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SOUND PROPAGATION FROM A SUPERSONIC JET FLOWING THROUGH A RIGID-WALLED DUCT WITH A J-DEFLECTOR

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Abstract

An experimental study is performed on the acoustical characteristics of a scale-model, perfectly expanded, cold supersonic jet of gaseous nitrogen (Mach 2.5, nozzle exit diameter of 1 inch) flowing through a rigid-walled duct having an upstream J-deflector. The nozzle is mounted vertically, with the nozzle exit plane at a height of 73 jet diameters above ground level. Relative to the nozzle exit plane, the location of the duct inlet is varied at 10, 5, and −1 jet diameters. Far-field sound pressure levels were obtained at 2 levels (54 jet diameters and 10 jet diameters above ground) with the aid of 9 acoustic sensors equally spaced around a circular arc of radius equal to 80 jet diameters. Comparisons of the acoustic field were made with and without the duct.

INTRODUCTION

In recent years there has been considerable interest in the design of exhaust ducts for jet noise mitigation systems for launch vehicles devoid of water injection. Excellent reviews of rocket noise are presented by McInerny and Sutherland [1,2]. Along with analytical methods, scale-model testing is helpful in designing such systems as a means of predicting the full-scale acoustic environment [3,4]. At NASA Kennedy Space Center (KSC), a Launch Systems Testbed (LST) is under development to establish a capability to simulate small-scale launch vehicle environment for use in testing and evaluation of launch pad designs for future space vehicles.

This report summarizes the effect of a rigid-walled exhaust duct in mitigating the sound from a supersonic cold nitrogen jet. The nozzle has an exit diameter of 1 inch and is ideally expanded to an exit Mach number of 2.5.

DESCRIPTION OF THE TEST FACILITY

Test Facility

The Trajectory Simulation Mechanism (TSM), located at the Launch Equipment Test Facility (LETF) in the KSC Industrial Area, served as the primary facility for conducting these tests. It is designed to simulate $x - y$ launch trajectories for nonstationary scaled acoustic load on the launch vehicle, payload, and ground support equipment. TSM features a 1/10-scaled model of the Space Shuttle launch parameters. Presently only cold jet simulation capability is available. By cold jet, it is implied here that the nozzle exit temperature is colder than the ambient temperature.

A schematic of the TSM and related test setup is included in Figure 1. The TSM facility is outfitted with a chamber and a supersonic nozzle held in vertical position. The chamber is fed from pressurized gaseous nitrogen bottles (8000 psi) in conjunction with two pressure regulators in series. The pneumatic system was modified to facilitate a continuous supply of nitrogen for the duration of the tests. The TSM facility also provides necessary instrumentation for measurement of acoustic and exhaust flow field.

Supersonic Nozzle. The convergent-divergent nozzle was designed on the basis of characteristic method and is made of stainless steel (Figure 2). The Mach 2.5 nozzle has an exit diameter of 1 inch, compared with the 3-to-4-ft exit diameters typical of large rocket engines. Typical chamber and nozzle conditions for the scale-model test series considered here are displayed in Table 1.

Exhaust Duct. A scaled aluminum exhaust duct with an upstream J-deflector (30-degree inclination to the vertical) was fabricated and installed under the nozzle. A photographic view of the actual jet/duct setup is displayed in Figure 3. The exit cross section of the duct is 6 inches × 12 inches. The exhaust duct can be positioned at desired levels relative to the nozzle exit plane (NEP).

Instrumentation

Flow Measurements. The chamber conditions (pressure and temperature) are measured by a pressure gauge and thermocouple mounted on the chamber wall. From the measurement of the total pressure and the static pressure at the NEP, the exit Mach number is computed with the aid of Rayleigh's pitot tube formula [5].

Acoustic Measurements. The acoustic field surrounding the nozzle/duct configuration was measured by an array of acoustic transducers (microphones) placed azimuthally at 22.5-degree increments (Figure 4). Bruel & Kjaer microphones of 1/2-inch diameter were used for recording the sound pressure. The sensors were placed azimuthally at 80 nozzle exit diameters from the NEP, thus representative of far-field condition.

Data Acquisition

Flow Data. Time history measurements are made of chamber pressure, chamber temperature, and pitot and static pressures at the NEP. These measurements serve to indicate the time at which steady-state conditions are achieved. Generally, it takes about 60 s for steady conditions to prevail.

Acoustic Data. As soon as the flow becomes steady, recording of acoustic data begins. Pressure-time data from the microphones are processed by the data acquisition system. The data are sampled at a rate of 125,000 samples/s so that sound frequencies up to 60 kHz can be recorded. With the aid of LabVIEW software, the time domain data are processed in the form of narrowband spectra, 1/3-octave-band sound pressure levels and overall sound pressure levels (OASPL) at each location.

RESULTS AND COMPARISON

Overall Sound Power

Figure 5 shows a comparison of the OASPL for free jet with those of a jet passing through a closed duct, with the NEP located at different heights relative to the duct inlet. While there is axial symmetry of the OASPL for the free jet, there is considerable directivity of the OASPL in the presence of exhaust duct. For the nozzle-to-duct inlet distances of 5 inches and -1 inch (NEP inside the duct), the OASPL near 0 degree exceeds the value for the free jet case. When the NEP is held at 10 inches above the duct inlet, a reduction in OASPL of about 3 dB is achieved relative to the free jet case. These findings suggest that there is an optimum location of the NEP relative to the duct inlet plane, which results in the largest reduction in the OASPL.

Spectral Sound Power

The spectral content of the sound power level for the free jet and the closed-duct cases is shown in Figures 6 and 7, respectively. In the case of free jet, the spectral distribution is symmetric, independent of the azimuthal position of the microphone. A peak frequency of about 4 kHz is noted in this case and agrees well with the estimated value based on a Strouhal number ($St = fu_j / d_j$) of 0.2. Here f denotes the frequency, u_j the nozzle exit velocity, and d_j the nozzle exit diameter. In the closed-duct case, the peak frequency near $\theta = 0$ degree (corresponding to the duct axis) is about 4 kHz, which is close to the free-jet value. However, the peak frequency increases as the angle from the jet axis is increased. Differences in the spectrum for various angles are observed over a wide range of frequencies (roughly 1.5 decades).

CONCLUSIONS

With the use of a closed duct, the overall sound power of a Mach 2.5 supersonic jet is reduced by about 3 dB. The peak frequency is found to increase above the free-jet value as the angle from the jet axis is increased. The results also suggest that there is an optimum distance between the nozzle exit plane and the duct inlet for minimizing the sound power. With increased duct lengths and absorbing liners, larger reductions in sound power can be realized.

ACKNOWLEDGEMENT

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Table 1. Summary of Nozzle Parameters

Parameter	Value
Stagnation pressure, psia	250
Stagnation temperature, °R	500
Nozzle mass flow rate, lbm/s	1.7
Nozzle exit diameter, inch	1.0
Exit pressure, psia	14.7
Exit temperature, °R	222
Exit velocity, ft/s	1,820
Nozzle exit Mach number	2.5
Jet exit Reynolds number	4×10^6

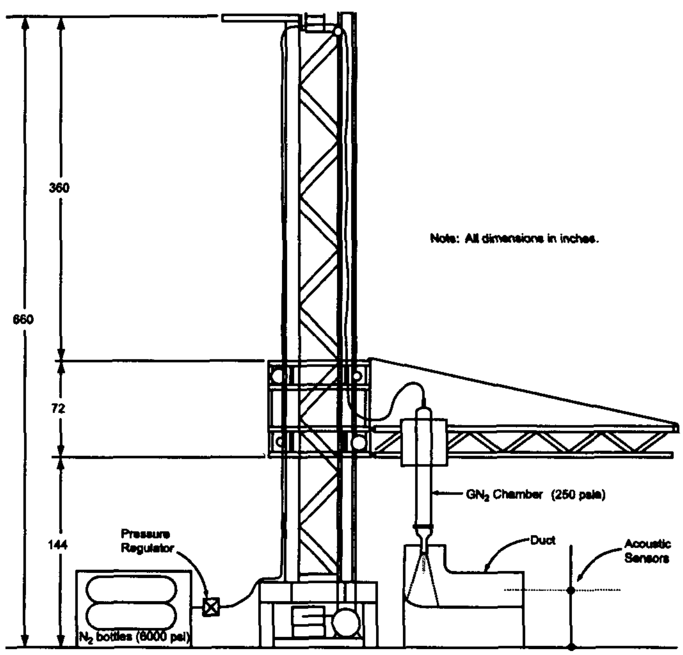

Figure 1. Overall test setup

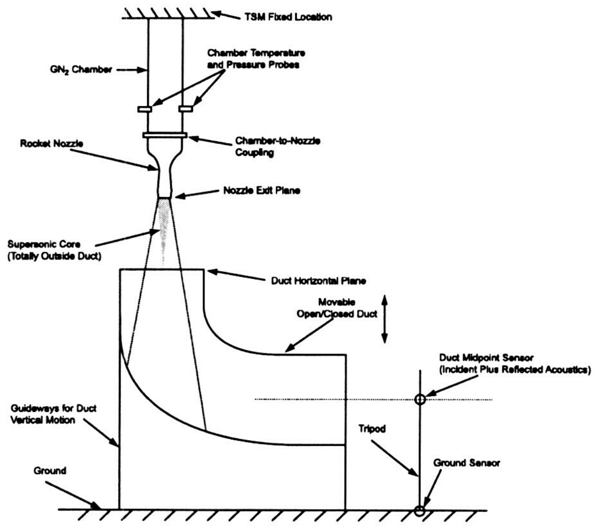

Figure 2. Schematic of the jet/duct configuration

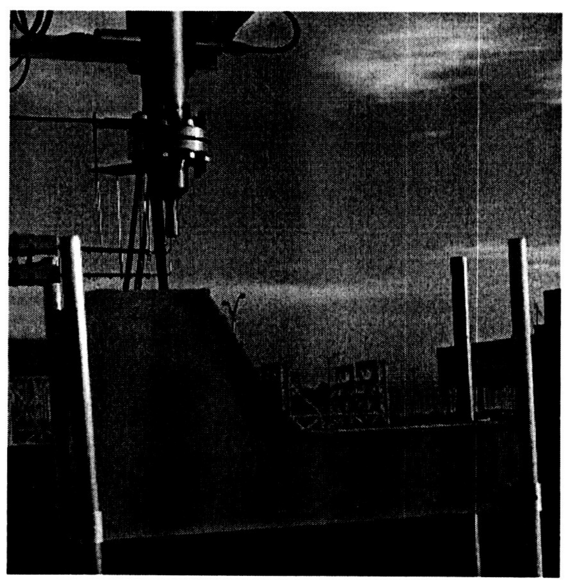

Figure 3. Jet/duct configuration

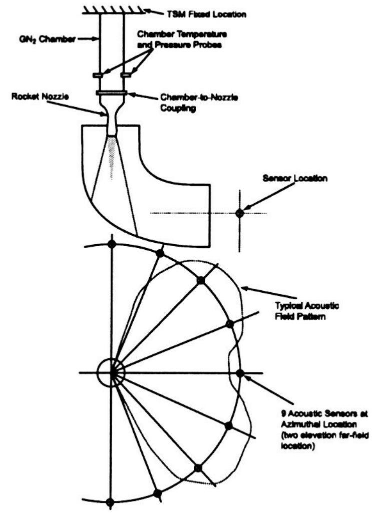

Figure 4. Acoustic measurement setup

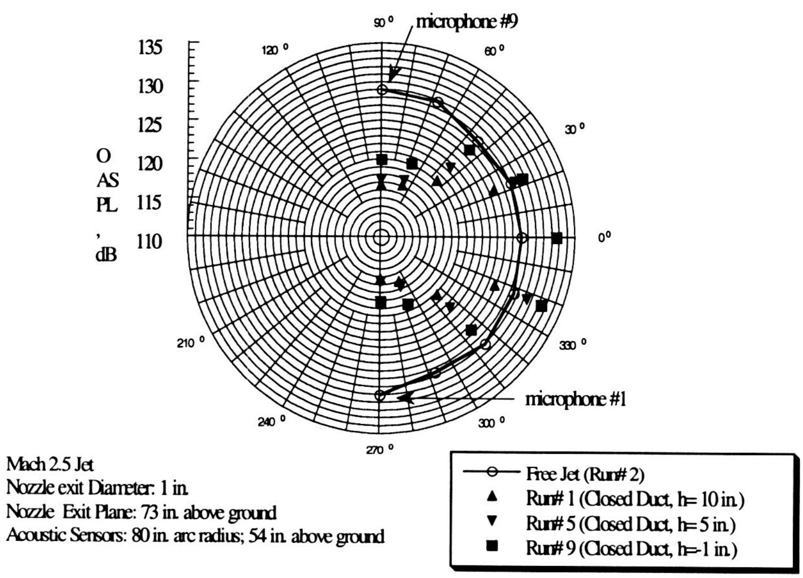

Figure 5. Comaparison of OASPL for free jet and with a closed duct

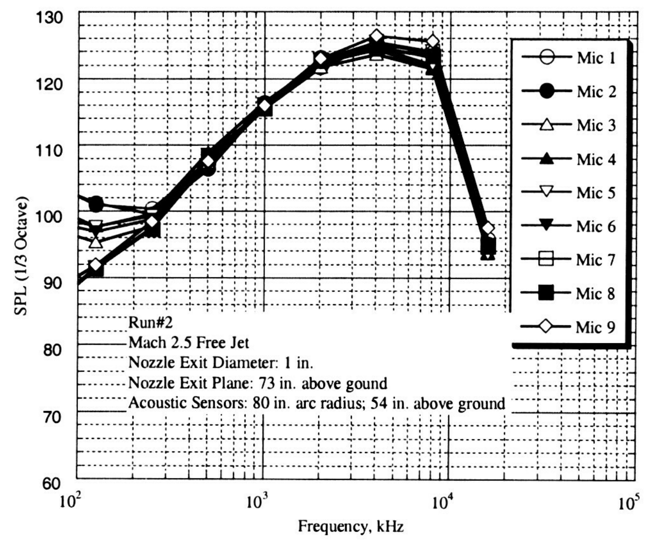

Figure 6. Spectral sound power for the free jet

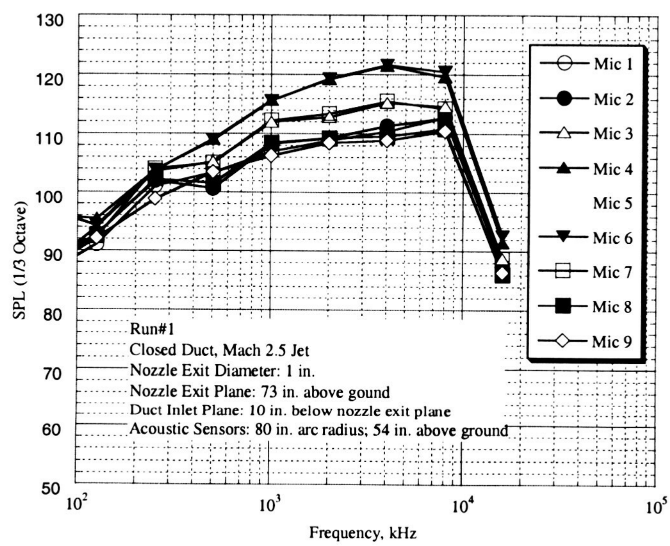

Figure 7. Spectral sound power for the jet flowing in a closed duct