UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 228

COOPERATIVE INVESTIGATION OF JET FLOWS

by

Roger E. A. Arndt

and

Dean F. Long

Prepared for

U. S. AIR FORCE
Office of Scientific Research
Contract No. F49620-80-C-0053

March, 1984
Minneapolis, Minnesota

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INTRODUCTION

The objectives of the Minnesota study were to determine the nature of acoustic radiation from turbulent jets, with both Reynolds and Mach number similitude. Acoustic data were to include intensity, directivity, spectra and narrowband spatial coherence. Emphasis in the initial study was to be on naturally developing jets. A second phase of the program was to be aimed at artificially excited jets.

In order to carry out the experimental program as originally envisioned, a special test facility had to be constructed. This test rig had to produce jets of varying diameter, with minimal turbulence levels at the nozzle exit and be essentially free of acoustic contamination. As it turns out, the latter requirement was essential to the successful completion of the project. The desire to model high subsonic Mach number at low Reynolds number necessitated high speed jets of very small diameter. The high frequency content in these jets necessitated that special emphasis be placed on both the acoustic design and on the design of the data acquisition system.

All of the original objectives of the program have been met as summarized below.

LOW REYNOLDS NUMBER JET NOISE

The most striking result of this study was that the overall noise level (OASPL) for these jets, which covered a Reynolds number range up to $Re \sim 2.5\times10^5$, was on the order of 5dB less than the noise for other experiments conducted at higher Reynolds number. We believe this to be a true Reynolds number dependence but have not completely ruled out the possibility that initial exit conditions and geometry play an important role. Careful scrutiny of the data revealed that Helmholtz number rather than Strouhal number was the appropriate frequency scaling parameter; the data collapsed better using Helmholtz number than it did using Strouhal number.

Spectra were obtained by a digital system rather than an analog system. Thus, the output is in constant bandwidth form rather than in 1/3 octave form. When viewed in this way, the well known "Reverse Doppler Shift" with increasing emission angle disappears. This suggests that the theories built up to describe how this shift occurs may need to be restructured or possibly even discarded.

ACOUSTICALLY EXCITED JETS

As a first step, a survey was made of previous research on acoustically excited jets. Previous experiments employed 1" ~ 2" diameter jets. To study the noise characteristics they were operated at high speed (high Mach number); to study the turbulence characteristics they were operated at low speed (low Mach number). To break away from this trend we chose a jet diameter of 7.1 mm. This allowed us to produce a sufficiently high Mach number to study noise characteristics while simultaneously keeping the Reynolds number below 10^5. The initial shear layer (laminar) was excited acoustically and the radiated noise was monitored. It was found that there was a narrow range of flow speeds at which the excitation could alter the jet structure. This occurred at $Re \sim 35\times10^3$, $M = 0.21$. At this condition the initial shear layer instability frequency was eight times the dominant frequency observed in the potential core. No effect of the excitation was observed at other velocities.

It was found that very slight changes in the flow speed could cause the broadband component of the radiated noise to be amplified or suppressed. This is apparently the first time that both these phenomena have been observed in the same test facility. Previously, amplification could only be observed at high speed (High Re, high M), and suppression occurred at low speed (low Re, low M). The amplified condition occurs at an excitation frequency corresponding to

$$St_\theta = \frac{f\theta}{U_{jet}} = 0.013$$

where θ is the exit momentum thickness. Associated with this are discrete tones which occur at the subharmonics of the excitation frequency. The suppressed condition occurs at an excitation frequency of $St_\theta = 0.017$. In this case there are no discrete tones. At excitation frequencies between these two Strouhal numbers various interactions or combinations between the two basic conditions occur.

Flow visualization showed that associated with the suppression was a general stretching of the jet flow field, and associated with the amplification is more rapid mixing. A source location technique known as polar correlation showed the same stretching under the suppressed condition but did not show meaningful results under amplification. This is because one of the assumptions in the polar correlation technique is that the noise is produced from small-scale uncorrelated turbulent eddies. The lack of a sensible result indicates that there is large scale coherence in the turbulent flow field.

In order to study the turbulence characteristics of this amplification/suppression phenomena, a 2.54 cm jet was excited in a similar manner. It turned out that the jet was sensitive to the excitation at the <u>same Reynolds number</u> as the previous experiment, thus we expected a similar trend to occur. Surprisingly, however, the jet only responded in the suppressed mode with discrete tones at the subharmonic frequencies; the amplification mode could not be found! Since Reynolds number and nozzle geometry were the same in both cases, the obvious difference between these experiments is the Mach number.

Apparently most previous experiments have implicitly assumed that variations in Mach number are not an important consideration for turbulent mixing. Most previous experiments were conducted at low Mach number (where hot wires are much easier to use) and the characteristics at high Mach number (where noise is produced) are inferred. We currently believe this to be an invalid influence. The results from the excitation experiments indicate that even at low Mach number, compressibility is an important factor in the turbulent mixing process.

The reason why the excitation at the shear layer frequency affects the jet differently depending on Mach number has to do with the Helmholtz number defined by

$$H_e = \frac{D}{\lambda_e} .$$

where λ_e is the wavelength of the excitation. In the 25.4 mm jet, it turns out that this Helmholtz number is much smaller than one or that the excitation wavelength is much larger than the jet diameter. In other words the excitation is basically axisymmetric implying that the downstream development is also axisymmetric. In the 7.1 mm jet the wavelength of excitation is on the same order as the jet diameter implying that the excitation may have a complicated modal structure. The ensuing jet development is quite diverse. Amplification, suppression, discrete subharmonic tones and discrete fractional tones are all observed over a very narrow range of excitations.

Spatial Structure of the Acoustic Nearfield

Throughout the entire contract, we have been interested in the nearfield pressure signal as a means of studying the large scale turbulence structure. We have determined that the measured nearfield pressure spectrum can be divided into four distinct regions: a low wave number region; an energy containing region; an inertial subrange; and a farfield. We have also broken down the nearfield structure into its wavy components by the proper orthogonal decomposition theorem. At any particular frequency the wavy structure grows, saturates, and decays all within about three wavelengths as it convects downstream. High frequencies saturate early in x and low frequencies saturate further downstream.

The decomposition also produces the energy of pressure fluctuations associated with each azimuthal mode. The axisymmetric or m=0 mode contained 50% of the total; the m=1 mode contained 23%; the m=2 mode contained 14%; and the m=3 mode contained 5% of the total. We consider this to be the baseline situation because the jet was operated at low Reynolds number and low Mach number. If either of these parameters increases, it is expected that the higher order modes will contain a greater proportion of the total, consistent with the presence of smaller scales. The true meaning of the above numbers will not be known until similar experiments are performed over a wider range of Reynolds number and Mach number.

Since the wavy structure is broken down into discrete frequency components, the phase velocity can be determined from

$$f\lambda = U_c$$

where f is the frequency, U_c is the phase velocity and λ is the wavelength of the disturbance measured near the saturation point. This is important; all previous measurements of phase velocity suffer from the probe locations being located on different phases of the growth-saturation-decay cycle. There is a bias when the measurement takes place in the growth or decay phase; only in the saturation region is a true estimate of phase velocity obtained. The phase velocity determined from the orthogonal decomposition was determined as $U_c = 0.58\ U_{jet}$, independent of frequency. That is, all frequencies convect downstream at the same rate. There is no dispersion.

The characteristic signal form (characteristic eddy or characteristic event) can be reconstructed from the results of the orthogonal decomposition using the shot effect decomposition. Results showed that even at this low Reynolds number vortex pairing was a violent but rather rare occurrence. Most of the time the signal was relatively quiet, implying that the eddies evolve slowly. When conditions are right, two similarly sized structures merge together and produce a large pulse in the pressure signal. This implies that jet excitation experiments do not simply remove the phase jitter that is present in a naturally developing jet, but it changes the intrinsic structure of the development.

Relation to Other Research

As an outgrowth of this work, other research has been initiated in the general area of flow noise. The results of this investigation have been applied to work on cavitation in turbulent jets with particular emphasis on cavitation noise. This effort was complimentary to an investigation of noise from bubbles imbedded in turbulent boundary layers. Much of the computer software and analysis techniques developed during this study are currently in use in an ONR sponsored program on hydroacoustics. Some of the topical areas are low wavenumber boundary layer pressure fluctuations, wall turbulence structure interaction and acoustic radiation from cavitating tip vortices in steady and unsteady flow. Because of this interaction, the publications produced under sponsorship of this program cover a wider range of topical areas that would normally be expected.

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12. Long. D. "Controlled Suppression or Amplification of Turbulent Jet Noise," presented at Aerospace Sciences meeting of the American Institute of Astronautics and Aeronautics in Reno, Nevada, Jan., 1984.