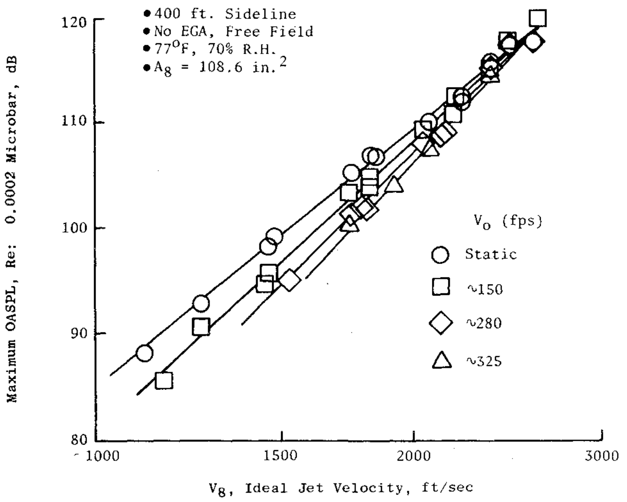

Fig. 3 Conical nozzle peak OASPL characteristics of the freejet test.

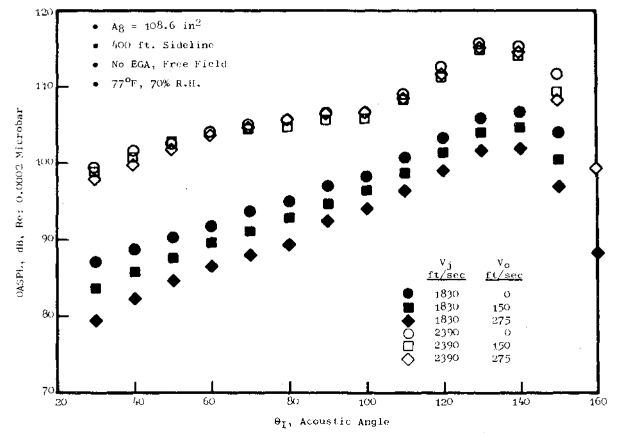

Fig. 4 Conical nozzle OASPL directivities of the freejet test.

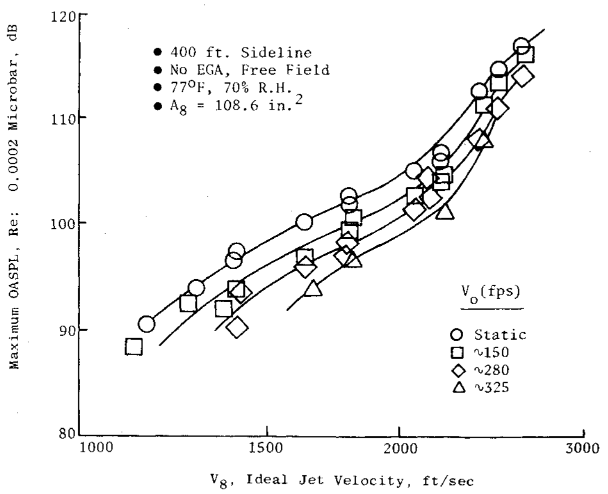

Fig. 5 8-lobe daisy nozzle peak OASPL characteristics on the freejet test.

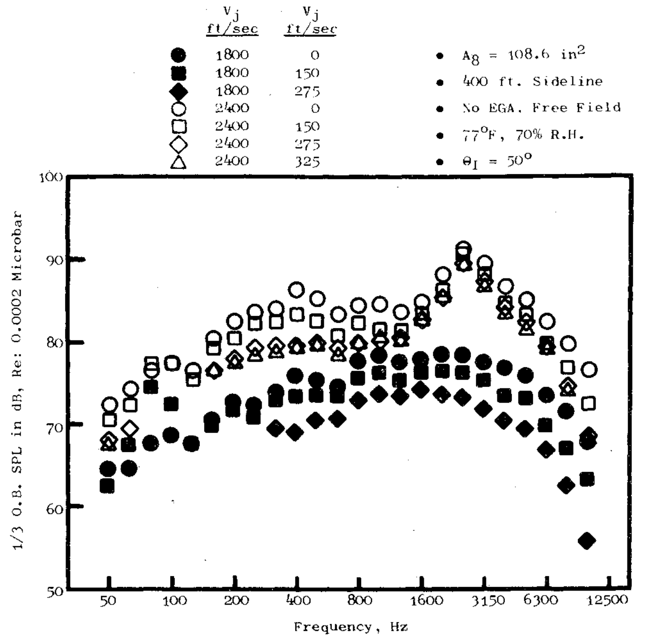

Fig. 6 8-lobe daisy nozzle SPL spectra at $\theta_I = 50$ deg on the freejet test.

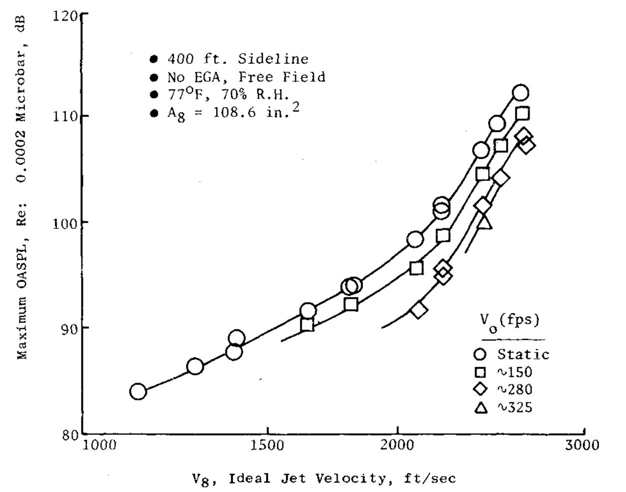

Fig. 7 104-tube nozzle peak OASPL characteristics of the freejet test.

increasing forward flight velocity. Background noise at the high freejet velocities, combined with the inherent low noise characteristics of the 104-tube nozzle, limited the jet velocity range of interest over which acoustically clean data could be utilized. The $V_o = 150$ fps peak OASPL trends exhibit the typical multielement suppressor noise characteristic discussed previously for the 8-lobe nozzle (a wide-angle "V") and appear to be insensitive to jet velocity.

The directivity plots of Fig. 8 (for jet velocities of 2625 and 2135 fps, respectively) exhibit much more directionality than their conical and 8-lobe nozzle counterparts, especially at the higher jet velocity. This corresponds to the area of supercritical nozzle operation. The noise reduction with increasing freestream velocity also is seen to be constant with angle. The high jet velocity directivity plots suggests that shock related noise may not be a factor.

While flight testing provides the best basis for examining the flight velocity effect on the jet noise signature under actual operating conditions, there are inherent disadvantages associated with this technique as previously discussed. Nevertheless, high-quality flight test data, with appropriate confidence bands, are required to assess the validity of the results from any flight simulation techniques. Independent tests were conducted using a Gates Learjet-25C and F106 aircraft to provide this flight assurance data.

The Gates Learjet tests were completed in 1973 under a joint General Electric/Gates Learjet program at Fresno, California. The aircraft used was powered by two CJ610-6 engines (basically commerical versions of the J85). Both a baseline conical nozzle and an 8-lobe suppressor nozzle were

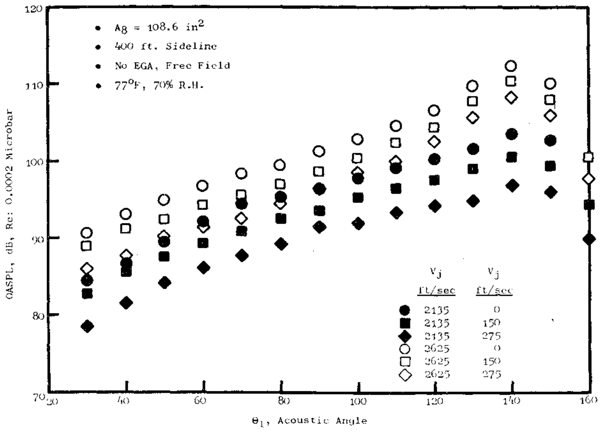

Fig. 8 104-tube nozzle OASPL directivities of the freejet test.

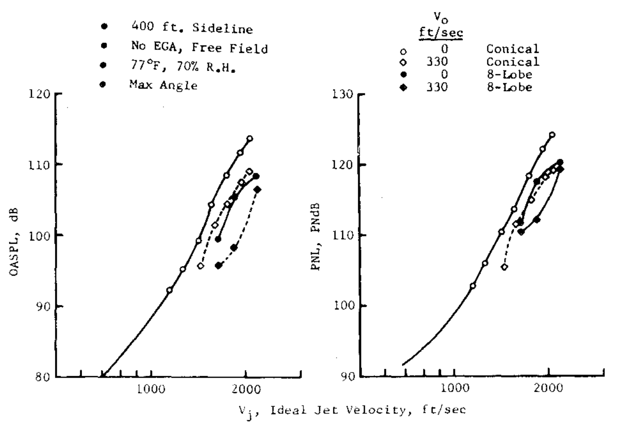

Fig. 9 Peak OASPL and PNL characteristics of the Gates and Learjet flyover test.

evaluated. Five jet velocities from 1400 fps to 2100 fps were run at altitudes of 1000 ft and 400 ft, with flight velocities of 304 to 371 fps. In all cases, the two engines were adjusted to the same power settings and several repeat test points were averaged. Static data at jet exhaust velocities corresponding to those tested in flight were obtained on a 100-ft arc with only one engine running to eliminate possible fuselage shielding problems with the other engine.

The acquisition of the Learjet level flyover acoustic data was accomplished for the conical and 8-lobe nozzles using an array of nine microphones. The arrays were positioned to achieve statistically independent data samples. The data were adjusted from actual test day conditions to an ISA + 10°C Standard Day and corrected to freefield conditions. The static and flight maximum perceived noise level (PNL) and OASPL levels as a function of jet velocity are summarized in Fig. 9. The in-flight peak noise level reduction is observed to be of the same magnitude on both OASPL and PNL basis for the conical nozzle. The 8-lobe nozzle, in contrast, shows significantly more reduction on the basis of OASPL than PNL, and it is most effective at a jet velocity of 1800 fps. The changes from static to flight at the 90 deg acoustic angle are substantially different than those observed at the maximum-noise acoustic angle. The conical-nozzle noise levels generally increase in flight relative to the static noise. The magnitude of the increase is on the order of 1 dB. The 8-lobe nozzle is different in that the static and flight noise levels are equivalent on the basis of PNL, while OASPL levels are reduced slightly. The forward quadrant trends at the 50-deg acoustic angle most aptly accentuate the difference between the two configuration noise levels, for the conical increases by approximately 4 dB in-flight, whereas the 8-lobe nozzle shows little change or even a slight decrease. The conical nozzle

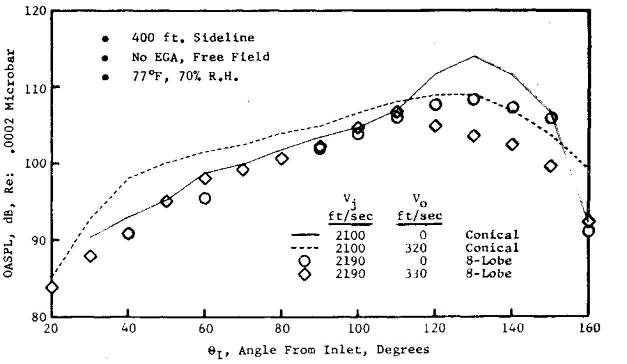

Fig. 10 Gates Learjet conical and 8-lobe nozzle OASPL directivity patterns.

trends are relatively insensitive to jet velocity, but the 8-lobe nozzle trends are not.

Typical static and flight OASPL directivity patterns for the two configurations are presented in Fig. 10. The analysis of the directivity patterns for the conical nozzle revealed that, at the two high-velocity conditions, the flight noise levels are less than the static noise levels for acoustic angles greater than 100-deg and greater than the static noise levels for angles less than 100-deg. The peak-noise angle shifts toward the 90-deg angle from static to flight. The amount of suppression in the aft quadrant is a strong function of jet velocity, whereas the amount of increase in the forward quadrant is a weak function of jet velocity.

In general, the acoustic angle at which the static and flight noise are equivalent is a function of jet velocity. Spectra comparisons at the maximum-noise angle show a reduction that is relatively constant with frequency, except in regions where ground reflection corrections have a dominant influence. At this particular condition, the 8-lobe nozzle realizes substantially more noise reduction from static to flight than the conical nozzle. This is because the 8-lobe nozzle is representative of a conical nozzle operating at a low jet velocity, due to the increase in mixing effectiveness of the 8-lobe nozzle. Examination of the 90-deg spectra reveals markedly different trends than those observed at the maximum noise angle. The conical nozzle spectra shows a slight increase or no change from static to flight in the low-frequency portion of the spectra, whereas the 8-lobe nozzle has static and flight spectra that are essentially equivalent. This point is emphasized because, based on classical theory, the 90-deg spectra are considered to be indicative of pure source reduction which, based on these test results over the range of conditions examined, is not observed.

In summary, for both the Learjet conical nozzle and the 8-lobe nozzle, PNL, OASPL, directivity and spectra comparisons show that significant reduction from static to flight is observed at the angle of maximum noise. This reduction varies as a function of jet velocity and nozzle configuration. At the 90-deg acoustic angle, indicative of pure source noise reduction, no change or a slight increase is observed. The forward quadrant trends are observed to be a function of nozzle type. The conical nozzle exhibits an increase from static to flight, whereas the 8-lobe nozzle exhibits a slight reduction or no change, depending on the condition being examined.

The F106 tests were performed using the NASA Lewis Research Center aircraft. This aircraft, equipped with a J85 engine, is used as a flying test bed for acoustic and aerodynamic research. Data from two types of nozzles were obtained using the NASA/F106 aircraft. The baseline nozzle was tested during a joint NASA/General Electric flight test program performed at Selfridge Air Force Base in November 1974. The 104-tube nozzle was tested at Selfridge in early 1973 and the resulting data[7] provided to General Electric by

NASA/Lewis for inclusion in this study. It should be noted that the baseline nozzle was not a true conical nozzle but a low-area-ratio no-flow ejector system.

The F106 program was chosen to complement the Learjet program because it was desirable to demonstrate the applicability of the inflight simulation technique for a complex geometry suppressor configuration such as the 104-tube nozzle. The test data presented in this section will show that changes in the noise signature from static to flight conditions for the baseline and 104-tube nozzles have distinctly different trends. The static and flight maximum PNL and OASPL are summarized in Fig. 11. The reduction from static to flight for the F106 baseline nozzle is significantly greater than that observed for the Learjet conical nozzle. These differences in the observed flight effects are attributed to the differences between the designs of the two exhaust nozzle systems.

The 104-tube nozzle maximum-noise angle characteristics exhibit a significant amount of reduction from static to flight at the 2100 fps condition. However, as the jet velocity is decreased, significantly less flight effect is observed. The 90-deg angle indicative of pure source reduction showed a significant reduction in the noise signature from static to flight. The magnitude of reduction is observed to be a function of jet velocity, as well as the exhaust nozzle configuration. A typical directivity characteristic for the two nozzles on the basis of OASPL is presented in Fig. 12. In general, significant reduction from static to flight is observed at all angles for the baseline nozzle. The amount of reduction in the aft quadrant tends to decrease with decreasing jet velocity. The forward quadrant may or may not have reduction depending on the condition being examined. The 104-tube nozzle exhibits similar trends to those of baseline nozzle. The magnitude of the reduction is observed to be less than that exhibited by the baseline nozzle in the aft quadrant. The forward quadrant trends cannot be assessed due to lack of static test data.

The moving-frame validation test program was conceived to provide a highly controlled set of simulated flight data for

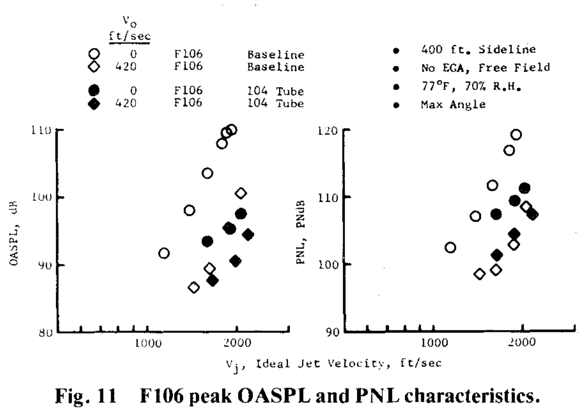

Fig. 11 F106 peak OASPL and PNL characteristics.

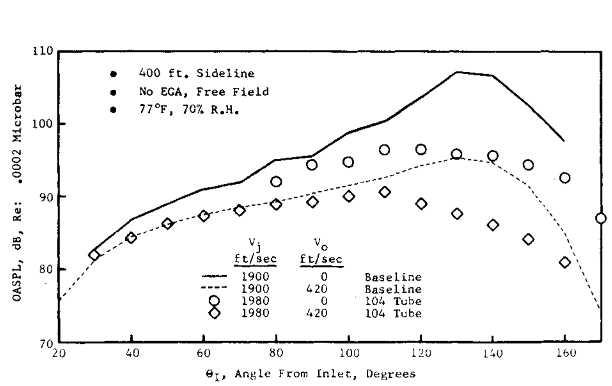

Fig. 12 F106 baseline and 104-tube nozzle OASPL directivity patterns.

verification of the inflight simulation technique. Based on the evaluation phase, the Aerotrain was found to have the unique capability to provide this complimentary data base for the J85 cycle. A joint General Electric/SNECMA** test program was formulated utilizing this vehicle to determine the static and noise signature of three exhaust nozzle systems for a range of engine power settings. The exhaust nozzles were a conical nozzle, 8-lobe nozzle, and 104-tube nozzle. The range of jet velocities and flight velocities investigated were from 1400 fps through 2200 fps and 0 fps through 275 fps, respectively. The 8-lobe and 104-tube were the same nozzles that were tested on the Gates Learjet-25C and F106 aircraft, respectively.

Internal noise,[8,9] may have a severe impact on the flight effects observed on an engine system or what are called jet noise flight effects may be a combination of many engine noise sources, not just jet noise. The influence of combustion noise on the Aerotrain data was assessed. The results of these analyses suggested that the J85 combustion noise was not of sufficient level to cause significant changes in the Aerotrain data on the basis of OASPL directivity patterns. Based on predictions, selective suppressor nozzle one-third-octave bands would appear to be contaminated; but the comparisons with scale model data in these regions indicate that the prediction procedure, derived from the conical nozzle, calculates levels higher than actually observed. It was concluded that this data was of sufficient quality for the validation of the inflight simulation technique.

Presented in Fig. 13 are the maximum OASPL levels for each of the nozzles as a function of jet velocity and flight velocity. The conical nozzle peak noise level reduction is observed to increase with increasing flight velocity and with decreasing jet velocity. In contrast, for the two suppressor nozzles, the peak noise reduction was only a function of forward velocity.

A typical OASPL directivity pattern is presented in Fig. 14 for the three configurations. The trends on this basis are similar in some respects but different in others, the salient points being that the angle of maximum noise is observed to occur generally from 110 deg to 120 deg, whereas, for the conical nozzle, it is 130 deg to 140 deg. At the extreme angles in the aft quadrant, i.e., $\theta_I = 140$ deg through 160 deg, a decrease in OASPL is observed relative to static conditions. The magnitude of this reduction is significantly greater than the peak noise reduction observed. This conclusion is valid for the suppressor configurations at all three jet velocities. However, the conical nozzle at 2200 fps indicates the opposite trend.

The 90-deg OASPL show little or no change from static to flight for all three nozzle configurations. Based on the results of the internal noise study, this apparent lack of reduction cannot be attributed to combustion noise. The forward quadrant directivity trends are different from those exhibited in the aft quadrant. For example, there is little or no reduction from static to flight on the basis of OASPL. In fact, for acoustic angles of 20 deg through 70 deg, the flight noise levels are slightly higher (1 to 3 dB) than the corresponding static noise levels. This conclusion is valid for the three nozzle geometries evaluated.

The most dramatic differences between the conical, 8-lobe, and 104-tube nozzles are best illustrated by the typical one-third-octave band spectra comparisons presented in Figs. 15-17. The spectra comparisons were analyzed at three acoustic angles, i.e., 130 deg, 90 deg, and 50 deg, and at three jet velocities. For the conical nozzle at 130 deg, the reduction from static to flight increases with increasing flight velocity and decreasing jet velocity. The reduction is relatively constant with frequency. The 8-lobe spectra show a reduction that increases with flight velocity but is not a strong function of jet velocity. The reduction is somewhat frequency-dependent.

**SNECMA – Société Nationale D'Etude et De Construction De Moteurs D'Aviation.

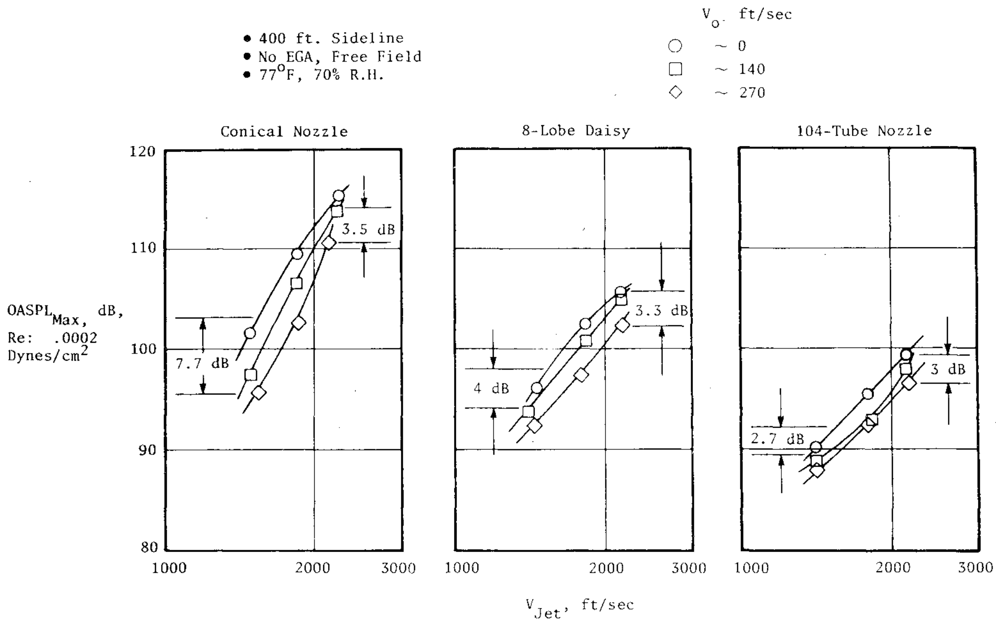

Fig. 13 Summary of peak OASPL charcteristics.

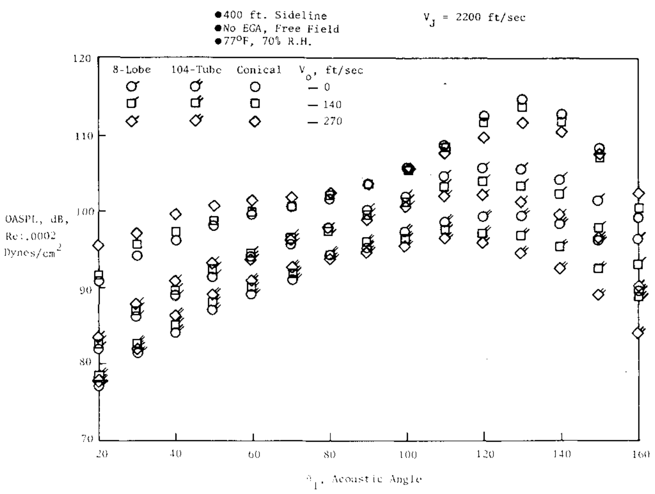

Fig. 14 Bertin Aerotrain OASPL directivity patterns, V_J = 2200 fps.

The 104-tube nozzle shows different trends than the conical or 8-lobe nozzles. The low-frequency portion of the tube spectra shows significantly more reduction from static to flight than the conical nozzle.

The typical 90-deg spectra (Fig. 16), in contrast to the 130-deg spectra, show the same trend for the conical and 8-lobe nozzles over the range of jet velocities and flight velocities evaluated. Careful study will reveal that there is little or no change from static to flight conditions. The 104-tube does show low-frequency reduction for the 2200 fps and 1800 fps conditions; however, no reduction is observed at the 1400 fps condition. This apparent lack of low-frequency reduction at 1400 fps is due to the influence of background noise.

The typical 50-deg spectra (Fig. 17) show substantially different characteristics than those observed at 130 deg and 90 deg. The conical nozzle at 2200 fps shows a strong influence of shock noise, whereas the 8-lobe and 104-tube nozzles indicate no influence of shock noise. In general, an increase on the order of 1 to 2 dB is observed from static to flight for all the configuations at this condition. The 1800 fps and 1400 fps spectra (not shown) are not influenced by shock noise and do show increases from static to flight on the order of 3 to 5 dB. However, the magnitude of this increase is frequency- and configuration-dependent.

In summary, the changes from static to flight for the three configurations evaluated on the Aerotrain vary as a function of configuration, jet velocity, flight velocity, acoustic angle, and frequency. This data, because of the inter-relationship of all these parameters, provided a strong test for the validation of the inflight simulation technique and accomplished the objective of the Aerotrain test program.

IV. Conclusions

Evaluation of fixed- and moving-frame facilities formed the basis for the selection of the hybrid technique to be verified. In general, fixed-frame facilities have three advantages: they were more flexible in regard to range of test conditions; they could use diagnostic instrumentation; and they were more economical in providing the capability for producing a large acoustic data base. The results of the rocket sled study demonstrated that a functional system meeting the program objectives could be developed. However, its undertaking was considered a "high-risk" item due to the uniqueness of the endeavor and limited experience in developing a facility of this type.

The data accumulated in the course of conducting the flight assurance testing (e.g., with Gates/Learjet and NASA/Lewis F106 aircraft), as well as the Bertin Aerotrain moving-frame validation testing, provided a comprehensive series of static and flight data for validation of the hybrid technique. Comparison of flight assurance and moving-frame results for the conical, 8-lobe, and 104-tube indicated that directivity and spectra have exhibited similar trends when different flight velocities were considered. The trend is that the effect of flight on the aft quadrant noise levels causes significant reduction relative to the static data for both the baseline and suppressor nozzles. Little or no change is observed at the 90-deg angle for the range of flight velocities and jet velocities evaluated. The effect of flight on the forward quadrant noise levels is to cause the noise levels to be slightly less than or slightly greater than the static levels depending on the configuration and condition being examined. The effect of flight on spectral characteristics appears to be strongly configuration-dependent.

The peripheral study to determine the impact of combustion noise on the Aerotrain data indicate that this noise source was not of sufficient level to cause significant changes in the Aerotrain OASPL directivity patterns. Based on predictions, selective third-octave bands would appear to be contaminated; however, comparisons with scale model data in these regions indicate that the prediction procedure, particularly for the suppressor nozzles, calculates combustion noise levels higher than the total noise actually observed. Aerotrain background noise was found to significantly

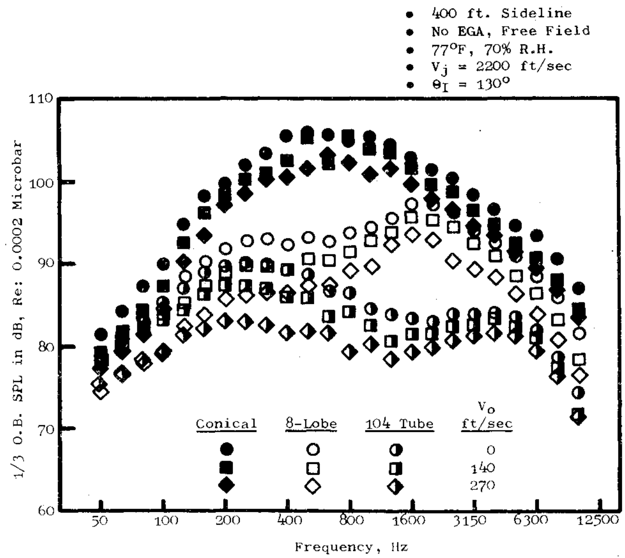

Fig. 15 Bertin Aerotrain moving-frame validation test at maximum θ_I.

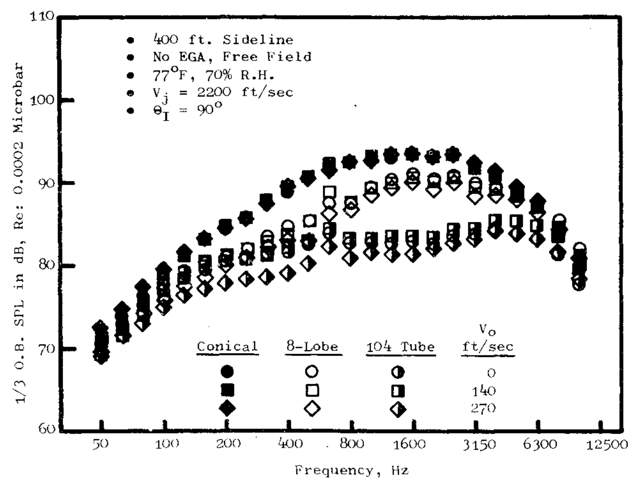

Fig. 16 Bertin Aerotrain moving-frame validation test at $\theta = 90$ deg.

contaminate the 104-tube nozzle flight data at the lower power setting conditions. Contamination was not a problem for the conical nozzle. However, in future moving frame test vehicle designs, background noise should be considered since it may be the limiting factor in determining the inflight noise signature of high suppression exhaust nozzle systems.

A high quality data base has been established for the comparison with transformed freejet data to evaluate the

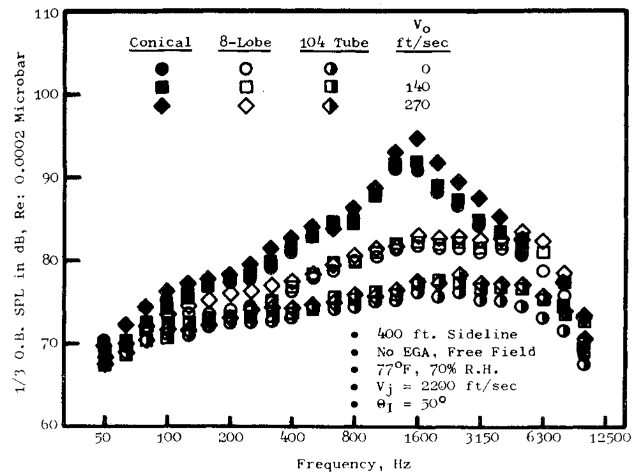

Fig. 17 Bertin Aerotrain moving-frame validation test at $\theta_I = 50$ deg.

validity of the hybrid technique. These comparisons are discussed in Ref. 3.

Acknowledgments

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