Understanding the Aeroacoustic Radiation Sources and Mechanism in High-Speed Jets

Dissertation

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By

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Abstract

Who reads a dissertation abstract?

This work is dedicated to Science ...

Acknowledgments

I should probably acknowledge someone here . . .

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Publications

Research Publications

M. Crawley, C.-W. Kuo, and M. Samimy, "Identification of the Acoustic Response in the Irrotational Near-field of an Excited Subsonic Jet." submitted to *International Journal of Aeroacoustics*.

M. Crawley, R. Speth, D. V. Gaitonde, and M. Samimy, "A Study of the Noise Source Mechanisms in an Excited Mach 0.9 Jet - Complementary Experimental and Computational Analysis." AIAA Paper 2015-0736, *53rd AIAA Aerospace Sciences Meeting*.

M. Crawley, A. Sinha, and M. Samimy, "Near-field and Acoustic Far-field Response of a High-Speed Jet Forced with Plasma Actuators." *AIAA Journal*, expected 2015.

M. Crawley and M. Samimy, "Decomposition of the Near-Field Pressure in an Excited Subsonic Jet." AIAA Paper 2014-2342, *20th AIAA/CEAS Aeroacoustics Conference*.

M. Crawley, A. Sinha, and M. Samimy, "Near-field Pressure and Far-field Acoustic Response of Forced High-Speed Jets." AIAA Paper 2014-0527, *52nd AIAA Aerospace Sciences Meeting*.

M. Crawley, H. Alkandry, A. Sinha, and M. Samimy, "Correlation of Irrotational Near-Field Pressure and Far-Field Acoustic in Forced High-Speed Jets." AIAA Paper 2013-2188, *19th AIAA/CEAS Aeroacoustics Conference.*

H. Alkandry, **M. Crawley**, A. Sinha, M. Kearney-Fischer, and M. Samimy, "An Investigation of the Irrotational Near Field of an Excited High-Speed Jet." AIAA Paper 2013-0325, *51st AIAA Aerospace Sciences Meeting.*

M. Crawley, M. Kearney-Fischer, and M. Samimy, "Control of a Supersonic Rectangular Jet Using Plasma Actuators." AIAA Paper 2012-2211, *18th AIAA/CEAS Aeroacoustics Conference.*

Fields of Study

Major Field: Mechanical and Aerospace Engineering

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Chapter 1: Introduction

1.1 Motivation

The advent of the turbojet engine led to a transformation in both commercial and military aviation, allowing for much faster flight than previously possible with propellor-driven aircraft. However, the increased thrust of turbojets has come at great cost; significant acoustic radiation is generated by the rotating components (compressor, turbine, fan), by the combustion process, and ultimately by the free jet itself. On the commercial side, the escalating number of flights, encroachment of urban and residential areas near airports, and tightening of environmental regulations have combined to force airports to institute curfews, surcharges and flight path restrictions to combat noise pollution. For the military, hearing damage inflicted on nearby personnel (particularly on aircraft carriers) has necessitated the implementation of noise reduction concepts on tactical aircraft. During takeoff and landing, when acoustic radiation is most problematic to ground crew and surrounding urban and residential areas, the dominant noise source of the jet engine is the aeroacoustic radiation generated by the high velocity engine exhaust. This has spurred extensive research, spanning over six decades, into the acoustic source mechanism in high speed, high Reynolds number jets.

While progress has been made in the field of aeroacoustics, both experimentally [4, 6, 5] as well as theoretically [1], understanding of jet noise sources and their radiation mechanisms remains incomplete [2]. This is due to the large number of interrelated parameters (e.g. Reynolds number, temperature ratio, acoustic Mach number, nozzle geometry, et cetera) as well as the large disparity in the associated length and time scales of the turbulent phenomena and the radiated noise. Simulations of controlled free shear layers have suggested that there is significant potential for noise reduction, on the order of 11 dB in some cases [Wei 2006]. However, these simulations relied on non-physically defined actuation (that is, forcing was applied over a defined region by arbitrary energy, momentum, and body force terms), and a physical interpretation of the forcing parameters was not immediately clear to the researchers. Current noise-mitigation technologies for free jets have largely been applied in an adhoc fashion, due to our incomplete understanding of the aeroacoustic sources. Fully realizing this maximum noise reduction potential will require a much more detailed understanding of the mechanism (or mechanisms) by which free jets radiate to the far-field.

It is generally agreed that the dominant noise sources are related to the large-scale turbulent structures present in the mixing layer of the jet. What remains to be determined is what aspects of the large-scale structure evolution and interactions are relevant to the noise generation process. Theoretical models of spatially- and temporally-modulated wavepackets have shown great promise in replicating the observed characteristics of the dominant far-field noise [Cavalieri/Jordan?]. However, direct experimental data linking this structure evolution to the acoustic emission is still lacking. It is on this vein that the current work is focused. Until recently, experimental data acquisition techniques have been unable to capture the flow physics with

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enough fidelity (lacking in either spatial or temporal resolution) in order to accurately model the large-scale structures and aeroacoustic sources. By combining contemporary data acquisition methods (free-field microphones and non-time-resolved particle image velocimetry) with novel post-processing algorithms this work aims to directly link the relevant vortex dynamics of the large-scale structures to the acoustic emission events, and in the process identify a simplified aeroacoustic source mechanism.

1.2 Background

1.2.1 Flow Control

Controlling the development of the jet plume, and hence controlling the rate of mixing or intensity and characteristics of the emitted acoustic radiation, is a long running goal of the aeroacoustic community, spanning many decades of research. Passive, permanent modifications to the nozzle have been shown to be quite adept at this task; some examples of these include tabs [citations], lobed mixers [citations], and chevrons [citations]. However, these passive modifications have an associated penalty to the engine performance, one that is in effect over the entire duration of the flight regardless of whether or not the modifications are needed. To improve engine efficiency, active control techniques are desired, since they can be deactivated when unneeded, such as after a commercial airliner reaches cruising altitude. Active control techniques, which seek to manipulate instabilities in the jet shear layer, have been studied in low-speed, low-Reynolds number jets, the most common of which is acoustic drivers [citations]. However, as the speed and Reynolds number of the jet is increased (to match those in practical applications), so too does the required bandwidth and

energy of the active drivers. Hence, acoustic or magneto-hydrodynamic drivers lose control authority in these regimes, and more powerful actuators are required.

TO DO:

- passive vs active flow control

- shear layer / jet instabilities

- large-scale structures / energy cascade / wavepackets

1.2.2 Components of Jet Noise

A simplified model of the noise generation process in stationary free jets can be found in Fig. [INSERT FIGURE]. This model is based off of the work of Tam et al [4, 5], who observed that the far-field spectra could be represented as a combination of two similarity spectra based on polar angle of the observer, regardless of jet Mach number or temperature. At observer angles close to the jet downstream axis, the spectra exhibited a clearly defined spectral peak (F-spectrum), whereas at sideline or upstream angles the spectra were broadband (G-spectrum). From this observation the two-component acoustic source model was born: fine-scale turbulence, dominant in the near-nozzle region, is responsible for the omni-directional acoustic radiation that dominates the sideline and upstream polar angles. On the other hand, the large-scale turbulent structures which exist further downstream produce the superdirective radiation that is readily apparent at aft polar angles.

Additional noise source mechanisms have been identified for supersonic jets. In imperfectly expanded jets, shock cells are produced in the jet. As turbulent structures pass through these waves, the sharp pressure gradients cause them to emit

acoustic radiation. This is observed directly in the far-field as a broad-band amplification at high frequencies, referred to simply as broad-band shock-associated noise (BBSAN). In stationary or subsonic airframes this radiation can generate a feedback loop, whereby the noise travels upstream to the nozzle exit, excites the initial shear layer, and produces new structures at the same frequency. A high-amplitude, narrow-band tone (screech noise) is the end result of this feedback loop. Lastly, supersonically-convecting (relative to the ambient) large-scale structures (which exist in supersonic and heated jets) produce high-amplitude, strongly-directional acoustic radiation towards aft angles. This Mach wave radiation can be explained by a wavy-wall analogy (Tam again?). In the present work, the jet is unheated and subsonic; as such these noise sources are not present and therefore neglected throughout the rest of this work.

TO DO:

- Create simplified figure of free jet showing high frequency versus low frequency radiation (based off of Tam 2008)

- Explain Tam's "two-component" source model, with additional experimental evidence?

1.2.3   Acoustic Source Models

By rearranging the Navier-Stokes equations, Lighthill [3] was able to transform the governing equations for fluid dynamics into an inhomogeneous convected wave equation. In this acoustic analogy, the source term comprises Reynolds stress, shear stress, and density fluctuation terms (commonly referred to as *Lighthill's stress tensor*). As this formulation is exact (aside from the assumption of a constant sound

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speed), complete knowledge of the source field will yield an exact solution for the acoustic far field. In practical applications (e.g. high-speed, turbulent jets) however, the full source field cannot be measured using current experimental capabilities nor simulated with sufficient fidelity, thereby requiring certain simplifications.

Chapter 2: Experimental Methodology

2.1 Anechoic Chamber

All experiments were conducted at the GDTL within the Aerospace Research Center at the Ohio State University. Compressed, dried, and filtered air is supplied to the facility from two cylindrical storage tanks with a total capacity of 43 m3 and maximum storage pressure of 16 MPa. The air may be routed through a storage heater (not used in this study), which allows the jet to operate with a stagnation temperature up to 500 C, before expanding through a nozzle and exhausting horizontally into an anechoic chamber. Opposite the nozzle, a collector accumulates the jet and entrained air and exhausts to the outdoors. A schematic of the anechoic chamber can be seen in [INSERT FIGURE]. The dimensions of the chamber are 6.20 m wide by 5.59 m long and 3.36 m tall, with internal wedge-tip to wedge-tip dimensions of 5.14 m by 4.48 m and 2.53 m, respectively. The design of the chamber produces a cutoff frequency of 160 Hz, below the frequencies of interest for this study. A more detailed description of the GDTL anechoic chamber properties and validation has been given by [Hahn?].

For this study a converging, axisymmetric nozzle with exit diameter D of 25.4 mm was used. The internal contour of the nozzle was designed using a fifth order polynomial. The nozzle utilized a thick-lipped design in order to simplify the mounts

for the LAFPA extension, which housed the eight actuators used in this study. For the experiments reported in this paper, the jet was operated at a Mach number (M_j) of 0.90, and with a total temperature ratio of approximately unity. The Reynolds number based on the jet exit diameter was 6.2×10^5; previous investigations using hot-wire anemometry have indicated that the initial shear layer is turbulent for this operating condition with momentum thickness 0.09 mm and boundary layer thickness 1 mm [Kearney?].

2.2 Data Acquisition

2.2.1 Near- and Far-field Pressure

Near-field and far-field pressure measurements were acquired simultaneously, using Brel & Kjr inch 4939 microphones. The signal from each microphone is band-pass filtered from 20 Hz to 100 kHz using a Brel & Kjr Nexus 2690 conditioning amplifier, and recorded using National Instruments PXI-6133 A/D boards and LabVIEW software. The microphones are calibrated using a Brel & Kjaer 114 dB, 1 kHz sine wave generator (model # ???). The frequency response of the microphones is flat up to roughly 80 kHz, with the protective grid covers removed.

2.2.2 Particle Image Velocimetry

2.3 Localized Arc-Filament Plasma Actuators

Chapter 3: Near-field Signature of Aeroacoustic Sources

Chapter 4: Stochastic Estimation of Time-resolved Velocity Fields

Chapter 5: Dilatation as the Aeroacoustic Acoustic Source

Chapter 6: Conclusions

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