

# Technical Notes

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## Mach Number Effects on Jet Noise Sources and Radiation to Shallow Angles

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### I. Introduction

ALL jets have noise generation due to turbulent mixing; such mixing leads to the production of Reynolds stresses, the source term within the Lighthill acoustic analogy [1]. In addition to this source, a jet that possesses coherent, large-scale structures that travel with velocities exceeding the local speed of sound will emit Mach wave radiation, a highly efficient noise production mechanism. The amplitude of jet noise scales with the jet area and the exit velocity to an angle-dependent power  $n$ . There is disagreement, however, in the value of  $n$ . Based on dimensional analysis, Lighthill [1] found  $n$  to be 8. In an extensive examination of jet noise scaling, Viswanathan [2] observed that  $n = 9.8$  for the measurement location (30 deg) and ambient to total temperature ratio of unity examined in this work. Venkatesh et al. [3] presented an extensive set of subsonic jet noise measurements that show the region of maximum noise generation coincides with the collapse of the uniform, irrotational jet core. This technical note examines the impact of Mach number on the mechanism of jet noise generation, the scaling of jet noise, and the region of maximum noise generation. It does this through examination of the time and frequency domain properties of the shallow angle jet noise from Mach 0.9, and ideally expanded Mach 1.3 and 2.0 jets.

A recent set of experiments showed that a Mach 1.3 jet possesses large amplitude acoustic peaks within the time-domain data and these peaks could be used to relate the generation of far field radiated sound to the evolution of the mixing layer [4–7]. These acoustic peaks are examined in this technical note to characterize the noise generation mechanism and source region of the three jets. For all Mach numbers studied, the large amplitude acoustic peaks originate from an ellipsoid-shaped region that is centered past the end of the potential core and the noise source region narrows in the cross-stream with increasing Mach numbers. Unlike at Mach 0.9 and 1.3, the Mach 2.0 acoustic peaks have temporal asymmetry, which is related

to the change in noise generation mechanism from turbulence mixing to Mach wave emission.

### II. Experimental Arrangement and Techniques

All of the experiments were conducted in the optically accessed anechoic chamber of the Gas Dynamics and Turbulence Laboratory (GDTL) of The Ohio State University. This facility is equipped for the measurement of jet flows via optical diagnostics in a fully anechoic environment. Details of the facility can be found in Hileman [7]. Data from the 30 deg location (aft of the jet) are presented and discussed here, whereas data from the 60 and 90 deg positions are available in Hileman [7]. Details of the three jets are summarized in Table 1. Theoretical convective velocities (average velocity of the large-scale structures) were estimated using the techniques of Papamoschou and Roshko [8]. A recent set of measurements on the Mach 2.0 jet under study showed it possesses turbulence structures with supersonic velocities [9], and so it should have Mach wave radiation. Potential core lengths were defined as the intersection of lines that were fitted to the uniform velocity and linear decrease regions of centerline pitot probe data [7]. Acoustic data that are summarized in the table will be discussed later. The two nozzles for the supersonic jets were designed using the method of characteristics for uniform flow at the nozzle exit. Although set for ideal expansion, small pressure variations, due to the presence of weak shock cells, were observed in centerline Mach number measurements from the Mach 2.0 jet. The nonideal expansion could be due to under/over estimation of the boundary layer displacement thickness that was used to determine the nozzle contour. Such pressure variations were not observed in the Mach 1.3 jet.

### III. Time and Frequency Domain Characteristics

The scaling of Viswanathan [2] (for an ambient to total temperature ratio of unity) was used to collapse the acoustic power spectral density data (hereafter referred to as spectra) presented in Fig. 1. The frequency spectra for these shallow angles have frequency and amplitude that scale with the Strouhal number and velocity to the power 9.8, respectively. For reference, the peak values before scaling were 83.5, 95.0, and 108.5 dB, respectively, for the Mach 0.9, 1.3, and 2.0 jets. The discrepancy in the high frequency roll-off between the Mach 1.3 jet and the other two jets was probably

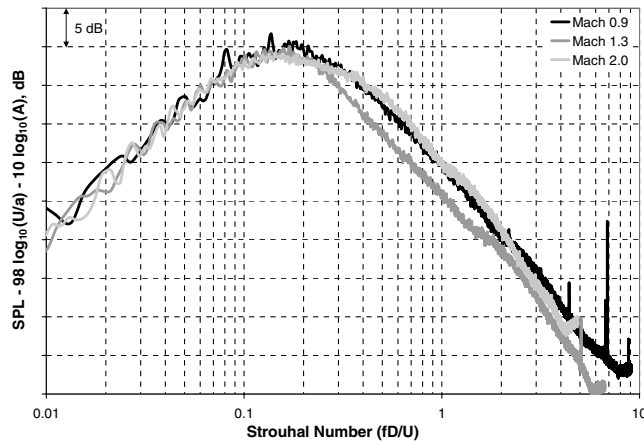
Table 1 Parameters for the three jets examined in this study

Nozzle	Converging	Mach 1.3	Mach 2.0
Exit diameter, mm, $D$	25.4	25.4	25.4
Exit lip thickness, mm	2.5	2.5	0.8
Measured Mach number	0.9	1.28	2.06
Reynolds number, $\rho U D / \mu$	$6.0 \times 10^5$	$1.0 \times 10^6$	$2.6 \times 10^6$
Exit velocity, m/s, $U$	289	385	524
Theoretical convective velocity, m/s, $U_c$	150	206	302
Potential core length, $x/D$	7	8	11
Mean noise source location, $x/D$	9.0	9.6	11.3
Array low pass frequency, Hz, $Sr_D = 0.5$	5700	7600	10,100
Acoustic data skewness	0.06	0.06	0.18

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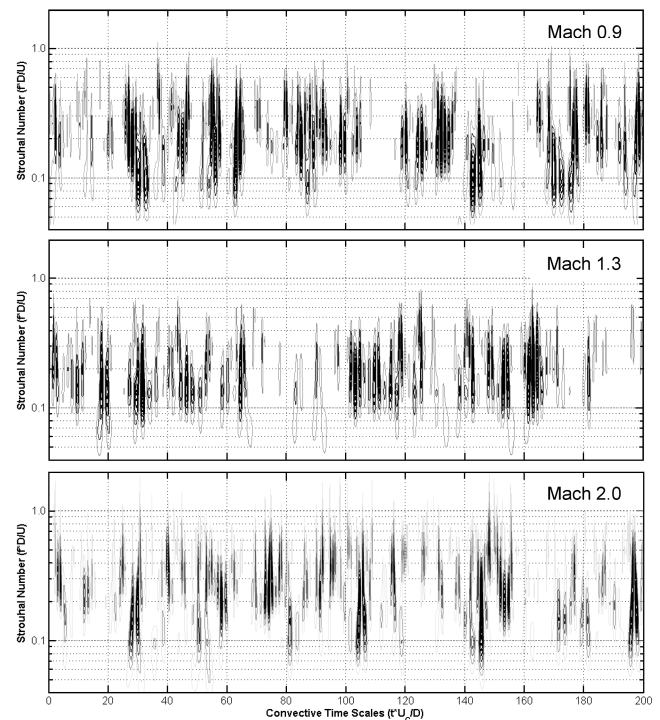


**Fig. 1** Acoustic pressure spectra for Mach 0.9, 1.3, and 2.0 jets. Frequency  $f$  normalized by nozzle diameter  $D$  and exit velocity  $U$ . Sound pressure level (SPL) scaled by exit velocity, ambient speed of sound  $a$ , and exit area  $A$ .

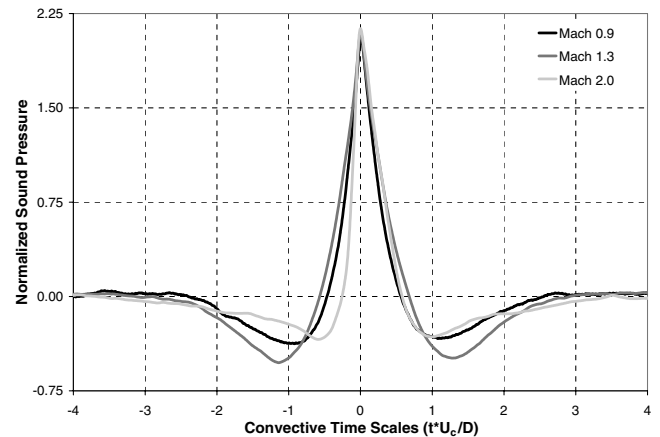
caused by several small, threaded holes on the nozzle lip. These holes were used to hold delta tabs in a separate study by the authors [10]. The spectra of Fig. 1 all reach a maximum amplitude at a Strouhal number of 0.15 ( $Str_D = \text{frequency} \times \text{exit diameter} / \text{exit velocity}$ ). In a separate set of acoustic measurements acquired at the GDTL, subsonic jets with a Mach number between 0.6 and 0.98 were all found to have maximum amplitude at  $Str_D \sim 0.15$  for the 30 deg location [11]. It appears that the 30 deg spectra from high velocity jets collapse with a Strouhal number and not a Helmholtz number (frequency  $\times$  exit diameter / ambient sound speed) as was observed by Ahuja and Bushell [12]. The tones at Strouhal numbers above 3 were created by high frequency electronic noise entering the microphone equipment.

In previous work by the authors, distinct large amplitude peaks were observed within Mach 1.3 acoustic time-domain data [4]. Subsequent work focused on relating these peaks to the time evolution of large-scale turbulence structures [4–7]. These large amplitude acoustic peaks can be observed in the time-frequency acoustic pressure maps presented in Fig. 2 for the three jets under study. These time-frequency data were created by first normalizing all of the temporal acoustic data by their respective standard deviations and then transforming the time-domain data with the Mexican hat wavelet transformation [5]. Each set of data are plotted on identical intensity contours. The time scale has been normalized by the theoretical convective velocity and exit diameter of the respective jets (values listed in Table 1). Each of the time-frequency acoustic pressure maps has distinct large amplitude peaks with  $Str_D \sim 0.15$ . These peaks are interspersed among periods that lack such peaks (referred to as periods of relative quiet in previous works by the authors). Kastner et al. [13] found similar large amplitude peaks in the acoustic radiation from the direct numerical simulation of a low Reynolds number Mach 0.9 jet. It thus seems that aft quadrant jet noise possesses distinct peaks within the time domain that possess similar frequency content to the acoustic spectra and these peaks could be analyzed to determine the overall acoustic properties of the jet.

The average time-domain characteristics of the acoustic data are presented in Fig. 3 in terms of an average acoustic waveform. Such a waveform is created by phase aligning many large amplitude acoustic peaks and then ensemble averaging the data. The sound pressure has been normalized by the respective standard deviations. All three waveforms have opposite sign side lobes on either side of the main peak and have shape similar to the Mexican hat wavelet [5]. The differences in the acoustic waveform widths in Fig. 3 can be directly correlated to the previously given acoustic spectra. The period of the Mach 1.3 waveform is  $\sim 0.3$  ms, which corresponds to a frequency of 3 kHz or  $Str_D$  of 0.2. This is close to the broadband peak of the 30 deg spectrum (around  $Str_D = 0.15$ ) shown in Fig. 1 and the



**Fig. 2** Comparison of time-frequency sound pressure data for the Mach 0.9, 1.3, and 2.0 jets (sound pressure maps obtained with the Mexican hat wavelet transformation). Data normalized by respective standard deviations before transformation and all maps are on identical contours.



**Fig. 3** Average acoustic waveforms for Mach 0.9, 1.3, and 2.0 jets.

Mexican hat energy distribution shown in Fig. 2. The increased side lobe amplitude of the Mach 1.3 jet over the Mach 0.9 (within Fig. 3) was unexpected because compressibility dictates that the large-scale turbulence structures within a Mach 1.3 jet should have lower spatial correlation than those from a Mach 0.9 jet.

In contrast to the Mexican hat wavelet shape of the average acoustic waveform of the 30 deg measurement location, waveforms created from data acquired at 60 or 90 deg are temporally narrow (under 0.1 convective times scale widths) and they do not possess side lobes [7]. The delta functionlike shape of these waveforms corresponds to the broadband spectral character of the 60 and 90 deg measurement locations [7]. Such observations also match the low spatial coherence observed at 60 or 90 deg in Hileman et al. [14] and support the theory that noise in these directions originates from dynamics of smaller, less coherent turbulence scales.

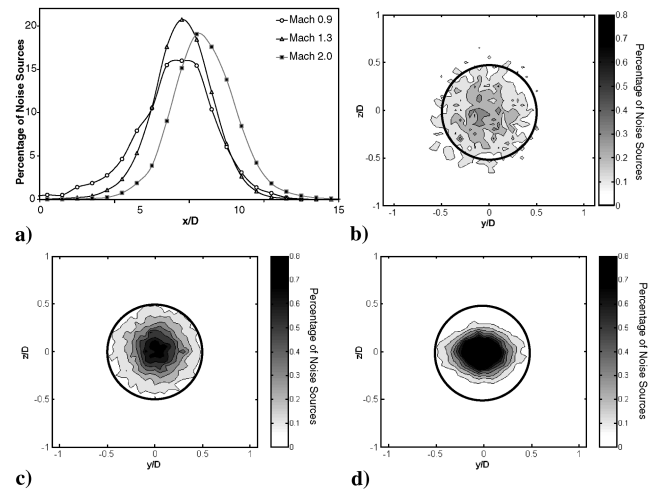
Unlike the Mach 0.9 and 1.3 jet waveforms of Fig. 3, which are largely symmetric with respect to the peak, the Mach 2.0 waveform is asymmetric with a short compression and long rarefaction.

One might think this asymmetry is due to wave steepening, which is a nonlinear wave propagation phenomenon caused by larger amplitude sound waves overtaking slower moving sound waves and then coalescing with them. Eventually, this process leads to an N-shaped wave front indicating the presence of a shock wave. Such propagation will have varying wave speeds, which negates the key assumption of noise source location that all waves reach the array with uniform velocity. However, the average waveforms created from varied amplitude bands all show similar asymmetry [7]. This is unexpected because waves possessing larger amplitude will steepen over a shorter distance than those of lower amplitudes. The larger amplitude waves should have more dramatic steepening than those with lower amplitude. The distances required to achieve wave steepening (for the peak amplitude of the Mach 2.0 jet) are at least an order of magnitude larger than those between the jet and the microphones, [7] which is in agreement with the measurements of Petitjean and McLaughlin [15]. Thus, the asymmetric shape is likely due to some source phenomena, a speculation originally put forth by Ffowcs-Williams et al. [16] in their analysis of crackle (a strong form of Mach wave emission). The source nonlinearity is accompanied by increased skewness (values listed in Table 1), a statistical parameter used to define crackle. The skewness of the pressure data quantifies the asymmetry of the waveform shape and can be used to ascertain the mechanism of noise generation. The skewness of the lower velocity jets is small because their noise is created by turbulence mixing, whereas the skewness of the Mach 2.0 jet increased because the noise is created by Mach wave emission from the supersonic convection of large-scale structures.

#### IV. Distribution of Noise Sources

Noise source distributions were acquired with an eight element, three-dimensional microphone array that determined the origins of large amplitude sound peaks in the time domain [14]. These are the wavelike features observed in Fig. 2. The array has been used to estimate the source region of a Mach 1.3 jet [6] as well as tabbed Mach 1.3 jets [10]. The sources of noise from a sinusoidally pulsed plasma arc and a set of small fluidic actuators were located with the microphone array, and for frequencies under 10 kHz the array predicted that the noise originated from a location within  $0.4x/D$ ,  $0.1y/D$ , and  $0.1z/D$  of the actual arc location. The predicted noise source region of the fluidic actuators also matched the region of peak vortical activity further confirming the accuracy of the microphone array [14]. For a Mach 2.0 jet, a frequency of 10 kHz corresponds to a Strouhal number  $St_D$  of 0.5, thus each acoustic data set was low pass frequency filtered at this  $St_D$  before analysis (the various cutoff frequencies are listed in Table 1). This ensured accurate source localization and comparison of the same nondimensional frequencies for the three jets. Of note, the noise source location should be regarded as an average location over frequencies under the cutoff. Additional details on this microphone array can be found in Hileman [7] and Hileman et al. [14].

The region of noise generation shifted with the increasing Mach number in a manner consistent with the lengthening of the potential core. The probability distribution of large amplitude peaks exceeding 1.5 standard deviations for the three Mach numbers are compared in Fig. 4. Figure 4a shows the downstream distribution ( $x$ -direction) with respect to the nozzle exit while 4b–4d show the cross-stream probability distribution ( $z$ -direction is height) for all downstream locations with respect to the nozzle exit center. The mean streamwise noise source locations for the Mach 0.9, 1.3, and 2.0 jets are  $9.0x/D$ ,  $9.6x/D$ , and  $11.3x/D$ , respectively, and they are all downstream of the measured potential core lengths of 7, 8, and  $11x/D$  (listed in Table 1). For comparison, Venkatesh et al. [3] measured the noise source region for a Mach 0.9 cold jet and found the  $St_D = 0.3$  noise originated from  $8.5x/D$ . This is typical of Mach 0.9 jet noise measurements in the literature and is within  $0.5x/D$  of the Mach 0.9 measurement presented here. For all three jets, the ellipsoid-shaped region of peak noise generation coincides with the end of the jet potential core where the sides of the mixing layer interact. In addition to shifting the noise emission region downstream, increasing the



**Fig. 4 Noise source location distributions for the Mach 0.9, 1.3, and 2.0 jets. a) Streamwise distribution for the three jets. Cross-stream distributions for the three jets with respect to nozzle exit, b) Mach 0.9, c) Mach 1.3, and d) Mach 2.0.**

Mach number leads to larger noise source concentration along the jet centerline (shown in Fig. 4b–4d).

#### V. Conclusions

This work examined the impact of the Mach number on jet noise emission at 30 deg. The acoustic spectra collapsed well with velocity to the power 9.8 while the peak frequency collapsed with the Strouhal number (not the Helmholtz number). Large amplitude temporal peaks were observed within the acoustic data for all three jets and these were interspersed among periods of lower sound pressure. The impact of Mach wave radiation on the acoustic radiation was observed within the Mach 2.0 jet in terms of the asymmetry of the large amplitude temporal peaks and the increased skewness of the acoustic pressure. For all three jets, the regions of maximum noise emission occurs just past the end of the potential core with the Mach 2.0 jet being the closest to the end of the core, whereas the cross-stream noise distribution showed an increase in source concentration along the jet centerline with increased Mach number. The narrowed distribution of the Mach 2.0 jet seems to indicate the region of maximum Mach wave emission is from large structures that are near the jet centerline, immediately past the end of the potential core.

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