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**DAVID W. TAYLOR NAVAL SHIP
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Bethesda, Md. 20084

NOISE RADIATION FROM SUBSONIC AIRFLOW THROUGH SINGLE AND MULTIHOLED
ORIFICE PLATES

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**NOISE RADIATION FROM SUBSONIC AIRFLOW THROUGH
SINGLE AND MULTIHOLED ORIFICE PLATES**

by

F.C. DeMetz, M.F. Matis
R.S. Langley, J.L. Wilson

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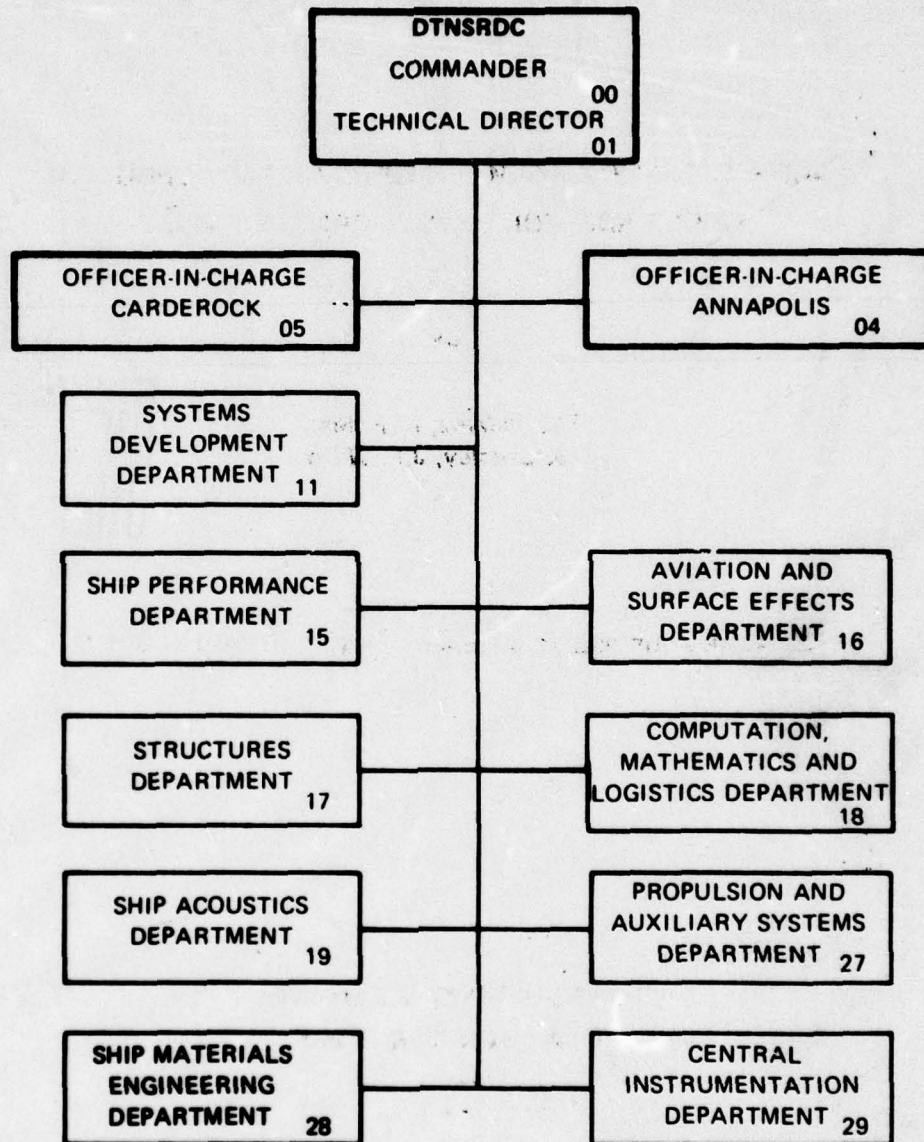
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from 1 to 31 holes, were placed at the termination of a quiet 76-millimeter inside diameter airflow facility. The characteristics of the broadband and tonal components of the radiated noise field are evaluated in terms of: (1) the orifice plate hole geometries and flow interactions and (2) the downstream jet features.

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NOTATION

c	Speed of sound in undisturbed fluid
d	Diameter of orifice
F	Frequency
M	Mach number ($= U/c$)
N	Number of holes in orifice plate
$\overline{p^2}$	Time-averaged mean square acoustic pressure in the free field
P_{ij}	Stress tensor (Reference 24)
$q(F)$	Amplification factor
R	Radius of orifice
r	Distance from sound source to observation point
S, S_i	Surface increment
T_{ij}	Tensor (Reference 24)
t	Streamwise length of orifice
U_c	Convection velocity of fluctuating velocity component in orifice jet
U_e	Maximum orifice jet exit velocity
U, \bar{U}	Mean flow velocity in orifice
$\overline{u'^2}_{PEAK}$	Peak value of time averaged fluctuating velocity
V	Volume increment
v_i	Velocity component at point in fluid
W	Radiated broadband sound power
x	Streamwise distance from downstream edge of orifice plate
x_i	Spatial coordinate

\vec{x}	Vector spatial coordinate
\vec{y}	Vector spatial coordinate
y	Transverse distance from center of orifice
Δp	Pressure drop across orifice plate
δ_{ij}	Kronecker delta
η	Feedback effectiveness
λ	Wavelength of disturbance
ρ	Density of undisturbed fluid
ν	Kinematic viscosity of fluid

ABSTRACT

The mechanisms and scaling laws for noise radiated from subsonic airflow through single and multiholed orifice plates have been studied experimentally. Simultaneous measurements were conducted of the velocity field and radiated pressure associated with jets formed downstream of sharp-edged, multiholed orifice plates. The orifice plates, containing from 1 to 31 holes, were placed at the termination of a quiet 76-millimeter inside diameter airflow facility. The characteristics of the broadband and tonal components of the radiated noise field are evaluated in terms of: (1) the orifice plate hole geometries and flow interactions and (2) the downstream jet features.

ADMINISTRATIVE INFORMATION

This study was supported by the In-House Research Program of the David W. Taylor Naval Ship Research and Development Center under Task Area ZR 0110801, Element Number 61152N, Work Unit 1942-089.

INTRODUCTION

The generation of noise when air moves through multiholed orifice plates is associated with vortex creation. The complex structure of the velocity and pressure fields associated with these vortices requires the utilization of experimental methods in conjunction with similarity theory and dimensional analysis to provide insight into sound generation and prevention mechanisms. This report presents measurements of noise produced by turbulent pipe flow through orifice plates containing single and multiple cylindrical holes. An understanding of both the broadband and tonal noise generation processes of the orifice related flow is desired.

Extensive experimental work on tones produced by flow through single orifice elements was conducted by Anderson^{1-7*} over two decades ago. He determined relationships between jet-tone Strouhal number, the orifice Reynolds number, and the orifice thickness to diameter ratio.

*A complete listing of references is given on page 27.

Other relevant studies address acoustic and hydrodynamic feedback processes in flow-oscillators⁸⁻¹¹ and flow-sound interaction processes.^{12,13}

Iudin¹⁴ developed a methodology for an experimental investigation of primarily broadband noise created by flow through air-duct elements. Many other informative articles on the features of broadband noise associated with subsonic air jets are available.¹⁵⁻²⁰ Noise from flow through air gratings is discussed in Beranek's book on noise control.²¹ Other articles relevant to noise by flow through vibrating multiholed plates are given in a paper by Chen²² on vibrations of tube arrays excited by crossflow. Of course, studies of aeolian tones generated by vortex shedding from isolated cylinders goes back into the 19th century, as discussed in papers by Stowell and Deming²³ and Phillips.²⁴ There are also numerous purely hydrodynamic studies on periodic and random eddy structure in jets which are relevant to the present study.²⁵⁻³⁴

The objective of the present study is to experimentally determine the basic features of flow-structure and flow-acoustic field interactions of multiholed orifice plates. The experiments were designed to determine the scaling laws for the tonal and broadband noise radiated both from the flow through single and multiple orifice openings and from the subsonic air jets. Simultaneous measurements were made of the velocity field and radiated pressure associated with jets formed downstream of sharp-edged orifice plates. The orifice plates, containing from 1 to 31 holes with diameter to thickness ratios d/t from $0.25 < d/t < 8$, were placed at the termination of a quiet 76-mm inside diameter (I.D.) pipe airflow facility. The properties of the single and multiple orifice and jet-flow-generated noise were measured for a range of Reynolds numbers, based on orifice streamwise thickness and orifice flow velocity U_e , from $10,000 < U_e t / \nu < 760,000$.

REVIEW OF NOISE GENERATION MECHANISMS

Figure 1 illustrates the basic radiated noise-producing mechanisms of flow through rigid, multiholed, orifice plates producing turbulent downstream jets. The possible noise-generation mechanisms are those associated with monopole sources in the orifice-plate openings, dipole sources due to fluctuating drag forces on the plate structures or interacting vortices, and quadrupole sources in the turbulent jets downstream of the plate.

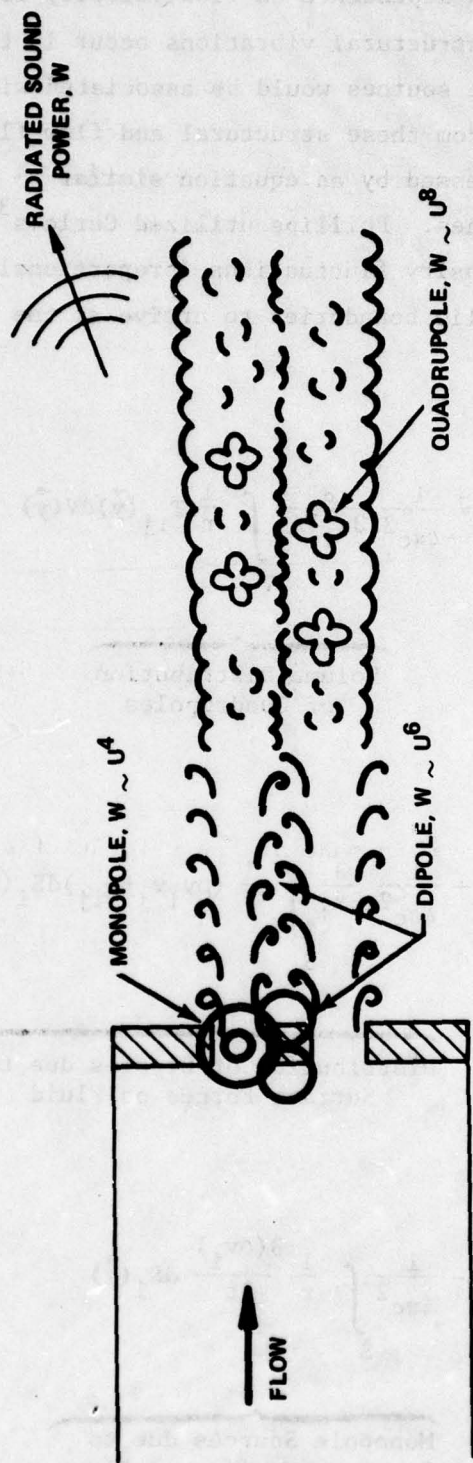


Figure 1 - Mechanisms of Noise Radiation from Interacting Air Jets

The radiated sound power W dependence on flow velocity is shown for each type of source.^{14,21} If structural vibrations occur in the orifice plate, additional monopole sources would be associated with boundary motion.

The noise produced from these structural and flow fluctuations acting independently can be expressed by an equation similar to that given by Phillips²⁴ for aeolian tones. Phillips utilized Curle's³⁵ adaptation of Lighthill's theory for density fluctuations (proportional to sound pressure) due to flow over solid boundaries to arrive at the following expression

$$\rho(\vec{x}) - \rho = \frac{1}{4\pi c^2} \frac{\partial^2}{\partial x_i \partial x_j} \int_V \frac{1}{r} T_{ij}(\vec{y}) dV(\vec{y})$$

Volume Distribution
of Quadrupoles

$$+ \frac{1}{4\pi c^2} \frac{\partial}{\partial x_i} \int_S \frac{1}{r} (\rho v_i v_j + p_{ij}) dS_i(\vec{y}) \quad (1)$$

Distribution of Dipoles due to
Surface Forces on Fluid

$$- \frac{1}{4\pi c^2} \int_S \frac{1}{r} \frac{\partial(\rho v_i)}{\partial t} dS_i(\vec{y})$$

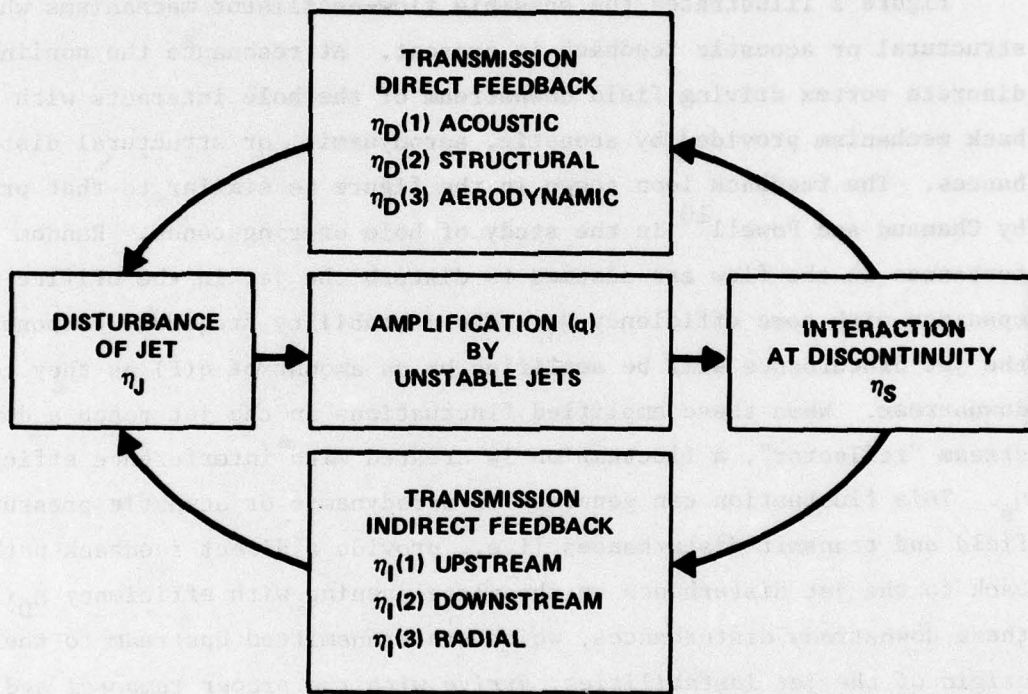
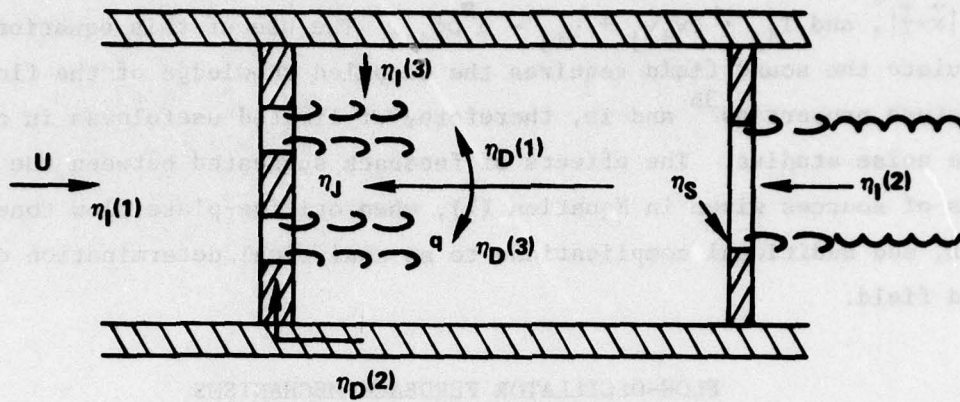
Monopole Sources due to
Boundary Motion and Flow
Fluctuations in Hole

where ρ and c are the density and sound velocity in the undisturbed fluid, v_i and p_{ij} are the velocity and stress tensor in the fluid, $r = |\vec{x} - \vec{y}|$, and $T_{ij} = \rho v_i v_j + p_{ij} - c^2 \rho \delta_{ij}$. The use of this equation to calculate the sound field requires the detailed knowledge of the flow and structure properties³⁶ and is, therefore, of limited usefulness in orifice plate noise studies. The effects of feedback suggested between the three types of sources given in Equation (1), when orifice-plate flow tones occur, add additional complications to an analytical determination of the sound field.

FLOW-OSCILLATOR FEEDBACK MECHANISMS

Figure 2 illustrates the possible flow-oscillator mechanisms when structural or acoustic feedback is present. At resonance the nonlinear discrete vortex driving field downstream of the hole interacts with a feedback mechanism provided by acoustic, aerodynamic, or structural disturbances. The feedback loop shown in the figure is similar to that proposed by Chanaud and Powell¹⁰ in the study of hole or ring tones. Random disturbances in the flow are assumed to disturb the jet in the orifice plate openings with some efficiency η_j . The instability frequency components of the jet disturbance will be amplified by an amount of $q(F)$ as they convect downstream. When these amplified fluctuations in the jet reach a downstream "reflector", a fluctuation is created with interference efficiency η_s . This fluctuation can generate an aerodynamic or acoustic pressure field and transmit disturbances (i.e., provide a direct feedback path) back to the jet disturbance on the plate opening with efficiency $\eta_D(1)$. If these downstream disturbances, which are transmitted upstream to the origin of the jet instabilities, arrive with the proper temporal and spatial relationships they can amplify the instability fluctuations and close the feedback loop to provide a large amplitude resonance in the flow-oscillator system.

The other possible direct feedback mechanisms for the jet instabilities are shown as the vibrations transmitted through the structures, $\eta_D(2)$, and the interjet interactions, $\eta_D(3)$.



η = FEEDBACK EFFECTIVENESS
 q = AMPLIFICATION FACTOR

Figure 2 - Flow/Oscillator Mechanisms
 (Structural and/or Acoustic Feedback)

Other disturbances which may be of sufficient magnitude to interact with the jet instabilities are denoted in the figure as possible indirect feedback mechanisms. These are disturbances arriving from upstream $\eta_1(1)$, downstream $\eta_1(2)$, or perpendicular to the jets $\eta_1(3)$, which are produced by fluctuations or reflections from obstructions or boundaries somewhat remote to the orifice plate.

It is important to note that all the direct and indirect disturbances considered in this functional diagram originate ultimately from the unstable jet fluctuations. It is conceivable, however, that externally excited acoustic, aerodynamic, or structural disturbances could also create the conditions necessary for strong acoustic tone generation by the orifice flow-oscillator.

EXPERIMENTAL APPARATUS

TURBULENT AIR PIPE FLOW FACILITY

The turbulent air pipe flow facility in which the experiments were conducted is shown schematically in Figure 3. The air from the high-pressure storage tanks is passed through a filter and regulator system which provides constant flow velocity at the test section (orifice plate). The low-pressure settling tank and fiberglass-lined, baffled muffler reduces control system noise and provides a fully turbulent, low-noise flow into the orifice plates. The pipe flow velocity and orifice velocity are determined from strip chart recordings of the pressure drop along a length of the test pipe and across the orifice plate, respectively.

INSTRUMENTATION

Figure 4 shows a photograph of a 7-hole orifice plate at the termination of the 76-mm test pipe and the location of the free field pressure transducer. Small hot film and hot wire sensors were mounted on the positioning device and used to survey the mean and fluctuating features of the jet flow field downstream of the orifice plate. For some measurements a pinhole microphone was mounted flush with the pipe wall 0.6 m upstream of the orifice plate to measure orifice noise inside the

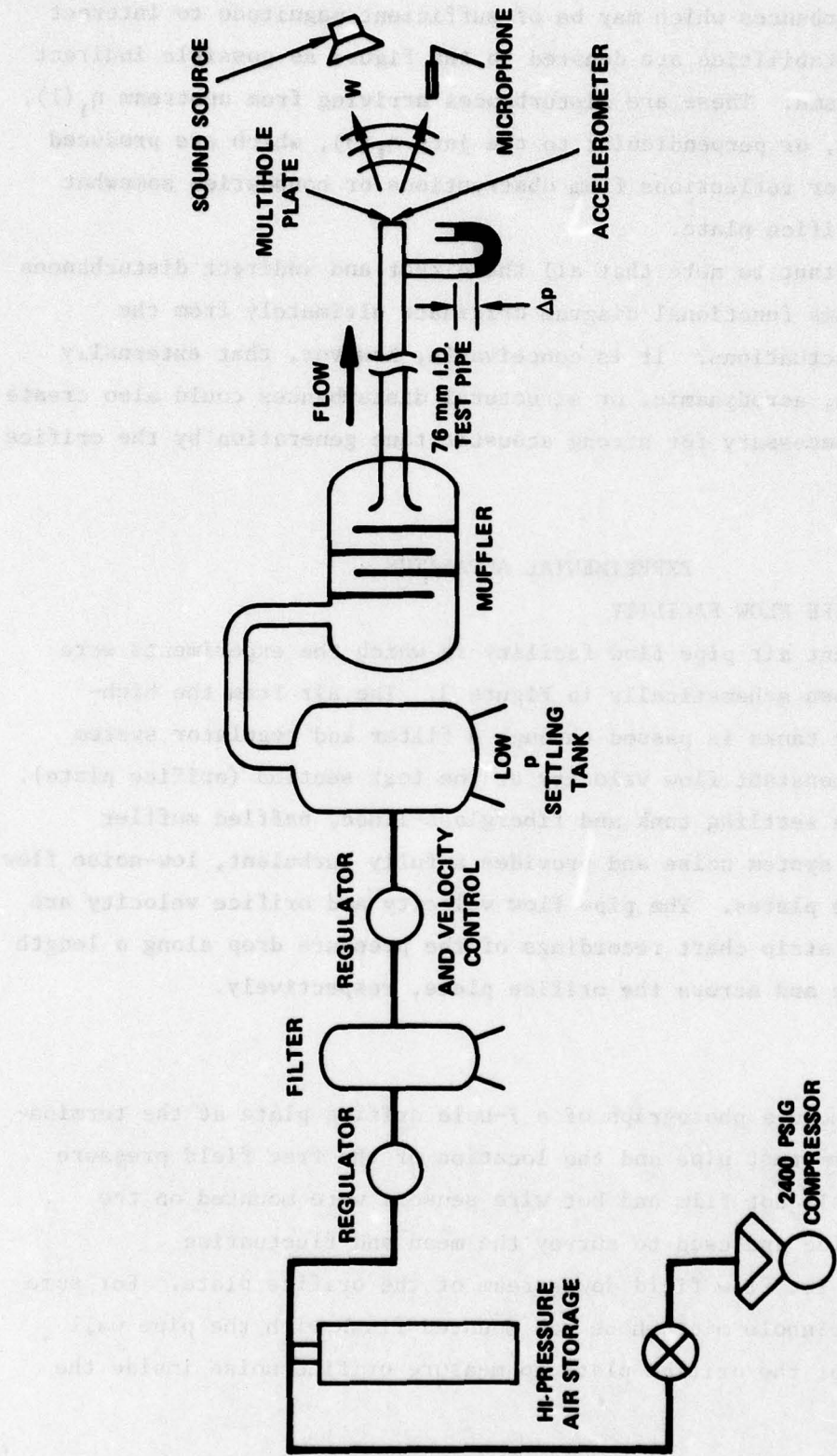


Figure 3 - Turbulent Air Pipe Flow Facility

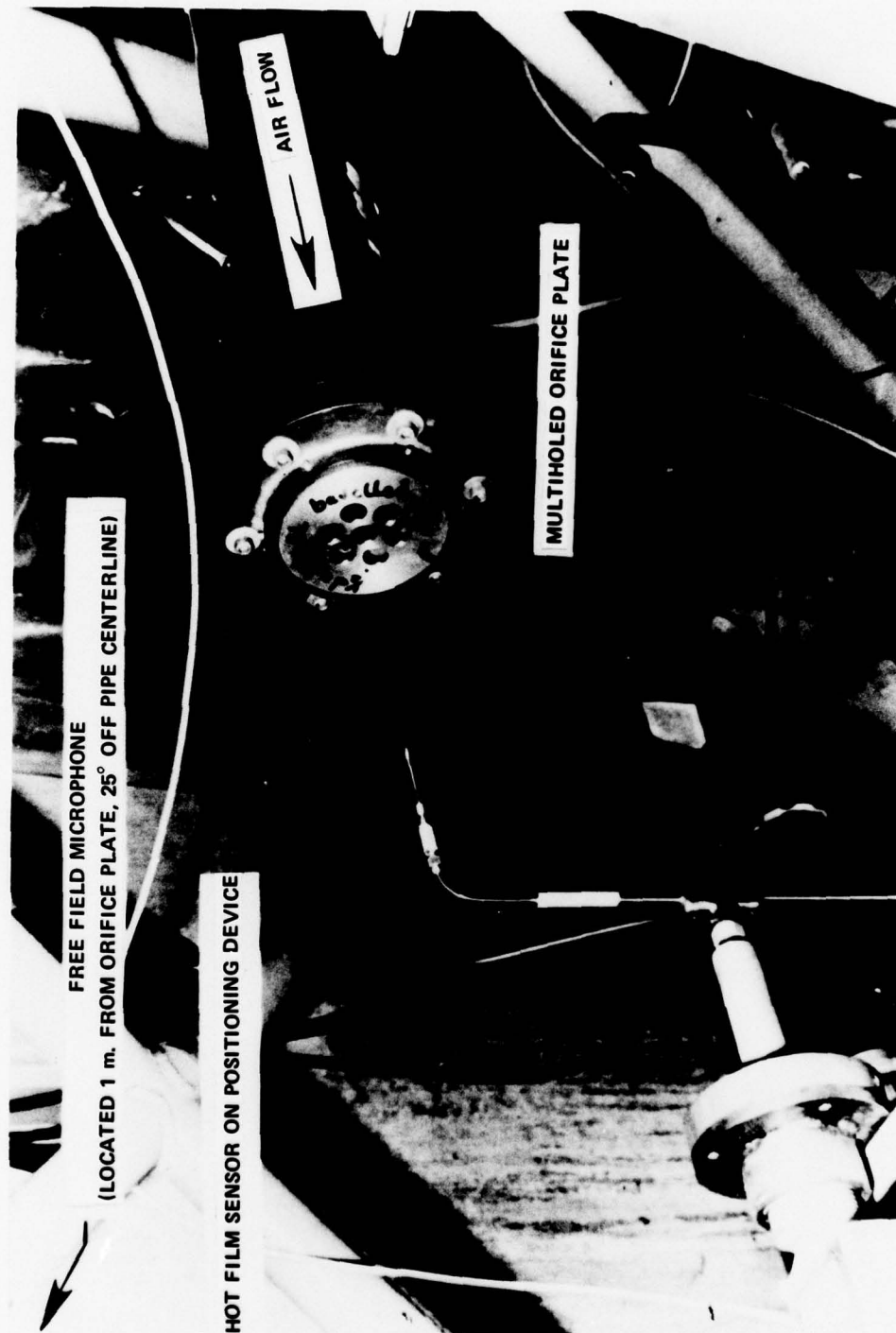


Figure 4 - View of 7-Hole Orifice Plate at Termination of 76-Millimeter Inside Diameter Air Pipe

test pipe. No acoustic absorption material was utilized on the steel, wood, and concrete structures located in the test area.

ORIFICE PLATES

Figure 5 shows a photograph of the types of orifice plates tested to study the noise radiated from single and multiholed orifice plates and air jets. The results reported in this paper include measurements for sharp-edged steel and aluminum plates with 1, 3, 7, and 31 holes, with diameter to thickness ratios from $0.5 < d/t < 4$. Some plates were also tested with approximately 0.8 mm bevels on the hole edges.

EXPERIMENTAL RESULTS

SPECTRAL FEATURES OF RADIATED NOISE

Radiated noise spectra from a single jet (orifice 25.4 mm d by 7.6 mm t, $d/t = 3$) for a range of jet exit velocities U_e is shown in Figure 6.

The typical peak in the broadband features of the noise is seen for $U_e = 61$ m/sec.¹⁷ At $U_e = 91$ m/sec, a tone is seen to rise out of the broadband radiated noise at a frequency $F = 5400$ Hz. The tone reaches a maximum amplitude at $U_e = 107$ m/sec, with higher frequency components also present. As jet velocity is increased still further, however, to $U_e = 122$ m/sec, the tone components drop out. Notice also that the presence of the tone at $U_e = 107$ m/sec increased the broadband radiated noise by approximately 10 decibels (dB) over the levels at the higher velocity $U_e = 122$ m/sec.

These spectral variations with flow velocity are generally representative of those for both the single and multiholed orifice plates tested.

TONE FREQUENCY VARIATION WITH FLOW VELOCITY

Figures 7 and 8 compare the two observed types of orifice-tone frequency variations with orifice exit-flow velocity U_e . It is seen in Figure 7 that the tone frequency increases uniformly with orifice flow velocity for a 7-holed plate, with $d/t = 1$. For the thinner 7-holed plate, with

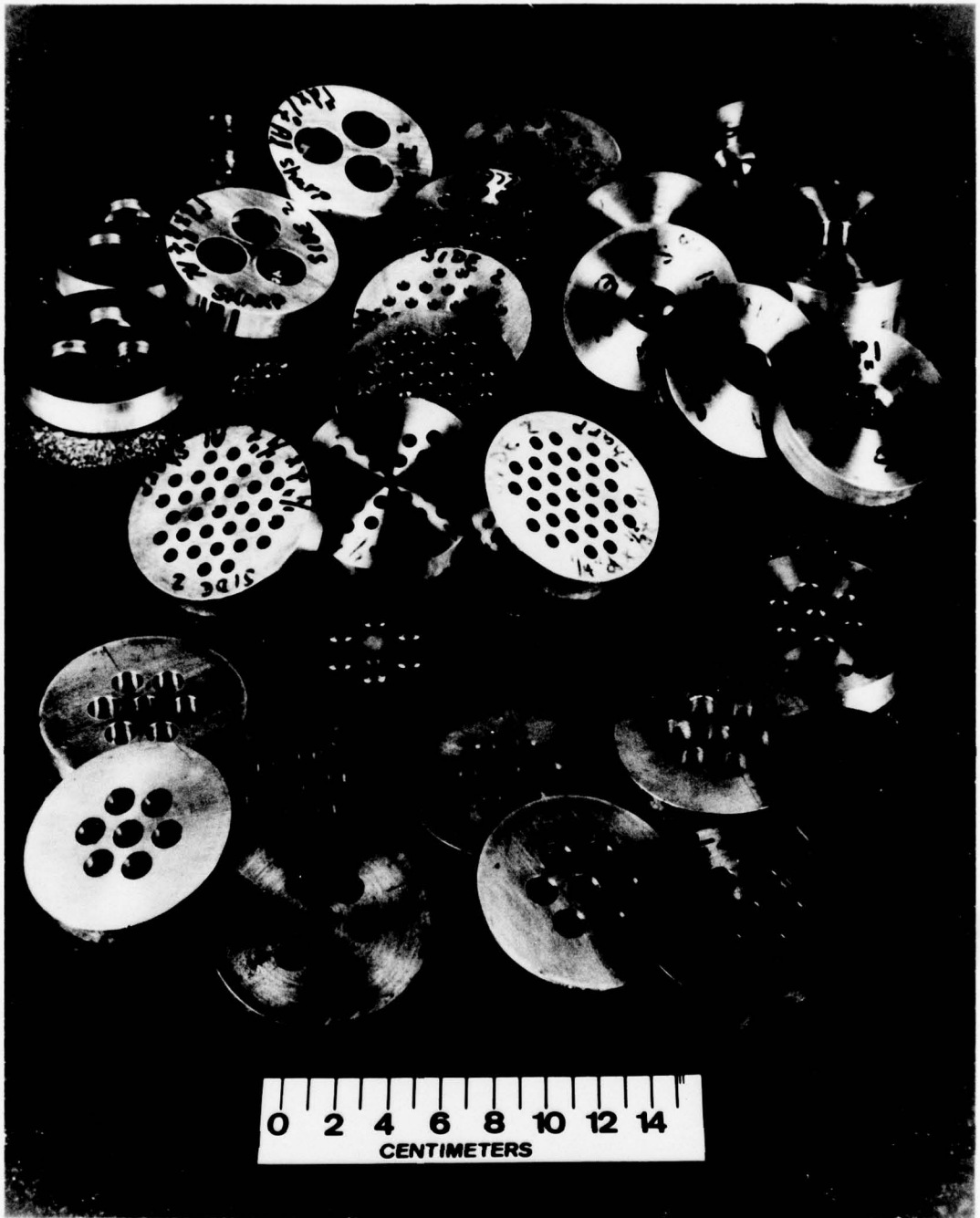


Figure 5 - Types of Orifice
Plates Tested

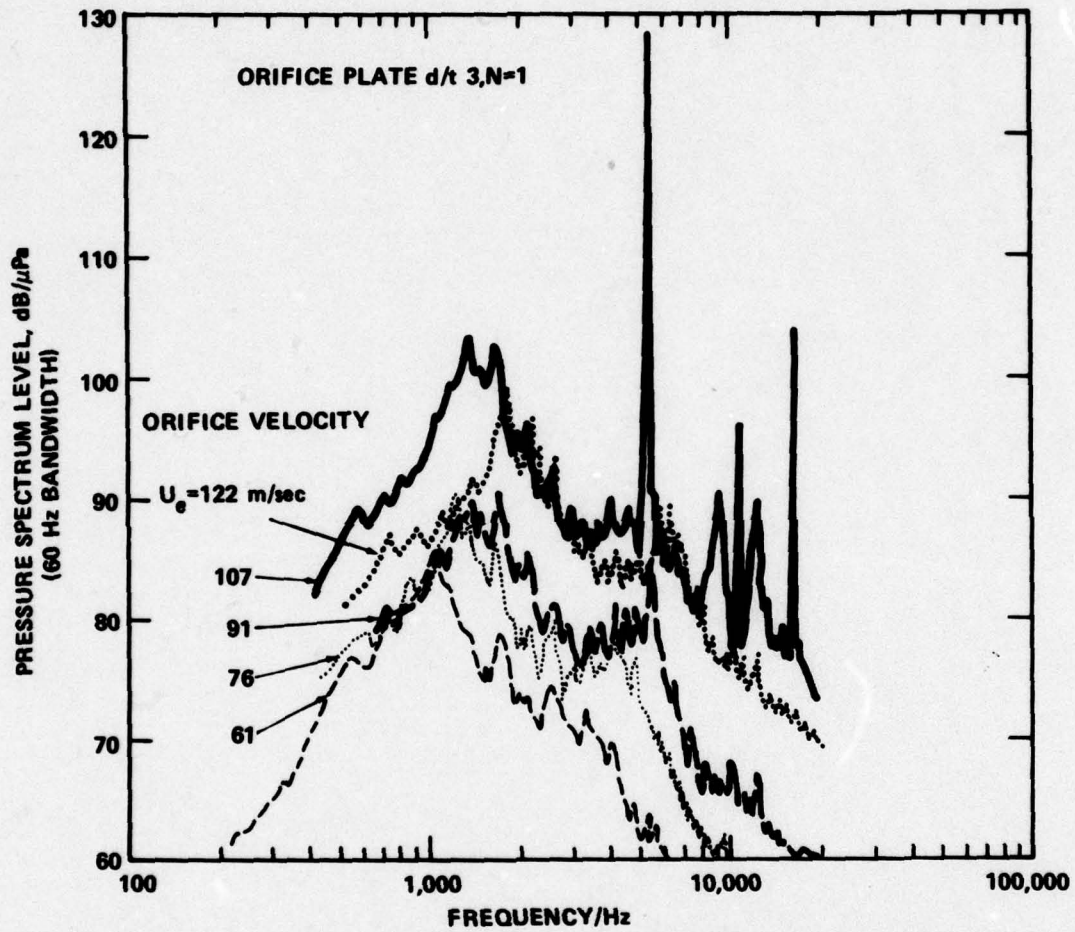


Figure 6 - Radiated Noise Spectra Velocity Dependence for a Single Jet

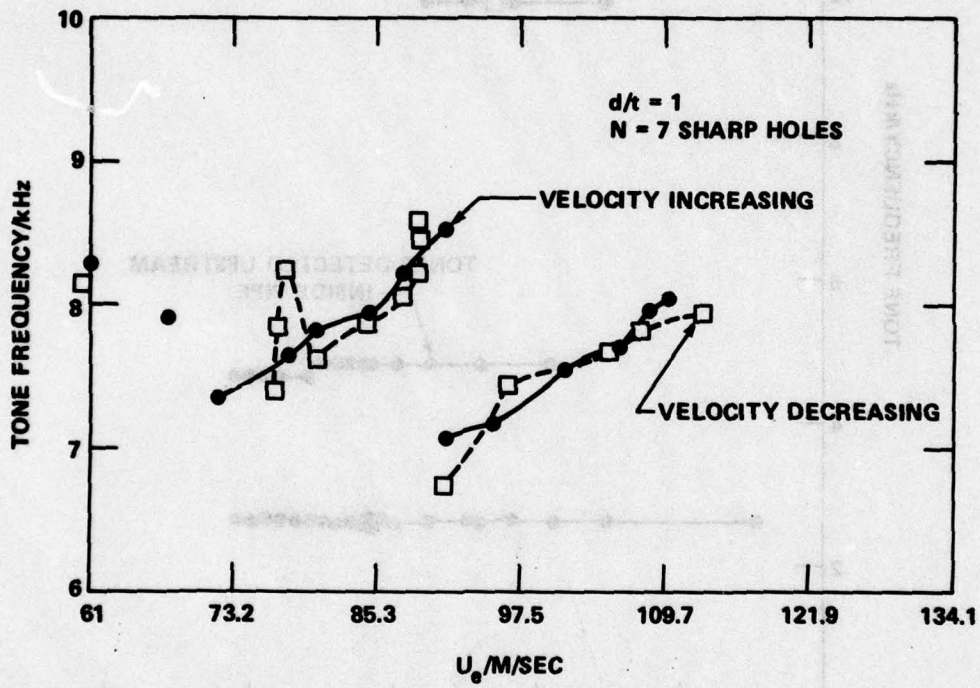


Figure 7 - Frequency versus Flow Velocity for Acoustic Tones Generated by Flow through Multiholed Orifice Plate ($d/t=1$, $N=7$)

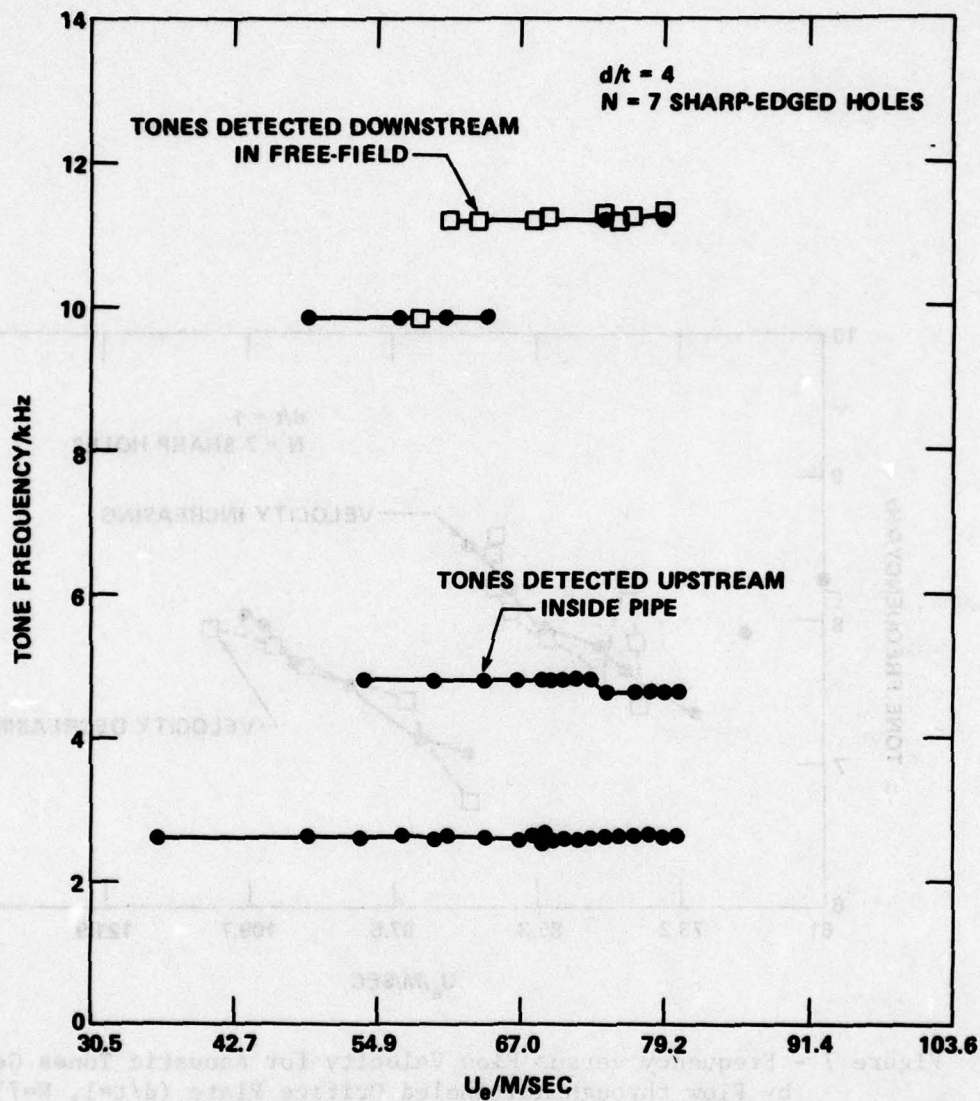


Figure 8 - Frequency versus Flow Velocity for Acoustic Tones Generated by Flow through Multiholed Orifice Plate ($d/t=4$, $N=7$)

$d/t = 4$, the tone frequencies remained constant for increased flow velocities as shown in Figure 8. Some "hysteresis" effects are shown in Figure 7 between the increasing and decreasing velocity data. No accelerometers were used to monitor plate vibration amplitudes during the noise measurements.

Figure 9 shows the observed Strouhal numbers Ft/U_e versus d/t for the acoustic tones detected for the single and multiholed orifice flows. The range of Strouhal numbers decreases significantly with increasing d/t over the range of test parameters shown. The widest range of tone frequencies is seen to occur for $d/t = 1$.

Figure 10 displays the Strouhal number versus Reynolds number for a range of d/t ratios and number of holes.

NOISE AMPLITUDE

Broadband Levels

A summary of the radiated broadband noise level dependence on orifice-jet exit velocity U_e is shown in Figure 11. These noise levels were determined from the broadband root mean square (rms) levels of the microphone spectra (with no tones present) using a Spectral Dynamics model 335 spectrum analyzer. It is observed that power laws from U_e^4 to U_e^8 occur with no apparent systematic dependence on d/t or the number of orifice openings N . Comparison of the broadband noise generated by the flow through the sharp and beveled edged orifices indicated that the 0.8 mm bevel reduced the levels by 2 to 4 dB.

Figure 12 shows the variation in the maximum normalized radiated broadband noise level detected for each d/t ratio studied. The noise level p^2 is normalized in terms of the orifice-jet dynamic pressure, the total cross-sectional open area of the orifice plate, and the distance from the orifice plate to the free-field microphone. It is seen that the maximum nondimensional broadband noise level occurs when $d/t = 1$ for both $N = 1$ or $N = 31$.

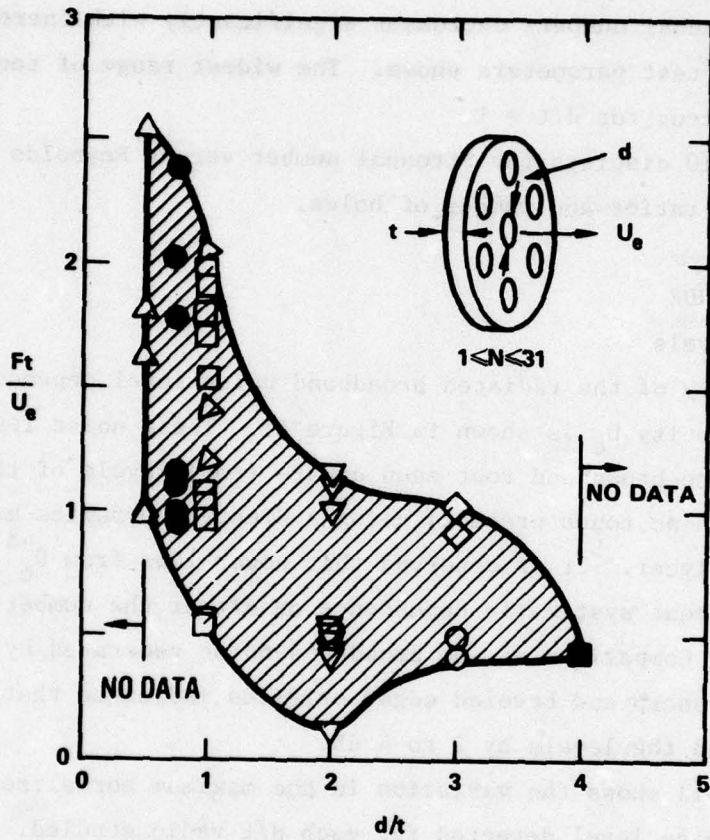


Figure 9 - Strouhal Number versus d/t for Acoustic Tones Generated by Flow through Single and Multiholed Orifice Plates

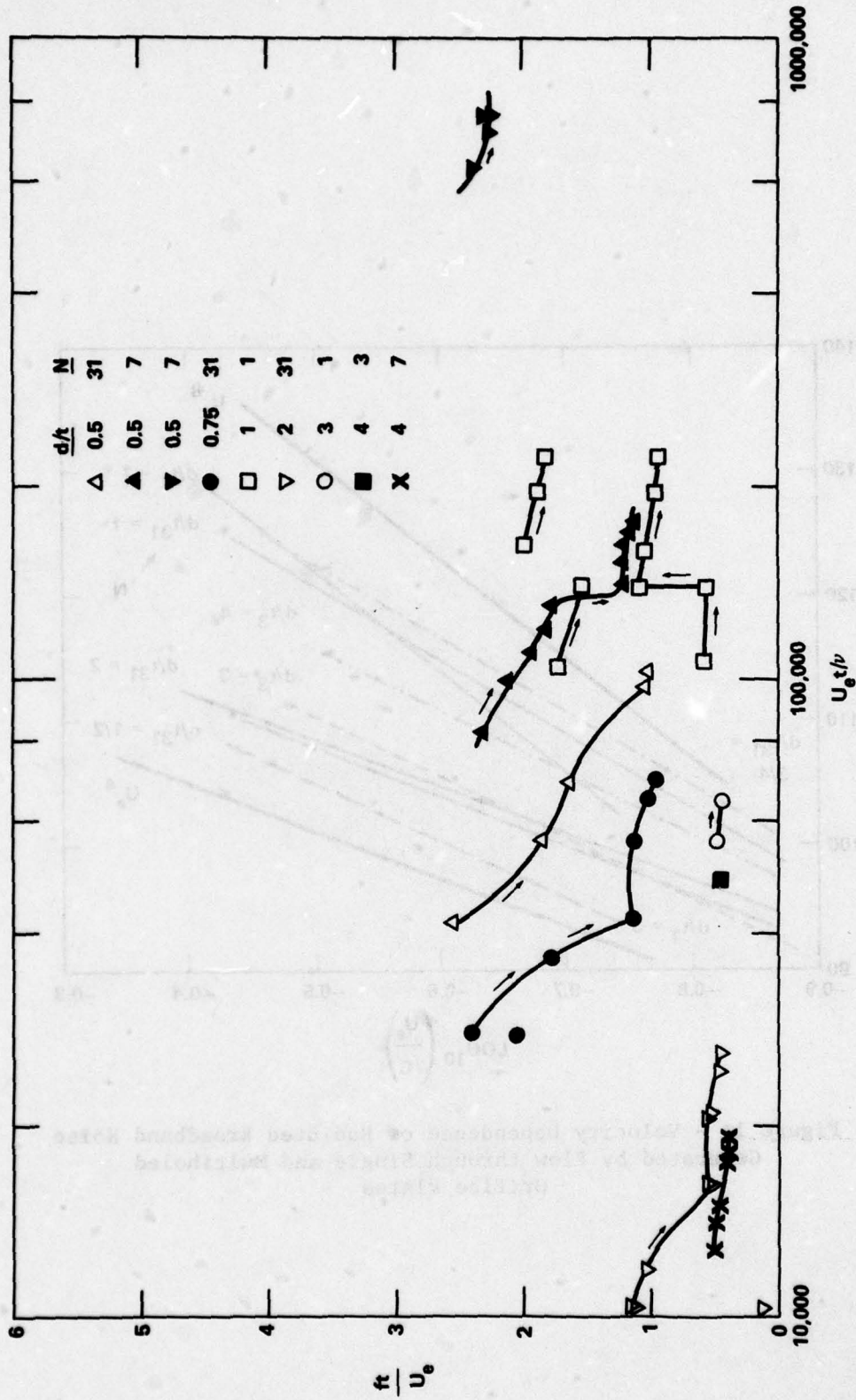


Figure 10 - Strouhal Number versus Reynolds Number for Acoustic Tones Generated by Flow through Single and Multiholed Orifice Plates

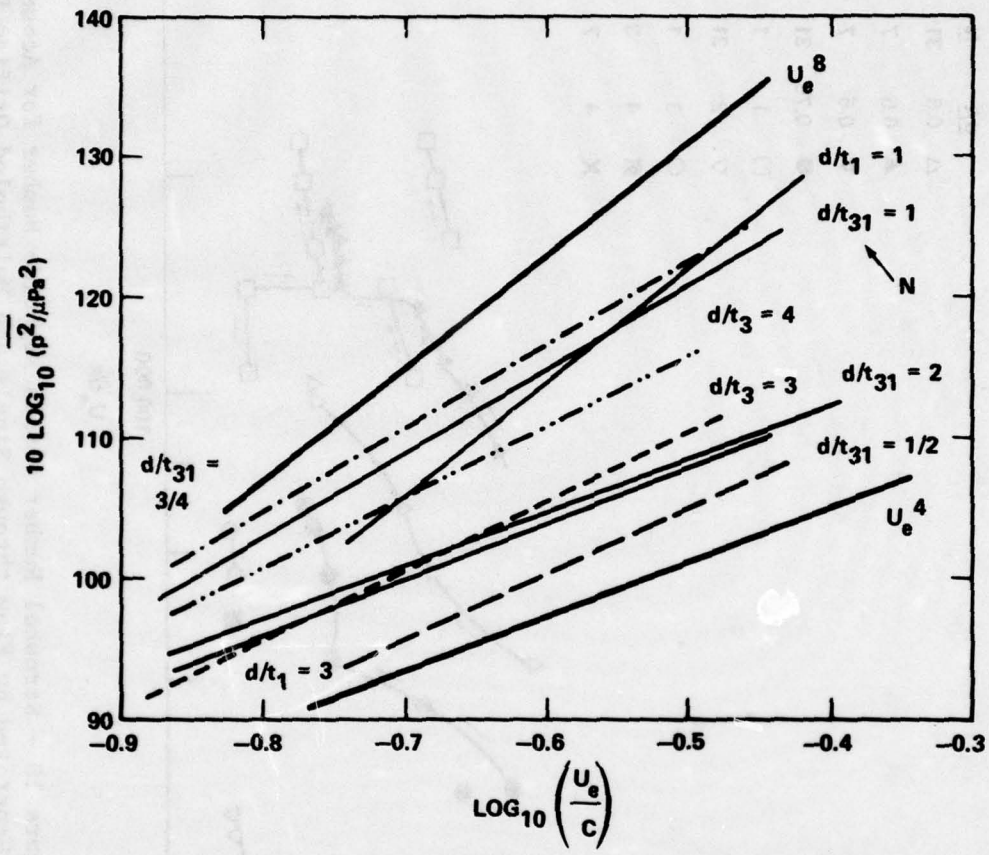


Figure 11 - Velocity Dependence of Radiated Broadband Noise Generated by Flow through Single and Multiholed Orifice Plates

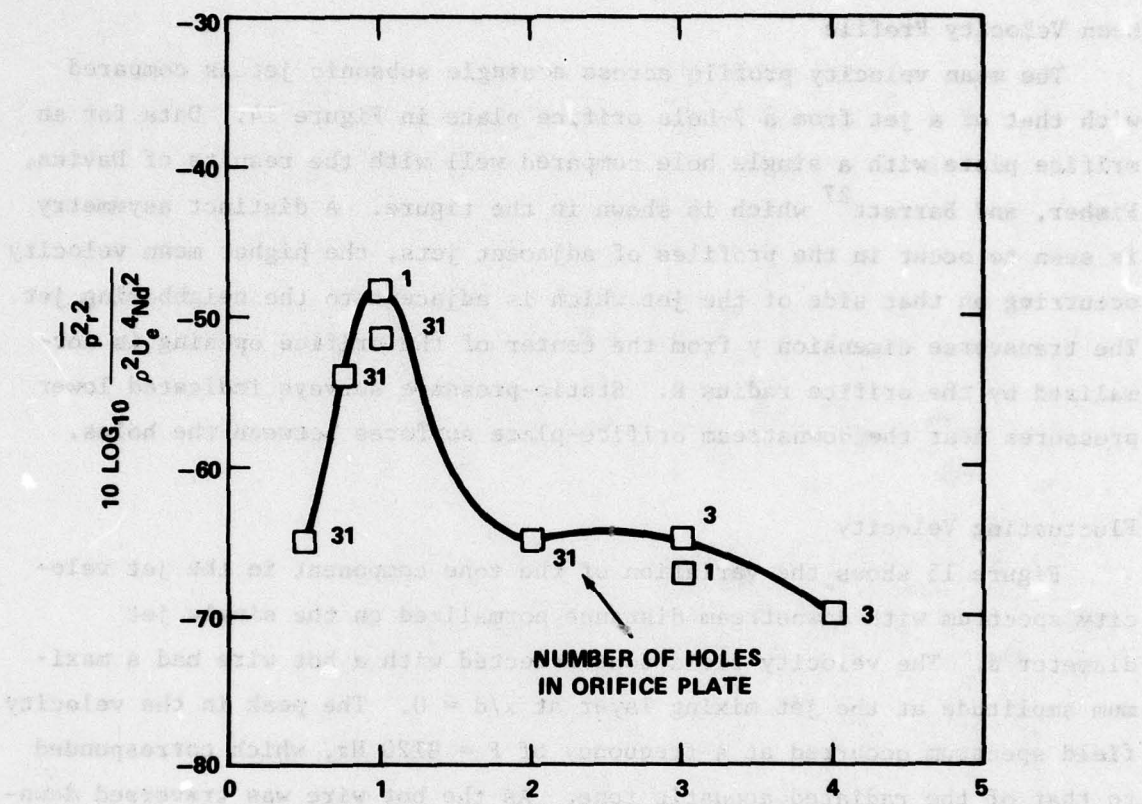


Figure 12 - Normalized Maximum Radiated Broadband Noise Levels versus d/t at $U_e/c = 0.32$

Tone Levels

The variation of the maximum radiated tone levels from a multiholed orifice plate ($N=7$) with d/t is shown in Figure 13. As was the case for the broadband noise level, the peak tone level also occurs when $d/t = 1$.

ORIFICE-JET VELOCITY FIELD

Mean Velocity Profile

The mean velocity profile across a single subsonic jet is compared with that of a jet from a 7-hole orifice plate in Figure 14. Data for an orifice plate with a single hole compared well with the results of Davies, Fisher, and Barratt²⁷ which is shown in the figure. A distinct asymmetry is seen to occur in the profiles of adjacent jets, the higher mean velocity occurring on that side of the jet which is adjacent to the neighboring jet. The transverse dimension y from the center of the orifice opening is normalized by the orifice radius R . Static-pressure surveys indicated lower pressures near the downstream orifice-plate surfaces between the holes.

Fluctuating Velocity

Figure 15 shows the variation of the tone component in the jet velocity spectrum with downstream distance normalized on the single jet diameter d . The velocity field tone detected with a hot wire had a maximum amplitude at the jet mixing layer at $x/d \doteq 0$. The peak in the velocity field spectrum occurred at a frequency of $F = 8120$ Hz, which corresponded to that of the radiated acoustic tone. As the hot wire was traversed downstream (increasing x/d) the peak fluctuating velocity indicated that a stationary wave existed in the jet mixing layer. Based on a wavelength determined from the successive crests in the figure for the level of the fluctuating velocity, it is seen that for the wave to appear stationary it must be moving upstream at $U_c/U_e = 0.7$, which is approximately the speed at which the mixing layer disturbances convect downstream.

DISCUSSION

The general features of the radiated noise for varying orifice flow velocities shown in Figures 6-13 were representative of those obtained for both single and multiholed orifice plates. The noise characteristics

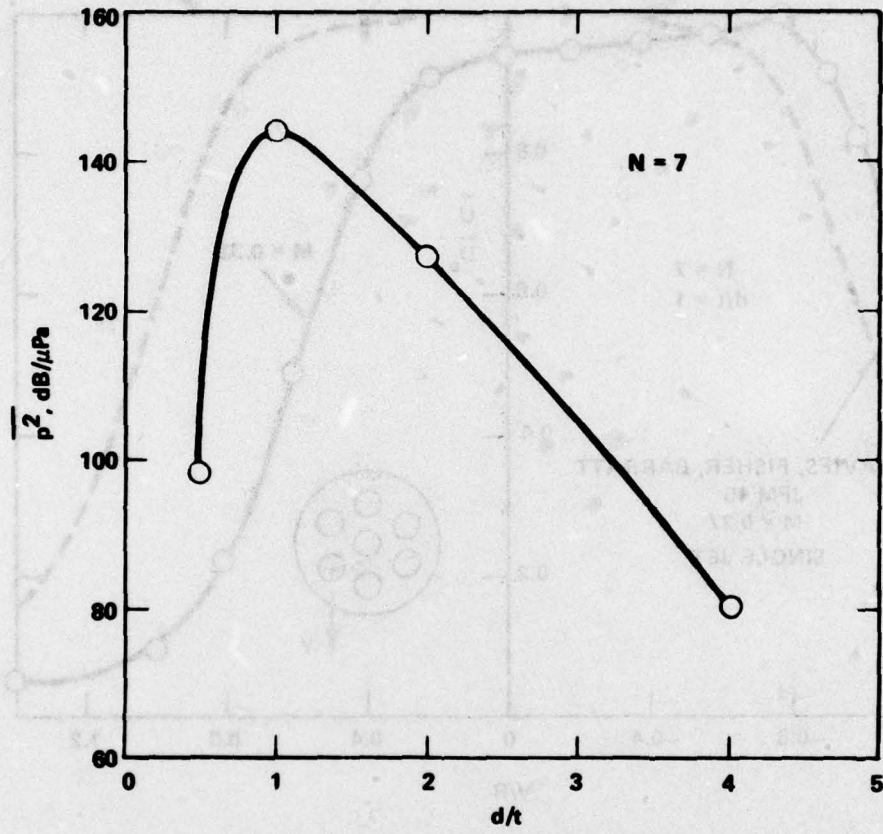


Figure 13 - Maximum Radiated Tone Levels Generated by Multiholed Orifice Plate versus d/t ($N=7$)

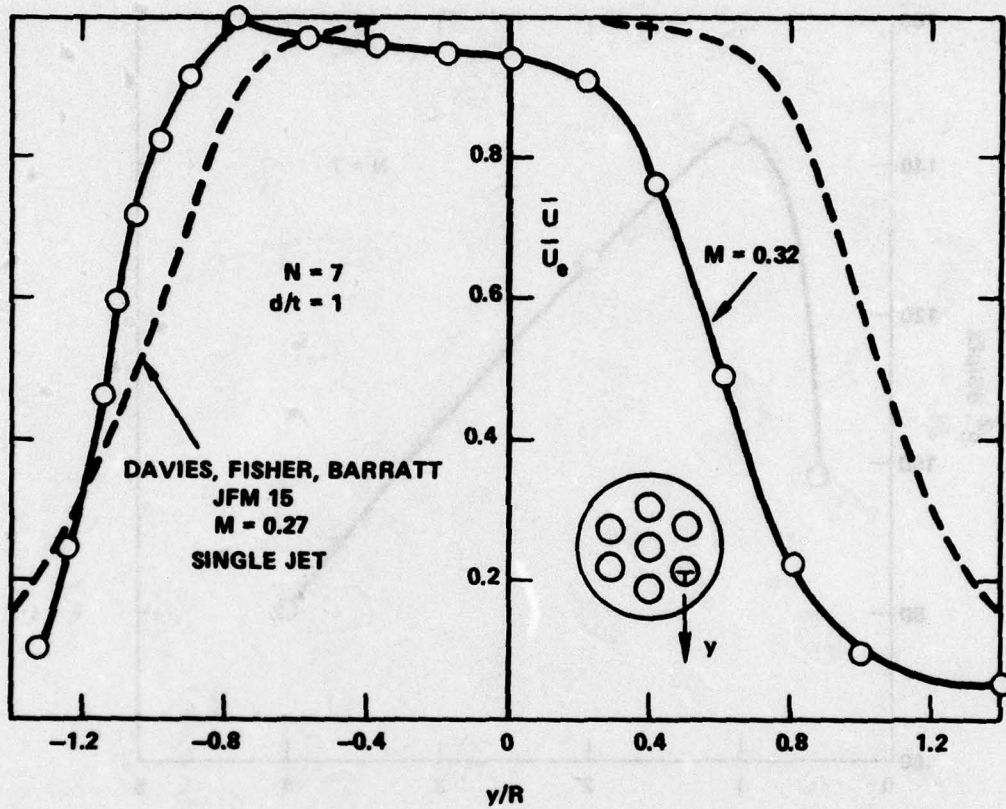


Figure 14 - Comparison of Mean Velocity Profile of Adjacent Jets with that of Single Jet

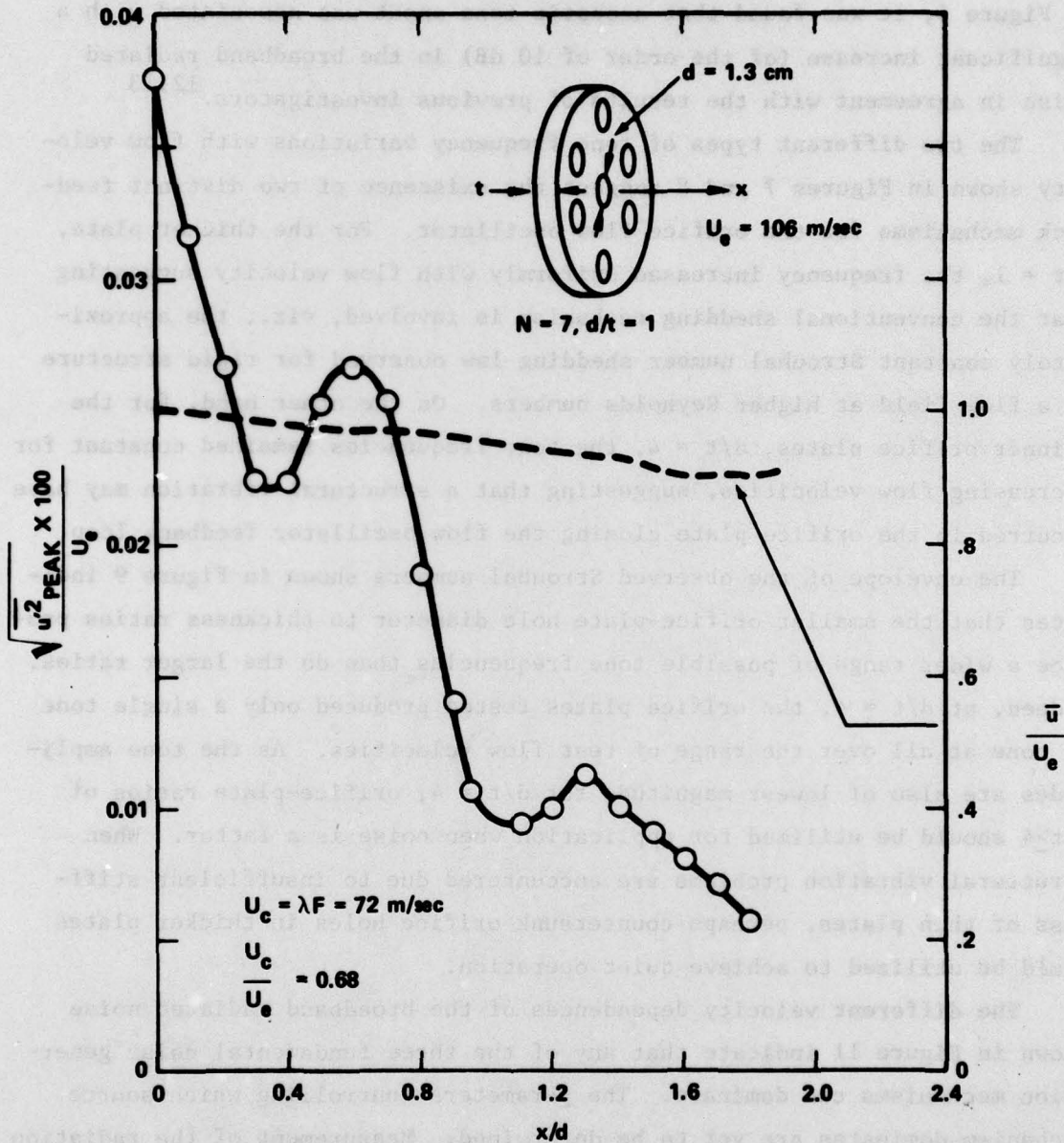


Figure 15 - Peak Fluctuating Velocity at $F = 8120$ Hertz versus x/d

did not change with small changes in the free-field microphone position and thus the lack of anechoic treatments to the test environment was not considered to have significantly affected the reported results. As shown in Figure 6, it was found that acoustic tone onset was associated with a significant increase (of the order of 10 dB) in the broadband radiated noise in agreement with the results of previous investigators.^{12,13}

The two different types of tone frequency variations with flow velocity shown in Figures 7 and 8 suggest the existence of two distinct feedback mechanisms for the orifice flow oscillator. For the thicker plate, $d/t = 1$, the frequency increased uniformly with flow velocity suggesting that the conventional shedding mechanism is involved, viz., the approximately constant Strouhal number shedding law observed for rigid structure in a flow field at higher Reynolds numbers. On the other hand, for the thinner orifice plates, $d/t = 4$, the tone frequencies remained constant for increasing flow velocities, suggesting that a structural vibration may have occurred in the orifice plate closing the flow oscillator feedback loop.

The envelope of the observed Strouhal numbers shown in Figure 9 indicates that the smaller orifice-plate hole diameter to thickness ratios produce a wider range of possible tone frequencies than do the larger ratios. Indeed, at $d/t = 4$, the orifice plates tested produced only a single tone or none at all over the range of test flow velocities. As the tone amplitudes are also of lowest magnitude for $d/t = 4$, orifice-plate ratios of $d/t > 4$ should be utilized for application when noise is a factor. When structural vibration problems are encountered due to insufficient stiffness of thin plates, perhaps countersunk orifice holes in thicker plates could be utilized to achieve quiet operation.

The different velocity dependences of the broadband radiated noise shown in Figure 11 indicate that any of the three fundamental noise generation mechanisms can dominate. The parameters controlling which source mechanism dominates are yet to be determined. Measurement of the radiation patterns for the orifice-plate noise would indicate whether the source mechanism was omnidirectional and hence that of a monopole or that associated with a higher order source. Detailed velocity field measurements inside the orifice opening would also be useful in defining the noise source mechanism.

The maximum radiated broadband noise levels were shown in Figure 12 to collapse for both the single and 31 hole orifice plates on the exit jet dynamic pressure (determined by the center orifice exit velocity U_e) and the total open area of the orifice plates. This indicates that the flow fluctuations in each orifice opening may act, for example, as a small vibrating piston, each contributing independently to the radiated sound level at the field point. The radiated noise was found to be greatest when $d/t = 1$ for both the tonal and broadband noise.

The mean velocity field profiles shown in Figure 14 indicate that the mean flow field of a given orifice is disturbed by the presence of adjacent jets. This did not seem to be a significant factor in the broadband noise production process, however, due to the success of the normalization of noise data for 1 and 31 holes shown in Figure 12. There also appeared to be no unique differences in the spectral features of the radiated noise from the single or multiholed orifice plates. Hence, these results tend to minimize the significance of interaction effects in the broadband or tonal noise producing mechanisms.

The radiated tones were found to be associated with strong periodic fluctuations in the jet mixing layers (see Figure 15). It was observed that the introduction of a pencil point at a critical location in the jet flow field within one or two diameters of the orifice could eliminate the tone. More detailed experiments to determine the fluctuating flow features inside and downstream of the orifice are needed to clarify these important aspects of the tone generation (and elimination) mechanisms.

CONCLUSIONS

1. The velocity dependence of broadband noise levels radiated from subsonic airflow through single and multiholed orifice plates varies between U_e^4 to U_e^8 .
2. Maximum tone and broadband radiated noise levels occur when $d/t = 1$.
3. The range of Strouhal numbers for tones radiated by single and multiholed orifice plates decreases with increasing d/t .
4. Acoustic tone onset significantly increases the jet radiated broadband noise levels.

5. Tone generation is associated with stationary waves in the jet mixing layer velocity field.

6. Small beveling of the edges of the orifice holes reduces the levels of the broadband and tonal components of the radiated noise by 2-4 dB.

RECOMMENDATIONS

The following aspects of orifice flow noise are recommended for further study.

1. Conduct simultaneous measurements of the tone pressure field and the fluctuating velocity field inside and downstream of the orifice openings.

2. Conduct flow visualization studies utilizing smoke and high-speed stroboscopic photographic techniques synchronized with the tone pressure field to determine the features of the orifice-jet stationary waves.

3. Experimentally determine the effects of rounded orifice inlets and "scalloped" downstream orifice-hole edges on the tonal and broadband noise levels. The reduction of the correlation length of the ring vortices shed from the orifices could significantly reduce tonal noise levels.

4. Measure the orifice-plate acceleration levels to determine if structural oscillations play a role in closing the feedback loop in tonal noise production.

5. Build an anechoic chamber around the test region and measure the radiation patterns of the orifice-plate noise to determine whether monopole, dipole, or quadrupole noise sources mechanisms dominate.

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