Validation of the Small Hot Jet Acoustic Rig for Jet Noise Research

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The development and acoustic validation of the Small Hot Jet Aeroacoustic Rig (SHJAR) is documented. Originally conceived to support fundamental research in jet noise, the rig has been designed and developed using the best practices of the industry. While validating the rig for acoustic work, a method of characterizing all extraneous rig noise was developed. With this in hand, the researcher can know when the jet data being measured is being contaminated and design the experiment around this limitation. Also considered is the question of uncertainty, where it is shown that there is a fundamental uncertainty of 0.5dB or so to the best experiments, confirmed by repeatability studies. One area not generally accounted for in the uncertainty analysis is the variation which can result from differences in initial condition of the nozzle shear layer. This initial condition was modified and the differences in both flow and sound were documented. The bottom line is that extreme caution must be applied when working on small jet rigs, but that highly accurate results can be made independent of scale.

I. Motivation

In 2000, NASA Glenn Research Center hosted a Jet Noise Workshop to assess the state of jet noise research. From that workshop several broad themes arose. Challenges were raised to the acoustic analogy underpinnings of classical jet noise theory. Jet noise prediction schemes, both ad hoc and based upon acoustic analogies were unable to predict the strong directivity of jet noise. Theoreticians were concerned by the conflicting experimental jet noise databases. Not enough data were available on turbulence in hot jets. These issues drove the development and subsequent validation efforts of the Small Hot Jet Acoustic Rig (SHJAR), a research rig located at the Aeroacoustic Propulsion Laboratory at NASA Glenn. The rig was expected to allow advanced measurements of hot jets, both flow and sound, to address the concerns of the theoreticians, and to allow noise reduction concepts to be tested in hot jets with reasonable scalability to commercial aircraft. To meet these expectations, the rig and supporting measurement technologies would have to be flexible and inexpensive to operate, be defensible in flow and acoustic quality, and be well documented. This paper highlights the documentation of the acoustic performance of the SHJAR.

In documenting the acoustic performance of the SHJAR the common 'calibration' mindset that says a rig is good if it matches some 'standard' set of data was avoided. There is no recognized standard, and matching spectra at one flow condition does not guarantee that data from either a lower noise condition or nozzle configuration will not be contaminated. There are also reasons to believe that two good rigs should get different answers unless very minute aspects of their test nozzles are the same. The main goal should be to obtain noise results which are independent of scale and facility.

We did wish to incorporate the knowledge of our predecessors and peers in making good jet noise measurements. The recent work of Viswanathan[1] and Ahuja[2] were very valuable, along with their personal interactions. We pursued a process whereby all noise sources present during test runs would be characterized, in much the same way as the various contributions of a turbofan engine are decomposed (fan, core, jet, etc.). In this way we could say with some confidence where the valve noise, the background sound level, the combustor, and of course the jet noise lay in any measured spectra.

Pursuing this vision we want to be able to find all the reasons for variations in jet noise experimental data. One area where we had some advantage over previous experimentalists was in giving equal weight to detailed flow measurements. Since much of the mission for SHJAR was to provide cutting edge turbulence

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measurements[3], such as two-point space-time correlations, we have access to more information about how changes in flow condition and nozzle geometry change the turbulence, which in turns changes the far-field acoustics.

II. Rig Description

The detailed guidance of Ahuja[2] was followed in designing and validating the rig and facility. With only a few exceptions, primarily in the area of recommendations for a combustor, all his criteria for good jet noise experiments were met.

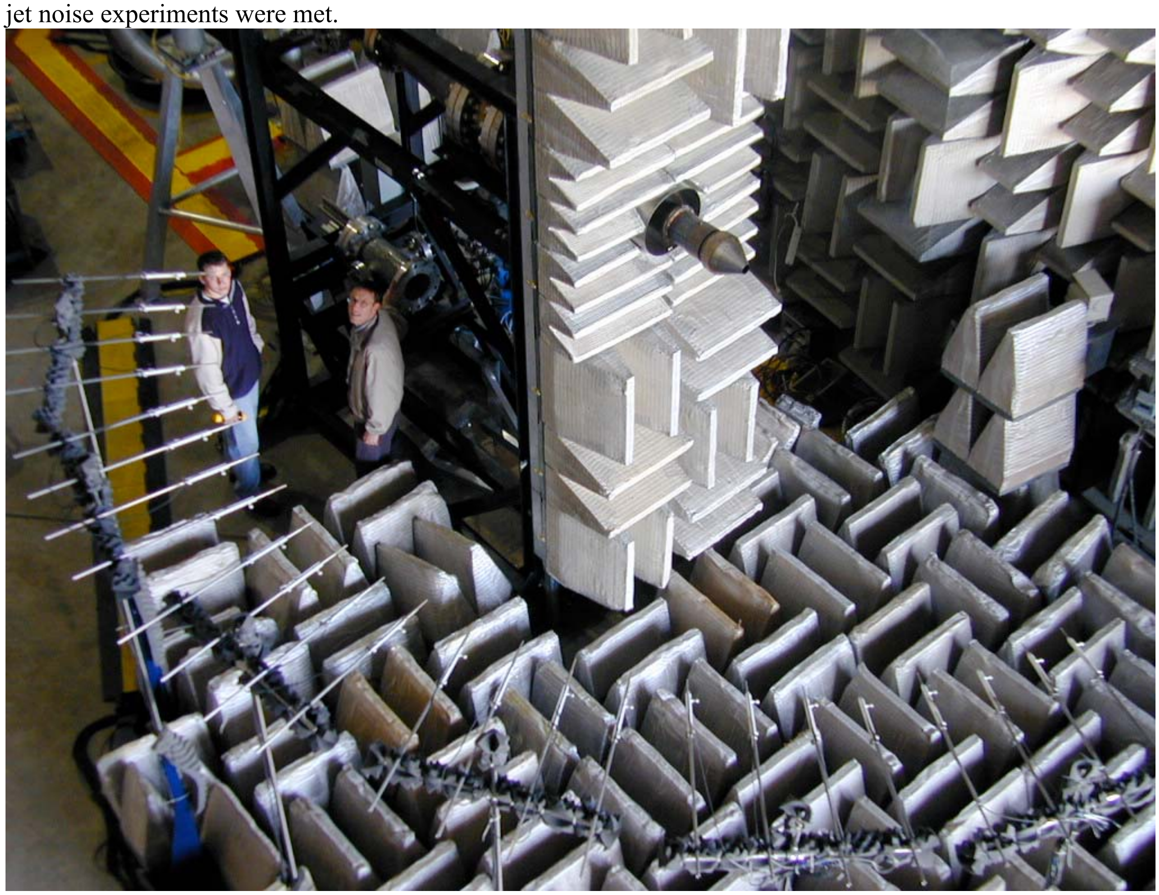

Figure 1 Small Hot Jet Acoustic Rig with microphone array.

A. Anechoic environment

The Small Hot Jet Acoustic Rig (SHJAR) is located in the AeroAcoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center in Cleveland, Ohio. The AAPL, which houses the SHJAR, is a geodesic dome (60-foot radius) lined with 24" long sound absorbing wedges which remove sound reflection at all frequencies above 200 Hz. The floor and all surfaces around SHJAR are covered by the fiberglas wedges. The jet exhaust from SHJAR is directed outside through a large door. The large door is good in that we have no problems with collector noise and reverberation; it is bad in that we have a relatively high background noise level from the surrounding lab and airport. The inset in Figure 2 shows the location of SHJAR within the AAPL dome.

B. Piping, support, valves, combustor, muffler, flow conditioning

SHJAR is a single flow rig which uses 150-psi air from a group of compressors located in another building on the lab. The sketch in Figure 2 shows the various components of the rig. Because the rig is used to measure hot flow and because the combustor is located substantially upstream of the nozzle, thermal growth of the piping must be considered. Large loops in two planes of the 4" supply pipe, along with floating pipe supports remove the thermal growth, keeping the nozzle fixed in space to within 0.3" at all conditions. A critical flow venturi measures the mass flow in a long leg of the supply pipe before the control valves, as far from the acoustic arena as possible. Two valves control the flow rate: a large, low-noise, main valve and a small vernier valve for fine adjustment. This combination provides fine control over the entire range of operating conditions. A hydrogen-burning combustor directly in the air line provides fine control over air temperature with minimal impact on gas constants needed to set flow conditions. The air passes through a seven-baffle line-of-sight muffler and 14" diameter settling chamber before contracting first to a 6" diameter pipe and finally reaching the nozzle. An optional series of fine screens are placed in the 6" settling chamber 8" upstream of the nozzle. Nozzles ranging from one to three inches in diameter are tested. Total pressure and total temperature are measured in the 14" plenum. The maximum mass flow rate is 6 lbm/second and the maximum temperature is 1300 °F. The maximum temperature is limited by the maximum metal temperature allowed on piping components shortly downstream of the watercooled combustor chamber. All components of SHJAR downstream of the combustor are fabricated from 316H series steel or equivalent so that all pieces can be replaced by easily available material. The maximum nozzle pressure ratio is limited by losses in the piping and the 150psia air supply to be just short of the 7.66 needed to hit Mach 2 in the jet.

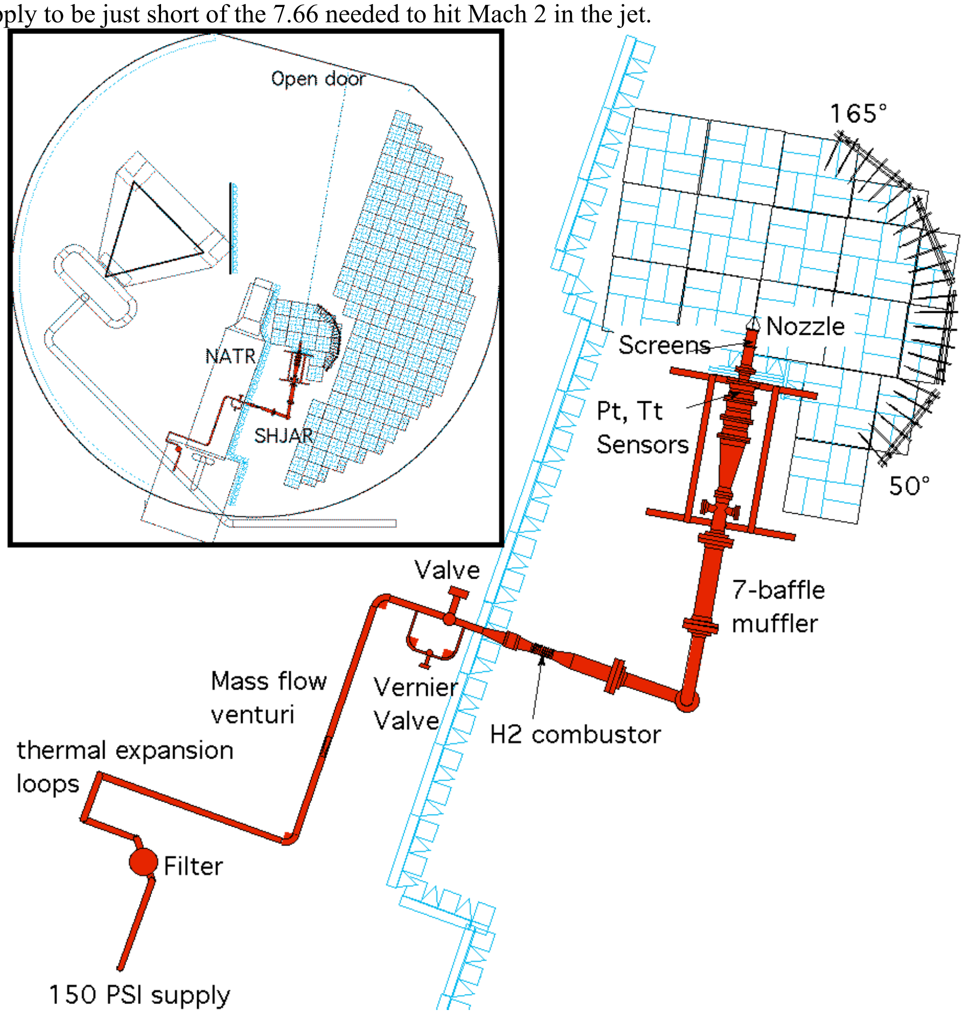

Figure 2 Floor plan of SHJAR, showing location within AAPL (inset) and denoting important rig components.

III. Instrumentation and data processing

A. Rig and facility instrumentation

In addition to the mass flow venturi, the rig is instrumented with a variety of measurements for both safety and research quality control. The combustor is instrumented with a cross-flow thermocouple rake and with flange thermocouples to monitor the health of the combustor, injector, and pressure housing. The limiting condition for high temperatures on SHJAR is the temperature of the combustor housing. Several other flanges have been instrumented with thermocouples for safety as well. In the 14" plenum static pressure and temperature are measured with simple taps and minimal penetration thermocouples. Cylindrical penetrations into the airflow have been minimized at all costs, and with the velocity so low the error in using static pressure instead of total is less than 0.1%.

The rig conditions are only part of the information needed to set flow conditions for jet noise experiments. The ambient conditions, temperature, pressure, and relative humidity, are measured locally to within 0.1°R, 0.005psi, and 1% respectively. These measurements are actively used to set the control valves on the air and fuel as we are controlling set points of jet velocity relative to ambient speed of sound and jet static temperature relative to ambient temperature.

B. Acoustic data acquisition instrumentation

Acoustic measurements were performed using an array of 24 microphones placed on an arc at five-degree intervals from 50 to 165 degrees relative to the jet upstream axis (Figure 1). For 1" and 2" diameter nozzles the microphone array arc was made with a radius of 100", being sufficiently in the geometric far field that data at any further distance could be nondimensionalized to within 0.5dB by assuming spherical spreading from a point at the nozzle exit[4]. For the 3" nozzle, the array was constituted on an arc 150" in radius to achieve the same nondimensional distance. To minimize reflection from the microphone stands, six stands, each holding four microphones, are used, with the microphones mounted on 18" stings, themselves offset from the crossbar by an 8" long, 1/2" rod. For some tests single microphones were placed on a moveable pole to acquire data at different distances along a radial line (referred to as a 'walkback' test). Acoustic measurements were also performed using two microphones placed on moveable poles to acquire data at different distances along a radial line. Bruel & Kjaer 1/4" 3949 microphones are used with matching preamps, connected to Bruel & Kjaer Nexus™ signal conditioning amplifiers via 100m of cable. A DataMAX® Instrumentation Recorder, from RC Electronics Inc., simultaneously recorded data from both microphones at a bandwidth of 90 kHz (200 kHz sample rate) for a period of 8 seconds at each flow setpoint. In practice, the trusted bandwidth is closer to 75 kHz than the 90 kHz set on the recorder itself.

Before and after daily test runs, the microphones were calibrated using a Bruel & Kjaer 4220 pistonphone. The recorded calibration coefficients were applied to the time domain data before the data was transformed to frequency domain using a 2^{13} point, Kaiser-window-averaged Fourier transform. All further data processing programs operated on the narrowband power spectral density. The background noise, measured immediately before the data set was acquired, was subtracted from the data In frequency bands where the measured data fell within 3 dB of the background was flagged and not considered in future processing and final plotting. The data were next corrected for microphone spectral response characteristics based on the certified actuator response of each individual microphone (obtained within one year of the test). Atmospheric attenuation was added back to the power spectral density measurement over the approximate distance from the microphone to the jet using the value of attenuation calculated from ISO 9613-1:1993 and applied at each narrowband frequency. Test parameters such as rig temperatures, pressures, and mass flows as well as ambient temperature, pressure, and humidity were recorded during the acoustic recording time and these values were used to calculate the speed of sound and atmospheric attenuation coefficients.

From this point, the data were scaled to a common distance by dividing the power spectral density by $(D_{new}/D_{old})^2$. The power spectral density data were normalized to Strouhal scaling by multiplying the frequency by D/U and dividing the amplitude by this same factor.

After spectral manipulation is complete, the power spectral density data were often converted to third octave spectra by integrating the narrowband spectral densities to proportional band spectra. This was done in software in a manner consistent with IEC 1260:1995—specifically an ideal third-octave filter. An extension of the one-third-octave band convention was made to allow data from different sized nozzles to be compared directly on common center frequencies. Once the narrowband data were normalized in amplitude, a set of bands were defined with bandwidth $0.231f_o$ centered on Strouhal numbers f_o defined by

$10^{(N/10)}$ where N is a positive or negative integer. The narrowband spectral density were integrated over the bands to produce third-octave spectra in a way that allowed direct comparison of data from different scaling factors on common center frequencies. As a matter of convention, when expressing the power spectrum in dB, the common reference value of 20 microPascals was used.

C. Setpoint definitions, tolerances

Often overlooked in jet noise testing is the importance of picking the proper flow conditions to obtain consistent noise measurements. Jet noise scales on jet velocity (or velocities) relative to the ambient speed of sound. This is commonly referred to as acoustic Mach number (here denoted Ma), not to be confused with gas dynamic Mach number M., The relative temperature of the jet (static) to the ambient must be maintained to keep relative densities the same. Again, this is not the same as total temperature ratio. Keeping these the same day after day when the ambient conditions range from 10°F to 90°F requires care. The particular method of specifying setpoints, attributed to Tanna et al. [5], produces a matrix of constant Ma and static temperature ratio. The matrix of reference 5 was slightly modified to lower the highest temperature ratio from 3 to 2.7 to accommodate limitations in SHJAR.

The SHJAR control system allows the operator to view the flow conditions of the rig in terms of the research variables, and displays the variance from the desired reading to assure that the proper setpoints are being set. Variance in both acoustic Mach number and static temperature ratio were monitored to be less than 0.5% in all test runs. A subset of the Tanna matrix which encompasses the subsonic test points described in this paper is given in Table 1.

Table 1 Flow setpoint conditions commonly used for subsonic jet noise studies.

Tanna Set Point	*Temp. Ratio T_j/T_{amb}*	*Acoustic Mach V_j/c_{amb}*		*Tanna Set Point*	*Temp. Ratio T_j/T_{amb}*	*Acoustic Mach V_j/c_{amb}*		*Tanna Set Point*	*Temp. Ratio T_j/T_{amb}*	*Acoustic Mach V_j/c_{amb}*
1	0.980	0.350		13	1.400	0.350		25	1.764	0.700
2	0.970	0.400		14	1.400	0.400		26	1.764	0.800
3	0.950	0.500		15	1.400	0.500		27	1.764	0.900
4	0.925	0.600		16	1.400	0.600		28	1.764	1.185
5	0.900	0.700		17	1.400	0.700		29	1.764	1.330
6	0.870	0.800		18	1.400	0.800		30	2.270	0.350
7	0.835	0.900		19	1.400	0.900		31	2.270	0.400
8	1.000	0.500		20	1.400	1.185		32	2.270	0.500
9	1.000	0.600		21	1.764	0.350		33	2.270	0.600
10	1.000	0.700		22	1.764	0.400		34	2.270	0.700
11	1.000	0.800		23	1.764	0.500		35	2.270	0.800
12	1.000	0.900		24	1.764	0.600		36	2.270	0.900

IV. Test hardware

The rig verification methodology pursued requires that spectra from different size nozzles all collapse to one spectrum when scaled to a common nozzle size. Three Acoustic Reference Nozzles (ARN) where designed for this purpose with some common characteristics: overall length, final straight section length, lip thickness, external nozzle angle, and cubic contraction profile. These also make the nozzles easy to define for CFD study. The nozzle family consists of a 1-inch diameter nozzle (ARN1), a 2-inch diameter nozzle (ARN2), and a 3-inch diameter nozzle (ARN3). It is important to note that, because the nozzles have the same contraction profile and overall length but different areas, the rate of contraction is not the same. CFD for these nozzle was not available at the time of design and, therefore no attempt was made to match flow characteristics such as boundary layer thickness or initial turbulence levels between the nozzles. Testing has shown that the flow characteristics, which appear very dependent on rate of contraction, are more important than the other geometric characteristics when trying to match the scaled acoustics, a point studied by Viswanathan[6].

During testing of jet reduction concepts a nozzle was designed that had a contraction style more similar to that used by industry, namely with a simple straight contraction cone. This also allowed the final section to be made removeable so various nozzle lip treatments could be tested easily[7]. This nozzle family had as its baseline the simple 2” diameter nozzle designated SMC000. This provided a fourth nozzle which helped shed light on the importance of the nozzle design in establishing a ‘baseline’ jet noise dataset. Figure 3 shows the design drawings for ARN1, ARN2, ARN3, and SMC000.

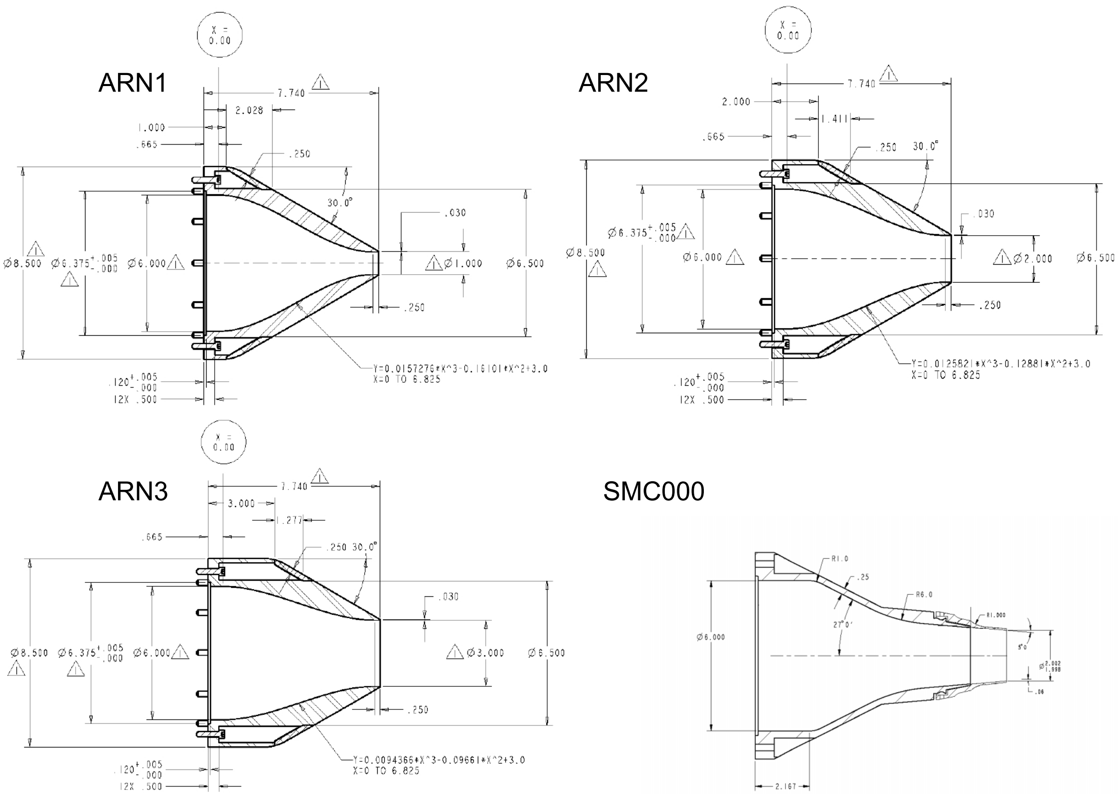

Figure 3 Drawings of Acoustic Reference Nozzles (ARN) used, and the straight contraction nozzle SMC000.

As will be covered later, the smaller acoustic reference nozzles were found to have nominally laminar exit boundary layers, causing anomalous noise signatures. These models were modified with a removeable boundary layer trip feature, a frustum of a cone made of 0.2” thick reticulated foam metal (Figure 4). This caused the exit boundary layer of the nozzle to exhibit turbulent boundary layer characteristics, adding a configuration to our study. We have also found that removing the fine mesh screen located 8” upstream of the nozzle also causes the boundary layer to be turbulent in ARN2, at least for cold flows. The configurations resulting from addition of the reticulated foam metal to nozzles ARN1 and ARN2 were referred to as AR1R and AR2R respectively.

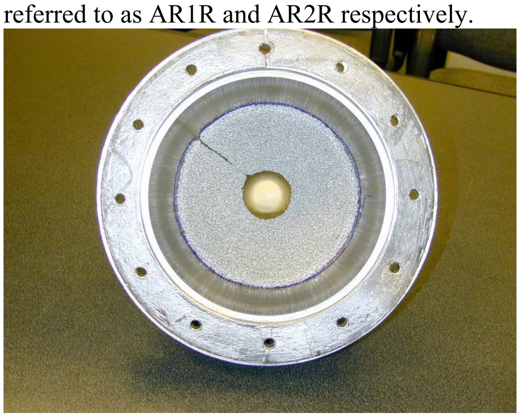

Figure 4 Reticulated foam metal inserted into ARN1 as a boundary layer trip device.

V. Modeling rig noise sources

The goal of a jet noise rig validation is to know the acoustic contribution of all noise sources at all flow conditions. To this end, techniques such as insertion loss, where components are removed from the rig, were used to map out the noise of each source. The sources being tracked at this time that could be measured in this manner include the background sound level, the muffler, the unfired combustor, and flow conditioning screens. Some sources are indirectly measured by independently changing other sources. For example, the valve noise was mapped out for each flow valve by running the rig at the same mass flow conditions with different (and without) nozzles. This is shown for the main control valve in Figure 5. Interestingly, valve noise was relatively independent of the backpressure and back reflection of the nozzle. As an aside, the direct transmission of valve noise to the microphones had to be addressed early on by the application of pipe wrapping around the valve itself and was not a main contributor to the overall valve noise in the end.

Among the sources not currently being modeled are the venturi, which is currently lumped in with the valve noise source, and the noise of the combustor. This latter source has recently arisen as a problem at high temperature, low flow rates due to a design change which solved a problem of combustor liner burnthrough. This points up the need to go back and confirm the rig noise source models periodically as these may change due to small, apparently insignificant changes to the rig.

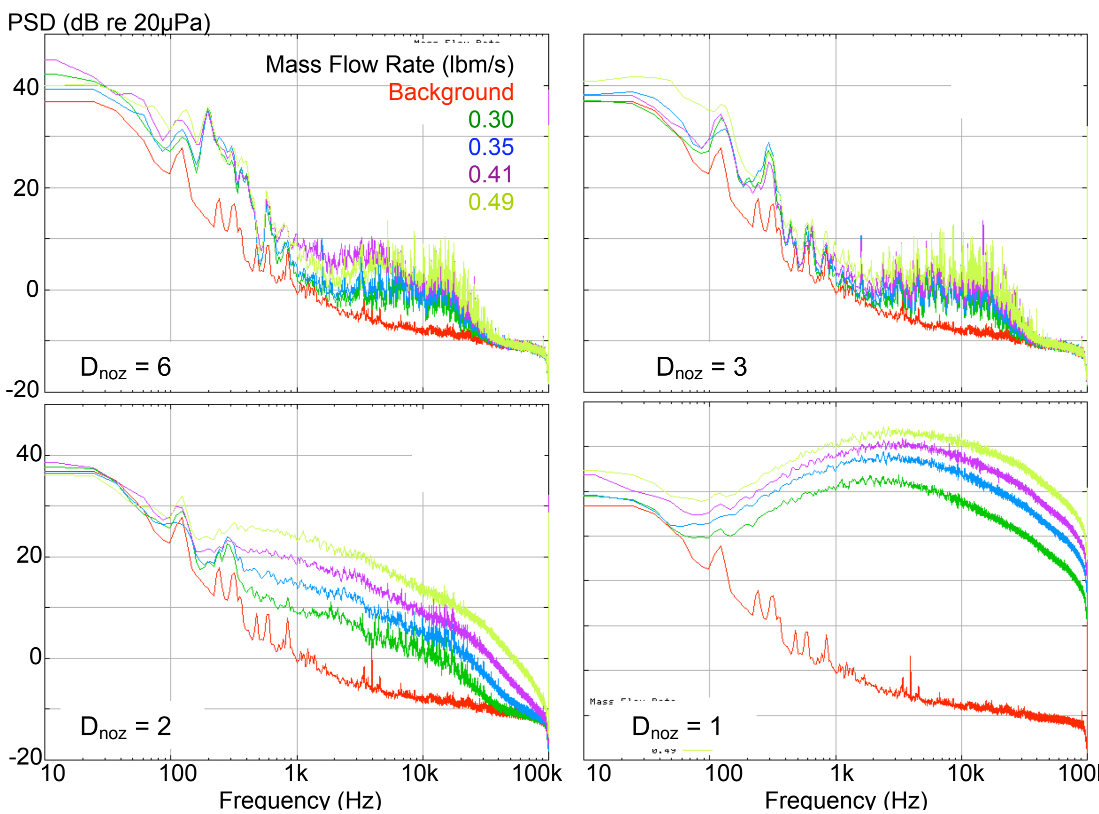

Figure 5 Raw spectra at 90° for different nozzle diameters run at the same mass flows to determine noise contribution of the main control valve. Raw power spectral density dat acquired at 100" distance from jet.

D. OASPL model

A simple test to show the general bounds of where the rig noise relative to the jet noise is plot OASPL vs velocity and compare with the well-established U^8 law. As pointed out by Viswanathan[1], this is not a rigorous test, but serves to show the salient scaling parameters. In a the OASPL of the 90° microphone are plotted before noise control components of the rig were put into place. Here various combinations of control valves were used to obtain the flow, showing the strong contribution of the valve noise. b shows the

OASPL after noise reduction features were applied for various nozzle sizes. The 6” no nozzle case deviates strongly from the scaling law at all subsonic jet velocities, while the 1” ARN1 nozzle hugs the scaling law line until it runs into the background sound level of the facility around Ma=0.2.

Spectral models have been worked up for the various noise sources which show that, for a 2” nozzle, all rig-related noise sources are more than 6dB below the jet noise for flows above Ma=0.4. The only caveat to this is that the very highest temperature points now have a combustor rumble evident at Ma less than 0.7.

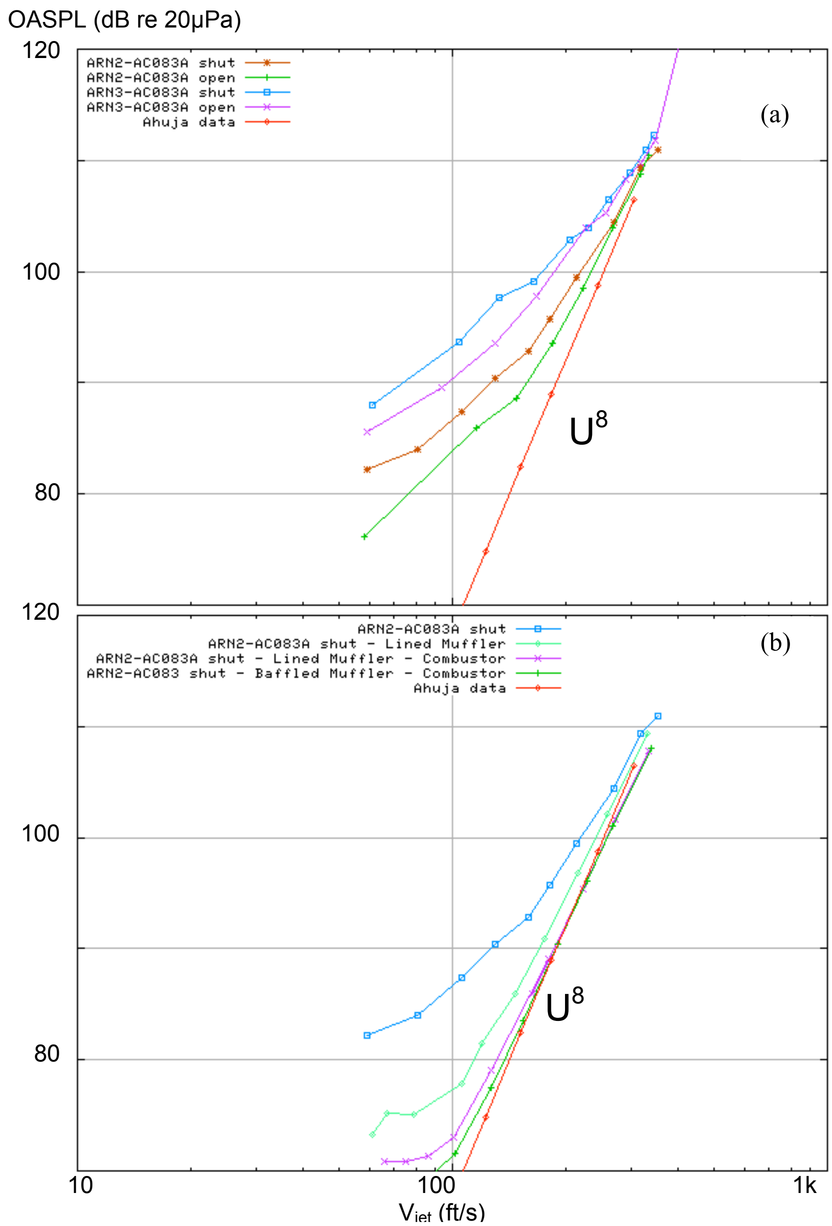

Figure 6 OASPL at 90° vs V_{jet}—comparison to U^8 scaling. (a) Different valve combinations being used before acoustic muffler and other rig noise reduction devices in place. (b) Different nozzles (including no nozzle) from 1” to 6” diameter after rig noise reduction devices in place.

VI. Repeatability and expected variance

As part of creating a database of fundamental data, one has to determine the expected error, both in accuracy and precision of the measurements. Accuracy has been addressed by identifying and modeling rig-related noise sources. Precision can be addressed either by working up the uncertainties in each component of the final answer or by direct repeatability measurements. First we consider the known sources of uncertainty in the measurements of jet noise in SHJAR.

Consider four sources of uncertainty. First is the uncertainty in the calibration of the microphones, which for the Bruel & Kjaer 4220 pistonphone is given as 0.15dB at 250Hz. The spectral response calibration done by the manufacturer is guaranteed to within 0.25dB across the useable spectra. The second uncertainty considered is in measuring atmospheric conditions which feed the calculation of atmospheric attenuation. This turns out to be rather small, ~0.1dB, given the measurement uncertainty of 1°F, 2% relative humidity, and it only impacts the very highest frequencies, e.g. the last few one-third-octave bands. The third source of uncertainty is in setting the jet flow conditions. We maintain a 0.5% tolerance on the jet velocity as part of our test procedure and have calibrated transducers that assure us that we are within that error band. This translates into an uncertainty of +/-0.17dB. The fourth uncertainty considered is that of the averaging of the spectral data. Using chi-square analysis on one-third-octave bands, which are the result of many narrowband estimates of power spectral density, the biggest uncertainty comes at the low frequency end where there are relatively few narrowbands being integrated over to obtain the statistic. Here, at a 90% confidence interval, the uncertainty for the roughly 450 sample measurement (5 narrowbands with 90 ensembles each) is +/-0.33dB. As each one-third-octave band picks up 1.25 times as many samples as the previous band, within a decade the value is +/-0.1dB. Summing these uncertainties, we see that at the lowest bands we have 0.35 + 0.17 + 0.33 = 0.85dB uncertainty. This reduces to below 0.5dB by mid-frequency and then increases at the highest bands up to 0.35 + 0.1 + 0.17 + 0.03 = 0.65dB on the last band.

In practice, repeatability is usually somewhat better than these worst-case scenarios if care is taken, Figure 7 is an example of data taken over a period of two years on the same nozzle at the same setpoint, a cold Ma=0.9 case. Both 90° and 150° polar angles (measured from upstream axis) are shown along with details of the critical areas of the curves. From these curves we have come to expect a repeatability of roughly 0.5dB in the third octave spectra. These data span variations in ambient condition of 27°F – 52°F and 25%-87% relative humidity.

VII. Comparisons with other rigs

Having downplayed the value of comparisons of jet noise between rigs as a measure of rig quality, some comparison of SHJAR results with other rigs is in order. Of particular note here is the extensive dataset of Tanna et al[5]. This is particularly appropriate having adopted the test matrix for the current work. Figure 8 presents comparisons of the Lockheed Georgia data with that acquired in SHAJR using the SMC000 nozzle, concentrating on two key polar angles (90° and 150° inlet angles), three temperature ratios (cold, 1.76, 2.27), and two acoustic Mach numbers (Ma=0.5, 0.9). In the detailed documentation accompanying the cited test report, exact rig and ambient conditions were given; the data shown here have been adjusted to the nominal set points using simple U^8 scaling. This involved a maximum of 0.6dB change, but when comparisons are this tight, having the exact flow condition becomes critical.

While there is surprisingly good agreement at 150° and at low frequencies at 90°, it is the disagreement near the peak and at higher frequencies that catches one's attention in the plots. Interestingly, this disagreement disappears at the highest temperature, Ma = 0.9 (setpoint 36), where the two data cases agree to within a fraction of a decibel nearly everywhere. In the Ma = 0.5 high temperature cases (setpoints 23 and 32), however, there is a definite disagreement at high frequencies, especially at 90°. This will be addressed in the next section.

One other comparison is in order. Given the very thorough work of Viswanathan and his comparison to the Tanna data, we have added our data to Figure 5 from his paper and reproduced it here as Figure 9. Interestingly, our data acquired using the conic SMC000 nozzle falls somewhere between the data given in his paper, but has a stronger fall-off with frequency. Based on what follows it seems likely that the discrepancies in spectra are due to differences in the nozzle design, although all three data sets were acquired with a 2" diameter nozzle.

In the preceding sections we have shown how we have taken care to assure that the noise measured in SHJAR at these conditions is not contaminated by rig and facility noise. In this section it has been shown that the SHJAR data agrees within some error band of other highly regarded datasets (actually splitting the difference in the cold jet comparison). In the next section we will show that level of disagreement found in the low temperature comparisons is quite reasonable due to small differences in the flow near the nozzle, differences which stem from different nozzle designs and even different flow conditioning. The reasoning would also explain the discrepancies noted for low speed, high temperature cases as well.

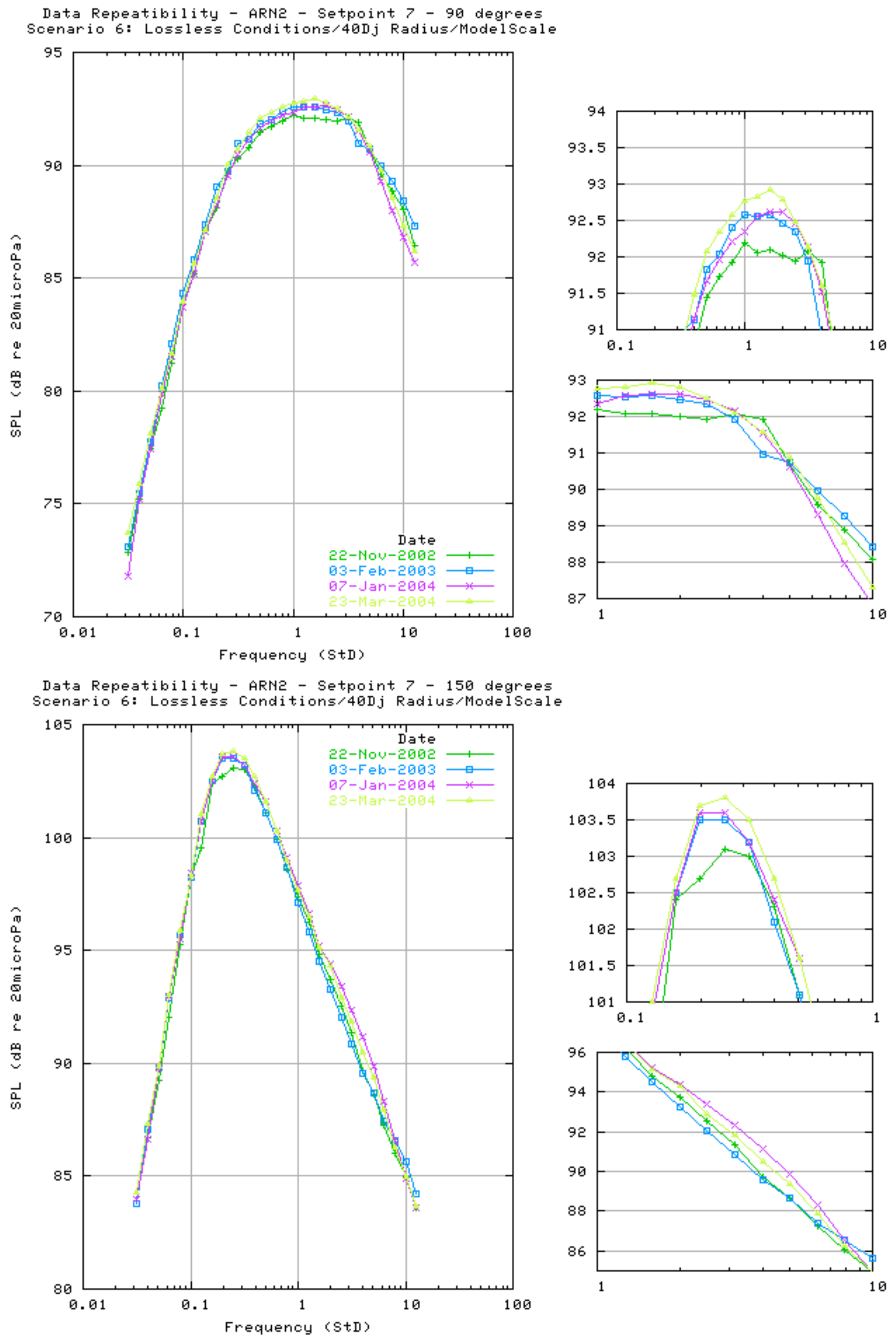

Figure 7 Data repeatability for the ARN2 nozzle at set point 7 (M_a=0.9, cold) at the 90 degree (top) and 150 degree (bottom) microphone locations. The data is scaled to a distance of 40×(jet diameter) in a lossless condition. Strouhal frequency scaling is also applied. These data were acquired during tests from 2002 to 2004.

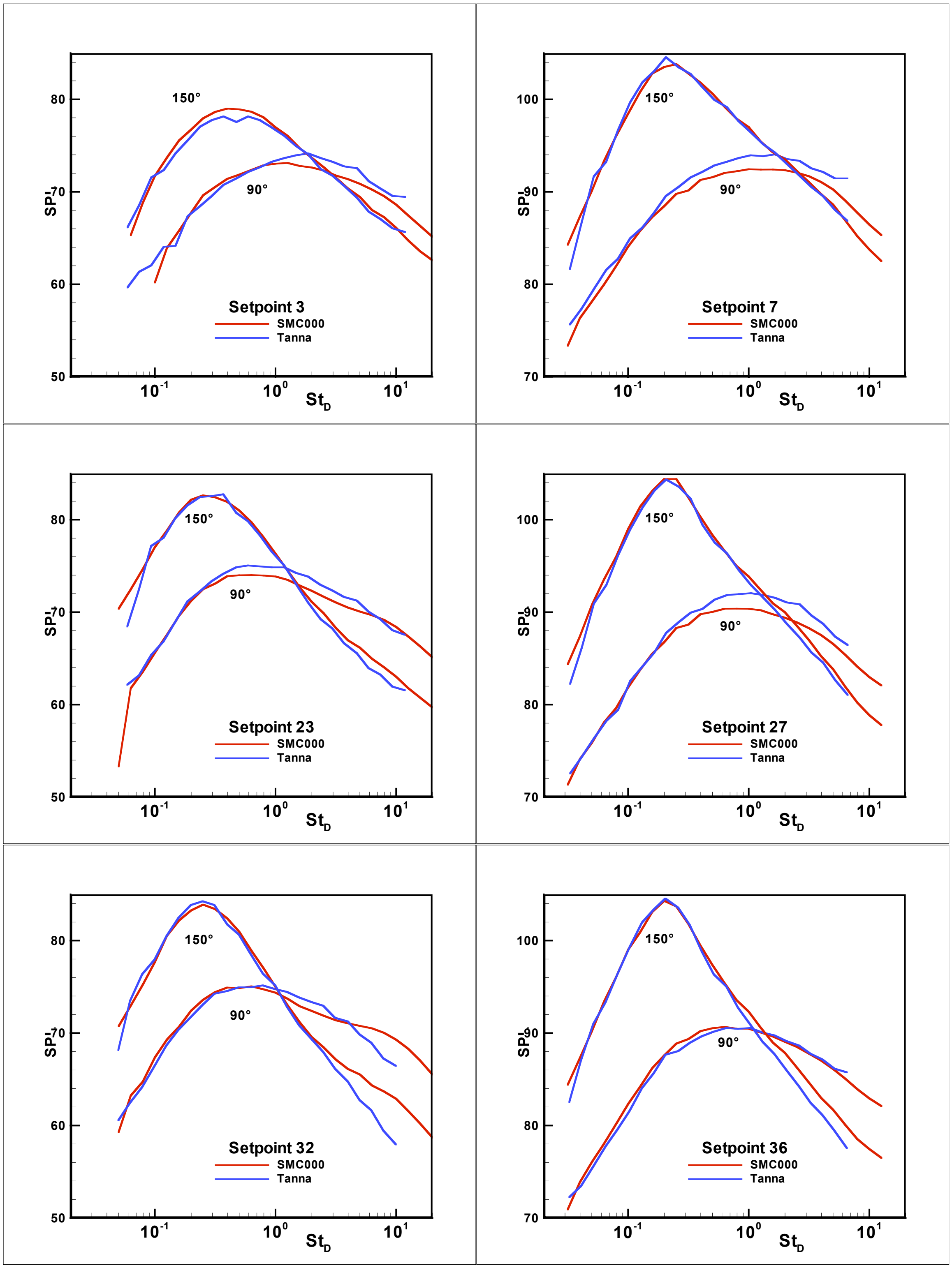

Figure 8 Comparisons of 1/3 octave spectra from Reference 5 and SHJAR for Ma=0.5 (left column), and Ma=0.9 (right column). Cases in rows are different static temperature ratios: cold, 1.76, 2.27. Data normalized to 40 jet diameters distance.

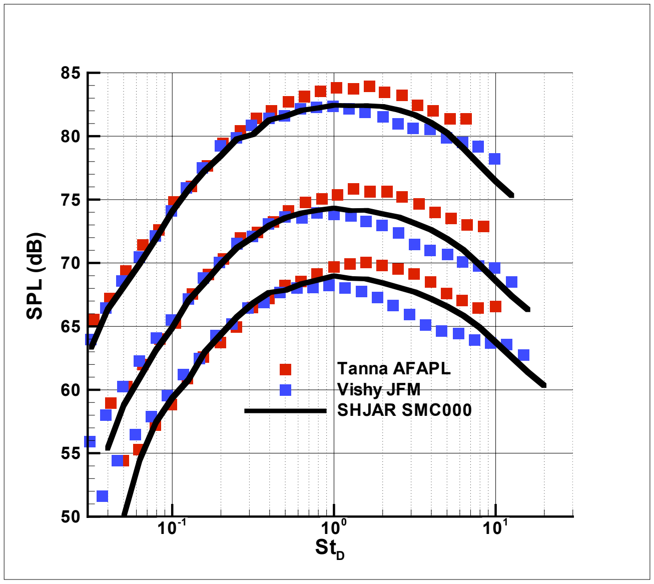

Figure 9 Comparison of 1/3 octave jet noise spectra 2" diameter jets at 90° emission angle. Data from reference 8, reported as having atmospheric attenuation removed, plotted vs. Strouhal number. Curves (from bottom) are for Tanna setpoints 4, 5, and 7. Data plotted at 12 foot distance from jet.

VIII. Nozzle-dependent spectra for 'round jets'

As was stated in the beginning, the goal of jet noise experimentalists is to make measurements in small scale rigs which directly scale up to measurements one would make at full-scale without the cost of full-scale tests. That is, one would want to show that one's results are scale-independent.

When SHJAR was first being put through its paces with the different size ARN nozzles, the data were processed as explained above and should have collapsed into a single curve for any given flow condition. In the beginning there were issues with rig noise sources which contributed differently for the different size nozzles. But as the rig was made quiet, (and when the largest nozzle as measured at a large enough distance to be in the geometric far-field) some interesting differences in noise from the different nozzles were noted. This was particularly true of the smallest nozzle, ARN1. Figure 10 shows raw spectra from the 90° microphone at a succession of Ma, beginning with Ma=0.2 and proceeding to Ma=0.6. The 'haystack' which peaked at roughly 8kHz at Ma=0.2 clearly increases with flow velocity but not linearly in frequency as it would if it were a typical shedding noise from some rig component. Indeed it actually scales as the square of the velocity.

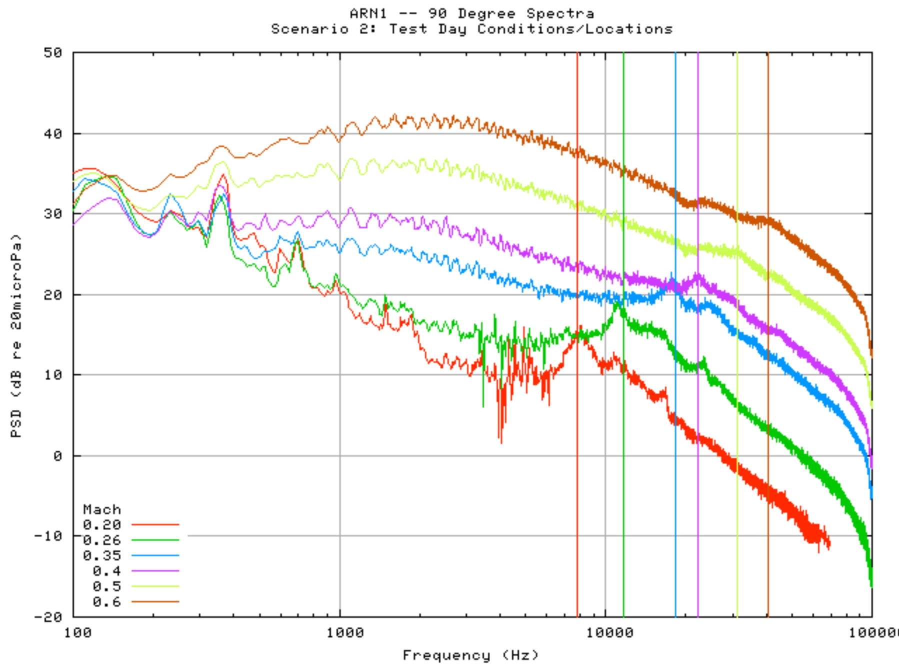

Figure 10 Raw sound spectra from ARN1 at 90° with various Ma (0.2, 0.26, 0.35, 0.4, 0.5, 0.6). Vertical colored lines track the peak of the anomalous acoustic source traced to the laminar initial shear layer. Raw power spectral density dat acquired at 100" distance from jet.

The issue is actually one of lack of Reynolds number invariance. Specifically, the spectral haystacks in Figure 10 can be identified as occurring at the subharmonic of the initial shear layer instability for the initially laminar shear layer. Subsequent hotwire measurements confirmed this. A paper by Zaman[9] serves as a fine reference for understanding how nozzles which relaminarize through their contraction and do not retransition to a fully turbulent state do not exhibit similar jet noise spectra. Perhaps the most extreme example of this is the high Mach, low Reynolds number (3,600) jet studied by Stromberg et al.[10] which purely laminar at its exit. What is further a problem not addressed in these papers is that hot flows relaminarize more readily, meaning that this is a big problem for small hot jets with strong contractions and short nozzles. This is probably the reason for the greater disagreement at high frequencies and low speeds between jet rigs with small nozzles.

To directly remove this 'source', comparable to the insertion loss methods employed while identifying rig noise sources, a boundary layer trip mechanism was arranged. Because the trip would have to withstand high temperatures, a metal open-cell foam sheet was used to roughen the boundary layer. The sheet was laid inside the nozzle, stopping at an axial location where the nozzle was twice the exit area, giving the flow time to reattach and settle before exiting. Hotwire measurements documented how the cold flow turbulence in the boundary layer increased from less than 0.5% to roughly 4%, in line with asymptotically turbulent boundary layers. And noise measurements showed that the 'haystack' was removed from the noise spectra. However, applying the trip to ARN1 (called AR1R) and ARN2 (AR2R) did not cause them to collapse on to a curve with each other or ARN3. In addition, the nozzles had changed their discharge coefficients, making comparison even more difficult. Finally, the straight contraction nozzle SMC000 was also tested and showed yet other slight differences in spectral detail. These differences, as seen in Figure 11, are pervasive and affect most of the noise spectrum by 1-2dB. This in spite of the fact that the plenum conditions have been set to produce flows with sound fields shown previously to be repeatable to within 0.5dB.

Upon reflection it seems not unreasonable that such variations can take place among nozzles of different design, especially with different initial shear turbulence intensities and velocity profiles. After all, we all hope that we can find some variation of initial condition that makes jets quieter! However, this causes a problem for efforts at producing a small jet which simply scales to a full-scale exhaust nozzle. Clearly, more careful exploration will be required to understand how subtle variations in flow create the observed variations in sound. And to create an appropriate small-scale nozzle which properly mimics full-scale behavior so that useful explorations of noise reduction concepts can be carried out economically.

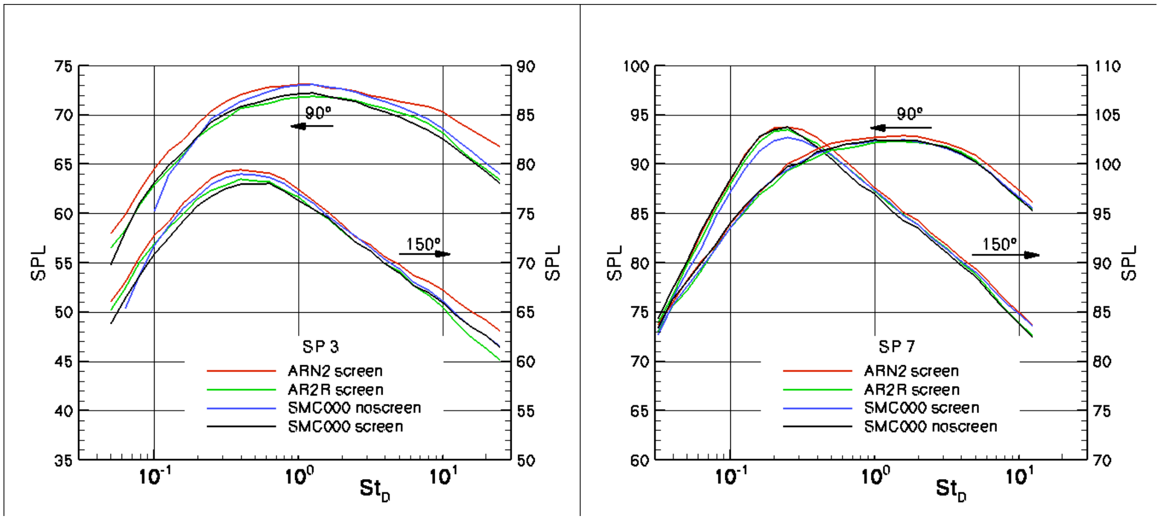

Figure 11 Spectra at 90° and 150° for various 2" diameter nozzles (ARN2, AR2R, SMC000, SMC000 with flow conditioning removed). (a) Ma=0.5, cold, (b) Ma=0.9, cold. Data normalized to 40 jet diameters distance.

IX. Conclusions

A new Small Hot Jet Acoustic Rig (SHJAR) has been established at NASA's Glenn Research Center. The rig is aimed at fundamental flow and acoustic studies of jet noise and at providing low cost experiments on noise reduction concepts with hot flow. The rig was designed following the advice of jet noise experts and a course of validation was pursued to assure that research results are not contaminated by rig noise and poor test technique. In the process, a large amount of flow and sound data have been acquired, extraneous noise sources have been identified and modeled, and the rig has shown repeatability in jet noise third octave spectra of less than 0.5dB.

Although the measured 'baseline' jet noise spectra agree to within the repeatability of similar nozzles tested in historic rigs, it has also been discovered that such comparisons are inherently flawed unless more care is taken to replicate the upstream unsteady flow condition and the nozzle contraction details. This has been shown by finding reproducible differences between sound fields of different nozzles with features which change the initial shear layer turbulence, flows which are typically considered to be the same for modeling purposes. The validation study has clearly demonstrated the need for more detailed understanding of the flow-sound relationship, and the need for detailed documentation of the flow field along with sound spectra when creating a jet noise database.

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[1] Viswanathan, K., "Jet aeroacoustic testing: Issues and Implications," *AIAA J* Vol. **41**, 2003, pp. 1674-1689.

[2] Ahuja, K.K., "Designing clean jet-noise facilities and making accurate jet-noise measurements," *Int'l J Aeroacoustics* Vol. **2**, 2003, pp. 371-412.

[3] Bridges, J. & Wernet, M.P. "Measurements of the aeroacoustic sound source in hot jets," AIAA 2003-3130 (2003).

[4] Koch, L.D., Bridges, J., Brown, C.A., and Khavaran, A., "Experimental and analytical determination of the geometric far field for round jets," to appear in *Noise Control Eng. J.,* 2005.

[5] Tanna, H.K. et al. *"The generation and radiation of supersonic jet noise, part III, Turbulent mixing noise data,"* AFAPL-TR-76-45, 1976.

[6] Viswanathan, K., and Clark, L.T. "Effect of nozzle internal contour on jet aeroacoustics," *Int'l J Aeroacoustics* Vol. **3**, 2004, pp. 103-135.

[7] Bridges, J. and Brown, C.A., "Parametric testing of chevrons on single flow hot jets," *AIAA paper 2004-2824*, 2004.

[8] Viswanathan, K., "Aeroacoustics of hot jets," J Fluid Mech, Vol. 516, 2004, pp. 39-82.

[9] Zaman, K.B.M.Q., "Effect of initial condition on subsonic jet noise," *AIAA J* Vol. **23** 1985, pp. 1370-1373.

[10] Stromberg, J. L., McLaughlin, D. K., and Troutt, T. R., "Flow field and acoustic properties of a Mach number 0.9 jet at a low Reynolds number," *J. Sound Vib*. Vol. **72**, 1980, pp. 159-172.