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**ACOUSTIC SPECTRUM SHAPING BY IMPINGING
GAS JETS FOR SATELLITE TESTING:
A PARAMETRIC EXPERIMENT**

by

MARK A. HENDRYCKS, M. Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Engineering in Mechanical Engineering

Department of Mechanical and Aerospace Engineering

Ottawa-Carleton Institute

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ACOUSTIC SPECTRUM SHAPING BY IMPINGING
GAS JETS FOR SATELLITE TESTING:
A PARAMETRIC EXPERIMENT

submitted by

Mark A. Hendrycks, B.Eng.
in partial fulfilment of the requirements for
the degree of Master of Engineering

Thesis Co-Supervisor

Thesis Co-Supervisor

Chair, Department of Mechanical and Aerospace Engineering

Carleton University
November 1993

Abstract

Acoustic impinging gas jet tests were performed in the reverberation chamber at the National Research Council's Institute of Aerospace Research Aeroacoustics Facility. The impinging acoustic gas jets were tested as a possible alternative high frequency noise generating device for use in acoustic testing of satellites.

The tests involved varying the controlling parameters of supply air pressure, jet orifice size, wall standoff distance, and jet geometry. The OASWL for the impinging gas jets follows Lighthill's U^8 Law (eighth power of jet exit velocity). The result of mixing and impingement of the two jets increases the OASWL by 14 to 20 dB. On average the peak Strouhal number was between 0.23 to 0.26 as compared to the theoretical value of 0.2. The test data has lead to the development of an automated jet assembly and two methods of selecting the jet configuration for a given test spectrum.

Acknowledgements

I would like to thank my supervisor, Frank Slingerland for his idea of using impinging gas jets as a high frequency noise source. Also I would like to express my appreciation for his assistance in providing many new ideas for interesting test cases and vast theoretical content.

Thanks also must be extended to my co-supervisor, Professor James Kirkhope for his guidance and support in the organization and editing of this thesis.

At the IAR/SML facility, I would especially like to thank Luc Hurtubise for his direct assistance with the assembly of the jet apparatus, and assistance in the performance of the many tests.

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CHAPTER 6

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List of Symbols

Symbol	Description of Symbol
$A(\eta, t)$	Source Strength Distribution
α	Yaw Angle from jet centreline, degrees
A_j	Area of the Jet, ft^2
C	Convection Factor
c_∞	Speed of sound in ambient air, ft/sec
dB	Units of noise, decibel
d_{jet}	diameter of jet, in
eM^5	Radiated Efficiency
f_r	Resonance Frequency, Hz
f_{max}	Peak Frequency in the Spectrum, Hz
Hz	Frequency in Hertz
I_d	Intensity of a directional source, Watts/ft^2
I_p	Intensity of a point source, Watts/ft^2
I.D.	Inner Diameter, ft
K	Constant for Radiated Efficiency $\times 10^{-5}$
M	Mach number
OASPL	Overall Sound Pressure Level, re 0.00002 Pa
OASWL	Overall Sound Power Level, re 1.0 F-12 W
O.D.	Outer Diameter, ft
PWL	Sound Power Level, Watts
psia	Pressure in pounds per square inch absolute
psig	Pressure in pounds per square inch gauge
π	Constant of pi

Symbol	Description of Symbol
P	Local pressure, psi
P_o	Stagnation Pressure, psi
P_{atm}	Atmospheric Pressure, psi
Q_θ	Directivity Factor of a Directional Source
Q_s	Directivity Factor of a Point Source
r	Radial Distance from point source, ft
ρ	density of air, lb_m/ft^3
ρ_∞	density of ambient air, lb_m/ft^3
ρ_j	density of exiting jet air, lb_m/ft^3
S	Strouhal Number, typical value 0.2
scfm	Standard cubic feet per minute
t	time, seconds
τ	retarded time, seconds
T_{ij}	Viscous Stress Tensor
θ	Pitch Angle from jet centreline, degrees
U_j	Velocity of the Jet, ft/sec
u_x	turbulence component of velocity in x-direction, ft/sec
U_x	Mean Flow Velocity in x-direction, ft/sec
v_x	Instantaneous Velocity in x-direction, ft/sec
v	local velocity, ft/sec
W	Total Sound Power in decibels, dB
x	distance in downstream direction, ft
y	vertical distance from centreline, ft

Note to the Reader:

The National Research Council's IAR/SML Aeroacoustics Facility, U-66A was built in 1965 with the additions of the reverberation chamber and inner preparation bay in 1980, and the outer preparation bay in 1984. The IAR/SML facility performs daily operations in both Metric and English units, depending on the client and the application. Much of the physical apparatus for this work is in standard English units. Since this thesis was a joint funded project between Carleton University and the NRC, the units of choice are English. A conversion table is provided in Appendix A to convert all pertinent units to Metric form.

CHAPTER 1

Introduction

This thesis reports experimental studies of noise generated by acoustic gas jets in the triple corner of a reverberation chamber. Data of this type is of particular interest in the aerospace industry where structural integrity tests are performed on satellites using acoustic gas jets as a noise source. A description of the aeroacoustic facility and how acoustic tests are performed will follow. A discussion of the existing noise generating devices and the associated problems with the devices will give insight into the reason why the acoustic gas jet tests were performed. After this discussion, a review of pertinent literature will be made. Following the literature review there will be a statement of the thesis objectives and goals.

1.1 Aeroacoustics Facility

The National Research Council's, Institute for Aerospace Research, Structures Materials Laboratories, Aeroacoustics Facility is located at the Uplands Laboratories. The Uplands Facility is located in building U-66 Annex which is adjoining the High Speed 5 ft Blowdown Windtunnel Facility in U-66. A layout of the aeroacoustics facility and the reverberation chamber is shown in Figures 1.1 and 1.2.

At the IAR/SML Aeroacoustics Facility, satellites, antennae, and structure panels are tested for their structural integrity based on predicted noise levels from the rockets which will launch them into space. The client will generally specify the acoustic levels and their tolerances in $\frac{1}{3}$ octave bands in the frequency range of 25 to 20000 Hz in advance of the test date. The IAR/SML group will then use the various noise generating devices to match the given spectrum in the 536 m³ reverberation chamber. Once the spectrum is matched, the settings for the control devices are recorded and await the arrival of the test specimen.

The aeroacoustic facility is well situated since an abundant compressed air supply is available from the High Speed Blowdown Windtunnel in U-66. Compressed air is sent through the piping network to the six controllable stem valves. Attached to these valves are flexible pressure hoses which connect to the various noise generating devices. The existing noise generating devices used are the Wyle Acoustic Source (WAS) 3000, NAE Hartmann generator and the LING EPT. The LING EPT has recently been removed from operation because of corrosion problems. The noise generating devices are then coupled to the reverberation chamber through exponentially increasing horns with the following cut-on frequencies : 25, 32, 100 and 200 Hz. The horns are used to couple the sound produced by the noise generating devices and prevent the reflection of sound waves to the devices. Inside the

reverberation chamber there are four microphone stands shown in Figure 1.3. The microphone stands used are approximately 10 and 15 feet tall. At this height the microphones can sufficiently measure the noise levels in the centre of the reverberation chamber. The microphones are connected to preamplifiers and their signals are sent to the measuring amplifiers. The signals are multiplexed and averaged during the test time. The signals are then received by a real-time spectrum analyzer. The analyzer has the capability to store the data in disk files for later analysis.

1.2 Noise Generating Devices

1.2.1 Wyle Acoustic Source

The Wyle Acoustic Source is manufactured in Huntsville, Alabama. The acoustic source shown in Figure 1.4 & 1.5 consists of an exterior shell and a modulator. The modulator contains two concentric aluminum cylinders approximately 4 inches in diameter and 8 inches in length. The inner cylinder is solid aluminum with the last quarter of its length made up of small circumferential slits $1 \frac{3}{16}$ inches in length and $\frac{1}{16}$ to $\frac{1}{32}$ inches in width. The slits are in columns of 22, and there are 12 columns around the circumference. The outer cylinder is identical except for an electrodynamic voice coil wrapped around the bottom of the cylinder and connected to the terminals at the top of the modulator. The concentric sleeves

are placed inside the Wyle shell and the flexible hose is connected to the shell for the air supply. When the cylinders are placed in the Wyle shell, the electrodynamic voice coil is exposed to a permanent magnetic field. The Wyle is then connected to the power amplifier and receives the drive current. The resulting force causes the outer cylinder to move over the inner cylinder. The resulting action is an axial oscillation of the outer cylinder against the inner cylinder. The overlapping slits continually open and close, changing the effective area available for air flow. The spectrum produced from this action is high intensity, low frequency noise. The Wyle modulator units are a one-dimensional system, and can be modelled as mass on a spring. The natural frequencies for the two Wyle modulator units are calculated by the square root of the stiffness of the spring slots divided by the mass of the material near the slits. The natural frequencies for the MU-110 and MU-111 are 500 and 1000 Hz respectively. The Wyle Acoustic Source still produces noise above these frequencies through a phenomenon known as upspill. When a sound pressure of 180 to 185 dB is generated in the throat of an acoustic horn, the higher pressure region is at a higher temperature than the low pressure region. Since sound travels faster at higher temperatures than at low temperatures, the higher temperature region overtakes the previous low pressure region. When this happens, a situation develops in the horn throat where a sine wave will change to

a sawtooth wave, having essentially zero rise time and a long decay to the next low pressure region. A Fourier analysis of the sawtooth wave will show that half of the original energy in the sine wave has transferred to harmonics of the original frequency with theoretical amplitudes falling off at 3 decibels per octave. When random noise is generated by the modulator, the same result occurs, except the sawtooth has random amplitude and spacing. In actual practice, the harmonic generation rolls off at approximately 4 decibels per octave.

The WAS-3000 must be supplied with a gas flow of 3000 scfm at a pressure of 30 psig for maximum power operations. This flow is converted to approximately 10 Acoustic Watts per cfm. This airflow also cools the voice coil so that no external cooling is required. Since the magnetic field around the voice coil is provided by a permanent magnet, there is no need for a magnet power supply or cooling of the magnet, as required by the LING EPT.

1.2.2 NAE Hartmann Generator

The NAE title refers to the National Aeronautical Establishment, which is the former name of the present Institute for Aerospace Research. The NAE Hartmann Generator is a patented design in which an original Hartmann generator is inserted perpendicular to the air flow in a special adaptor plate fitted to the exit plane of a Wyle Acoustic Source and

either the 25 or 32 Hz horn. The configuration in which four Hartmann generators are inserted in the adaptor plate on the 25 Hz horn is shown in Figure 1.6.

The Hartmann generator is simply a sonic jet impinging into a resonant cavity of circular or rectangular cross-section. The Hartmann generators implemented in this application have rectangular cavities controlled through servo-mechanisms. The noise spectrum produced by a Hartmann generator is narrowband tones with associated harmonics and is illustrated in Figure 1.7. The frequencies of the tones and harmonics are controlled by the depth of the cavity. When the Hartmann generator's narrowband tones and harmonics are mixed with the high intensity, low frequency broadband noise the resulting noise spectrum is broadband noise. The Hartmann generators will add supplementary noise levels above the cut-off frequencies of the Wyle Acoustic Source. A typical combined spectrum is shown in Figure 1.8.

1.3 Basis for Jet Test Experiments

The Wyle Acoustic Source simply can not produce sufficient noise levels at frequencies greater than the cut-off frequency of the modulator unit. Any attempt to modulate at higher frequencies has no effect on the noise levels produced.

The problem with the Hartmann generators is that they have a characteristic decay rate or roll-off rate (dB/octave) which can not be varied with supply pressure and cavity depth. If the decay rate is different from that of a targeted noise spectrum supplied by a client, then the spectrum can not be matched effectively.

It was determined that to remain competitive in the aerospace testing market, an improvement was needed in the ability to match the high frequency range of the noise spectrum. The idea for exploration in the acoustic gas jet area was based upon successful implementation of acoustic gas jets in the Tsukuba Acoustic Facility of NASDA in Japan. Fujita and Iide [1] found that two opposed gas jets fixed on the side wall of the chamber provided sufficient noise in the higher frequency bands. The shape of these spectra can be seen in Figure 1.9. Initially, it was hypothesized that the sound pressure level results that the Japanese achieved could be improved by taking advantage of the directivity factor of a noise source. The directivity factor, Q_θ , is defined as the ratio of the intensity of a directional source, I_θ , to the intensity of a point source, I_s .

$$Q_\theta \equiv \frac{I_\theta}{I_s} \quad (1.1)$$

Where intensity, I_s , is defined as the ratio of total sound power, W , divided by the surface area over which it spreads.

$$I_s = \frac{W}{4\pi r^2} \quad (1.2)$$

It is well known that an omnidirectional source emits sound in all directions and therefore has a directivity factor of one. If the same source is located near a non-absorptive wall the directivity factor increases by a factor of two because the same intensity is reflected into half the surface area. Similarly, placing the source near a double wall (floor and wall) the directivity factor becomes four. Finally, placing the source in a triple corner increases the directivity factor to eight times the omnidirectional source. It was found that the directivity factor of a noise source in a reverberation chamber does not yield the expected results, since any energy produced by the noise source is reflected around the chamber and then dissipates slowly with time. The advantage of the north-east corner, or any other triple corner for that matter, is that the reverberation chamber contains thousands of cosine wave modes and each of these modes has an anti-node in the triple corner. By exciting the anti-node in the corner, one can achieve equal excitation of all of the chamber's modes, especially the modes in the low frequency region.

The acoustic gas jets have an advantage over the other high frequency noise sources in the number of parameters which may be varied to adjust the spectrum. Thus the experiments performed in this work will vary the following parameters: (a) supply pressure, (b) diameter of the jet (symmetrical or

asymmetrical), (c) wall standoff (symmetrical or asymmetrical), (d) nozzle geometry (sudden contraction, smooth conical nozzle and rectangular orifice), (e) single sudden contraction jet, (f) separate pressure feed nozzles. A schematic layout of the impinging jet apparatus is shown in Figure 1.15.

1.4 Literature Review

1.4.1 General Theory

Jet noise first became a concern for man with the use of jet engines in military aircraft during the Second World War. Jet noise falls into a category known as aerodynamic noise which is a combination of acoustics and unsteady aerodynamic flow. In the late 1940's there had been few actual measurements on the intensity of far-field noise from turbulent jets. These experiments showed that the sound power level was proportional to the eighth power of the jet exit velocity.

Present day knowledge of aerodynamic noise has its foundation from Lighthill's work on "sound generated aerodynamically". There have been many subsequent studies which stemmed from Lighthill's work that not only verified the eighth power law, but also confirmed his theories on convective amplification with Mach number and changes in the directivity of the sound.

Lighthill's theory is derived from the exact flow equations for a perfect gas, namely conservation of mass, momentum and energy. Lighthill found that the energy radiated outward as sound was a very small fraction of the flow's kinetic energy. He stated that any approximation in solving these equations for the fluctuating density could lead to a solution which is physically wrong. To overcome this difficulty Lighthill used an analogy which today is known as Lighthill's Acoustic Analogy. Here, unsteady flow is replaced by volume distributions of equivalent acoustic sources throughout the flow. In this analogy the fluid is at rest, but the sources may move. All the fluid dynamics, generation of noise, and interaction with the flow are included in the strength and distribution of the noise sources. Lighthill's theory can be used when a good approximation of the equivalent acoustic source field is known. When the properties of unsteady flow are known, the details of the source field can be determined.

A basic knowledge of Lighthill's theory is essential to understand noise generation of turbulent jets and its propagation to the far field. This theory is difficult to apply when acoustic interaction occurs in the flow field and therefore modifications to his theory are required to include flow-acoustic interaction [2]. Lighthill's theory assumes all solid boundaries are absent from the flow field. Curle [3] and many other researchers have modified the theory to include

solid surfaces, and thereby developed a theory for boundary-layer noise.

Only the final results of Lighthill's theory on sound produced aerodynamically are given in this work. For further information on Lighthill's derivation and the assumptions used refer to references [4,5].

Lighthill's solution for the sound generated aerodynamically, in a moving coordinate frame is given below,

$$\rho(x, t) = \frac{1}{4\pi c_\infty^2} \iiint \frac{A(\eta, \tau)}{|x-y| - M(x-y)} d\eta \quad (1.3)$$

where τ is the retarded time.

If the instantaneous flow properties ρ, p, τ and $\mathbf{v}$ are known everywhere within the flow, then T_{ij} and $A(\mathbf{y}, \tau)$ are also known everywhere, and the far-field density perturbations can be obtained by quadrature throughout the flow volume. It is assumed that $A(\mathbf{y}, \tau)$ vanishes beyond the flow boundaries, and the far-field observer is at a distance that is large compared with the finite dimensions of the flow field.

This exact solution to the fluid flow equations represents one of the major advances in the study of unsteady fluid flow problems and is one of the most significant advances in the study of acoustics following the work of Lord Rayleigh.

An immediate deduction from Lighthill's theory is that the total acoustic power W_t radiated by a jet is given by the following equation.

$$W_t = \frac{K \rho_j^2 A_j U_j^8}{\rho_\infty c_\infty^5} \quad (1.4)$$

Since the kinetic energy flux is proportional to $W_j = \rho_j A_j U_j^3$, we see that the ratio of total acoustic power radiated to kinetic energy flux is given below.

$$\frac{W_t}{W_j} = K \left(\frac{\rho_j}{\rho_\infty} \right) \left(\frac{U_j}{C_\infty} \right)^5 \quad (1.5)$$

The constant K is of order 10^{-5} and ρ_j , A_j , and U_j are the values of density, cross-sectional area, and velocity at the jet exit. Thus, the total acoustic power is a small fraction of the flow kinetic energy flux.

Although Lighthill's theory is exact, it does not help the reader envision the mechanisms occurring in the jet flow. Bell's overview on jet noise [6] and Ribner's paper [7] satisfy this oversight.

Bell [6] states that as the pressure ratio P_o/P_{atm} is increased over 1.893, flow through the nozzle is sonic; and any further increase in the pressure ratio has little effect on increasing the exit velocity. The noise from these gas jets is a broad band high frequency which can be qualified as a "hiss". Actual generation of noise results from creation of fluctuating pressures due to turbulence and shearing as the

high velocity air interacts with ambient air. Radiating sources called "eddies" are then formed with high frequency noise being generated in the mixing region and potential core, while low frequency noise is generated downstream in the large turbulence region. The frequency peak can be predicted by the following formula, where S is the Strouhal number:

$$f_{peak} = \frac{S * U_{jet}}{d_{jet}} \quad (1.6)$$

From Lighthill's work, the total sound power level, W_t , in watts is given by the following equation.

$$W_t = eM^5 \rho U^3 A \quad (1.7)$$

Where eM^5 is the radiation efficiency given in Table 1.1, ρ is the ambient density, and U and A are respectively the jet velocity and jet area. This equation is good in the range of $0.15C < U \leq C$.

In Ribner's paper [7], the irregular eddying flow is idealized as a random assortment of tiny 'jetlets' imbedded in and swept downstream with the main jet flow (Figure 1.10). Considering the momentary collision of two 'jetlets' causing a stagnation region which is compressed, and then rebounding through jostling of adjacent 'jetlets', an emitted sound wave will occur. The dilatation mechanism which is illustrated in Figure 1.10 is applied to an elemental sphere.

$$\frac{\partial(\text{volume})}{\partial t} \sim \frac{\partial(\text{pressure})}{\partial t} \quad (1.8)$$

$$\frac{\partial^2(\text{volume})}{\partial t^2} \sim \frac{\partial^2(\text{pressure})}{\partial t^2} \quad (1.9)$$

The effectiveness in generating sound depends on the radial acceleration of the elemental sphere and therefore the second time derivative. Ribner stated that the pressure in equation 1.9 was the local pressure, and that the far field conditions could be attained by suitable integration over the source pattern. In Figure 1.11, the pluses and minuses designate correlation volumes where the source strength is either positive or negative. The distribution is random, but there is a certain sorting in a statistical sense. Integration over the source pattern will yield a different sound pressure in different directions. The basic pattern is swept downstream through convection and refracted by temperature and velocity gradients in the flow. The resulting pattern is shown in Figure 1.12. Ribner noted that the main source of noise has been identified as pressure fluctuations; however, a momentum balance allows pressure to be replaced by momentum flux, ρv_x^2 . This yields the same result as Lighthill's theory and is given below.

$$p(x, t) = \frac{1}{4\pi c^2 x} \int_V \frac{\partial^2(\rho v_x^2)}{\partial t^2} dV \quad (1.10)$$

From the theory and measurements with hot-wires, there is more knowledge about turbulent velocity fields in a jet than

pressure fields. Considering the instantaneous velocity, v_x , which is composed of the turbulence, u_x , and the mean flow, U_x , the squared velocity becomes, $v_x^2 = u_x^2 + 2u_xU_x + U_x^2$. The first term represents the self noise term while the middle term corresponds to the shear noise, the final term does not produce any noise since there is no fluctuating term. The arrows in Figure 1.13 differentiate the self noise from turbulence alone and the shear noise as the cross product term. When equation 1.10 is squared and time averaged to obtain p^2 , the noise producing terms in v_x^2 appear as two point correlations with time delay. Ribner performed the integration, and the result was that self noise provides a nondirectional noise source, while shear noise resembles a figure eight with the lobes aligned with the flow, as seen in Figure 1.13. Before discussing the combined pattern, if the turbulence, u_x , has a dominant frequency which is considered as $u_x \sim e^{i\omega t}$, then the self noise term, u_x^2 will be $u_x^2 \sim e^{i2\omega t}$. From the terms given above self noise, u_x^2 , tends to higher frequencies than the shear noise component, $2u_xU_x$, in fact there is a doubling of the frequency. The high pitch self noise tends to be along the sides of the jet while the low pitch shear noise tends to be fore and aft. Ribner used a retarded time to modify his modelled theory to account for convection and agree with Lighthill. Ribner did this through a convection factor, C , which multiplies with the basic source pattern:

$$C^{-5} = [(1 - M_c \cos \theta)^2 + \alpha^2 M_c^2]^{-\frac{5}{2}} \quad (1.11)$$

The enhancement due to source motion is associated with a crowding of the sound waves in the downstream sector. This shift to higher frequencies suggests a Doppler effect that is illustrated in Figure 1.14 by a Doppler arrow. This shift opposes the symmetrical high-low distribution of the basic pattern. The final flow effect of refraction bends the sound rays away from the jet axis, with marked increase at higher frequencies which tends to counteract the Doppler shift.

1.4.2 Mechanisms of Jet Noise

In summary, Lighthill and Ribner have established the known theories and it is apparent that the sources of noise comes from pressure fluctuations. However, the cause of these pressure fluctuations had not been successfully explained through experimentation until, individually, Wagner [8], Neuwerth [9] and Nossier, et. al [10] discovered the feedback phenomenon when a high speed turbulent jet impinges on rigid surface.

Wagner [8] provides the most comprehensive paper on sound and flow field of a free jet upon impact of a wall. Wagner achieved his results by experimenting with circular jets at a Mach number greater than 0.6 and wall standoffs of less than 5 to 6 diameters. Using continuous flash schlieren photography, Wagner noticed a stationary wave pattern in the

jet's potential core and periodical ring vortices at the jet boundary. This phenomena was found to be caused by the feedback mechanism between the flow and the pressure fields. This mechanism starts in the free boundary layer near the nozzle exit, where the ring vortices are formed. These ring vortices flow downstream in intervals of order in magnitude of nozzle diameter while absorbing energy. During this process, the vortices cause periodic pressure variations in the area of the dynamic pressure head of the jet core. The pressure variations propagate in part externally as sound waves and in part internally as periodic pressure interferences against the flow. The pressure interferences are dubbed back pressure waves and cause the periodic formation of new ring vortices upon reaching the nozzle outlet. Due to feedback of pressure waves, the frequency of vortex formation and release is synchronous with the frequency of the periodic pressure variations at the wall. Wagner found that during continuous flash schlieren photography the standing wave pattern was prominent. During the flash exposure schlieren photography these standing waves were absent which suggests that the pattern is alternating density or pressure. This suggestion would agree with Lighthill's theory. Wagner also found that the wave pattern did not begin at the nozzle exit, but at the location of the first ring vortex.

Nossier, et. al [9] discovered a resonance phenomenon which occurs when a high speed turbulent jet impinges on a

large flat plate. Feedback of pressure waves between the nozzle and plate is found to be the mechanism responsible for the resonance. The feedback loop is formed by downstream travelling large coherent structures; the resulting upstream travelling acoustic waves propagate in the nearby stagnant region around the jet. The upstream acoustic waves are generated by the impingement of large scale structures on the plate. Near the nozzle exit these waves are locked in-phase with the oscillations of the thin shear layer, which is forced to roll into large eddies at the resonance frequency, f_r . The period of the feedback loop is an integer N times the resonance period, N being constant over a resonance frequency stage. High frequency noise sources are confined to a short distance from the nozzle exit (potential core), and radiate sound directly to the far field. Enhanced large scale structures, due to feedback and vortex stretching, radiate low frequency noise when they impinge on the plate.

1.4.3 Gas Jet Results From Literature

At this point, the literature review will focus on some of the experimental results which specifically concentrate on the impingement region, and the effect of nozzle geometry on the noise levels produced by acoustic jets. Many of these papers found on jet noise are from earlier experiments which measured flow quantities in the jet efflux through physical and visual techniques, like hot wire anemometer and schlieren

photography. Economic restraints prevented the use of hot wire anemometer in the chamber, and physical location prevented the use of reflective surfaces for schlieren photography. Also, noise levels in the IAR chamber during test runs required that the chamber be cleared of personnel which restricted visual observation of the jets. Because the vibration levels are extremely high, video cameras must be isolated from these levels if they are to perform well inside the chamber. The results of these papers shall be mentioned so that these ideas may be used later in the explanation of the acoustic gas jet results. Olsen et. al [11] performed experiments involving jet impingement angle, nozzle shape and size, jet velocity, and wall standoff from a rigid board. The impingement noise was correlated to the 8th power of the peak impingement velocity and the first power of impingement area. The spectral data was correlated by Strouhal number, based on peak impingement velocity as well as the impingement diameter. Olsen et.al [11] found that during impingement experiments the shape of the total noise radiation is essentially independent of nozzle velocity. Nozzle shape did not change the Strouhal characteristics as the various jet configurations still peaked at roughly 0.2. The results show that impingement of a jet generates additional noise to that of free jet levels. There is less low frequency noise produced when the jet is brought closer to the rigid board. At certain configurations, where wall standoff is small and jet velocity is high, feedback

noise can occur increasing the overall levels and causing tonal spikes in the spectrum.

Impingement experiments performed by Kleis [12] found that the peak frequency increased as the wall spacing was reduced from 3 diameters to 0.75 diameters. When the wall standoff was reduced below 5 to 6 nozzle diameters, the effect of normal wall impingement on sound power level was approximately a 10 dB increase above nominal free jet levels. It can also be said that the OASPL will increase inversely to the wall standoff.

Some important results on gas jets have come from researchers who performed experiments on the reduction of jet noise through various nozzle exit geometries. Seiner [13] performed acoustic experiments on free jets with various geometries such as round, elliptical, and rectangular nozzles. The tests were performed on nozzles with design Mach numbers of 1.5 and 2.0. Seiner found that non-round geometries mix much faster than equivalent round geometries. Both the ADEN (augmented deflector exhaust nozzle) and elliptical jets provide 6 to 7 dB reduction of noise along the major axis direction of the jet. Shock noise processes are eliminated in elliptical nozzles but are still prevalent in rectangular jets. It appears that the geometry of elliptical jets increases the mixing process of jet efflux and the ambient air and leads to lower average jet velocities.

Wlezien [14] performed experiments of nozzle installation effects on the noise from supersonic exhaust plumes. Wlezien tested sensitivity to screech coupling in supersonic jets as a function of nozzle shape, spacing, and orientation. The coupling phenomenon was a function of geometry for twin asymmetric and rectangular jets as well as single jets in close proximity to a solid surface. Twin impinging jets have a more complex field and their near field is dominated by screech and impingement tones.

Other researchers have found basic results which provided a framework to begin the testing in this thesis. Some of the most pertinent works are mentioned below.

Lord et.al [15] found that the most noise produced by acoustic gas jets occurred in the first 10 diameters from the nozzle exit. Increasing the wall standoff past 10 diameters caused the impinging jet to exhibit more free jet characteristics, which are namely symmetric roll-up and roll-off rates, as well as drastically reduced noise levels. As a result of his work, all of the acoustic jet tests were performed below 10 diameters.

Jones [16] performed experiments on noise prediction for the first few diameters of an impinging jet. The intensity measurements showed that the noise levels peaked at four diameters from the nozzle exit. Beyond that distance there was a rapid readjustment of the flow to the free mixing layer. The peak levels attained from the acoustic jet tests will be

compared against the results by Jones to verify his predictions.

Schloth's [17] research on impinging jets at 20, 10, and 5 diameters above the rigid surface provided many acoustic and flow results. The acoustic results showed that the total acoustic radiation was due to normal jet impingement and jet noise as well as impingement noise sources. Since the impinged region is large, acoustic radiation will include reflection of loud acoustic quadrupole sources of flow. At a wall standoff of 20 diameters, the sound power levels varied only ± 1 dB from free jet results. As the wall standoff was lowered to the 10 and 5 diameter tests, the sound power levels increased. The results also correlate to the U^8 law for all conditions except the closest standoff and highest velocities. A unique feedback at this setting resulted in higher levels. The normalized power spectrum correlated very well for all cases when the peak Strouhal number was 0.2 or greater.

The flow results showed that an impinging jet is divided into four distinct regions. The first region is the jet mixing region, which extends from the nozzle exit to the end of the jet potential core. Here the uniform velocity core interacts with ambient air forming a highly turbulent surrounding region. The second region is the transition region located at the end of the potential core. Here axial decay of velocity and spreading outward of the flow becomes proportional to downstream distance. The third region is the

impingement region and is characterized by unsteady turbulent flow and deflected flow patterns induced by the back pressure from impingement. The impingement region is marked by axial deceleration and a region of increased static pressure. The final region is called the wall jet region and begins where the radial surface velocity starts to decay due to spreading, and the surface boundary layer thickness increases. The transition from the impingement region is rapid and the wall jet forms a radial flow with self-similar mean velocity profiles.

1.4.4 Literature on Acoustic Gas Jets Used For Spectrum Shaping

In the literature there was no evidence that impinging jets located in a triple corner of a reverberation chamber have ever been used for spectrum shaping. The two closest cases are Fujita and Iide [1] in the Japanese facility at Tsukuba Space Centre and an in-house design used for Boeing by Herman Kan [18]. The first case involved opposed jets shown in Figure 1.9, which were mounted on the side wall of the 1600 m³ reverberation chamber in Japan. The facility simulates high intensity sound field which can be expected from the H-2 launch vehicle. The Japanese use the opposed jets to supplement the high frequency range on the spectrum. The results suggest that the peak frequency of the spectrum increased with increasing supply pressure. Fujita & Iide [1]

found that it was impossible to control the frequency spectrum of the jet nozzle's sound intentionally, but the sound pressure level of the jet nozzle can be varied intentionally. Because spectrum shaping is the principal concern of the aeroacoustics facility, the location of the peak frequency and the roll-off rate are important factors. From the results provided by Fujita and Iide the roll-off rate (dB/Octave) of their opposed jets decreased with increasing pressure except at the lowest supply air pressure reading. The average roll-off rate for a 1.5 inch nozzle diameter was 4.3 dB/Octave.

In the second case, Herman Kan [18] performed experiments using articulated air jets mounted on a platform in Boeing's test chamber. From the information provided the platform was located near the corner of the chamber, but not significantly close enough to include wall effects. The testing involved varying supply pressure and included angle between the opposed jets. Kan [18] discovered that the jets produced the greatest noise levels when the included angle was between 90 to 130 degrees. Tests on two 1½ inch nozzle achieved a maximum OASPL of 144 dB at a manifold pressure of 50 psi. Further increase of pressure did not increase the noise levels. Kan reported the relation between diameter of the jet, d , and the desired peak frequency, f_p , in the following equation. The value of 950 is denoted as Herman's constant and its validity could not be established by this work or in any other literature.

$$d_{jet} = \sqrt{\frac{950}{f_{max}}} \quad (1.12)$$

1.5 Thesis Objectives and Goals

It is the objective of this thesis work to perform experiments involving perpendicularly impinging jets in a triple corner to investigate if these jets can be used successfully as a supplementary high frequency noise generating device. Validation of the test results against the two theoretically known equations, namely Lighthill's U^8 law (equation 1.7) & the peak frequency (equation 1.6). After the data has been verified against Lighthill's theories, the effects of the various parameters on the sound levels and shape of the spectrum will be discussed. An attempt to explain these trends with reference to literature will be made. Suggestions for future tests will also be given. As a final goal of this thesis there will be a discussion on the design and implementation of an automated high frequency jet noise assembly, and two control & search methods.

- A GRANDE CHAMBRE RÉVERBÉRANTE
(536 m³, 155 dB)
- B SALLE D'OBSERVATION
C CORNET
D SIRÈNE
E SALLE DE PRÉPARATION INTÉRIEURE
F HANGAR DE RÉCEPTION ET DE PRÉPARATION
G SALLE DES ÉQUIPEMENTS
H SAS

- I PETITE CHAMBRE RÉVERBÉRANTE
(80 m³, 165 dB)

- J TUBE D'ONDES PROGRESSIVES
K SALLE D'OBSERVATION
L PORTE DE TRANSMISSION
M CHAMBRE D'EXTINCTION SONORE
N SALLE DE CONTRÔLE
O RÉSERVOIR DE STOCKAGE D'AIR

- A LARGE REVERBERANT CHAMBER
(536 m³, 155 dB)

- B OBSERVATION ROOM
C HORN
D SIREN
E INNER PREPARATION BAY
F LARGE PREPARATION AND RECEIVING BAY
G EQUIPMENT BAY
H CLEAN AIR-LOCK ENTRY

- I SMALL REVERBERANT CHAMBER
(80 m³, 165 dB)

- J PROGRESSIVE WAVE TUBE
K OBSERVATION ROOM
L TRANSMISSION DOOR
M TERMINATION ROOM
N CONTROL ROOM
O AIR STORAGE TANKS

Figure 1.1 Layout of IAR/SML aeroacoustics facility

Figure 1.2 **Layout of IAR/SML 536 m³ reverberation chamber**

Figure 1.3 **Microphone Positions in the IAR Chamber**

Figure 1.4 **Wyle Acoustic Source WAS-3000 outer shell**

Figure 1.5 Wyle Modulator Units MU-110 & MU-111

Figure 1.6 NAE Hartmann Generator & Adaptor Plate

Figure 1.7 NAE Hartmann Generator Noise Spectrum
(courtesy of Westley [21])

**Figure 1.8 Combined Spectrum of WAS-3000 and
NAE Hartmann Generator**
(courtesy of Westley [21])

Figure 1.9 Spectrum from the Opposed Jets in the Tsukuba Facility
 (courtesy of Fujita and Iide [1])

Figure 1.10 Sound Generation from the Idealized Sources

(courtesy of Ribner [7])

Figure 1.11 Basic Noise Pattern
(courtesy of Ribner [7])

Figure 1.12 Effect of Convection and Refraction on the Basic Noise Pattern
(courtesy of Ribner [7])

**Figure 1.13 Components of the Basic Noise Pattern:
Self Noise and Shear Noise**

(courtesy of Ribner [7])

Figure 1.14 Countering Doppler Effect of Convection and Refraction

(courtesy of Ribner [7])

Figure 1.15: Schematic of Impinging Gas Jet Experiment

CHAPTER 2

Experimental Apparatus

At the aeroacoustics facility, experiments were conducted by individually varying the supply pressure, jet diameter, wall standoff, nozzle geometry, and pressure feed method for the acoustic gas jets. Inside the large reverberation chamber noise spectra were generated through acoustic gas jets located on the floor level, and in the north-east corner. The following sections describe the experimental apparatus and data acquisition systems used for the acoustic gas jet experiments in a systematic approach from the supply air to the real-time analyzer.

2.1 Equipment and Set-Up Apparatus

The air supply for the jets is obtained from the air storage tanks for the High Speed 5 ft Blowdown Windtunnel located in the adjoining building. There are three pressurized storage tanks approximately 200 feet in length and 12 feet in diameter, and connected in series. The tanks hold 47 tonnes (55000 cubic feet) of dry air at approximately 2 % humidity. The IAR/SML's air supply piping from the tanks is a schedule 40, 6 inch pipe with two main valves. The first is a manual globe valve which is either open fully or closed. The second valve is a pneumatically controlled stem valve

which can only be opened when the system key is inserted and engaged. The air supply line continues vertically upwards into the siren level. Once inside the siren level the air supply line is tapped with six separate lines, each having a controllable pneumatic valve. The valve type, number, and sizes are given in Table 2.1. Connected from each of the six lines are flexible pressure hoses, which in turn connect to the various noise generators. To maintain consistency all of the acoustic gas jet tests were performed when connected to valve number three (2 " valve). Any subsequent tests performed on other valves will be duly noted. From valve number three the compressed air is transported through 32 feet of 4 inch (I.D) reinforced pressure hose on the siren level, followed by another 55 feet of 4 inch (I.D) hose in the inner preparation bay which connects to a Cam-Lock fitting in the reverberation chamber's East wall. Inside the chamber are three supply lines of 4 inch (I.D) hose, namely the centre line , east line and north line. The centre line is 8 feet long and carries the air supply into the centre branch of the t-section. From the exiting branches of the t-section are the north supply line and the east supply line with lengths of 6 feet and 7 feet respectively. The north and east air supply hoses connect to the north and east wall jets respectively. In the case of single jet testing, one of the supply lines is blocked at the jet exit by a pipe end cap. For the separate pressure feed nozzles tests, the t-section is removed. Two 2

inch (I.D) lines are inserted and connected to both the jets and the respective valves on the siren level. The supply lines and jet assembly in the Tee arrangement are shown in Figure 2.1, and the separate pressure feed system is shown in Figure 2.2.

The acoustic jets were constructed out of four 1 foot lengths of 4 inch (I.D) schedule 40 steel pipe and two 4 inch (I.D) 45° elbows. The straight lengths of pipe were welded at each end of the 45° elbows. The jet end of the pipe has an external thread fitted with a 8 inch long, 4.5 inch (I.D) collar. On the inner surface of the collar is an internal thread that allows either sudden contraction steel pipe reducer nozzles or aluminum machined conical nozzles to be inserted. A rectangular orifice plate can be attached when the collar section is removed. Figures 2.3 & 2.4 illustrates the size and geometry of all the various nozzles used in testing.

2.2 Mounting Apparatus for Acoustic Jets

The rectangular base plate shown in Figure 2.5 served to protect the floor's epoxy finish from scratches during operation of the jets, and secondly, to secure the jets against the thrust which they produce. The base plate was constructed with the following material : (a) quantity 1 : $\frac{1}{4}$ inch thick, 2 ft by 2 ft steel base plate, (b) quantity 1 :

length of 12 ft, $\frac{1}{2}$ inch thick, $2\frac{1}{2}$ inch wide flat steel plate, (c) quantity 1 : C-Channel length 5 ft , 4 inch width with $1\frac{1}{2}$ inch long flanges, (d) quantity 1 : O-Channel 5 inch length, 4 inch by 4 inch and $\frac{1}{4}$ inch thick.

The acoustic gas jets each sit in a C-Channel guide of length 5 inches. The guides are located between the bolt patterns in the base plate. There are six $\frac{1}{2}$ inch holes on both the north and east sides of the base plate. The hole spacings are shown in Figure 2.5. The jets are held in place by eight $\frac{1}{2}$ inch threaded rods which are bolted to the base plate with $\frac{1}{2}$ inch nuts through the previously mentioned holes. Curved cast hose clamps fit over both the threaded rods and the acoustic jets. When the jets are set in the desired position the clamps are tightened above the jets with $\frac{1}{2}$ inch nuts. The supply pressure hoses are connected to the appropriate jet through Cam-Lock fittings and the apparatus is ready for testing.

2.3 Measuring and Data Acquisition Equipment

When a noise spectrum is produced by the acoustic jets or any of the other noise generators, the noise levels are recorded by six Brüel & Kjær (B & K) 4134 $\frac{1}{2}$ inch condenser microphones located on the four stands in the reverberation chamber. The microphones are connected to six B & K 2639 Preamplifiers which match the impedance of the microphones,

and the measuring amplifiers. Each signal is sent through a microphone cable to the B & K 2609 Measuring Amplifier which has variable gains and measuring ranges. The signals from the microphones are sampled by the B & K 5619 Multiplexer and sent into the B & K 2133 Frequency Analyzer where the spectra are recorded on diskettes in 1/12 octave bands. During a client's satellite environmental test acoustic signals are sent through the computer to close the feedback loop. The equipment used for measurement and data acquisition is shown in Figure 2.6.

2.4 Pressure Control System

The pressure control system was designed by PSI Mechanical Services for the IAR/SML facility. The pressure control system can only be initiated once the three pre-run safety procedures are implemented. First, the line actuation pressure must be set to 25 psig on the regulator in the siren level. Secondly, the safety panic stop buttons are released inside the chamber, and finally, the key is inserted in the main start up switch. To stop the system in case of accidental start-up and/or an emergency the panic stop buttons can be activated or the key switched off.

The main body of the pressure control system is the TA 6505 remote processing unit which houses a mother board, terminal board, and an operator's control panel board complete with keypad. The static pressure for each valve is sensed by

a static tap which is located 2 feet downstream of each valve. The manual keypad allows the user to select the valve to be controlled, and then key in the static pressure which is desired on the downstream side of the valve. The controlled pressure generally fluctuates between ± 0.1 psig of the desired value. The upstream pressure in the tanks is taken as a constant since little flow is being used, and the compressor is constantly restoring the levels in the tanks. Approximately 2 feet upstream of the jet nozzles are pitot tubes which record the total pressure in the jets which yields information to the magnitude of the jet exit velocity and Mach number. This information is later used in the analysis of the data to verify Lighthill's U^8 Law and the peak frequency versus Strouhal number.

**Table 2.1 : Valve Type , Valve Number and Valve Sizes
on the Siren Level at the IAR/SML
Aeroacoustics Facility**

Valve Name and Type	Valve Number	Valve Size (in) (mm)
Kieley & Mueller Series 6600 Stem Valve	1	2.0 in 52.8 mm
Fisher Stem Valve	2	4.0 in 105.6 mm
Kieley & Mueller Series 6600 Stem Valve	3	2.0 in 52.8 mm
Kieley & Mueller Series 6600 Stem Valve	4	1.0 in 25.4 mm
Kieley & Mueller Series 6600 Stem Valve	5	2.0 in 52.8 mm
Kieley & Mueller Series 6600 Stem Valve	6	1.5 in 38.1 mm

Figure 2.1: T-Section Supply Hoses and Couplings

Figure 2.2: Separate Feed Nozzle Assembly

Figure 2.3: Sudden Contraction Pipe Reducer Nozzles

Figure 2.4: Machined Conical Nozzles, Rectangular Sliding Plate, and Diamond Sliding Nozzles

Figure 2.5: Rectangular Base Plate For Acoustic Jets

Figure 2.6: Data Acquisition Equipment in Control Room

CHAPTER 3

Experimental Results for Sudden Contraction Pipe Reducer Nozzles

The results from the sudden contraction pipe reducer nozzles are discussed in the following sections. These types of nozzle were chosen for the initial tests because they were economical and easily interchangeable. Most of the acoustic gas jet tests were performed using these nozzles. The knowledge gained from these tests allowed a reduction in the number of tests performed on other nozzle geometries. Also special cases were investigated to yield information about wall impingement effect and locations of spikes in the spectrum.

Generally, most of IAR/SML's client specified spectra which are matched during the environmental tests are smooth in nature. An acoustic jet test result which contains a spike or peak in a particular band would not be useful in matching these spectra. For this reason, a test criteria called the 'spike criterion' was created. This criterion states that no sound pressure level in any $\frac{1}{3}$ octave band will be greater than 3 dB above or below the neighbouring bands. Tests that were performed on the SCPR nozzles monitored the existence of spikes versus supply pressure, wall standoff, and diameter of the jet. The purpose of these tests were to yield information about when spikes occur in the spectrum, where to set the jets

to avoid spikes, and what jet nozzle geometries may be used to avoid spikes.

Tests using symmetric diameters with asymmetric standoffs were performed for the purpose of observing the change in the shape of the spectrum, OASPL, and roll-off rate.

The asymmetric diameter tests can not be validated to Lighthill's U^8 Law because of the dissimilar diameters. These tests were performed to see which jet is dominant near the peak frequency of the spectrum.

Single jet impingement tests were performed to investigate the effects of wall standoff, and jet diameter on the creation of spikes. Results of these tests should indicate if the spike is caused by the wall impingement of the jets alone, or the mixing of the two jets and then impingement onto the wall.

The original data has been converted from 1/12 octave bands to $\frac{1}{4}$ octave bands for analysis. Data was initially compared to the two pertinent theories, namely Lighthill's U^8 Law and the Peak frequency correlation. The variations to these theories are discussed and the results are said to be in agreement or non valid. If the results are in agreement then the trends of the various parameters are discussed in terms of their effect on the sound spectrum. An explanation will be attempted to explain the non valid results.

3.1 Comparison of OASWL With Lighthill's U^8 Law

The SPL results of the symmetric diameter sudden contraction pipe reducer nozzles tests were converted to OASWL using the Sabine equation, whose values depend on the one third octave band and relative humidity in the chamber. The IAR/SML facility utilizes a computer program called VARPRN which calculates the room absorption as a function of relative humidity for each of the one third octave band levels from 25 to 20000 Hz (Table 3.1). These values represent the decibel difference between the sound pressure level, L_p and the sound power level, L_w . By subtracting the values in Table 3.1 from the sound pressure measurements in their respective $\frac{1}{3}$ octave bands, the sound power levels in each $\frac{1}{3}$ octave band are achieved. Performing a decibel addition, the overall sound power level was calculated for each appropriate test. The tests cases used here for verification in Lighthill's law were the symmetric diameter jets with symmetric wall standoffs. For given size of SCPR nozzles, (two 2 inch nozzles) the total pressure readings yielded distinct exit Mach numbers for each of the dial-in pressure settings. The exit Mach numbers attained varied from 0.58 to 1.0 and were independent of varying wall standoffs. The theoretical value for the OASWL for two free jets were calculated based on equation 1.7 given by Bell [6]. Bell provides a calibration chart for the radiation efficiency (eM^5) versus Mach number, M , given in

Table 3.2. This chart provides a range or band of radiated efficiencies for Mach numbers between 0.15 to 1.2. This chart was used to plot the theoretical values in the comparison of experimental OASWL versus Lighthill's U^8 law. The two extreme values were used to illustrate the entire band of the predicted OASWL by Bell, as shown in Figure 3.1. The total pressure measurements from the pitot tubes were used to calculate the exit velocity of the jet assuming isentropic flow conditions. Using the area of the jet and the density of the medium the theoretical OASWL was calculated. From Figures 3.1 - 3.5 the results indicate that the SCPR nozzles generally followed the slope of Lighthill's U^8 law, especially in the region of Mach 0.58 to 0.9. The region between Mach 0.9 and 1.0 diverges from the theory since the tests tend to be biased at these higher Mach numbers. The dial-in pressures of 15, 20, and 25 psig caused the smaller jets to become choked. The results at the choked conditions had to be averaged over three pressure settings. These averaged choked conditions caused the slope of the sound power to deviate from the U^8 dependency. The tests on all jet diameters should have been performed over more intermediary Mach numbers instead of having only three or four data points. Ideally all of the tests should have been performed at selected dial-in pressures to yield similar Mach numbers, to help in the comparison of the data. The increased OASWL varies from a maximum of 28-34 dB for the 1.25 inch diameter jets at $h/d=4$ and with a supply

pressure of 25 psig, to a minimum of 7-14 dB for the 2.0 inch diameter jets at $h/d=10$ and with a supply pressure of 10 psig. Schloth [17] and Lord et. al [15] performed experiments on a single jet impinging on a flat plate and found an increase in the overall free jet noise level of 10 dB. The results suggest that two jets impinging in a triple corner produce on average between 16 - 22 dB more sound power than two free jets of similar dimensions. In acoustic terms, the levels produced are more than double those produced by two single impinging jets. Bell's original calibration chart, Table 3.2 was changed into a new form, Table 3.5 to predict the radiated efficiency for impinging jets and extend Lighthill's U^8 law to cover impingement. In order to accomplish this task the overall sound power levels were compared to the sound power levels for free jets. The comparison between these levels determined the correction factor to be applied for impingement. The results of the comparison are provided in the Table 3.5. Table 3.5 will be used to predict the sound power levels for the machined conical nozzles and rectangular nozzles in Chapters 4 and 5 respectively.

In conclusion the impinging jets verify the slope of Lighthill's U^8 law, but the sound power level produced are higher because of the mixing and impingement of the two jets. Adjusting Bell's calibration chart could prove to be very valuable in predicting the levels achieved for impingement.

3.2 Comparison of SPL With Peak Strouhal Number

In Figures 3.1 to 3.30, the sound pressure levels, in $\frac{1}{2}$ octave bands adjacent to the peak of the spectrum, were plotted against Strouhal number for the various sized SCPR nozzles. The plots show the effect of increasing dial-in pressure, and increasing wall standoff. Using the Brüel & Kjær 2133 analyzer the $\frac{1}{2}$ octave band sound pressure levels around the peak of each spectrum were recorded and used as the abscissa on these plots. The exit jet velocity was calculated using the total pressure measurements from the pitot tubes, and assuming isentropic flow conditions. Since the velocity in the 4 inch pipe is very low and there is no heat added to the system this is a valid assumption. With these values and along with the jet diameter, the Strouhal number can be calculated using equation 1.6. The results given in these figures show that the averaged peak Strouhal number for impinging jets is approximately 0.24, as compared with the theory for a free jet which is a peak Strouhal number of 0.2. Considering the accuracy of the pitot tubes, and that the flow is not exactly isentropic, the theory for free jets can be extended to include impinging jets. The smaller impinging jets did exhibit the general trend of increasing peak Strouhal number as the wall standoff was decreased and dial-in pressure was increased as shown in Figures 3.15-3.18 & 3.24-3.25. This trend was also found in experiments by H.K Lee and H.S Ribner

[19], and the results of Fujita and Iide [1] in Figure 1.9. However, the evident trend for the larger impinging jets (2 & 1.5 inch diameters) was either no increase in peak Strouhal number or an actual decrease in peak Strouhal number with decreasing wall standoff and increased dial-in pressure. At the present time the testing has not lead to a physical explanation of this observed trend.

3.3 Effect of Various Parameters on Noise Spectrum

Since the SCPR nozzle results follow the known theories on acoustic jets, the effects that the various parameters have on the noise spectrum can now be discussed. The IAR/SML facility is specifically interested in the effect that the wall standoff, supply pressure, and jet diameter have on the following characteristics: OASPL, roll-up and roll-off rates, peak frequency, and spike criteria.

3.3.1 Effect of Wall Standoff on OASPL

The results from the SCPR nozzles indicate that reducing wall standoff from $h/d = 10$ to $h/d = 3$ caused increasing OASPL. This result was expected because a jet located at 10 diameters or more operates primarily as a free jet. Moving this jet closer to the wall allows for a wall-jet interaction. The increased noise levels have been discussed in terms of a feedback phenomenon by researchers Wagner [8], and Neuwerth [9]. The testing that was performed could not validate the

feedback of pressure waves since visual techniques were not used.

3.3.2 Effect of Wall Standoff on Roll-Up and Roll-Off Rates

The roll-up and roll-off rates required calculation of the slopes in the octave bands adjacent to the peak of the spectrum. The slopes were calculated from the stored spectra using the B & K 2133 analyzer. By plotting these values versus wall standoff for the SCPR nozzles it was determined that the roll-off rate was proportional to the wall standoff distance. The roll-up rate did not vary substantially with wall standoff. Evidence of these trends can be seen in a typical spectrum plot of two 2 inch SCPR nozzles at 15 psig (Figure 3.36).

The spectrum shape of the classical free jet has been described as a haystack shape with symmetrical roll-up and roll-off rates. McInerny [20] plotted noise levels versus a non-dimensional frequency (Strouhal number) for various types of rocket noise and modelled jet noise. The data showed a roll-up rate of 5.7 dB/Octave and roll-off rate of 5.4 dB/Octave with a peak Strouhal number of 0.2. A sample result of Fujita and Iide (Figure 1.9) indicated that the jet roll-off rates are slightly effected by the near proximity to the wall, since the spectra are not symmetrical. Figure 3.36 shows that the roll-up rates of the jet do not vary much with standoff. Using Table 3.3 and Figure 3.36, it was observed

that between 25 Hz (Number 1 Band) and 160 Hz (Number 9 Band) there is almost no difference between any standoff. After 160 Hz there is a dispersion of levels with $h/d = 3$ producing the most noise and $h/d = 10$ producing the least amount of noise. The close proximity standoff $h/d = 3$ to 5 diameters shows peaks in the spectra which corresponds to the length that the potential core is placed from the wall, as stated in the literature. The roll-off rate increased with greater wall standoffs which was confirmed by the decrease in overall noise levels as the jets are brought further from the walls.

3.3.3 Effect of Wall Standoff on Strouhal Number

In order to calculate the peak Strouhal numbers, the peak frequency of each spectrum was required. It was observed that for a specific sized SCPR nozzle the peak Strouhal numbers remained relatively constant over the range of wall standoffs greater than h/d of 5 or 6. The peak Strouhal number increased to higher values ($S = 0.26$ to 0.3) for close wall standoffs with the smaller diameter jets (1.25 and 1.0 inch diameters). Conversely, at very close wall standoffs the larger diameter jets' peak Strouhal numbers tended toward the theoretical Strouhal number of 0.2.

3.3.4 Effect of Wall Standoff on Spike Criteria

The spike criteria term is given to a noise spectrum when any $\frac{1}{2}$ octave band level in the high frequency region reaches

more than 3 dB higher than the neighbouring $\frac{1}{2}$ octave bands. Jet tests with this spike occurrence should generally not be used in spectrum matching since this spike would be outside of the client's tolerance levels. In Figures 3.31-3.35, spike occurrence was plotted versus wall standoff and pressure. The trend observed shows that spike occurrence diminishes dramatically when both jets are beyond wall standoffs of six diameters. Any spikes occurring when both jets are beyond six diameters are restricted to the higher dial-in pressures (choked jet) and smaller diameter jets. Because of the lack of visual techniques for verification, the wall standoff argument could not be validated.

Another possibility is that spike criteria occurs because of a physical numerical distance from the wall. By examining the data for the spike occurrence with the greatest wall standoff and converting this normalized quantity into a physical distance, it was found that spikes occur most often when the jets are less than ten to twelve inches from the wall. For possible validation of either or both of these hypotheses refer to the recommendations given in section 7.2.1.

3.3.5 Summary of Wall Standoff Effect

Wall Standoff does effect the mechanisms of noise generation by an acoustic gas jet. As discussed in the literature, jets produce noise in at least two known different

regions; a high frequency potential core and a low frequency turbulent mixing region. When the jets are in close proximity to the wall ($h/d = 1$ to 6 diameters) , it appears that there is a feedback mechanism or noise reinforcement of the high frequency noise which sometimes results in a spike in the spectrum. In other cases, higher noise levels are attained but without a spike appearing.

Placing the jets at further standoffs ($h/d > 6$) allows more length scales for the turbulent mixing region to expand. The literature has stated that there is a phenomena of mach eddy shedding in the turbulent mixing region where pressure disturbances and entrained stagnant air is brought into the jet stream. Eddies are then produced at the jet exit and continue to move downstream growing in size and slowing in velocity as the jet flow expands. The levels of noise produced in the turbulent region are increased but, the magnitudes do not compare to the levels of the plateau in the high frequency region. The result of the increase in standoff is to produce lower OASPL in the high frequency region because the feedback phenomena is damped by the physical distance that the wall reflections have to travel back to the nozzle exit plane.

3.3.6 Effect of Supply Pressure on OASPL

While performing each acoustic test, the total pressure was measured via a pitot tube placed upstream of the 45 degree

elbow in the jet apparatus. The pitot tube was manufactured out of $\frac{1}{4}$ inch copper tubing, the horizontal length was set at 10 diameters and the tip was located approximately in the centre of the pipe. As the dial-in pressure was varied through the TA digital control pad the total pressures were recorded. To verify the results against the two known theories it was necessary to know the pressure ratio across the nozzle based on atmospheric conditions in the reverberation chamber. The Mach number for the various pressure tests were calculated using the isentropic flow assumption. It was observed that the OASPL varied directly with increasing pressure. The two theories both contain jet exit velocity in the numerator, and therefore any increase in pressure ratio would result in an increase in jet exit velocity. With higher pressures and smaller diameter jets there rose the condition where the pressure ratio was above the critical ratio and the nozzle was deemed choked. It would appear from the theory that any increase in the pressure ratio would not result in an increase in the OASPL since velocity is fixed at a maximum. The results of the testing showed increased noise levels above the critical pressure ratio. By design the sudden contraction nozzles that were used would only choke and not become supersonic, since a convergent-divergent nozzle is required for that condition. Therefore there must be another explanation for the extra increase in noise levels.

3.3.7 Effect of Supply Pressure on Roll-Up and Roll-Off Rates

Table 3.4 illustrates that the roll-up rates increase with increasing dial-in pressures. By increasing the dial-in pressure during the tests, the noise is simply being added between 160 Hz to 20000 Hz, as shown in Figure 3.36. The adding effect causes the slope of the roll-up rate to increase slightly while the roll-off rate decreases in value. These trends are evident in Figures 3.37-3.39

3.3.8 Effect of Supply Pressure on Strouhal Number

The peak Strouhal number for a given spectrum can be calculated by rearranging equation 1.6. The peak Strouhal number is inversely proportional to jet exit velocity. The flow in the jet piping assembly was assumed to be isentropic. Using the ratio of pipe area to exit area (A/A^*) it was determined that the velocity in the pipe was relatively low (Mach 0.15). Also there is no heat added to the system. Using the isentropic relationship for nozzle pressure ratio as a function of Mach number, the exit Mach number could be determined. Correcting for the changes in temperature, the jet exit velocity could be attained. As the pressure ratio was increased toward the critical pressure ratio, the jet exit velocity increased. The peak frequencies of the spectra also increased. Overall the two changes seemed to nullify each

other as the peak Strouhal number remained relatively constant between the values of 0.2 to 0.26. Averaging the values over the symmetric standoff tests for the SCPR nozzles yielded a peak Strouhal number of 0.24 as compared with the theoretical free jet value of 0.2.

3.3.9 Effect of Supply Pressure on Spike Criteria

Spikes which emerge from a noise spectrum are generally the most critical at higher pressures. The probability of a spike emerging from a test spectrum is greater when the dial-in pressure is beyond 15 psig (Figures 3.31-3.35). It would seem that, once the jet becomes sonic and the wall standoff is reduced below 6 diameters, the chances of a spike in the spectrum increase dramatically. Experimental results by Wagner [8] and Neuwerth [9] have shown that the phenomenon responsible for the spike is a feedback loop between pressure pulses, the solid wall, and the face of the jet exit. The frequency of the peak is dependent on the physical spacing between the jet exit and the solid wall. However, Wagner and Neuwerth did not determine what physical distance was required to eliminate this feedback loop.

3.3.10 Summary of Supply Pressure Effect

Supply pressure does affect the mechanisms of noise generation by an acoustic gas jet. As discussed in the literature, jets produce noise by the shearing of the velocity

in the gas jet and the surrounding medium. The sound power levels follow the slope of Lighthill's U^8 Law. Using the isentropic flow assumption, Lighthill's theory can be rewritten with the pressure ratio across the nozzle replacing the velocity.

It has been established that the acoustic gas jets produce noise in the high frequency region. In fact, it can be said that the acoustic gas jets tested only produce substantial noise levels above 160 Hz, and all frequencies below 160 Hz can be neglected. The effect of increasing the supply pressure caused the roll-up rates to increase, as more noise was produced in this region. Since the added noise is greater around the peak of the spectrum, the roll-up rate increases. In the upper high frequency region the added noise is magnified by the room absorptivity at high frequencies. The result caused the roll-off rate to decrease.

When increasing the supply pressure to the acoustic gas jets, the nozzle pressure ratio increases accordingly. As a result the peak frequency and jet exit velocity increase with the nozzle pressure ratio. The formula for the Strouhal number has frequency and diameter in the numerator and velocity in the denominator. The Strouhal number was consistently calculated in ranges of 0.2 to 0.26. This result suggests that the increase in peak frequency and jet exit velocity are proportional and nullify each other.

Increasing the supply pressure causes the nozzle pressure ratio to increase. Once the nozzle becomes choked, the jet exit velocity reaches sonic conditions. The spike criteria results show a comparison between increasing supply pressure and the occurrence of spikes in the spectrum. It appears that the feedback mechanism which reinforces the peak noise levels is connected to the jet exit velocity and the distance from the impinging wall.

3.3.11 Effect of Jet Diameter on OASPL

The test results of the sudden contraction nozzles indicated that the effect of diameter on OASPL (dB) is linearly proportional to diameter except for the case which involved the 2" diameter nozzles. Insight suggests that a larger nozzle with the same pressure ratio across the nozzle should produce more sound, but this trend was not apparent in the 2" nozzles. The only physical difference between the 2" and the 1½" and 1¼" nozzles, is the addition of another inserted pipe reducer to achieve the smaller diameters. Observation of the combined nozzles showed a second step reduction, whereas the 2" nozzle contains only one step reduction. Since all of the nozzles are choked, the difference in noise levels is not attributed simply to exit velocity, but to the addition of turbulence formed at the step reductions, and convected downstream. In the tests performed

on single, rectangular, and conical jets the larger the jet size, the greater the sound levels measured.

3.3.12 Effect of Jet Diameter on Roll-Up and Roll-Off Rates

By measuring the roll-up and roll-off rate of the octave band adjacent to the peak frequency versus diameter, the results in Table 3.4 show that decreasing diameter of the jet leads to a steeper roll-up rate. Conversely, decreasing diameter yields a flatter roll-off rate.

3.3.13 Effect of Jet Diameter on Strouhal Number

The experiments performed verified the theory that the peak frequency varies inversely to jet diameter. As the jet diameter was reduced, the peak frequency of the spectrum was observed to increase in frequency. Data of this type will specifically be useful for the computer pressure search method described later in Chapter 6.

3.3.14 Effect of Jet Diameter on Spike Criteria

In general, the effect of jet diameter on the spike occurrence is an inverse relationship. Reducing the diameter tends to increase the chances of a spike occurring. Figures 3.31 to 3.35 illustrate that the frequency of a spike occurring in a spectrum increases as the diameter is reduced from 2 inches down to 0.75 inch jets. It should be noted that in the 0.75 inch jet case, it appears that the spike

occurrence has dropped dramatically. But, because of physical constraints, tests at very close standoffs could not be performed with these jets. These closer standoffs did produce spikes in the other diameter SCPR nozzles at pressures between 10 to 25 psig. If these tests could have been performed the likelihood of a spike spectrum would be substantial.

3.3.15 Summary of Jet Diameter Effect

The plot for sound power level versus jet diameter show that as jet diameter increases the sound power levels increase. The trend is consistent except for the $1\frac{1}{2}$ and $1\frac{1}{4}$ inch diameter jets which produced greater levels than the 2 inch diameter jets. An attempt to explain this difference was made based on the insertion of a second pipe reducer nozzle to achieve the $1\frac{1}{2}$ and $1\frac{1}{4}$ inch diameters. It was believed that the second SCPR nozzle caused a second sudden contraction in the orifice which produced additional noise in the high frequency region. This hypothesis could not be proved without the use of visual techniques.

The roll-up rates increased as the jet diameter was decreased. From the results attained, the smaller jet diameter still produces sufficiently high levels around the peak frequency with lower levels around the lower frequencies. Higher roll-up rates are achieved near the peak frequency. The roll-off rates decreased with a decrease in jet diameter. A possible reason for this could be that the thickness of the

boundary layer in relation to the size of the jet diameter is becoming important. As a result the turbulence and other disturbances are now of the same magnitude. It is possible that these disturbances are swept downstream in the boundary layer where they become magnified with the turbulence mixing layer. Results in the literature or in the present work could not validate this hypothesis.

As the jet diameter is reduced, the peak frequency of the spectrum increases to higher frequencies. However, when examining the peak Strouhal number versus jet diameter, it can be said that the values are typically between 0.2 and 0.26. Overall, any change in peak frequency is accompanied by an appropriate change in the jet exit velocity and jet diameter. This results in the relatively constant value of the peak Strouhal number.

Generally, as the jet diameter was reduced, the spike occurrence gets progressively worse. The spike criteria graphs show that the spike occurrence diminishes as the jet diameter and supply pressure increases, and wall standoff distance increases. It should be noted that, due to the physical constraints of the jet apparatus, very close standoffs on both jets could not be tested for the smaller jets. In similar wall standoff cases with larger diameter jets there was a spike in the spectrum.

3.4 Results of Asymmetric Diameter Tests

The asymmetric diameter SCPR nozzle tests could not be validated against Lighthill's U^8 Law or the peak Strouhal number because of the two choices for jet diameter. The asymmetric diameter tests produce OASPL which are consistently below the levels of the symmetric diameter tests. The reason for the deficit levels is that the smaller diameter jet produces noise at higher frequencies but with lower levels. The advantage these tests have over the symmetric diameter tests is that they are more versatile. Now the peak of the spectrum is spread over a broader range. In cases where the diameters are drastically different in size, there can exist two peaks in the spectrum. The first peak which has higher sound pressure levels corresponds to the larger diameter jet. The second peak results from the smaller diameter jet.

These tests were initially tested using the t-section, so that the whole jet apparatus was fed by one valve. Later, the t-section was replaced with separate feed lines. Now each jet nozzle is fed by a single valve. As a result, the pressures could be varied independently. The levels produced by the smaller jet could be improved by increasing the supply pressure. As a result of separate pressure fed nozzles, the roll-off rate could be varied to give the most desirable sound pressure levels.

With increased wall standoff distances come increased roll-up rates. This trend was not observed for symmetric diameter tests. Since the tests could not be validated against the two theories, this result must be taken as a trend and not specific valid data. Increasing wall standoff also caused decreases in OASPL, roll-off rates, and spike occurrence. The decreases in OASPL and spike criteria were observed in the symmetric tests.

The OASPL increased as the jet diameter increased. Roll-up and roll-off rates, and spike criteria all increased with decreases to the jet diameter.

The roll-up rate increased with decreases to supply pressure. The OASPL, roll-off rate, and spike criteria all increased with increases to supply pressure.

3.5 Results of Single Jet Tests

The single jet tests were investigated to yield information about the creation of the spike criteria. The idea behind these tests was to check the levels created by a single jet impingement normal to a wall. If two similar single jet spectra are added the result is an increase of 3 dB. By comparing two added single jet tests to the original SCPR nozzle tests, it was found that the SCPR tests are acoustically more efficient as they produced more noise.

Therefore, it is worthwhile to have the jets mix and interact and then impinge on the wall surfaces.

Comparing the spike criteria in the single jets it was found that spikes were avoided as long as the wall standoff was greater than five diameters. Spike occurrence increased as the diameter of jet was reduced and the supply pressure increased. When two single jet spectra were added and compared to the original SCPR nozzles, the levels were on average more than 3 dB below the original values. This result suggests that there is added noise from the mixing of the two jets which is absent in the two single jets. The impinging jets also collide with the corner wall at approximately 45 degrees when they are set in the symmetric position. Results obtained from Boeing indicated that the range of angles which produce the most noise are between 90 and 130 degrees. It is believed that the difference in sound pressure levels between impinging jets and the two single jets would be even greater if the single jets were tested at 45 degrees to the corner.

Single jet data yielded the following trends for supply pressure, wall standoff, and jet size. The OASPL and roll-up rate increased proportionally with supply pressure and jet size. Both quantities were inversely proportional to wall standoff. The roll-off rate increased with reductions to supply pressure, wall standoff, and jet size. Spike occurrence increased with the combination of increased supply pressure, and decreased wall standoff and jet size.

Table 3.1: Chamber Absorption Versus Relative Humidity For The Frequency Range of 25 to 20000 Hz

Air Alpha = 0.01 to 0.031 S_Alpha = Variable Pressure = 101.325 kPa Volume = 536.85 cu.m. Area = 536 sq.m. Temp = 20.0 C									
R.H. >	0 %	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %
Hz									
25.0	-1.33	-1.44	-1.37	-1.34	-1.33	-1.33	-1.32	-1.32	-1.31
31.5	-1.33	-1.51	-1.40	-1.37	-1.36	-1.35	-1.34	-1.34	-1.33
40.0	-1.33	-1.61	-1.45	-1.41	-1.39	-1.38	-1.37	-1.36	-1.36
50.0	-1.33	-1.73	-1.52	-1.45	-1.42	-1.41	-1.40	-1.39	-1.39
63.0	-1.33	-1.89	-1.62	-1.51	-1.47	-1.45	-1.44	-1.43	-1.43
80.0	-1.33	-2.08	-1.77	-1.60	-1.54	-1.50	-1.49	-1.48	-1.47
100.0	-1.33	-2.28	-1.96	-1.73	-1.62	-1.57	-1.55	-1.53	-1.52
125.0	-1.42	-2.52	-2.29	-1.99	-1.83	-1.75	-1.70	-1.68	-1.66
160.0	-1.58	-2.82	-2.78	-2.40	-2.17	-2.05	-1.97	-1.93	-1.90
200.0	-1.74	-3.05	-3.27	-2.87	-2.56	-2.38	-2.27	-2.20	-2.15
250.0	-1.97	-3.30	-3.80	-3.45	-3.09	-2.84	-2.68	-2.57	-2.51
315.0	-2.29	-3.60	-4.37	-4.17	-3.77	-3.46	-3.25	-3.10	-2.99
400.0	-2.66	-3.91	-4.91	-4.94	-4.58	-4.22	-3.94	-3.74	-3.59
500.0	-3.00	-4.19	-5.34	-5.62	-5.37	-5.00	-4.68	-4.42	-4.23
630.0	-3.06	-4.25	-5.55	-6.12	-6.04	-5.71	-5.35	-5.04	-4.79
800.0	-3.76	-4.80	-6.08	-6.86	-7.01	-6.81	-6.50	-6.18	-5.90
1000.0	-4.12	-5.10	-6.37	-7.30	-7.69	-7.66	-7.42	-7.12	-6.83
1250.0	-4.49	-5.39	-6.63	-7.67	-8.26	-8.43	-8.32	-8.09	-7.81
1600.0	-4.85	-5.69	-6.89	-7.99	-8.76	-9.14	-9.22	-9.12	-8.91
2000.0	-5.18	-5.97	-7.12	-8.24	-9.11	-9.67	-9.93	-9.97	-9.86
2500.0	-5.50	-6.23	-7.33	-8.45	-9.39	-10.07	-10.50	-10.70	-10.73
3150.0	-5.79	-6.48	-7.53	-8.64	-9.61	-10.39	-10.95	-11.31	-11.49
4000.0	-6.10	-6.75	-7.75	-8.82	-9.81	-10.65	-11.31	-11.79	-12.12
5000.0	-6.41	-7.01	-7.96	-9.00	-9.99	-10.85	-11.57	-12.14	-12.57
6300.0	-6.78	-7.34	-8.23	-9.22	-10.18	-11.05	-11.60	-12.43	-12.94
8000.0	-7.27	-7.77	-8.58	-9.51	-10.43	-11.27	-12.03	-12.69	-13.25
10000.0	-7.84	-8.28	-9.01	-9.86	-10.72	-11.53	-12.28	-12.94	-13.52
12500.0	-8.59	-8.97	-9.60	-10.35	-11.13	-11.88	-12.59	-13.23	-13.81
16000.0	-9.65	-9.95	-10.46	-11.09	-11.75	-12.42	-13.06	-13.65	-14.20
20000.0	-10.82	-11.05	-11.45	-11.96	-12.51	-13.08	-13.64	-14.17	-14.67

Table 3.2: Bell's Calibration Chart For Radiated Efficiency of Free Jets versus Mach Number

Mach Number	Radiated Efficiency Range	Mach Number	Radiated Efficiency Range
0.4	0.5 - 6.0 E-7	0.72	3.0 - 15.0 E-6
0.42	0.9 - 9.8 E-7	0.74	3.5 - 17.0 E-6
0.44	1.3 - 14.0 E-7	0.76	4.0 - 19.0 E-6
0.46	1.7 - 17.0 E-7	0.78	4.5 - 21.0 E-6
0.48	2.1 - 21.0 E-7	0.80	5.0 - 23.0 E-5
0.50	2.5 - 25.0 E-7	0.82	1.2 - 25.4 E-5
0.52	3.6 - 32.0 E-7	0.84	1.5 - 27.8 E-5
0.54	4.7 - 39.0 E-7	0.86	1.7 - 30.2 E-5
0.56	5.8 - 46.0 E-7	0.88	2.0 - 32.6 E-5
0.58	6.9 - 53.0 E-7	0.90	2.2 - 35.0 E-5
0.60	8.0 - 60.0 E-7	0.92	2.4 - 37.0 E-5
0.62	11.0- 70.6 E-7	0.94	2.7 - 39.0 E-5
0.64	15.0- 81.2 E-7	0.96	2.9 - 41.0 E-5
0.66	18.0- 91.8 E-7	0.98	3.2 - 43.0 E-5
0.68	2.2 - 12.0 E-6	1.00	3.4 - 45.0 E-5
0.70	2.5 - 13.0 E-6		

2 of/de 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table 3.3: Corresponding 1/3 Octave Band Number to Frequency in the Range of 25 to 20000 Hz

Number	Frequency (Hz)	Number	Frequency (Hz)
1	25	16	800
2	31.5	17	1000
3	40	18	1250
4	50	19	1600
5	63	20	2000
6	80	21	2500
7	100	22	3150
8	125	23	4000
9	160	24	5000
10	200	25	6300
11	250	26	8000
12	315	27	10000
13	400	28	12500
14	500	29	16000
15	630	30	20000

Table 3.4: Roll-Up and Roll-Off Rates versus Supply Pressure and Jet Diameter

Roll-Up Rates for Sudden Contraction Nozzles

D.I.P	Diameter 2.0"	Diameter 1.5"	Diameter 1.25"	Diameter 1.0"	Diameter 0.75"
5	4.6	4.0	3.7	5.2	4.2
10	5.6	5.1	6.8	6.7	6.6
15	6.1	6.7	7.4	6.9	7.6
20	6.6	7.6	8.3	7.9	8.2
25	7.2	7.4	7.9	8.3	8.2
AVG	6.0	6.2	6.8	7.0	7.0

Roll-Off Rates for Sudden Contraction Nozzles

D.I.P	Diameter 2.0"	Diameter 1.5"	Diameter 1.25"	Diameter 1.0"	Diameter 0.75"
5	4.1	2.7	3.6	3.2	2.8
10	3.5	3.9	4.2	3.3	2.8
15	4.0	3.6	3.5	2.9	2.5
20	3.4	3.1	3.1	2.5	2.3
25	3.1	2.8	2.7	2.5	2.0
AVG	3.6	3.2	3.4	2.9	2.5

Table 3.5: Calibration Chart For Radiated Efficiency of Impinging Jets versus Mach Number

The data was fitted by a fifth order polynomial which yielded the following coefficients, and equation.

$$y = a_0 + a_1M + a_2M^2 + a_3M^3 + a_4M^4 + a_5M^5$$

$$a_0 = -0.04267$$

$$a_1 = 0.34924$$

$$a_2 = -1.11039$$

$$a_3 = 1.72488$$

$$a_4 = -1.31424$$

$$a_5 = 0.39517$$

M - Mach Number

Mach Number	Radiated Efficiency	Mach Number	Radiated Efficiency
0.56	1.10 E-4	0.80	3.81 E-4
0.58	1.04 E-4	0.82	4.26 E-4
0.60	1.03 E-4	0.84	4.79 E-4
0.62	1.11 E-4	0.86	5.44 E-4
0.64	1.26 E-4	0.88	6.26 E-4
0.66	1.46 E-4	0.90	7.32 E-4
0.68	1.72 E-4	0.92	8.70 E-4
0.70	2.01 E-4	0.94	1.05 E-3
0.72	2.33 E-4	0.96	1.29 E-3
0.74	2.67 E-4	0.98	1.59 E-3
0.78	3.40 E-4	1.00	1.98 E-3

Figure 3.1: Comparison of two 2 inch Impinging SCPR nozzles' OASWL with Lighthill's U^8 Law

Figure 3.2: Comparison of two 1.5 inch Impinging SCPR nozzles' OASWL with Lighthill's U^8 Law

Figure 3.3: Comparison of two 1.25 inch Impinging SCPR nozzles' OASWL with Lighthill's U^8 Law

Figure 3.4: Comparison of two 1 inch Impinging SCPR nozzles' OASWL with Lighthill's U^8 Law

Figure 3.5: Comparison of two 0.75 inch Impinging SCPR nozzles' OASWL with Lighthill's U^8 Law

Figure 3.6: SPL versus Strouhal Number for two 2 inch SCPR nozzles at Dial-in Pressure of 5 psig

Figure 3.7: SPL versus Strouhal Number for two 2 inch SCPR nozzles at Dial-in Pressure of 10 psig

Figure 3.8: SPL versus Strouhal Number for two 2 inch SCPR nozzles at Dial-in Pressure of 15 psig

Figure 3.9: SPL versus Strouhal Number for two 2 inch SCPR nozzles at Dial-in Pressure of 20 psig

Figure 3.10: SPL versus Strouhal Number for two 2 inch SCPR nozzles at Dial-in Pressure of 25 psig

Figure 3.11: SPL versus Strouhal Number for two 1.5 inch SCPR nozzles at Dial-in Pressure of 5 psig

Figure 3.12: SPL versus Strouhal Number for two 1.5 inch SCPR nozzles at Dial-in Pressure of 10 psig

Figure 3.13: SPL versus Strouhal Number for two 1.5 inch SCPR nozzles at Dial-in Pressure of 15 psig

Figure 3.14: SPL versus Strouhal Number for two 1.5 inch SCPR nozzles at Dial-in Pressure of 20 psig

Figure 3.15: SPL versus Strouhal Number for two 1.5 inch SCPR nozzles at Dial-in Pressure of 25 psig

Figure 3.16: SPL versus Strouhal Number for two 1.25 inch SCPR nozzles at Dial-in Pressure of 5 psig

Figure 3.17: SPL versus Strouhal Number for two 1.25 inch SCPR nozzles at Dial-in Pressure of 10 psig

Figure 3.18: SPL versus Strouhal Number for two 1.25 inch SCPR nozzles at Dial-in Pressure of 15 psig

Figure 3.19: SPL versus Strouhal Number for two 1.25 inch SCPR nozzles at Dial-in Pressure of 20 psig

Figure 3.20: SPL versus Strouhal Number for two 1.25 inch SCPR nozzles at Dial-in Pressure of 25 psig

Figure 3.21: SPL versus Strouhal Number for two 1 inch SCPR nozzles at Dial-in Pressure of 5 psig

Figure 3.22: SPL versus Strouhal Number for two 1 inch SCPR nozzles at Dial-in Pressure of 10 psig

Figure 3.23: SPL versus Strouhal Number for two 1 inch SCPR nozzles at Dial-in Pressure of 15 psig

Figure 3.24: SPL versus Strouhal Number for two 1 inch SCPR nozzles at Dial-in Pressure of 20 psig

Figure 3.25: SPL versus Strouhal Number for two 1 inch SCPR nozzles at Dial-in Pressure of 25 psig

Figure 3.26: SPL versus Strouhal Number for two 0.75 inch SCPR nozzles at Dial-in Pressure of 5 psig

Figure 3.27: SPL versus Strouhal Number for two 0.75 inch SCPR nozzles at Dial-in Pressure of 10 psig

Figure 3.28: SPL versus Strouhal Number for two 0.75 inch SCPR nozzles at Dial-in Pressure of 15 psig

Figure 3.29: SPL versus Strouhal Number for two 0.75 inch SCPR nozzles at Dial-in Pressure of 20 psig

Figure 3.30: SPL versus Strouhal Number for two 0.75 inch SCPR nozzles at Dial-in Pressure of 25 psig

Figure 3.31: Spike Occurrence versus Wall Standoff for two 2 inch SCPR nozzles

Figure 3.32: Spike Occurrence versus Wall Standoff for two 1.5 inch SCPR nozzles

Figure 3.33: Spike Occurrence versus Wall Standoff for two 1.25 inch SCPR nozzles

Figure 3.34: Spike Occurrence versus Wall Standoff for two 1 inch SCPR nozzles

Figure 3.35: Spike Occurrence versus Wall Standoff for two 0.75 inch SCPR nozzles

Figure 3.36: Spectra Shape versus Wall Standoff for two 2 inch SCPR nozzles at 15 psig

Figure 3.37: Spectra Shape versus Jet Diameter for SCPR nozzles at Wall Standoff $h/d=7$ and 5 psig

Figure 3.38: Spectra Shape versus Jet Diameter for SCPR nozzles at Wall Standoff $h/d=7$ and 15 psig

Figure 3.39: Spectra Shape versus Jet Diameter for SCPR nozzles at Wall Standoff $h/d=7$ and 25 psig

CHAPTER 4

Experimental Results for Machined Conical Nozzles

The results from the machined conical nozzles are discussed in the following sections. The machined conical nozzle configuration were specifically tested because it was believed that the smooth cone angle would produce greater roll-off rates than the step change in area of the sudden contraction pipe reducer (SCPR) nozzles. From the information gained from earlier SCPR nozzle tests, it was determined that the likelihood of a spike in the spectrum would increase when both jets were located within six diameters of the wall. To avoid the creation of spikes in the spectrum, the machined conical nozzles were tested only at symmetric wall standoffs of six, eight, and ten diameters. The acquired data was compared to the two pertinent theories, namely Lighthill's U^8 Law and the Peak Strouhal number. The variations to these theories are discussed and the results are said to be either in agreement or not. If the results are in agreement then the trends of the various parameters are discussed in terms of their effect on the sound spectrum.

4.1 Comparison of OASWL With Lighthill's U^8 Law

The OASPL results of the machined conical nozzles tests were converted to a OASWL using the same conversion table

(Table 3.1) as the SCPR nozzles. Performing a decibel addition on the spectrum's 1/3 octave sound power levels, the overall sound power level was calculated for each test. The OASWL were averaged for the three wall standoffs to provide a single point for plotting. The theoretical OASWL for two free jets were calculated based on equation 1.6 given by Bell [6]. Figures 4.1 - 4.4 illustrate the difference between the OASWL of the two impinging machined conical nozzles and the theoretical OASWL for two free jets. The results show that the slopes of the impinging machined nozzles follow the eighth power of velocity as Lighthill predicted. However, as with the SCPR nozzles, there is a vertical shift in levels above the low and high range as given by Bell's calibration chart. The maximum difference of 24-29 dB occurred for two 1.25 inch jets at $h/d=6$ and a supply pressure of 25 psig. The minimum difference of 11-19 dB occurred for two 1.0 inch jets at $h/d=10$ and a supply pressure of 5 psig. On average the shifted levels range from 16-23 dB over what is predicted by Bell's chart (Table 3.2) for free jets. Again, there is a definite acoustic advantage by using two impinging jets over two free jets.

4.2 Comparison of SPL With Peak Strouhal Number

In Figures 4.5 to 4.15, the sound pressure levels, in 1/3 octave bands adjacent to the peak of the spectrum, are plotted

against Strouhal number for the machined conical nozzles. The plots show the effect of increasing dial-in pressure, and increasing wall standoff. The results given in these figures show that the peak Strouhal number is higher for test at $h/d = 6$ than $h/d = 8$ or 10 . As the wall standoff distance is increased from 6 to 10 diameters the peak Strouhal number approaches values closer to the theoretical Strouhal number of 0.2. The actual values are given below in Table 4.1. Considering that the difference in results at $h/d = 8$ and 10 are small, the results from the machined conical nozzle are said to be in agreement with the Strouhal number theory. The impinging jets did exhibit the general trend of increasing peak Strouhal number as the wall standoff was decreased. This trend was also verified by experiments by H.K Lee and H.S.Ribner [19].

Table 4.1: Averaged Peak Strouhal numbers for the Machined Conical Nozzle Tests

Wall Standoff	Diameter 2 inch	Diameter 1.5 inch	Diameter 1.25 inch	Diameter 1.0 inch
$h/d=6$	.304	.322	.294	.303
$h/d=8$	.248	.245	.291	.242
$h/d=10$	n/a	.198	.201	.242

4.3 Effect of Various Parameters on Noise Spectrum

Since the machined conical nozzle results follow the known theories on acoustic jets, the effects that the various parameters have on the noise spectrum can now be discussed. The facility is specifically interested in the effect of the parameters on the following characteristics: OASPL, roll-up and roll-off rates, peak frequency, and spike criteria. The effect that wall standoff, supply pressure and jet diameter have on each of the different characteristics will be discussed in the following sections.

4.3.1 Effect of Wall Standoff

The results from the machined conical nozzles indicate that reducing wall standoff from $h/d = 10$ to $h/d = 6$ caused the OASPL to increase. The maximum level produced was 138.2 dB for two 2.0 inch diameter nozzles located at $h/d = 6$ and with a supply pressure of 25 psig. The minimum level produced was 111.6 dB for two 1.0 inch diameter nozzles at $h/d = 10$ with a supply pressure of 5 psig. On average the roll-up and roll-off rates decrease with increasing wall standoff. The roll-up rates fluctuated between a maximum of 7.0 dB/octave to a minimum of 4.1 dB/octave. The roll-off rates fluctuated between a maximum of 4.3 dB/octave to a minimum of 3.0 dB/octave.

The peak frequency was observed to increase as the wall standoff was decreased from $h/d = 10$ to $h/d = 6$. An example

of this trend comes from the 2 inch conical nozzle tests at $h/d = 6$ and 8, and supply pressure of 5 psig. The peak frequency increases from 800 Hz ($h/d = 8$) to 1250 Hz ($h/d = 6$).

From the information about spike generation gained through the SCPR nozzle tests, the machined conical nozzle were tested at wall standoffs beyond six diameters. The results indicated that there were no apparent spikes in any of the machined conical nozzle spectra.

4.3.2 Effect of Supply Pressure

The results from the machined conical nozzles indicate that reducing supply pressure from 25 psig caused the OASPL to decrease. The result is consistent with the trend observed with the SCPR nozzles.

The roll-up rate seem to increase with increasing supply pressure. The roll-off rate decreases with increasing supply pressure from a maximum of 4.5 dB/octave to a minimum of 1.6 dB/octave. The roll-up rates fluctuated between a maximum of 9.5 dB/octave to a minimum of 2.0 dB/octave.

The peak frequency was observed to increase as the supply pressure was increased from 5 psig up to 25 psig. This trend was expected based on the peak Strouhal number relationship. If the peak frequency increases with supply pressure, the jet exit velocity must also increase with nozzle pressure ratio. These two increases seem to nullify each other and leave the

peak Strouhal number relatively constant as given in Table 4.1.

The increasing supply pressure caused some pronounced peaks in the spectra, but the difference in neighbouring 1/3 octave levels did not approach the levels required to be deemed a spike.

4.3.3 Effect of Jet Diameter

The results from the machined conical nozzles indicate that reducing the jet diameter from 2 inch to 1.0 inch nozzles caused the OASPL to decrease. This result from the machined conical nozzles indicated that something was wrong with the results obtained for jet diameter versus OASPL from the SCPR nozzles. In theory a larger diameter choked jet should produce more noise than a smaller choked diameter jet with similar geometry.

The average roll-up and roll-off rate was observed to increase with increasing jet diameter. This trend for roll-up rate was observed for most of the tests, whereas this trend for the roll-off rate was observed for all of the machined conical tests.

The peak frequency was observed to increase as the jet diameter was decreased from the 2.0 inch nozzle to the 1.0 inch nozzle. This trend was expected based on the peak Strouhal number relationship. The peak frequency increases with both jet diameter reduction and exit velocity increase.

The decreasing jet diameter caused the peak frequency to move higher frequencies, but there was no appearance of spikes in the spectra.

4.4 Discussion on Machined Conical Nozzles

The results attained for the machined conical nozzles agreed with the two known theories for sound produced aerodynamically. The trends observed in the testing were similar to those cited from the SCPR nozzle test. The goal for increasing the roll-off rates by using a smooth cone angle never really materialized. It seems that neither the step contraction of the SCPR nozzles or the smooth angle of the conical nozzle is a controlling factor for achieving higher roll-off rates. However, the results of the tests have provided spectra which have already successfully been used in matching a satellite test.

Figure 4.1: Comparison of two 2 inch Impinging Machined Conical nozzles' OASWL with Lighthill's U^8 Law

Figure 4.2: Comparison of two 1.5 inch Impinging Machined Conical nozzles' OASWL with Lighthill's U^8 Law

Figure 4.3: Comparison of two 1.25 inch Impinging Machined Conical nozzles' OASWL with Lighthill's U^8 Law

Figure 4.4: Comparison of two 1 inch Impinging Machined Conical nozzles' OASWL with Lighthill's U^8 Law

Figure 4.5: SPL versus Strouhal Number for two 2 inch Machined Conical nozzles at Wall Standoff $h/d=6$

Figure 4.6: SPL versus Strouhal Number for two 2 inch Machined Conical nozzles at Wall Standoff $h/d=8$

Figure 4.7: SPL versus Strouhal Number for two 1.5 inch Machined Conical nozzles at Wall Standoff $h/d=6$

Figure 4.8: SPL versus Strouhal Number for two 1.5 inch Machined Conical nozzles at Wall Standoff $h/d=8$

Figure 4.9: SPL versus Strouhal Number for two 1.5 inch Machined Conical nozzles at Wall Standoff $h/d=10$

Figure 4.10: SPL versus Strouhal Number for two 1.25 inch Machined Conical nozzles at Wall Standoff $h/d=6$

Figure 4.11: SPL versus Strouhal Number for two 1.25 inch Machined Conical nozzles at Wall Standoff $h/d=8$

Figure 4.12: SPL versus Strouhal Number for two 1.25 inch Machined Conical nozzles at Wall Standoff $h/d=10$

Figure 4.13: SPL versus Strouhal Number for two 1.0 inch Machined Conical nozzles at Wall Standoff $h/d=6$

Figure 4.14: SPL versus Strouhal Number for two 1.0 inch Machined Conical nozzles at Wall Standoff $h/d=8$

Figure 4.15: SPL versus Strouhal Number for two 1.0 inch Machined Conical nozzles at Wall Standoff $h/d=10$

CHAPTER 5

Experimental Results for Rectangular Sliding Plate Nozzles and Diamond Sliding Nozzles

The results from the rectangular sliding plate nozzles and diamond sliding nozzles are discussed in the following sections. Both the rectangular sliding plate nozzle and the diamond sliding nozzle configurations were tested because of their potential for future automation. The configuration which provides similar spectra to the SCPR and conical nozzles would then be chosen for automation. The difference between the two geometries is shown in Figure 2.4. When the width is reduced in the rectangular sliding plate the nozzle becomes a rectangular slot with a high length to width aspect ratio. The diamond sliding nozzle maintains the diamond shape throughout the range on various size orifice tests.

The tests were performed at wall standoffs greater than six diameters to eliminate the occurrence of spikes. The acquired data were compared to the two pertinent theories, namely Lighthill's U^8 Law and the Peak Strouhal number. The variations to these theories are discussed and the results are said to be either in agreement or not. If the results are in agreement then the trends of the various parameters are discussed in terms of their effect on the sound spectrum.

5.1 Comparison of OASWL With Lighthill's U^8 Law

The OASPL results of the rectangular sliding plate nozzles and the diamond sliding nozzle tests were converted to a OASWL using the Sabine equation conversion table (Table 3.1). Performing a decibel addition on the spectrum's 1/3 octave sound power levels, the overall sound power level was calculated for each test. The theoretical OASWL for two free jets were calculated based on equation 1.7 given by Bell [6]. Figures 5.1 to 5.6 illustrate the difference between the OASWL of the two impinging rectangular sliding plate nozzles and the theoretical OASWL range for two free rectangular jets. Figures 5.7 to 5.13 illustrates the same type of results except for the diamond sliding jet configuration. The collective results show that the slopes of the impinging rectangular and diamond sliding nozzles follow the eighth power of velocity as Lighthill predicted. The agreement is especially good for the range of Mach numbers of 0.56 to 0.9. However, as with the SCPR nozzles, there is a change in slope above Mach 0.9. This change in slope is due to the averaging of two or three tests, all of which represent choked nozzle conditions. The OASWL also display a vertical shift in the noise levels produced as a result of jet mixing and impingement. The greatest difference between the OASWL for experiments and theory for the rectangular sliding plate nozzles was 22-27 dB with jet dimensions of 2 inches by 2

inches, and wall standoff of $h/d=6$, and dial-in pressure of 25 psig. Similarly, the smallest difference between experimental and theoretical values was 7-14 dB for two 2 inch by 2 inch rectangular nozzles at a wall standoff of $h/d=10$, and a dial-in pressure of 10 psig. The rectangular nozzles' shifted OASWL on average ranged between 12-19 dB for the range of wall standoff's of $h/d=6$ to $h/d=10$.

The diamond sliding nozzles' greatest difference between experimental results and theory was 19-28 dB with a side length of 1.75 inches and a dial-in pressure of 5 psig. The smallest difference is 7-12 dB with a side length of 0.71 inches and a dial-in pressure of 10 psig. The diamond sliding nozzles' shifted OASWL on average ranged between 12-20 dB above the theoretical free jet values. Table 3.5 was used to predict the theoretical OASWL attained by the impinging rectangular sliding and diamond sliding nozzles. The results of the comparison between the theoretical and experimental OASWL are shown in Table 5.3 and 5.4 for the rectangular and diamond nozzles, respectively. The average deviation from the theoretical OASWL values for the rectangular nozzles was between 3 to 5 dB. In the diamond sliding nozzle case this average deviation was 3.5 dB. These results illustrate that the revised chart in Table 3.5 makes a good approximation of the results of impinging jets regardless of the geometry.

5.2 Comparison of SPL With Peak Strouhal Number

In Figures 5.14 to 5.29, the sound pressure levels, in 1/3 octave bands adjacent to the peak of the spectrum, are plotted against Strouhal number for the rectangular sliding plate nozzles and the diamond sliding nozzles. The plots show the effect of increasing dial-in pressure, and increasing wall standoff. The results given in these figures show that the peak Strouhal number is higher for test at $h/d = 6$ than $h/d = 8$ or 10 . As the wall standoff distance is increased from 6 to 10 diameters the peak Strouhal number approaches values closer to the theoretical Strouhal number of 0.2. The actual values are given below in Tables 5.1 and 5.2. The results suggest that although impinging jets are different than free jets, the theory for the peak Strouhal number is still applicable. Considering the accuracy of the pitot tube, the results from the rectangular sliding plate and diamond sliding nozzles are said to be in agreement with the Strouhal number theory. When applicable, the impinging jets exhibit the general trend of increasing peak Strouhal number as the wall standoff was decreased. This trend was also verified by experiments by H.K Lee and H.S.Ribner [19].

With the data that the experiments have yielded it would suggest for future use in predicting the peak Strouhal number for impinging jets that a value between 0.23 to 0.26 be used instead of 0.2. Using this value for the Strouhal number and

the radiation efficiency for impinging jets in Table 3.5 would allow for a more accurate prediction of the peak frequency and the corresponding OASWL for a specified size of jet.

Table 5.1: Averaged Peak Strouhal numbers for the Rectangular Sliding Plate Nozzle Tests

Wall Standoff	Width 2 "	Width 1.75"	Width 1.5"	Width 1.25"	Width 1"	Width 0.75"
$h/d=6$	.255	.234	.214	.214	n/a	n/a
$h/d=8$	.226	.197	.213	.213	.180	n/a
$h/d=10$	.199	.180	.207	.201	.205	.155

Table 5.2: Averaged Peak Strouhal numbers for the Diamond Sliding Nozzle Tests

Side Length 1.75 "	Side Length 1.6 "	Side Length 1.4 "	Side Length 1.25 "	Side Length 1.1 "	Side Length 0.88 "	Side Length 0.71 "
0.255	0.239	0.203	0.208	0.195	0.154	0.125

5.3 Effect of Various Parameters on Noise Spectrum

Since the rectangular sliding plate and diamond sliding nozzles results follow the known theories on acoustic jets, the effects that the various parameters have on the noise spectrum can now be discussed. The facility is specifically interested in the effect of the parameters on the following characteristics: OASPL, roll-up and roll-off rates, peak

frequency, and spike criteria. The effect that wall standoff, supply pressure and jet diameter have on each of the different characteristics will be discussed in the following sections.

5.3.1 Effect of Wall Standoff

The diamond sliding nozzles were tested only at a distance of 10 inches and therefore the all effect is not pertinent to this configuration. The results from the rectangular sliding plate nozzle indicate that reducing wall standoff from $h/d = 10$ to $h/d = 6$ caused the OASPL to increase. The maximum OASPL produced was 137 dB for two 2.0 inch by 2 inch nozzles located at $h/d = 6$ and with a supply pressure of 25 psig. The minimum level produced was 108 dB for two 2.0 inch by 1.5 inch nozzles at $h/d = 10$ with a supply pressure of 5 psig.

The rectangular sliding plate nozzles produced roll-up and roll-off rates which decreased with increasing wall standoff. Roll-up rates varied between a maximum of 5.4 dB/Octave for the largest orifice size to 1.2 dB/Octave for the smallest orifice. The roll-off rates fluctuated between a maximum of 4.1 dB/Octave for the 2 inch by 1.75 inch nozzle to a minimum of 0.5 dB/octave for the smallest orifice.

The peak frequency was increased as the wall standoff was decreased from $h/d = 10$ to $h/d = 6$. The typical range of peak frequencies was between 800 Hz and 2500 Hz. The high end of this range represents the tests with closer wall standoffs,

higher dial-in pressure, and the smaller orifice sizes. By performing the acoustic tests at wall standoffs beyond six diameters the spike occurrence was avoided completely.

5.3.2 Effect of Supply Pressure

The results from the rectangular sliding plate and diamond sliding nozzles indicate that reducing the dial-in pressure down from 25 psig caused the OASPL to decrease. This result is consistent with the trend observed for all other types of nozzle geometry tested to date in this work.

The roll-up rate for the rectangular sliding plate nozzles seems to increase with increasing dial-in pressure. The roll-up rate for the diamond sliding nozzles decreased with increasing dial-in pressure.

The roll-off rate for the rectangular sliding plate nozzle increases with increasing dial-in pressure for the two largest sized orifices. The other sizes had very low roll-off rates, typically around 1.1 to 0.5 dB/Octave over the extent of the high frequency region. Because the rectangular sliding plate nozzles produced very flat roll-off rates at the specific geometries which would be useful for acoustic shaping, they were not considered for automation.

The roll-off rates for the diamond sliding nozzles were generally higher than those of their rectangular counterpart. These roll-off rates continued without much reduction through

the high frequency region. As a result the diamond sliding nozzles were chosen as the geometry for automation.

The peak frequency for both jet configurations was observed to increase between 800 and 2500 Hz as the dial-in pressure was increased. The increase of frequency was cancelled by a subsequent increase of velocity from the increased nozzle pressure ratio. The average peak Strouhal number remained relatively constant around a value of 0.21. The result of increased dial-in pressure did not produce any spikes in the spectrum.

5.3.3 Effect of Jet Orifice Size

The spectra results from the rectangular sliding plate and diamond sliding nozzles indicate that as the orifice size is reduced the OASPL decreased. This result was consistent with all geometries tested in this thesis.

The rectangular sliding plate and diamond sliding nozzles exhibited the trend of increased roll rates when the jet's orifice size was increased.

The peak frequency was observed to increase as the jet's orifice size was decreased. Typically the range of peak frequencies observed was between 800 to 2500 Hz. The peak frequency and jet exit velocity increase in a proportional manner, such that the peak Strouhal number remains relatively constant as shown in Tables 5.1 and 5.2.

By performing these tests at wall standoffs beyond six orifice sizes, no evidence of a spike occurrence was observed.

5.4 Discussion on Rectangular Sliding Plate and Diamond Sliding Nozzles

The results attained for the rectangular sliding plate and diamond sliding nozzles agreed with the slope of Lighthill's U^8 Law. The OASWL were higher than the predicted values by values between 12-19 dB and 12-20 dB for the rectangular and diamond sliding nozzles, respectively.

The peak Strouhal numbers for the rectangular sliding plate and diamond sliding nozzles were respectively, between 0.155 to 0.255 and 0.125 to 0.255. These results are similar to those of the SCPR and machined conical nozzles.

The roll-up rates for these two geometries were comparable to the SCPR and machined conical nozzles. The roll-off rates for the rectangular sliding plate nozzle were too flat, and therefore deemed undesirable for automation. As a result of steeper roll-off rates, the diamond sliding nozzles were chosen as the geometry for automation.

The trends of the parameters for the diamond sliding nozzles were very similar to the SCPR nozzles. The diamond sliding nozzles have been successfully implemented into the automated jet assembly. At the present time, the automated jet assembly has been mechanically tested for actuation, but

there have not been any test runs with the pressurized air supply.

Table 5.3: Averaged Error Between Experimental OASWL and Predicted OASWL For Rectangular Sliding Plate Nozzles

Rectangular Nozzle Dimensions (in)	Average Error (dB) at $h/d = 6$	Average Error (dB) at $h/d = 10$
2 x 2	3.3	5.1
2 x 1.75	2.4	5.2
2 x 1.5	2.7	5.8
2 x 1.25	2.1	5.3
2 x 1	n/a	3.2
2 x 0.75	n/a	4.8

Table 5.4: Averaged Error Between Experimental OASWL and Predicted OASWL For Diamond Sliding Plate Nozzles

Side Length Dimensions of Diamond Sliding Nozzle (inches)	Average Error (dB) for a Wall Standoff Distance of $h = 10$ inches
1.75	3.5
1.6	2.2
1.4	3.4
1.25	3.5
1.1	4.5
0.88	4.4

Figure 5.1: Comparison of Rectangular 2"x2" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.2: Comparison of Rectangular 2"x 1.75" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.3: Comparison of Rectangular 2"x 1.5" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.4: Comparison of Rectangular 2"x 1.25" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.5: Comparison of Rectangular 2"x 1.0" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.6: Comparison of Rectangular 2"x 0.75" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.7: Comparison of Diamond Cavity 1.75" x 1.75" nozzles' OASWL with Lighthill's U⁸ Law

Figure 5.8: Comparison of Diamond Cavity 1.6" x 1.6" nozzles' OASWL with Lighthill's U⁸ Law

Figure 5.9: Comparison of Diamond Cavity 1.4"x 1.4" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.10: Comparison of Diamond Cavity 1.25"x 1.25" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.11: Comparison of Diamond Cavity 1.1"x 1.1" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.12: Comparison of Diamond Cavity 0.88"x 0.88" nozzles' OASWL with Lighthill's U^8 Law

Figure 5.13: Comparison of Diamond Cavity 0.71" x 0.71" nozzles' with Lighthill's U^8 Law

Figure 5.14: SPL versus Strouhal Number for two 2"x 2" Rectangular nozzles at Wall Standoff $h/d=6$

Figure 5.15: SPL versus Strouhal Number for two 2"x 2" Rectangular nozzles at Wall Standoff $h/d=8$

Figure 5.16: SPL versus Strouhal Number for two 2"x 2" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.17: SPL versus Strouhal Number for two 2"x 1.75" Rectangular nozzles at Wall Standoff $h/d=6$

Figure 5.18: SPL versus Strouhal Number for two 2"x 1.75" Rectangular nozzles at Wall Standoff $h/d=8$

Figure 5.19: SPL versus Strouhal Number for two 2"x 1.75" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.20: SPL versus Strouhal Number for two 2"x 1.5" Rectangular nozzles at Wall Standoff $h/d=6$

Figure 5.21: SPL versus Strouhal Number for two 2"x 1.5" Rectangular nozzles at Wall Standoff $h/d=8$

Figure 5.22: SPL versus Strouhal Number for two 2"x 1.5" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.23: SPL versus Strouhal Number for two 2"x 1.25" Rectangular nozzles at Wall Standoff $h/d=6$

Figure 5.24: SPL versus Strouhal Number for two 2" x 1.25" Rectangular nozzles at Wall Standoff $h/d=8$

Figure 5.25: SPL versus Strouhal Number for two 2" x 1.25" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.26: SPL versus Strouhal Number for two 2" x 1.0" Rectangular nozzles at Wall Standoff $h/d=8$

Figure 5.27: SPL versus Strouhal Number for two 2" x 1.0" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.28: SPL versus Strouhal Number for two 2" x 0.75" Rectangular nozzles at Wall Standoff $h/d=10$

Figure 5.29: SPL versus Strouhal Number for two 1.75" x 1.75" Diamond Cavity nozzles at d=10 inches

Figure 5.30: SPL versus Strouhal Number for two 1.6" x 1.6" Diamond Cavity nozzles at d=10 inches

Figure 5.31: SPL versus Strouhal Number for two 1.4" x 1.4" Diamond Cavity nozzles at d=10 inches

Figure 5.32: SPL versus Strouhal Number for two 1.25" x 1.25" Diamond Cavity nozzles at d=10 inches

Figure 5.33: SPL versus Strouhal Number for two 1.1" x 1.1" Diamond Cavity nozzles at d=10 inches

CHAPTER 6

Computer Control Methods For Impinging Jets

A computer control system for the acoustic gas jets is presently in the final stages of design and assembly. The first stage of the control system is an automated jet assembly which can vary the orifice size when a signal is sent from the computer. The second stage of the system is the computer interface with the existing pressure control system and the automated jet assembly. The interface problem between the computer and the pressure control system was solved by Vincent Vinditti. The driver box provides the communication between the automated jet assembly and the computer. The driver box receives a binary signal from the computer and translates this signal into a change in the position of the stepper motor and hence a change in the orifice size.

Previously, the IAR/SMI's computer control system, written by Vincent Vinditti, governed over the Wyle modulators and NAE Hartmann generators. This system permitted the facility staff to control and match the low frequency end of the given spectrum up to the working range of the Wyle modulators (up to 1600 Hz including upspill effect). Matching frequencies above 1600 Hz has successfully been achieved with the aid of manually controlled acoustic gas jets.

The computer control of acoustic jets started by designing an automated jet assembly. The final design of the

automated jet assembly was chosen based on several design criteria including feasibility, similar results to SCPR nozzles, economy, and adaptability to the existing assembly.

During a calibration run or actual satellite test the computer monitors all readings and measurements from the Wyle modulators and sends out the applicable signals to the pressure control system, amplifiers, and shapers. During the pre-test or calibration run, the computer searches for the correct drive settings and then stores these settings for later use in a slam start. The present computer control of the spectrum does not extend above the useful working range of the low frequency modulators which is approximately 1600 Hz including upspill effect. There is no control of the jet spectrum other than the information of the pressure, jet configuration, wall standoff, and jet diameters found through experimentation. Results of experimentation have led to two distinct methods of controlling or selecting the jet set-up required to match a spectrum. The first method is called the Pressure and Orifice Search Method and the second method is called the Computer Look-Up method.

6.1 Pressure & Orifice Search Method

In this method the computer will have pressure and orifice size control over an automated jet assembly (discussed in 6.3). The automated jet assembly has two moveable sliding

plates responsible for the change to each jet's orifice size. During a calibration run, the computer control system for the automated jet assembly utilizes in-house code to search for the initial choice of orifice sizes based on an empirical relation between peak frequency and orifice size. The method of matching the high frequency spectrum will use a flip-flop control between orifice size and supply pressure. The computer will then vary the supply pressure to the jets in order to minimize the difference between client's target values and the levels produced from the jets. Once the supply pressure has been set and held constant, the computer will vary orifice size and examine the magnitude of the error signal. If the error signal can be reduced through this change in orifice size, then the initial choice of orifice sizes will be replaced by the latest setting.

The problem with the computer pressure search method is that it is not an exact solution. The selection of the two orifice sizes comes from empirical results which should provide an adequate first approximation. There could be occasions when varying pressures and orifice sizes does not provide the correct jet shape to match the target spectrum. In these cases the computer look-up method should be used to find jet configurations that would match the spectrum.

6.2 Computer Look-Up Method

The data acquired throughout all of the parametric experiments is converted from 1/12 to 1/3 octave bands in the 1 khz to 20 khz range. This information is stored in a master read only data file. During a calibration run for a test, (usually done months in advance of a test) the computer control system would match the spectrum only in the existing controllable range of 25 to 1600 Hz. Above this range the computer would calculate the deficit noise levels based on the difference between the client's input target values and the achieved levels through upspill of the Wyle modulators. These deficit values would be stored in a temporary array. The computer would implement a search algorithm throughout the master data file. The computer search code will utilize some sort of tolerance or least squares error to choose the data which best fits the spectrum. The computer would return the required file name(s) which corresponds to a particular jet configuration, pressure setting, wall standoff, and jet diameter or size. At this time the IAR/SML staff would set up the required apparatus and then proceed with another calibration test. The result of the acoustic jet testing, which makes the computer look-up method feasible is the repeatability of the acoustic tests. Once the environmental conditions have been achieved in the reverberation chamber, the repeated impinging jet test's OASPL values were within $\pm$

0.3 dB of the original data. The computer look-up method would be a dynamic system where the master data file would grow in size with each new test. This method will provide an exact result if the required test levels are located in one of the 1300 stored test files. Matching most spectra can be achieved with the assistance of the acoustic gas jets as long as the levels in the given spectrum do not vary too much from the neighbouring bands. Because of the size of the master data file, the computer look-up method could run off-line from the computer pressure search method to speed up the time to a solution.

A substantial change in neighbouring bands, usually requires the jet configuration to produce a small peak or spike at the required frequency. Problems in this area usually come from matching the roll-off rate of the client's spectrum.

6.3 Automated Diamond Sliding Jet Assembly

A preliminary automated jet assembly design was conceived by Frank Slingerland, and converted into a mechanical engineering fourth year design project at Carleton University. The prototype design used two rotating rectangular flaps attached to gears and driven by stepper motor with a rotating worm gear. This design was changed because of results from testing on the rectangular sliding plate nozzle. Results of

tests on a sliding rectangular plate produced noise spectra similar in shape to the SCPR nozzles when the aspect ratio was low. As the width of the rectangular nozzle was reduced the spectra changed, producing flat spectra. Diamond sliding nozzles maintained the same aspect ratio throughout the range of tests, and did not produce flat spectra. The final automated jet assembly (Figure 6.1) was designed by Frank Slingerland, Mark Hendrycks, and Leah Donovan. This assembly utilized the existing 4" to 2 " pipe reducer. A square orifice was scribed around the circular orifice and the corner material was removed. A vertical sliding plate is mounted into two side guides affixed with hexcap screws on the sides of the pipe reducer nozzle. The vertical plate slides on the machined front face of the pipe reducer. The rotating motion of the disk causes the eccentric pin to move in a horizontal slot. The resulting action is a vertical displacement of the sliding plate, and a change in the orifice size. The stepper motor will be connected to the computer so that orifice size will be controlled. The physical wall standoff must still be changed manually. This automated jet assembly can be used in the single jet configuration, separate pressure fed lines , and the T-section assembly.

Figure 6.1 **Automated Diamond Sliding Jet Assembly**

Figure 6.2: Sample Satellite Test Spectrum matched by the IAR/SML Aeroacoustics facility using the Impinging Jets in the high frequency region

CHAPTER 7

Conclusions and Recommendations

The observed trends for OASPL, Roll-Up, Roll-Off, and Spike Occurrence for each of the various nozzle configurations was converted into tabular form and is given as reference in Table 7.1. Jet results compared with Lighthill's U^8 Law and Peak Strouhal Number are given below for all nozzle configurations. The general results are also presented below in the following sections.

7.1 Summary of Results

- Impinging acoustic gas jets were found to be a successful supplementary high frequency noise generating device
- The sound power levels for all geometries tested followed the slope of Lighthill's U^8 Law, with an associated vertical shift in noise levels due to the increased radiated efficiency
- The peak Strouhal number observed was slightly higher than the theoretical value for all nozzle geometries tested
- The test results have helped define the effect that each parameter has on the noise spectrum, and subsequently lead to the two methods of computer control
- The jet tests will be used in two computer control methods that will select the jet configuration which best fits the given satellite spectrum
- The diamond sliding nozzle is the best geometry for an automated jet assembly

SCPR Sudden Contraction Pipe Reducer Nozzles

- sound power levels attained followed Lighthill's U^8 Law with an average increase between 16-22 dB
- the impinging SCPR nozzles' peak Strouhal number was observed to peak on average at 0.24 as compared to the theoretical free jet value of 0.2
- the maximum overall sound pressure produced was 143.3 dB for the 1.25 inch jet at a supply pressure of 25 psig and wall standoff of $h/d = 4$

Machined Conical Nozzles

- sound power levels attained followed Lighthill's U^8 Law with an average increase between 16-23 dB
- the machined conical nozzles' average peak Strouhal number was observed between 0.255 to 0.276 as compared to theoretical free jet value of 0.2
- the maximum overall sound pressure produced was 136.7 dB for the 2 inch jet at a supply pressure of 25 psig and wall standoff of $h/d = 6$

Rectangular Sliding Plate Nozzle

- sound power levels attained followed Lighthill's U^8 Law with an average increase between 12-19 dB
- the rectangular sliding plate nozzles' average peak Strouhal number was observed between 0.155 to 0.207
- the maximum overall sound pressure produced was 137.8 dB for the 2 inch by 2 inch jet at a supply pressure of 25 psig and wall standoff of $h/d = 6$

Diamond Sliding Nozzle

- sound power levels attained followed Lighthill's U^8 Law with an average increase between 12-20 dB
- the diamond sliding nozzles' average peak Strouhal number was observed between 0.125 to 0.255
- the maximum overall sound pressure produced was 137.1 dB with the side length of 1.75 inch, and a supply pressure of 25 psig and wall standoff distance of 10 inches

7.2 Recommendations

7.2.1 Future Tests

After 40 years of research on jet noise, some of the sound generation phenomena in the turbulent mixing layer and the potential core are still not fully explained. A suggested way to remedy this situation is through specific planned testing. Any testing for the purpose of validating or invalidating theories must utilize visual techniques. The use of Schlieren photography or shadowgraph techniques would assist in understanding the phenomena occurring in the flow. The additional tests suggested below may help answer questions both in theory and in practical applications in terms of the use of acoustic gas jets for spectrum shaping.

(1) Use Schlieren photography on the impinging gas jets to verify that the feedback mechanism is present. Try to establish that the feedback mechanism is responsible for the spikes in the spectrum.

(2) Automate a system to vary the jet wall standoff so the jets can be moved during testing. Vary wall standoff from free jet distances of $h/d = 10$ to 15, to impingement sensitive distances of $h/d = 1$ and observe the change in wave patterns in the flow through visual techniques.

(3) For the purpose of the IAR/SML facility, continue tests in areas not covered in this thesis. Perform additional tests with wall standoffs that were not tested because of time

constraints. Tests with two different nozzle configurations, like one conical nozzle with one rectangular slit nozzle could give unique results. Some of these tests could provide spectra capable of matching a future spectrum for a client.

(4) Investigate the possibility of having 2 jet assemblies in the chamber. The separate pressure fed nozzles in the NW corner and the T-section in the NE corner would increase efficiency because the facility would be more flexible in changing apparatus. The size of the piping system would have to be increased and additional valves would have to be used to suit the increased flow demands. Changes to the venting system in the chamber would be required.

(5) Perform tests using the in-house designed automated jet assembly. Vary supply pressure and orifice size through computer control at wall standoff, $h/d > 6$.

As a result of performing these tests, other additional tests might arise, but it should be noted here that this type of flow modulation has almost reached its useful limit, and there will be a need for investigation into a new method of generating noise in high frequencies.

Table 7.1: Observed Trends in Impinging Jet Experiments

Test Cases	Spectrum Quantity	D.I.P psig	h/d	Jet Size
Perform tests on SCPR nozzles symmetric diameters and symmetric wall standoffs	OASPL RollUp Rolloff Spikes	Incr Incr Decr Incr	Decr N/A Incr Decr	Incr Decr Incr Decr
Perform tests on SCPR nozzles symmetric diameter and asymmetric wall standoffs	OASPL RollUp Rolloff Spikes	Incr Incr Decr Incr	Decr N/A Incr Decr	Incr Decr Incr Decr
Perform tests on SCPR nozzles asymmetric diameters with h/d = {6:6,6:8,6:10,8:6,8:8,8:10,10:6,10:8,10:10} 1 st # large jet & 2 nd # small jet	OASPL RollUp Rolloff Spikes	Incr Decr Incr Incr	Decr Incr Decr Decr	Incr Decr Decr Decr
Perform tests on Single SCPR nozzles h/d=3 to h/d=10	OASPL RollUp Rolloff Spikes	Incr Incr Decr Incr	Decr Decr Decr Decr	Incr Incr Decr Decr
Perform tests on Mach. conical nozzles with symmetric diameters and h/d=6, 8, and 10	OASPL RollUp Rolloff Spikes	Incr Incr Decr None	Decr Decr Decr None	Incr Incr Incr None
Perform tests on Rectangular Sliding Plate Sizes 2x2, 2x1.75, 2x1.5, 2x1.25, 2x1, 2x0.75 in ²	OASPL RollUp Rolloff Spikes	Incr Incr Incr N/A	Decr Decr Decr N/A	Incr Incr Incr N/A
Perform tests on Diamond Shape Nozzles with Side Lengths of 1.75, 1.6, 1.4, 1.25, 1.1, 0.88, 0.71 inches & Standoff Distance 10 in	OASPL RollUp Rolloff Spikes	Incr Decr Incr N/A	N/A N/A N/A N/A	Incr Incr Incr N/A

Note: To increase any of the Spectrum Quantities, perform the changes in D.I.P, h/d, and Jet Size.

Incr Increase the given parameter

Decr Decrease the given parameter

N/A Not Available

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APPENDIX A

Conversion Table For Pertinent Units

	To Convert From			Multiply By
Length	in	to	m	0.0254
	ft	to	m	0.3048
Area	ft ²	to	m ²	0.0929
Volume	ft ³	to	m ³	0.0283
Pressure	psi	to	Pa	6894.7
Density	lb _m /ft ³	to	kg/m ³	16.018
Velocity	ft/sec	to	m/sec	0.3048

END

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