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ENGINE EXHAUST CHARACTERISTICS EVALUATION IN SUPPORT OF AIRCRAFT ACOUSTIC TESTING

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Summary

NASA Dryden Flight Research Facility and NASA Langley Research Center completed a joint acoustic flight test program. Test objectives were (1) to quantify and evaluate subsonic climb-to-cruise noise and (2) to obtain a quality noise database for use in validating the Aircraft Noise Prediction Program. These tests were conducted using aircraft with engines that represent the high nozzle pressure ratio of future transport designs. Test flights were completed at subsonic speeds that exceeded Mach 0.3 using F-18 and F-16XL aircraft. This paper describes the efforts of NASA Dryden Flight Research Facility in this flight test program. Topics discussed include the test aircraft, setup, and matrix. In addition, the engine modeling codes and nozzle exhaust characteristics are described.

Introduction

Environmental issues are a continuing concern for designers of new transport aircraft. To meet the strict noise requirements of Federal Aviation Regulation, pt. 36, stage III—Community Noise Standards (ref. 1), such designers need to improve the understanding of engine noise levels and sources. Because of these needs, flight test techniques were developed, and a series of flight tests were conducted at NASA Dryden Flight Research Facility (DFRF), Edwards, California, in conjunction with NASA Langley Research Center (LaRC), Hampton, Virginia. The DFRF role in the study was to set up the flight test, provide the test aircraft, and reduce the flight data into exhaust characteristics that have a major impact on jet noise. The LaRC incorporated the exhaust characteristics into the Aircraft Noise Prediction Program (ANOPP) for validation of theoretical acoustic data.

To understand the acoustical characteristics of engines representative of future transport airplanes, designers must study current aircraft and update the noise prediction codes. The aeronautics industry generally uses the ANOPP for subsonic transport noise prediction. This computer program has a wide range of noise-prediction modules that can be upgraded to assess advanced engine and aerodynamic concepts for reducing noise (ref. 2). However, ANOPP is semiempirical and does not include a large amount of flight data generated with engines operating at high nozzle pressure ratios (NPRs) or at speeds above Mach 0.3.

Future advanced transport design concepts will have engines designed for efficient flight at high speeds and will tend to have the thermodynamic cycle of a turbojet or a low-bypass turbofan. Such concepts will also have high NPR and jet velocities similar to current military fighter engines. High NPR and jet velocity raises concerns about takeoff, climb, and landing noise. Noise-suppression requirements are already in place for up to a radius of 5 n. mi. around airports for conventional airplanes. For future transports, new noise-suppression requirements may need to be determined for a radius of up to 50 n. mi.

To obtain a high-quality database, DFRF and LaRC conducted a joint study of the subsonic climb-to-cruise noise acoustics using aircraft with engines operating at high NPR and flight speeds above Mach 0.3. The flight study consisted of a series of flights over microphone arrays. The test vehicles were an F-18 and an F-16XL, ship 2, aircraft. In the subsonic climb portion of the study, the flight matrix consisted of flyovers at various altitudes and Mach numbers. For the ANOPP evaluation flyovers, the test points were conducted at a constant altitude, while the Mach number varied. Ground tests were conducted on both aircraft to establish baseline acoustic levels under static conditions. For these tests, the measured engine data were collected and later analyzed by an F404-GE-400 in-flight thrust code. The code predicted the engine exhaust characteristics of exhaust velocity and Mach number, which cannot be directly obtained from the measured engine data.

This paper describes the role of DFRF in this flight test program. Topics discussed include the test aircraft, setup, and matrix as well as the engine modeling codes and nozzle exhaust characteristics.

Aircraft Description

The flight tests were conducted using F-18 and F-16XL, ship 2, because the engines of these aircraft can simulate exhaust characteristics of future transports. Figure 1 shows an F-18 aircraft. This supersonic, high-performance fighter has excellent transonic maneuverability and is powered by two F404-GE-400 (General Electric Company, Lynn, Mass.) afterburning turbofan engines. Both engines are mounted close together in the aft fuselage. The F404-GE-400 engine is in the 16,000-lb thrust class (ref. 3). The standard F-18 maintenance data recorder was used to record a limited number of airplane and engine parameters on board the aircraft.

Figure 2 shows the F-16XL, ship 2. This two-seat, supersonic, fighter aircraft is modified with a cranked arrow delta wing and is powered by a single F110-GE-129 (General Electric Company, Lynn, Mass.) afterburning turbofan engine. The F110-GE-129 is in the 29,000-lb thrust class. This aircraft and engine were fully instrumented for flight research (ref. 4). Data were telemetered from the aircraft and recorded at DFRF.

Setup and Flight Test Matrices

The flight tests were flown over Rogers Lake (dry) adjacent to DFRF. At an elevation of 2300 ft, this dry lakebed provides a flat, interference-free area for acoustic testing. The LaRc personnel set up analog and digital microphone arrays on the lakebed. Figure 3 shows the array which consisted of 28 microphones placed along the "fly-by" line on the northeast side of the lakebed. This area was ideal for tracking because of its close proximity to the DFRF radar site. For the static acoustic tests, both aircraft were tied down on the thrust stand pad at the Air Force Flight Test Center, Edwards, California. Microphones were placed in an arc 70 ft from the tailpipes of these aircraft (fig. 4).

These flight tests were conducted in two segments: subsonic climb-to-cruise and ANOPP validation. The flight matrix for the climb-to-cruise segment consisted of level flight acceleration at various Mach numbers to simulate points along an optimum climb profile. Altitudes varied from 3,500 to 32,500 ft with speeds from Mach 0.3 to 0.95. To maximize NPR, a power setting of intermediate (maximum nonafterburning) was used. The ANOPP evaluation segment was flown at a constant altitude of 3,500 ft (1,200 ft above the ground) with speeds from Mach 0.3 to 0.95. Power settings varied depending on what was required to maintain steady flight at any given speed. To establish baseline acoustic levels under static Mach number and altitude conditions, additional tests were conducted for both aircraft on the thrust stand pad at the Air Force Flight Test Center, Edwards, California. The test matrices varied power lever angle (PLA) between part and intermediate power. Table 1 shows the flight test matrices for the climb-to-cruise and ANOPP validation segments:

Table 1. Flight test matrices

Climb-to-cruise matrix		ANOPP matrix
Altitude, ft MSL	Mach number	Mach number
3,800	0.3	0.0
7,300	0.6	0.3
12,300	0.65	0.6
22,300	0.75	0.8
32,300	0.9	0.95

Procedure

The DFRF pilots flew both aircraft over the acoustic array at desired conditions for ANOPP validation and subsonic climb-to-cruise noise generation. Using the ground track and distance displayed in the control room, the pilots were guided over the acoustic array (fig. 3). Such flight conditions as altitude or Mach number needed to be kept as constant as possible to get good quantitative runs. Speed brakes were used on some ANOPP flyovers for both aircraft to minimize the rate of acceleration. There were 120 recorded flyovers.

A single exhaust jet was desired, so the acoustics tests would have one distinct noise source. For the twin-engine F-18 aircraft, both engines were used before the beginning of the maneuver. Then the left engine was reduced to idle power, while the right test engine was operated at intermediate power or as required for ANOPP. This procedure simulated the effect of a single engine. Speed brakes were used on some ANOPP flyovers to minimize the rate of acceleration.

The F-16XL, ship 2, has a powerful engine, so holding the speed constant proved difficult. As a result, altitude was maintained, and the aircraft was allowed to accelerate.

These tests needed to be conducted with minimum wind, air traffic, and ground traffic noise to get acoustic data with little or no interference. Ground and air traffic, wind velocities, or both, were lightest in the morning; therefore, most of the tests were performed from 6:00 a.m. to

11:00 a.m. Testing was stopped if windspeeds exceeded 15 kts.

Ground acoustic tests were conducted on both aircraft at thrusts from idle to intermediate power. Approximately 2 min of data were recorded at each power setting. Temperature, windspeed, and wind direction were also recorded. Engine noise was recorded on tape in the DFRF acoustics van. These tests were conducted if the windspeeds were below 5 kts.

Results And Discussion

Jet-mixing and shock cell noises are the two primary sources of noise for takeoffs and subsonic climbs (ref. 5). These noise sources are affected by the aircraft velocity, the jet exit Mach number and velocity, and the NPR. For acoustic analysis, exhaust characteristics are normally defined at the nozzle exit and exhaust plume. Jet-mixing noise is a function of the difference between the fully expanded jet velocity (V_{jet}) and the free-stream velocity. Shock cell noise is a function of the difference between the fully expanded jet Mach number (M_{jet}) and the nozzle exit Mach number (M_9). Nozzle exit velocity (V_9) and M_9 are based on the aerothermodynamic characteristics of the flow at the nozzle exit plane. The V_{jet} and M_{jet} are based on the jet flow after it leaves the nozzle and goes through a series of shocks and expansion waves in the exhaust (fig. 5).

The LaRC operates the ANOPP code, and DFRF operates the engine performance codes. The DFRF was responsible for reducing the engine data to provide the jet characteristic values that LaRC needed to use to validate the ANOPP. Data obtained from the engine during the flight and ground tests included compressor speed and discharge pressure, fan speed, fuel flow, inlet and gas temperatures, and turbine discharge pressure. Measured engine data obtained from the flight tests do not directly give the values of M_9, V_9, M_{jet}, and V_{jet} needed for ANOPP. As a result, the measured engine data must be input into the engine performance codes. The resulting output provides the calculated values for M_9, V_9, M_{jet}, and V_{jet}.

Two engine performance codes were used for this test. The F404-GE-400 in-flight-thrust performance code (ref. 6) was used for the F404-GE-400 engines in the F-18 aircraft. The F110-GE-129 steady-state code (ref. 7) was used for the F-16XL, ship 2, engine. Developed by the General Electric Company for the U.S. Navy, the in-flight-thrust performance code provides an accurate calculation of F404-GE-400 engine airflow, thrust, and V_9 throughout the flight envelope. This code models the engine as a gas generator to calculate mass flow, pressure, and temperature of the nozzle exhaust and uses several engine measurements as input. With the exhaust nozzle performance characteristics known, the gross thrust, V_9, and M_9 may be calculated. The F404-GE-400 code calculates V_9, M_9, V_{jet}, and M_{jet}. The F110-GE-129 is a steady-code which predicts performance consistent with average F110-GE-129 engine levels. Input conditions at the engine inlet are obtained from the engine flight data. Only V_{jet} and M_{jet} were calculated by the F110-GE-129 steady-state code. The V_9 and M_9 were determined in a follow-on calculation.

Figure 6 shows the effect of Mach number on F404-GE-400 exhaust characteristics for climb-to-cruise tests at intermediate power. Each point on the curve represents a different altitude in the climb-to-cruise matrix. The nozzle is overexpanded at the beginning of the climb profile when M_∞ is approximately 0.3, and altitude is approximately 3800 ft (The V_9 is greater than V_{jet}.) The point where these data cross, M_∞ equals approximately 0.85, and V_{jet} equals V_9, indicates that the nozzle is fully expanded. The nozzle is underexpanded when the climb-to-cruise profile reaches an altitude of approximately 32,300 ft, and M_∞ equals approximately 0.9. (The V_9 is less than V_{jet}.) Overall, V_9 varies from a minimum of approximately 2750 ft/sec to a maximum of approximately 2800 ft/sec. Then V_9 drops to approximately 2750 ft/sec, while V_{jet} varies from 2300 to 2900 ft/sec.

Figure 7 show M_{jet} and M_9 as a function of M_∞. The values for M_{jet} and M_9 follow the same Mach number and altitude trends as those for V_{jet} and V_9. The values for M_9 vary between 1.69 and 1.8 then drop to 1.7. The values of M_{jet} vary between approximately 1.35 and 1.76. Above a free-stream Mach number of 0.85, the difference between these two values reduces significantly.

Figure 8 shows the effect that aircraft Mach number has on the exit velocity for the ANOPP with the F-16XL, ship 2. The changing PLA for the different test points is also shown. Power settings varied from part power at Mach 0.3 to intermediate power at Mach 0.95. The V_9 varied from 1400 to 2200 ft/sec and increased with Mach number and PLA. Exit velocity trends for the F404-GE-400 code are similar to those of the F110-GE-129 engine.

Figure 9 shows the V_9 for the ground tests made with F-16XL, ship 2. These ground tests were completed with constant speeds of Mach 0.0 and altitudes of 2300 ft; throttle setting was permitted to vary. The V_9 varied from 1400 to 2000 ft/sec and increased with PLA. The velocity trends for the F404-GE-400 code are similar to the F110-GE-129 steady-state code. By determining V_{jet} and V_9, LaRC can validate the ANOPP prediction code. With real quantitative flight data available, the upgrades will result in high-fidelity predictive codes for use on future transport design studies.

Concluding Remarks

Flight tests were conducted at NASA Dryden Flight Research Facility in support of an acoustic study for future transport aircraft. One objective was to determine climb-to-cruise noise, while another was to expand the database to validate the Aircraft Noise Prediction Program. Dryden Flight Research Facility supplied the aircraft, set up the flight and ground tests, and reduced the data to the values of nozzle exit velocity and exit Mach number as well as the fully expanded velocity and Mach number. These values were used by Langley Research Center to validate the Aircraft Noise Prediction Program.

An F-18 aircraft with the F404-GE-400 engine and an F-16XL, ship 2, with the F110-GE-129 engine were used for these tests. One hundred and twenty passes were made over microphone arrays that were placed on Roger's Lake (dry), Edwards, California. To further validate the Aircraft Noise Prediction Program code, a ground test was performed on both aircraft. Data taken from these aircraft were then entered into engine performance prediction codes that modeled the F110-GE-129 and F404-GE-400 engines. The values of exit velocity and Mach number produced by these codes were forwarded to Langley Research Center for use in the Aircraft Noise Prediction Program. These flight tests demonstrated the ability to create a quality noise database and made it possible to validate Aircraft Noise Prediction Program predictive codes. With this new database, these codes will be upgraded to predict noise generated by future transport aircraft.

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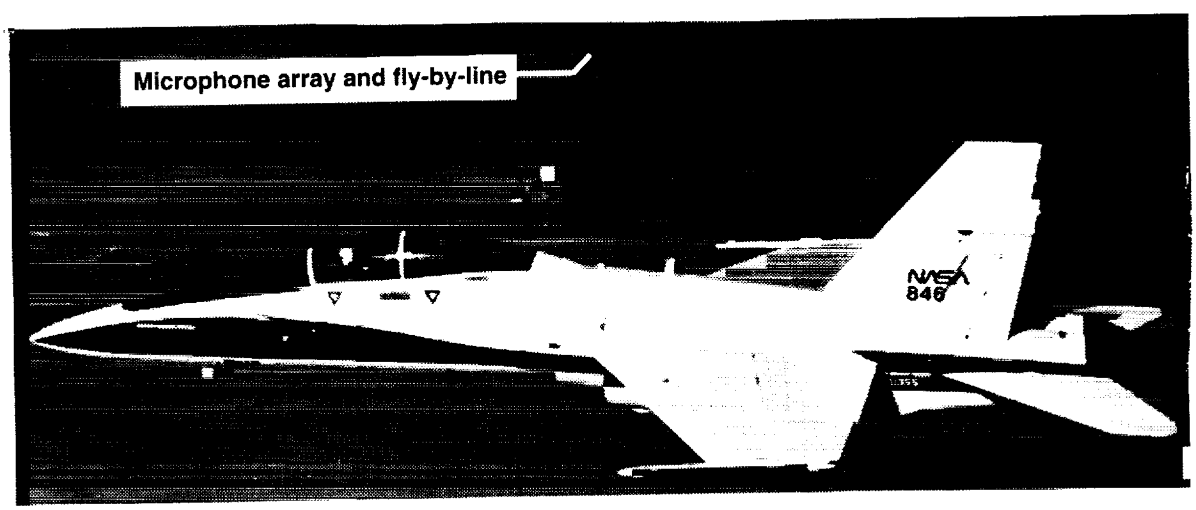

Figure 1. The F-18 aircraft.

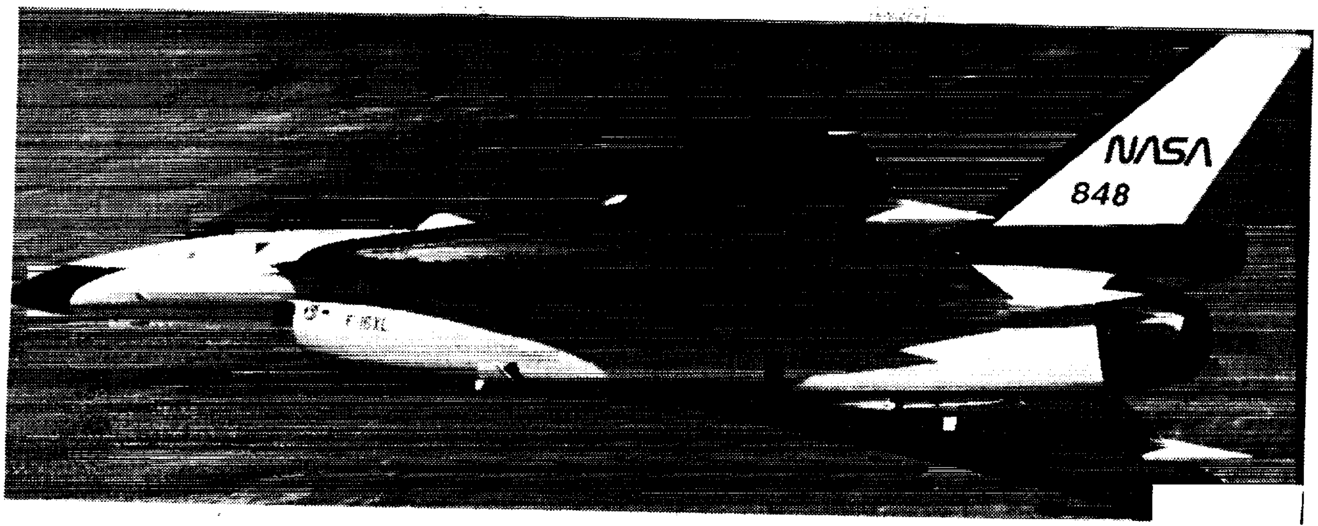

Figure 2. The F-16XL, ship 2, aircraft.

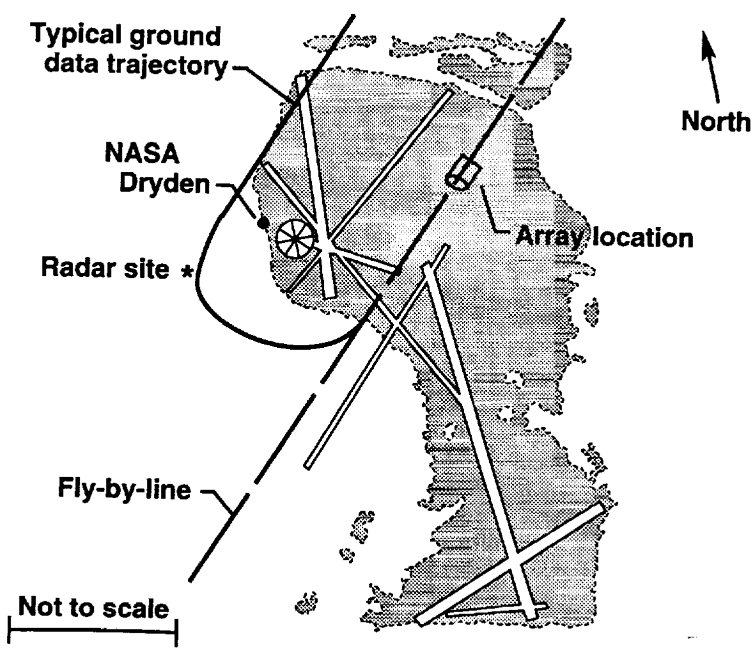

Figure 3. Ground-tracking and array layout at Rogers Lake (dry), Edwards, California.

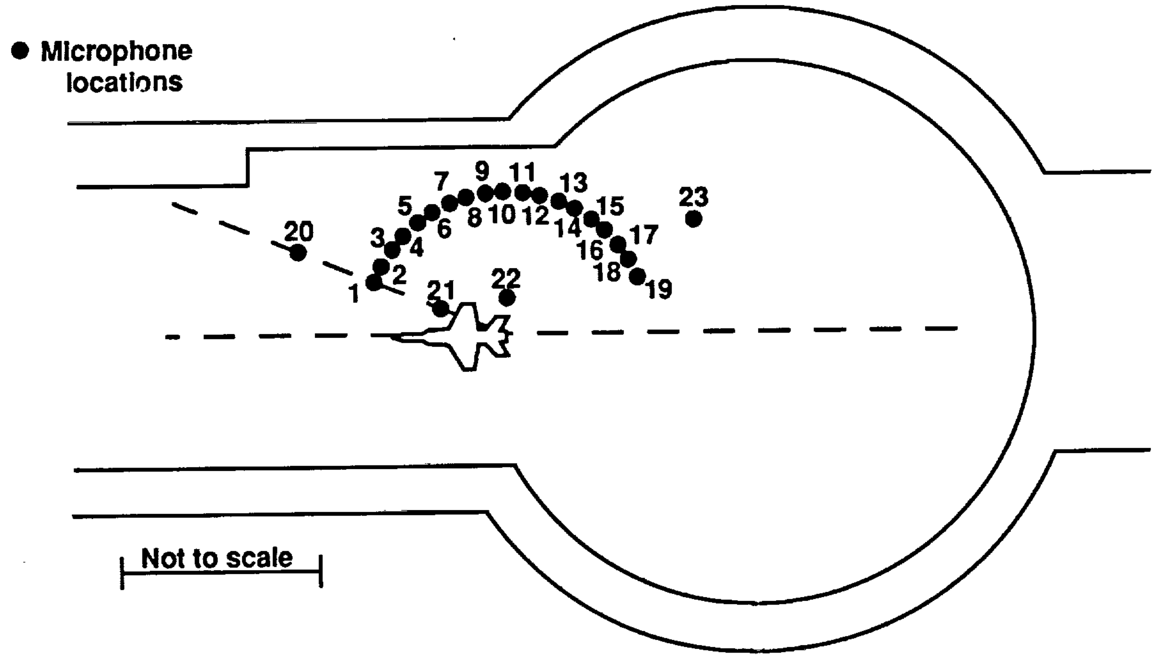

Figure 4. Test setup using the thrust stand at the Air Force Flight Test Center, Edwards, California. Microphones were placed in a 70-ft arc.

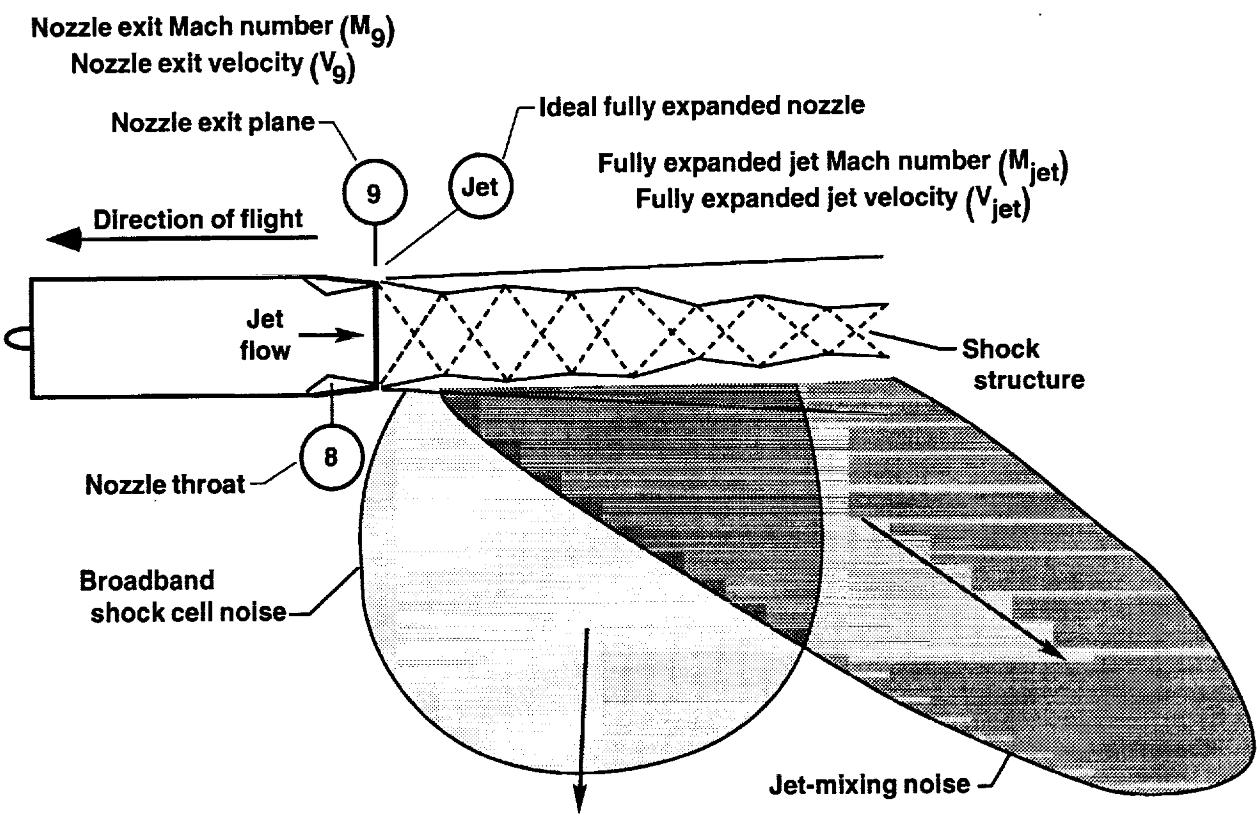

Figure 5. Noise sources for F-18 and F-16XL, ship 2, aircraft operating at high-nozzle-pressure ratios.

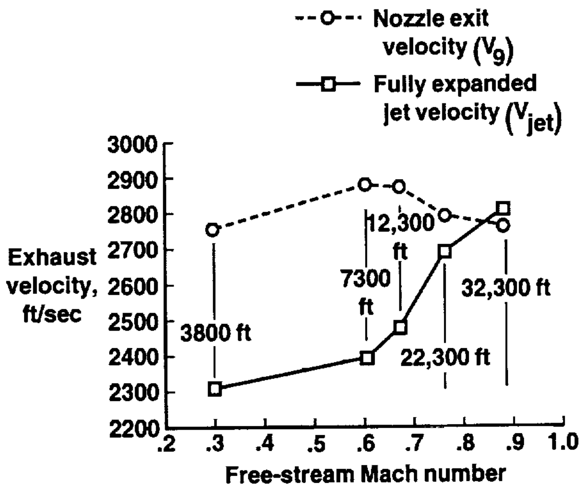

Figure 6. Climb-to-cruise exhaust Mach number test points for an F-18 aircraft at intermediate power.

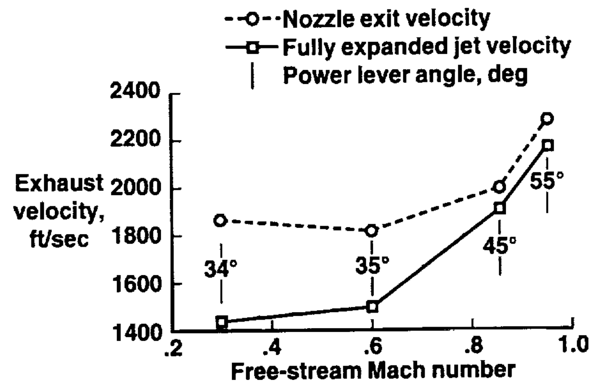

Figure 8. Fully expanded jet velocity for ground test points of an F-16XL, ship 2, aircraft at an altitude of 2300 ft amd at Mach 0.

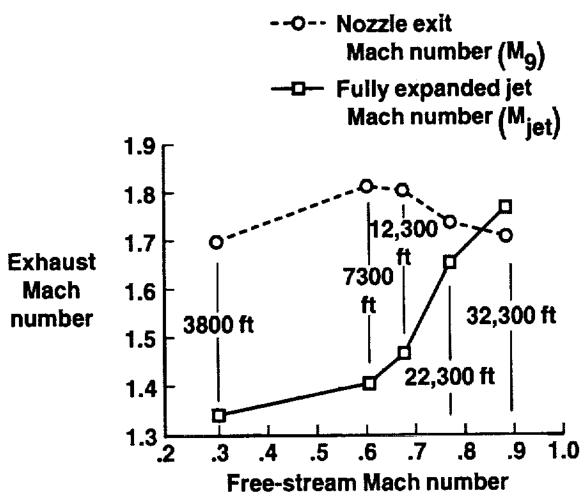

Figure 7. Aircraft Noise Prediction Program validation exhaust velocity test points for an F=16XL, ship 2, aircraft.

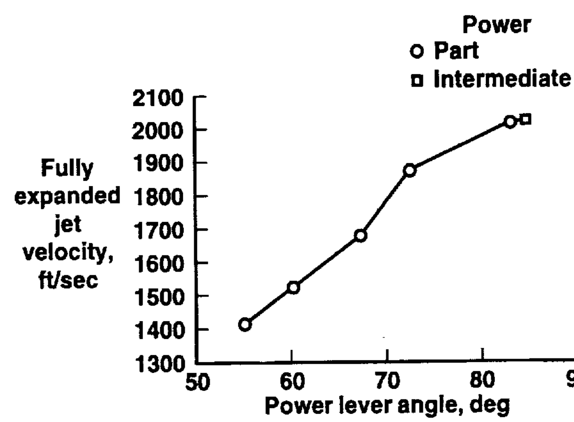

Figure 9. Fully expanded jet velocity for ground test points of an F-16XL, ship 2, aircraft at an altitude of 2300 ft and at Mach 0.

Biography

Kimberly Ennix has worked at NASA Dryden Flight Research Facility (DFRF) at Edwards, California, for two years as a propulsion analyst. During this time, she developed and conducted test plans for the acoustic research program. These tests involved the creation of flight plans for multiple passes over acoustic microphone arrays at varying altitudes and speeds. The research called for the reduction of the engine and radar data.

She also developed the analytical support plan for the combustor tests conducted at NASA Ames Research Center, Moffett Field, California. The combustor tests were in support of the High Speed Civil Transport (HSCT) Program. Ms. Ennix volunteers her time to speak to elementary and high school children about engineering and the aerospace industry. Before coming to DFRF, Ms. Ennix worked in rocket propulsion analysis at the Rocket Propulsion Laboratory at Edwards Air Force Base, California.