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Development of a near-field acoustical holography system for aircraft jet source noise measurements

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ABSTRACT

Military jet aircraft are exposing both ground maintenance personnel and the community to high levels of noise. The US Department of Defense is funding research to develop advanced modeling tools for noise reduction techniques and community noise exposure. For these tools to achieve their full potential, innovative measurement and analysis methods are necessary to characterize the jet noise source region. To meet this need a portable near-field acoustic holography (NAH) system is under development to characterize full scale jet noise emissions. This paper will describe the basic design of the measurement array and data acquisition system for the NAH system, which will employ a patch measurement approach. With the patch measurement approach, multiple NAH reconstruction techniques can be used in tandem to provide improved confidence in the resulting reconstructions.

1. INTRODUCTION

Advanced modeling tools are being developed to address the overall military jet noise problem[1,2], however, the lack of understanding of the actual jet noise source has been identified as a limiting factor. Near-field acoustic holography (NAH) offers the best general method to measuring the magnitude, directivity, and spectral content as well as the spatial distribution of the noise emitted from a jet. This detailed characterization of the jet noise may be used in projects such as environmental noise modeling, occupational noise exposure, and source noise

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reduction for military aircraft. If successful, this system will be used to reduce the testing time required for military aircraft noise characterization by allowing more detailed measurements to be made during ground run-up tests as opposed to dedicated flight tests. Moreover, this technology can be applied to commercial aircraft and proposed supersonic business aircraft to help evaluate and assess jet noise reduction methods.

2. APPROACH

NAH enables the mapping of complex pressure measurements at one set of locations to another set of locations via a propagator. The application of NAH processing to the characterization of a full-scale jet plume environment and the development of an appropriate measurement array poses several technical and logistical challenges. Accurate characterization of the near-field of a military jet aircraft requires the ability to record sound pressure levels up to 170 dB and frequencies from 5 Hz to 30 kHz. In addition, measurements must be made along the entire length of the plume. The NAH system must be semi-portable due to the limited set of locations where military jets can perform static high power engine run-ups. The system must integrate the technical requirements for NAH with the environmental conditions and the safety constraints involved with jet noise measurements.

For the system presented here, measurements are taken along the plume from the nozzle to a point downstream. The endpoint of the measurements is designed to capture the dominant noise emission based on the maximum sound emission angel from the plume. The measurement array is aligned parallel to the shear layer of the jet flow and placed as close to the shear layer as possible. A schematic of the measurement area is shown in Figure 1.

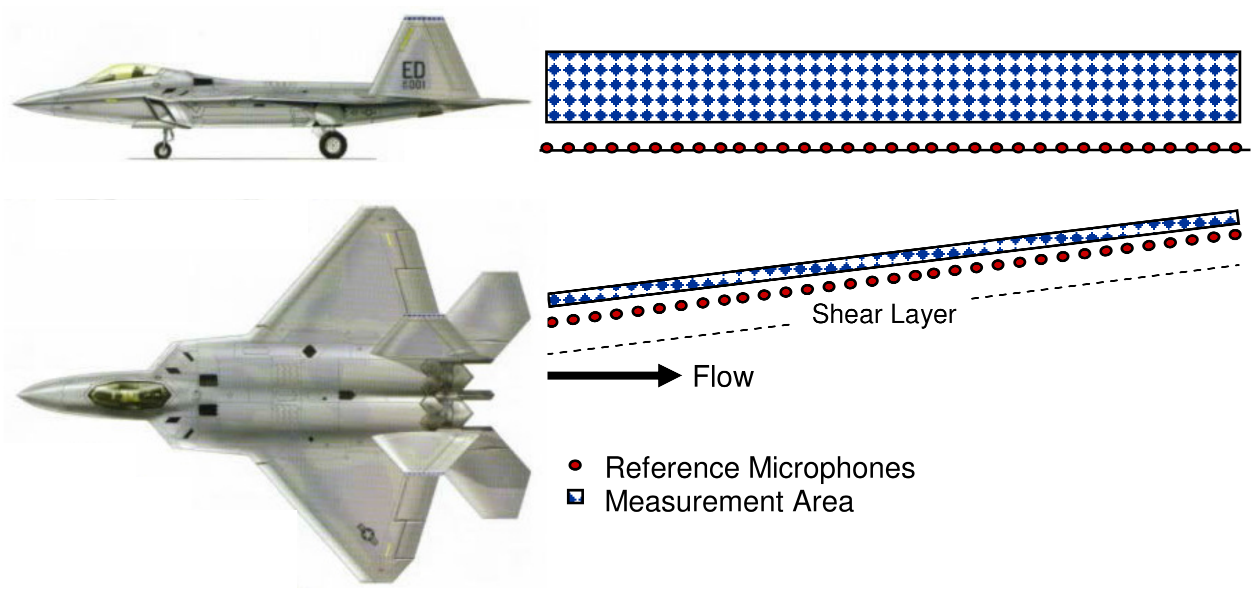

Figure 1. Plan and top view schematic of jet plume acoustic measurement area of interest.

Traditional Fourier holography techniques require that the measurement array area must be four times the size of the source, yet the microphone spacing can be no larger than half the wavelength of the highest frequency of interest. This restriction can lead to a prohibitively large microphone array (thousands of microphones) for extended sources where moderately high frequencies are of interest (e.g., a full-scale jet). To allow for characterization of the entire plume with a limited number of microphones, the “patch” holography measurement approach will be employed to reduce the measurement grid area.[3-8] In NAH, a patch holography method is one in which the entire source is not entirely surrounded with measurement microphones. Instead, measurements are made over multiple patches along the source region and used to reconstruct the noise sources in the vicinity of the patch. Patch NAH has been successfully used in the reconstruction of discrete portions of vibrating sources, where the size of the source and desired reconstruction frequency preclude surrounding the source with microphones.

Based on our Phase I measurements[9] and the findings of Lee and Bolton,[10-12] we have determined that a patch and scan based measurement approach is feasible for field measurements of full scale jet noise. The array will extend over a large ‘patch’ of the source field and will be moved parallel to the plume’s shear layer. This patch based scanning NAH system decreases the required number of microphones but increases the number of measurements and engine run time. Because scanning NAH measurements are not synchronized in time, stationary reference microphones must be used. Transfer functions are calculated between the reference and the array microphones to define the relative spatial phase relationship between measurements made on the holography plane. The patch measurement approach will also enable multiple NAH reconstruction techniques to be used in tandem to provide improved confidence in the resulting reconstructions.

For a coherent structural source, only one reference microphone is required to implement scanning NAH. However, in a jet, finite correlation lengths exist because of turbulence that begins to form, grows, and then decays as it is convected downstream. To address this type of source using NAH, Lee and Bolton[10-12] have implemented the “virtual coherence” technique which uses multiple reference microphones. This method breaks up the noise field into a number of mutually uncorrelated sound fields and then NAH is applied to each one. The resultant NAH-reconstructed fields can simply be added together on an intensity basis because each field is uncorrelated and thus orthogonal.

The findings from our Phase I measurements[9] provided insight which assisted in the development of the Phase II NAH measurement system. The engine power levels were restricted to intermediate power settings. The microphone array and the resulting sound pressure spectra recorded at 3.6 m off the centerline are presented in Figure 2. The spectra is plotted as a function of distance from the nozzle exit plane. As expected, the peak frequency decreases as the distance downstream increases as the turbulent structures within the plume increase in size. Based on these measurements it was determined that NAH measurements must be made over a length exceeding 20 m for this jet at military power to ensure the dominant features of the jet are captured.

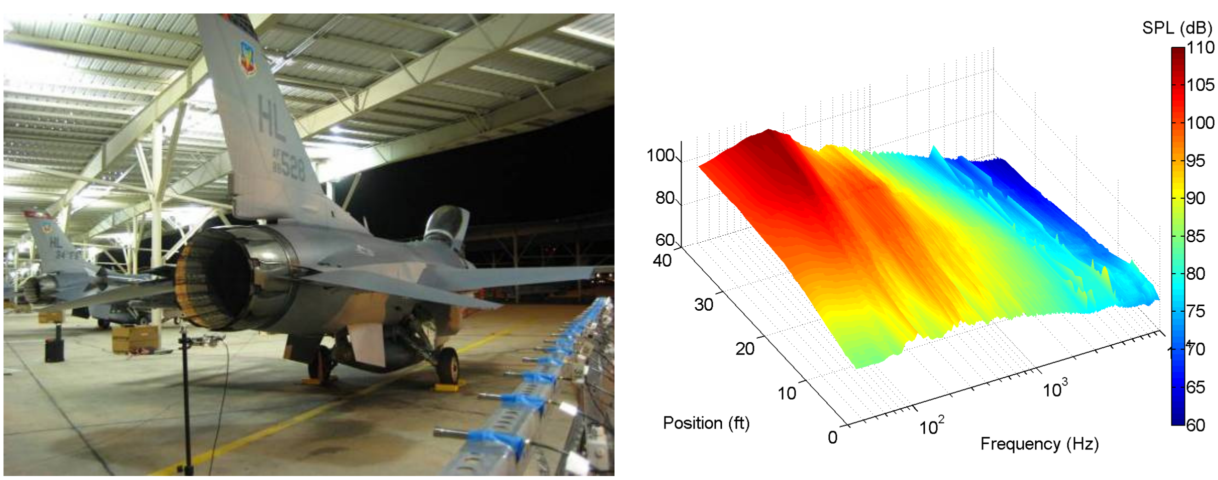

Figure 2. F-16C microphone array on left, SPL map of plume on right.

For patch measurements made over a limited length at a time, the number of reference microphones depends on the number and location of coherent sources. To gain insight into this issue, measured sound pressures were cross correlated and the peak correlation coefficient plotted as a function of separation distance. The Phase I measurements indicate small scale sources with a short correlation length near the nozzle exit plane (high frequencies). Downstream of the nozzle exit plane the correlation length increases noticeably.

Ground reflections in the measured data are complicated because of the extended source. The NAH array height and offset from the shear layer are constrained to minimize the effects of ground interference on the peak frequencies of the jet. In addition, reference microphones are placed at or near the ground to avoid ground interference at lower frequencies. Figure 3 shows a comparison of the spectra measured at the same location and power setting at 1.5 m and 0.038 m off the ground. The spectrum measured near the ground demonstrates constructive interference at low frequencies; the spectrum at 1.5 m shows a broad destructive interference dip from 150-250 Hz. Further analysis revealed low levels of coherence occur between the two sets of microphones at the dip. This result drove the decision to place the reference microphones on the ground to maximize the coherence between microphones.

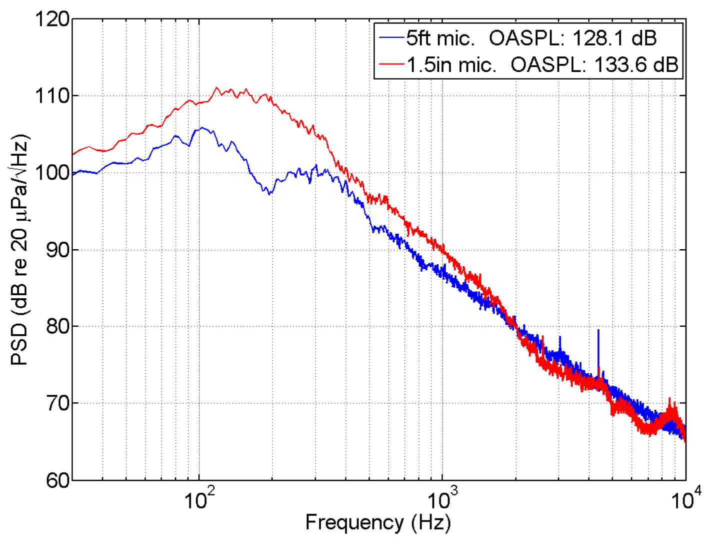

Figure 3. Comparison of spectra measured at the same downstream and lateral position, at heights of 5 feet (1.5 m) and 1.5 inches (0.038 m).

Finally, the spikes present in the 1.5 m spectrum in Figure 3 were caused by structural resonances of the rig. The design of any measurement rig must consider its structural response to minimize resonances of this type. Because of this, a dynamic analysis of the Phase II structure was conducted to insure the rig is not acoustically receptive and that significant structural resonances are not excited by the sound field in which it operates.

3. DESIGN OF NAH MEASUREMENT SYSTEM

One major design requirement for this high channel test rig was simplicity in design and packaging to minimize setup time and cost. The specifications required the system to fully characterize the near-field of a high amplitude jet noise source. This specification requires an overall measurement system that can measure levels up to 170 dB and a frequency bandwidth of 5 Hz to 30 kHz. In order to measure a surface large enough to characterize the entire jet noise source with fewer than 122 microphones, a scan based microphone array with stationary reference microphones was proposed. A conceptual drawing of the module array is shown in Figure 4.

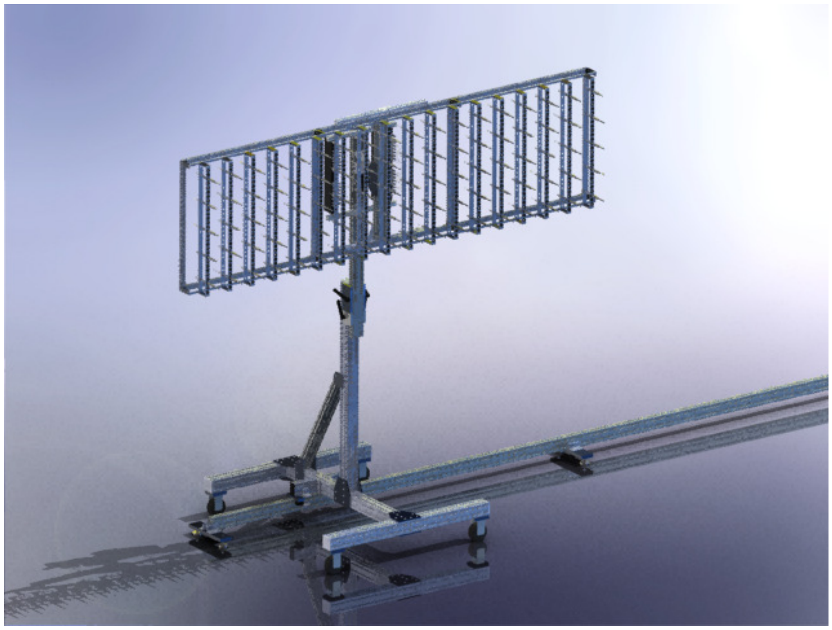

Figure 4. Conceptual image of the test rig structure positioned with the microphone array in its highest horizontal configuration.

Our NAH measurement system uses a 2-dimensional microphone array of 90 microphones which moves along the jet plume on a plane parallel to the shear layer through the use of four wheels and a guide rail as shown in Figure 4. The required measurement area will be broken up into multiple patches the size of the 2-dimensional microphone array. Use of a guide rail sets the position and orientation of the array using pins at infinitely adjustable predefined positions along the rail and allows for precise location of the test rig along the plume. The wheels of the test rig also may be locked into place. The support assembly's rails have rubber padded leveling feet.

The microphone array may be positioned in a horizontal or a vertical configuration shown in Figure 5. This system uses the horizontal configuration to minimize the time required to measure the length of the plume but offers the flexibility of detailed vertical profiles using the vertical configuration. The vertical measurements may help in understanding the effects of the ground plane. The center height of the microphone array is also adjustable between 0.91 m to 2.13 m from the ground to account for the nozzle height difference of the current fleet of fighter jets. In addition, the height adjustment allows alteration of the frequencies impacted by the ground interference dips (evident in the spectra in Figure 3). The microphone array pictured has a nominal spacing of 0.15 m for both the vertical and horizontal planes. However, the array spacing is adjustable in 0.05 m increments. A spacing of 0.15 m limits NAH frequencies to about 1.1 kHz due to the two measurements per-wavelength restriction.

The array design employs three separate microphone panels which break the array up into a smaller package for shipping, assembly, and setup flexibility. Each panel has a 32-channel breakout box located on the panel with 30 channels dedicated to microphones and two channels dedicated to accelerometers or meteorological sensors. This modular design allows for the individual array modules to be packed and shipped assembled with the cables, connectors, and microphone mounting assemblies intact. This feature minimizes set-up, cable runs, and connections required in the field.

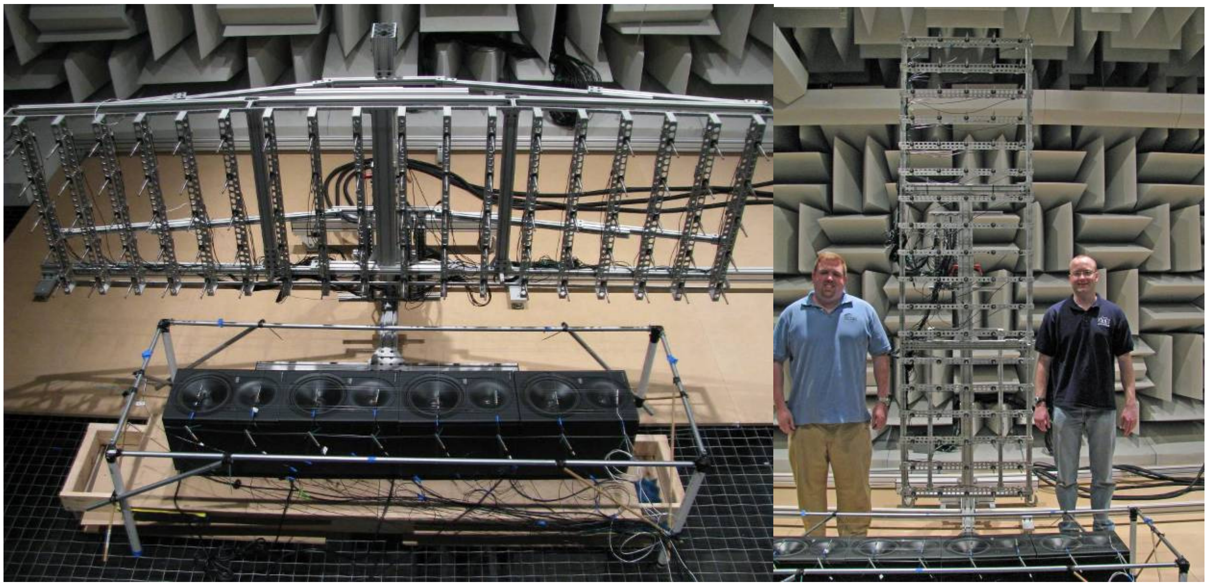

Figure 5. NAH measurement system pictured in horizontal configuration on left, and vertical configuration on right.

Additional reference microphones will be located at fixed locations along the source length. The number of reference microphones needed increases as the upper frequency of interest increases. Research is ongoing to guide the selection of the quantity and location of reference microphones. As many as 32 reference microphones will be used during tests with subsets of the data examined to determine the actual number required.

4. INSTRUMENTATION

The sensors, hardware, and software design has been developed in conjunction with our manufacturing partners: National Instruments (NI) and G.R.A.S. Sound & Vibration. These companies are world leaders in data acquisition hardware and sensors and have provided personnel to assist in the development and benchmarking of the test rig. All proposed instrumentation has been developed from standard off the shelf equipment, which will lower costs for both the initial system and its long-term maintenance.

The heart of the measurement system is a NI PXI data acquisition system chosen for its flexibility, scalability, and cost effectiveness. The ability to scale the number of data channels and microphones provides the ability to increase the surface area of the patch and therefore decrease measurement time. The overall design of the Dynamic Signal Acquisition (DSA) boards along with the microphones result in a frequency response of up to 204.8 kHz (although this may require a limited number of channels or additional equipment). An overview of the instrumentation chain from microphone to hard drive is shown in Figure 6.

The high amplitude pressure measurements are made by pairing a ¼ inch (6.35 mm) G.R.A.S. 40BE free-field microphone with a 26CB preamplifier. This microphone-preamplifier pairing has a frequency response of 4 Hz – 100 kHz ± 3 dB. Two design modifications customized the sensors for this specific application. The microphones were designed to have a nominal sensitivity of 1 mV/Pa allowing measurement of levels of up to 170 dB. In addition, the preamplifiers neck from the ¼ inch microphone to a ½ inch (12.7 mm) female BNC connector to minimize cable connections. The constant current preamplifiers are powered by the IEPE conditioning onboard the data acquisition system.

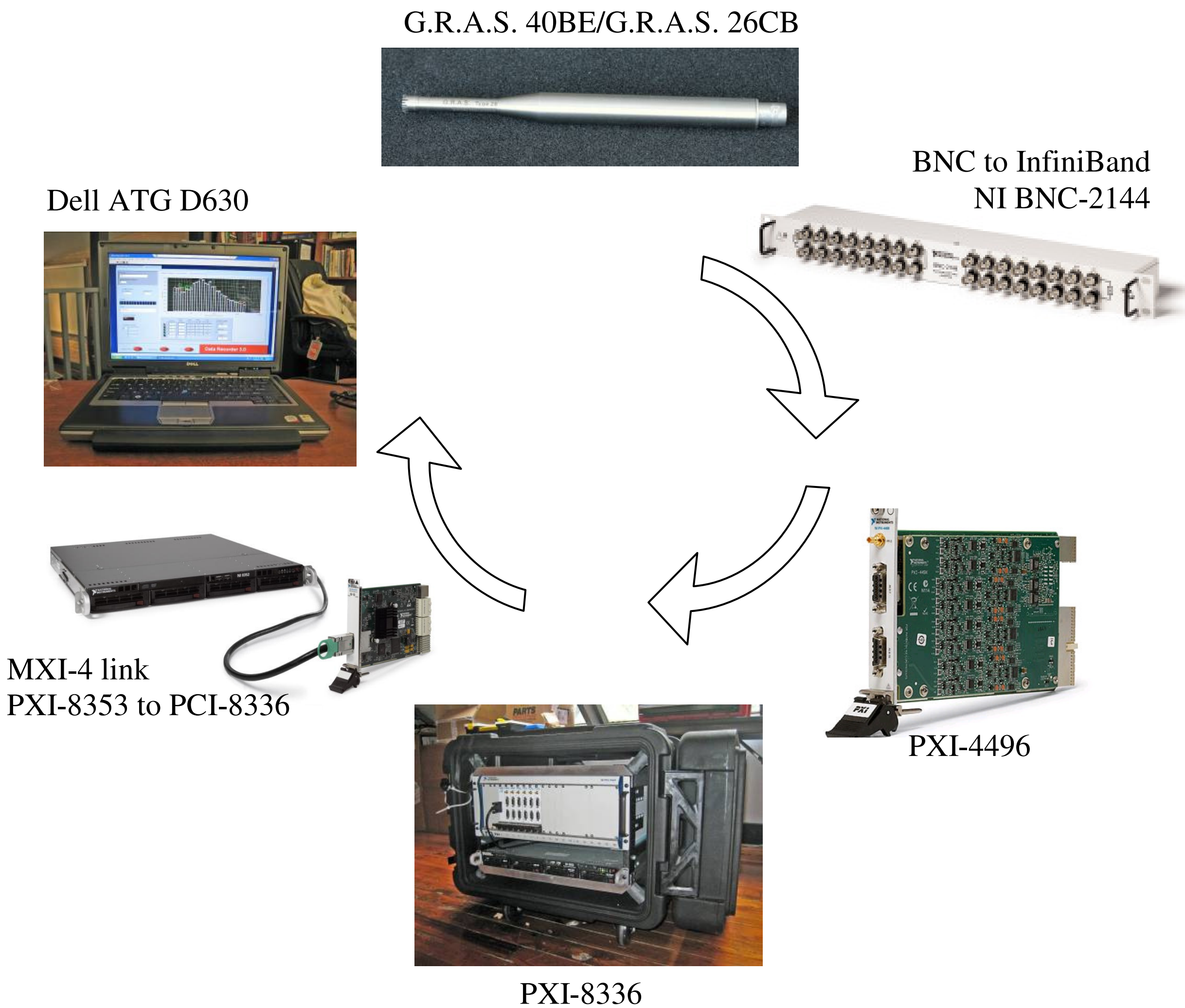

Figure 6. Measurement instrument chain from microphone to hard drives.

The signals from eight microphones will be routed through a NI BNC-2144 BNC to Infiniband breakout box to a single InfiniBand connecter which will connect directly to the DSA board. This grouping will limit the number of cables and complexity of the system by running one InfiniBand cable for every eight channels. Two InfiniBand connectors will be connected to each DSA board for a total of 16 channels per board. InfiniBand is a point-to-point bidirectional link intended for the connection of high speed peripherals and can support aggregate data rates of up to 8 Gbps.

The time waveforms from the microphones will be recorded on a multi-channel data acquisition system built on the NI PXI platform. The PXI chassis include nine 16 channel NI PXI-4496 DSA boards with simultaneous sampling to insure correct phasing of all 122 channels. With sixteen 24-bit analog inputs per module and IEPE constant current signal conditioning, the DSA modules are ideal for making precision microphone measurements. The modules deliver 113 dB of dynamic range and simultaneous sampling on all 16 channels at rates up to 204.8 kS/s. In addition, the modules include built-in antialiasing filters that automatically adjust to the sampling rate and software selectable input gains of up to 20 dB. The 113 dB dynamic range and software selectable gain adjustment allow for precise measurements of both low and high power conditions. In addition, the data are AC coupled at the recorder using a high pass filter with a 0.5 Hz corner frequency.

The data from all the channels are streamed over a single coaxial cable to a controller located on the PXI chassis. The controller contains a high powered Intel Core 2 Quad processor with four 250 GB hard drives in a RAID-0 configuration. The controllers RAID-0 configuration enables streaming to disk over 150 channels while running data monitoring and analysis software. Adequate storage is very important, considering 122 channels of data collected at 96,000 Hz over 30 seconds results in over 1.4 GB. The data are then saved in a non-proprietary binary format. Data acquisition control and monitoring are performed by a daylight readable portable Laptop using Windows Remote Desktop and can be used either wirelessly or wired to the controller. The data acquisition system will be housed in the Mil Spec Shipping case shown in Figure 6.

The data acquisition system will be located approximately 61 m from the jet nozzle. Custom made Infiniband cables will run from the data acquisition system to the test rig. This length will help minimize the vibration of the data acquisition hardware due to the harsh environment of the jet plume while still allowing the test rig to travel the entire length of the plume. This cable arrangement will also reduce the weight of the microphone array test rig.

Along with the acoustical data being collected by the system, supporting data is also acquired for the successful characterization of jet noise. These supporting data include aircraft engine operating conditions, temperature data near the array, and atmospheric data. For the operating conditions, performance data is provided by aircraft operators. For the array temperature, thermocouples may be integrated into the PXI system or used as stand alone sensors integrated with a surface weather data logging system.

Component testing has been performed to ensure proper functioning of the instrumentation. The acoustical instrumentation testing was straight-forward with the scalability of the data processing being the primary focus. The data acquisition system has been successfully tested with all 122 channels simultaneously sampled at a rate of 100 kHz. Future benchmarking will be conducted with the introduction of additional visualization tools.

5. DATA ACQUISITION

The design of the data acquisition system concentrated on two major aspects: Real-Time Monitoring and Data Visualization. The real-time monitoring is a crucial requirement for the system because of the expense of military aircraft testing time. Real-time feedback verifies the microphones are functioning properly, the signals are not clipped, the ranges are selected appropriately, and good data is being collected. In this testing environment, data quality checks reduce the risk and expense of re-testing. Data visualization is also important for the comprehension of the results. For visualization, the focus is on both real-time views and the end results. The flexibility of NI LabVIEW software enables the user to customize their monitoring and data verification experience. The control panel enables overload detection and bar graph overall or peak level representation of every channel. A toggle switch is incorporated which enables switching between Volts and Pressure (dB). ANSI and IEC compliant full and fractional octave analysis is also available for multiple channels.

After completion of the test, additional processing and data inspection is performed to validate the data. All post processing is performed in MATLAB, and the programs have the ability to generate the NAH reconstructed surfaces, overlay images, animations, and wav files of individual channels. Post processing includes all real-time software analysis in addition to the NAH algorithms, narrow band power spectrums, waterfall plots, and potentially 2-dimensional contour animations.

6. CONCLUSIONS

Performing NAH in the jet noise field is challenging, but has a potentially big payoff. Regardless of the choice of NAH method, a single array capable of characterizing the entire jet noise source region with a single measurement run is impractically large and requires thousands of microphones. This impractically drove the selection of a scanned patch NAH measurement approach to minimize the number of sensors and cost to characterize the entire jet plume. The developments of the NAH patch and scan methodology along with an innovative test system and instrumentation design enables high fidelity characterization of jet plumes.

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