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ACTIVE CHEVRONS FOR JET NOISE REDUCTION

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Jet noise is often a dominant component of aircraft noise, particularly at takeoff. To meet the stringent noise regulations, the aircraft industry is in a pressing need of advanced noise reduction concepts. In the present study, the potential of piezoelectrically-activated chevrons for jet noise reduction was experimentally investigated. The perturbations near the nozzle exit caused by piezoelectrically-activated chevrons could be used to modify the growth rate of the mixing layer and thereby potentially reduce jet noise. These perturbations are believed to increase the production of small-scale disturbances at the expense of large-scale turbulent structures. These large-scale turbulent structures are responsible for the dominant portion of the jet mixing noise, particularly low-frequency noise. Therefore, by exciting the static chevron geometry through piezoelectric actuators, an additional acoustic benefit could possibly be achieved. To aid in the initial implementation of this concept, several flat-faced faceted nozzles (four, six, and eight facets) were investigated. Among the faceted nozzles, it was found that the eight-faceted nozzle behaves very similarly to the round nozzle. Furthermore, among the faceted nozzles with static chevrons, the four-faceted nozzle with static chevrons was found to be most effective in terms of jet noise reduction. The piezoelectrically-activated chevrons reduced jet noise up to 2 dB compared to the same nozzle geometry without excitation. This benefit was observed over a wide range of excitation frequencies by applying very low voltages to the piezoelectric actuators.

Keywords: aircraft noise, jet noise, static chevrons, active chevrons, piezoelectric actuators

1. Introduction

Aircraft noise has become one of the major environmental constraints for the future growth of the aircraft industry. For example, the US Federal Aviation Administration has spent \$5 billion on airport noise abatement programs since the 1980s[1] and the US Veterans Affairs spends around \$100 million per year in hearing loss benefits to veterans often exposed to high aircraft noise levels[2].

Jet noise, which emanates from the exhaust jet of an aircraft engine, is a major component of aircraft noise, particularly at takeoff. Jet noise can be classified into three components: 1. turbulent mixing noise; 2. shock-associated noise; and 3. screech tones. In the case of subsonic flows, jet noise is predominantly due to turbulent mixing noise. Shock-associated noise and screech tones exist only in the case of supersonic flows and only when the nozzle is operated at off-design conditions. Civil aircraft engines have a constant-area nozzle, with the jet Mach number being subsonic at takeoff.

Researchers have been exploring various flow control methods to reduce jet noise. Tabs are effective in terms of mixing enhancement[3], but they cause major thrust loss. This led to the introduction of chevrons as part of NASA's High Speed Research Program and Advanced Subsonic Technology Program, which both addressed jet noise reduction concepts. Chevrons are sawtooth-like patterns (or v-shaped crenellations around the nozzle lip) at the trailing edge of aircraft engines[4]. They are similar to tabs with low penetration angles and greater in number along the nozzle circumference. Chevron nozzles were a breakthrough as they provided significant noise reduction without a noticeable thrust loss. Chevrons are implemented on civil aircraft engines, including Boeing 787 Dreamliner.

Some studies (Bridges and Brown [5]) were performed to maximise the benefit of chevron nozzles, in terms of jet noise reduction, by optimising their geometry. Chevrons introduce streamwise vorticity into the jet shear layer, increasing turbulent mixing and decreasing the jet potential core length. In turn, the low-frequency noise associated with large-scale turbulence is reduced, while high-frequency noise due to small-scale turbulence near the nozzle exit is increased. Hence, a tradeoff between low-frequency noise benefit and high-frequency noise penalty is vital for designing chevron nozzles.

This study investigates the use of piezoelectric actuators to enhance the noise reduction potential of static chevrons. The perturbations near the nozzle exit could be used to modify the growth rate of the mixing layer and, thus, reduce jet noise. The perturbations are believed to increase the production of small-scale disturbances at the expense of large-scale turbulent structures. These large-scale turbulent structures are responsible for the dominant portion of jet mixing noise, particularly low-frequency noise. Hence, by exciting the static chevrons through piezoelectric actuators (Butler and Calkins [6]), an additional acoustic benefit could be achieved. The piezoelectric actuation requires minimal power and differs from existing active jet noise control techniques such as plasma actuation (Samimy et al. [7]) and fluidic injection (Henderson [8]), which require substantial power and mass, respectively.

2. Experimental Setup

2.1 Facility

The Small Anechoic Jet Facility (SAJF) consists of a jet flow capable of delivering up to 2 lbm/s of air through the 1000 psi air line. A Chromalox heater of 275 W is used to raise the stagnation temperature of the jet stream. In the present study, the jet temperature is maintained at 100 ^{0}F for consistency throughout the experiments. The jet exhausts from the nozzle into an anechoic chamber. The interior walls of the SAJF are anechoic, treated with fiberglass woven acoustic wedges that absorb in excess of 99% of the incident sound for frequencies above 250 Hz. The internal dimensions of the SAJF (Figure 1) are 10.67 ft in height, 8.38 ft in width, and 12.67 ft along the streamwise direction. The temperature and relative humidity near the microphones are monitored using a General Eastern gauge, which is connected to a Fluke data logger that allows the data to be displayed remotely.

2.2 Nozzles

Figure 2 shows all the nozzles that were tested as part of the present experimental study: 4-faceted, 6-faceted, 8-faceted and round nozzles (the 1st row of Figure 2); 4-faceted, 6-faceted and 8-faceted nozzles with static chevrons (the 2nd row of Figure 2); 4-faceted and 8-faceted nozzles with active chevrons (the 3rd and 4th rows of Figure 2). For brevity, all these nozzles could be grouped into four categories: 1. round nozzle, 2. faceted nozzles, 3. faceted nozzles with static chevrons, 4. faceted nozzles with active chevrons. In the present study, all these nozzles have a throat area of 1.0 sq in, an exit area of 1.176 sq in, the jet Mach number is 0.5 and the jet temperature is 100 ^{0}F at the nozzle exit. All these nozzles are three-dimensional (3-D) printed nozzles.

2.3 Excitation

Several chevron excitation schemes were considered by Doty et al. [9], and two were downselected for initial testing. One scheme is a Macro Fiber Composite (MFC) piezoelectric patch actuator that was bonded to the outside of the chevron with strain gauge adhesive. The other scheme is a mechanical shaker with a sting attached to a clevis and nylon hinge arrangement. Although the mechanical shaker provided more significant displacement authority than the MFC, the shaker arrangement would not effectively operate at frequencies above 100 Hz. Therefore, the superior frequency response and robustness of the Macro Fiber Composite (MFC) piezoelectric patch actuator led to its downselection as the primary excitation method for the present experimental study.

2.4 Instrumentation

2.4.1 Tip Displacement Measurements

The determination of the chevron tip displacement during actuation was accomplished in one of several ways. An accelerometer was often placed directly on the chevron for initial characterization. However, to avoid the effects of the added mass of the accelerometer on the system during testing, a laser vibrometer was used for chevron tip displacement measurements. When inconsistencies with the vibrometer were discovered at low excitation frequencies, the vibrometer was replaced with a Keyence laser displacement sensor as the primary instrument for determining tip displacements.

2.4.2 Acoustic Pressure Measurements

Far-field acoustic measurements were made with a linear array of seven Brüel and Kjær (B & K) Model 4939 free-field microphones of 0.25 inch diameter in conjunction with Model 2670 preamplifiers and a B & K Multiplexer Model 2811. The polar range of the microphones was from 75 to 155 degrees (Table 1) from the upstream jet axis, and the microphones were located on an azimuthal plane 30 degrees above the jet centerline pointed toward the jet exit. The electrostatic and pistonphone calibrations were routinely performed on all the microphones.

2.5 Data Aquisition and Processing

The three main components (Figure 3) of the SAJF data acquisition system are the Sun UNIX server (jnldat), the Precision filter and amplifier system, and the Pacific analog-to-digital (ATD) converter boards. The Sun server is used to maintain all the programs to operate the data acquisition system. The Precision filter and amplifier system is a programmable analog band-pass filter (high-pass filter: 100 Hz; low-pass filter: 102.3 kHz). It has a built-in amplifier system that allows pregain and postgain up to 80 dB. The functions can be remotely controlled by the acquisition program in the Sun computer. Currently, a maximum of 8 channels can be used on the filter system. Lastly, the Pacific ATD boards have 12-bit resolution with a dynamic range of ± 10 volts. Each Pacific board is configured to a sample rate of 250 kHz, and capable of performing sample-and-hold up to 512 KB of words in its memory. These boards are mounted in a rack so that all the channels can be triggered to sample the signals simultaneously through the acquisition program in the Sun. The dynamic signal data are acquired at 210 kHz with 180 data averages, resulting in a 4096-point spectrum with a frequency resolution of 25.63 Hz. Microphone frequency response and free-field response corrections were applied, and atmospheric attenuation corrections to a lossless condition were applied according to the ANSI standard. These corrections were applied to all microphones unless otherwise stated.

3. Results and Discussion

All experiments were performed in the Small Anechoic Jet Facility of the Jet Noise Laboratory at the NASA Langley Research Center. Based on the present experimental research findings, the effect of facets, static chevrons and active chevrons on jet noise are briefly discussed.

The sound pressure level (SPL) is the root-mean-square value of the instantaneous sound pressures measured over a specified period of time, measured in decibels (dB). The immense range of human hearing means that logarithmic sound pressure levels (dB) are used. The SPL is mathematically defined as,

$$\mathrm{SPL} = 20 \log_{10} \left(\frac{p_{rms}}{p_{ref}} \right) \tag{1}$$

where p_{rms} is the root-mean-square of sound pressure and p_{ref} is the reference sound pressure, 20 μPa, which corresponds to the quietest sound at 1000 Hz that the human ear can detect.

The overall sound pressure level (OASPL) is the total energy contained within the SPL spectrum. In other words, it is simply the area under the SPL spectrum, which could be mathematically calculated by integrating the sound pressure levels (SPL) over the entire frequency range.

3.1 Effect of Facets

Figure 4 shows the effect of facets on jet noise. The SPL spectra at 90 degrees are relatively flat; whereas, the spectra have a broad peak and steeper roll-off at 150 degrees to the nozzle inlet. The peak frequency is found to be around 2000 Hz. The eight-faceted nozzle behaved very similar to the round nozzle. The four-faceted nozzle reduced jet noise by at least 2 dB compared to the round nozzle. This jet noise reduction benefit is observed over a wide range of frequencies. However, the noise reduction benefit is more noticeable at low frequencies compared to high frequencies. The four-faceted nozzle provided maximum jet noise reduction (up to 2 dB) compared to the other faceted nozzles.

3.2 Effect of Static Chevrons

Figure 5 shows the effect of static chevrons on jet noise. All faceted nozzles with static chevrons reduced jet noise compared to the round nozzle. In particular, static chevrons considerably reduced the low-frequency noise, but they also marginally increased the high-frequency noise, particularly at 90 degrees from the upstream jet axis. With static chevrons, the jet noise reduction potential of the four-faceted nozzle is significantly increased. Among the faceted nozzles with static chevrons, the four-faceted nozzle provided the most significant benefit – more low-frequency noise reduction (up to 10 dB) and less high-frequency noise penalty (up to 2 dB). Figure 6 shows that the OASPL directivity of the faceted nozzles with static chevrons. It is clear that the four-faceted nozzle with static chevrons provided maximum jet noise reduction (up to 4 dB) over a wide range of frequencies. This makes it the best case to pursue further with active chevrons, which are excited by piezoelectric actuators. After the four-faceted nozzle, the eight-faceted nozzle provided significant jet noise reduction at angles greater than 100 degrees from the upstream jet axis. However, the eight-faceted nozzle increased jet noise below 90 degrees from the upstream jet axis. Based on their capacity for jet noise reduction, the four-faceted and eight-faceted nozzles were chosen for further consideration and use with piezoelectric actuators to excite static chevrons to further increase their jet noise reduction potential.

3.3 Effect of Active Chevrons

Figure 7 shows the effect of active chevrons on jet noise at both 90 and 150 degrees from the upstream jet axis. The four-faceted nozzle with piezoelectrically-activated chevrons reduced jet noise up to 2 dB over a wide range of frequencies. The piezoelectrically-activated chevrons reduced noise penalty at high frequencies and increased noise benefit at low frequencies. Figure 8 shows the OASPL directivity of active chevrons at both low and high excitation frequencies. The excitation of the piezoelectrically-activated chevrons at 250 Hz provided a maximum benefit of 2 dB jet noise reduction compared to the same nozzle geometry with static chevrons. This noticeable jet noise reduction benefit was observed over a wide range of observer angles. The eight-faceted nozzle with piezoelectrically-activated chevrons reduced jet noise by at least 1 dB compared to the same nozzle geometry with static chevrons. Overall, the piezoelectrically-activated chevrons enhanced the noise reduction potential of static chevrons.

4. Conclusions

The conclusions that could be drawn from the present experimental study are: 1. the four-faceted nozzle provided jet noise reduction (up to 2 dB) compared to the round nozzle; 2. among the faceted nozzles with static chevrons, the four-faceted nozzle provided the most benefit – more low-frequency noise reduction (up to 10 dB) and less high-frequency noise penalty (up to 2 dB); 3. low excitation frequencies and amplitudes were found to be good operating conditions for piezoelectric actuators; 4. piezoelectric actuation reduced chevron penalty at high frequencies and increased chevron benefit at low frequencies; and 5. piezoelectrically-activated chevrons reduced jet noise up to 2 dB beyond the static chevron benefit, which is observed over a range of frequencies and observer angles.

Future work will focus on further increasing the chevron tip displacement. Prestressed piezoceramic actuators show an order of magnitude increase in displacement authority over conventional MFC actuators. Stainless steel substrates are being custom-designed to incorporate excitation of the entire chevron geometry. In addition, the extension of the control strategy beyond select frequencies is planned using various feedback control approaches. Finally, improving the fundamental understanding of the effect of piezoelectric actuation on the jet flowfield by Particle Image Velocimetry (PIV) measurements is considered.

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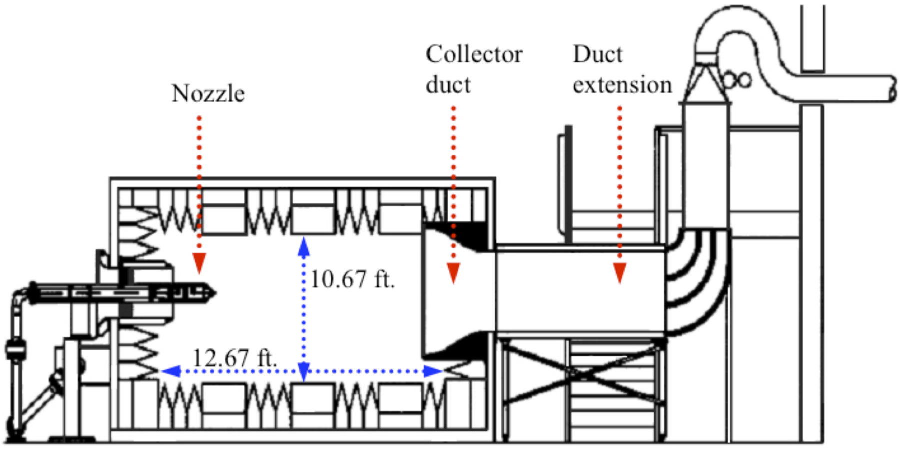


Figure 1: Small Anechoic Jet Facility (SAJF) at NASA Langley Research Center.

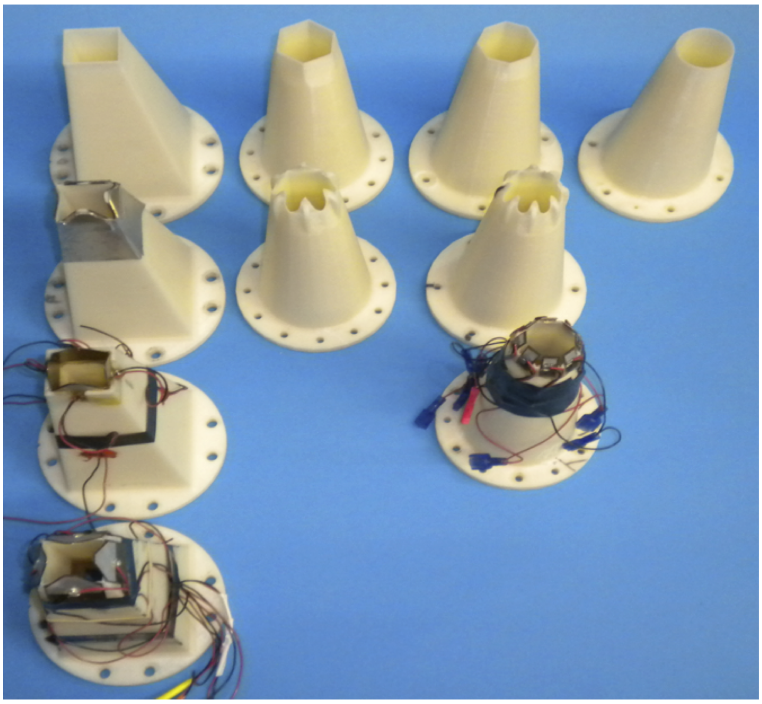


Figure 2: Nozzles that were tested as part of this study.

Table 1: Location of the microphones in the SAJF.

Microphone	1	2	3	4	5	6	7	8
Axial Location (in)	-19.69	0	26.75	42.44	61.67	87.59	105.0	111.7
Height from Floor (in)	98.75	98.75	98.75	98.75	98.75	98.75	92.31	88.05
Angle (deg)	75	90	110	120	130	140	150	155

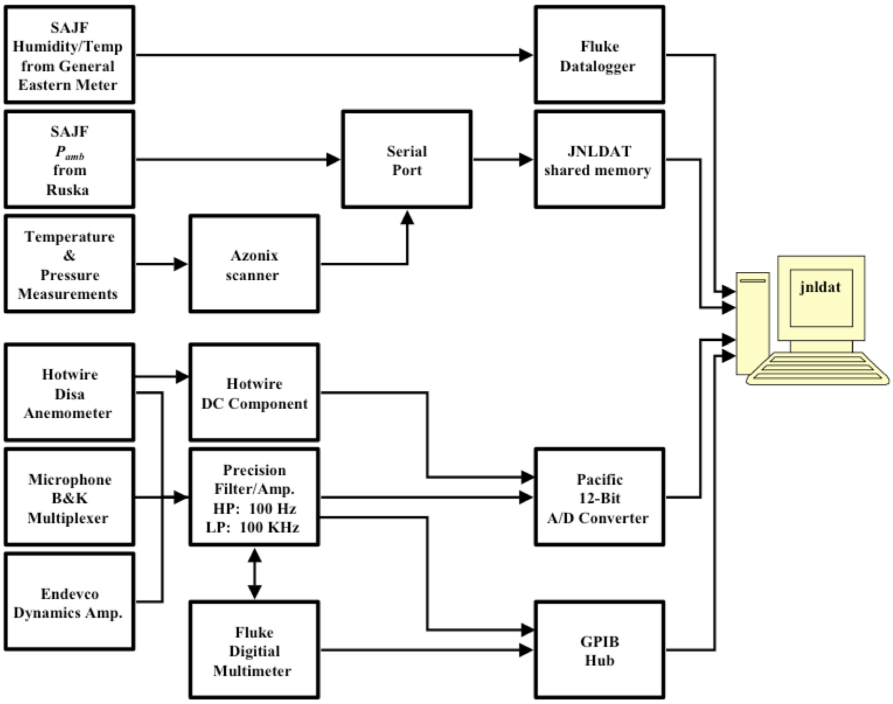
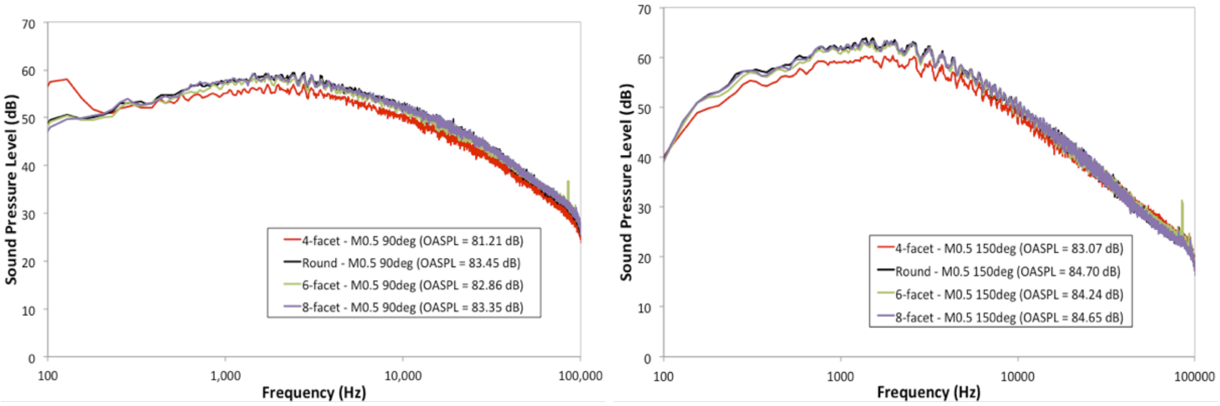
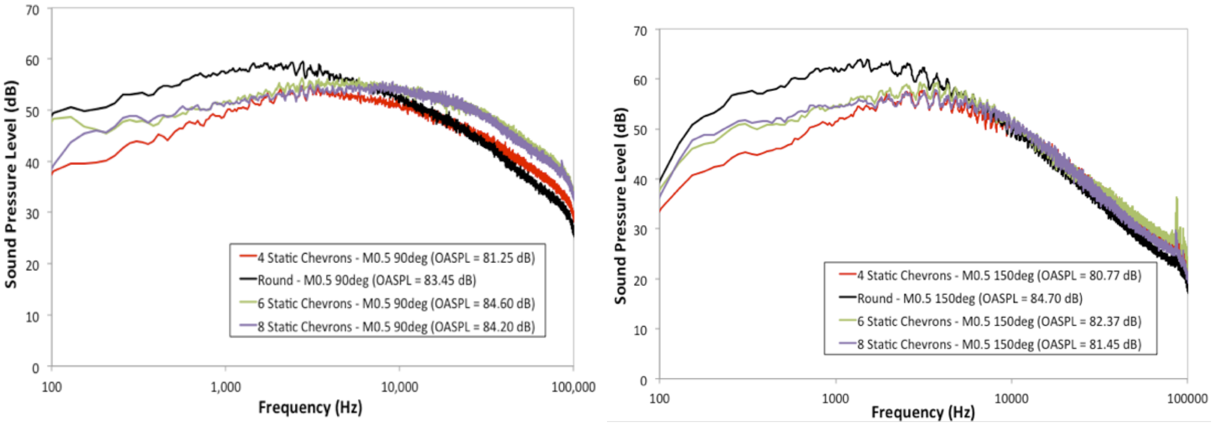


Figure 3: Flow chart of the data acquisition system (DAS) of the SAJF.



(a) 90 degrees (b) 150 degrees

Figure 4: SPL spectra of the faceted nozzles for a Mach 0.5 jet.



(a) 90 degrees (b) 150 degrees

Figure 5: SPL spectra of the faceted nozzles with static chevrons for a Mach 0.5 jet.

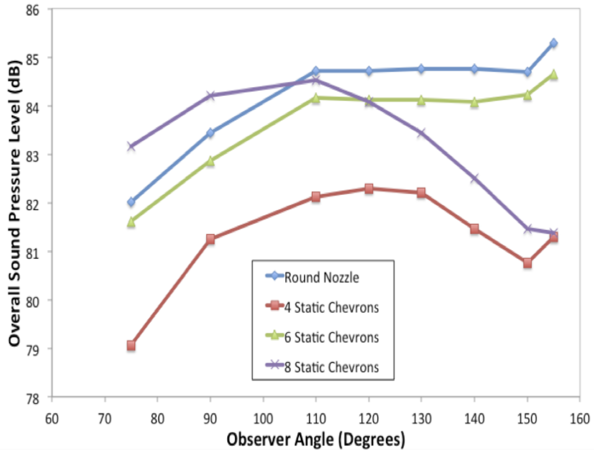
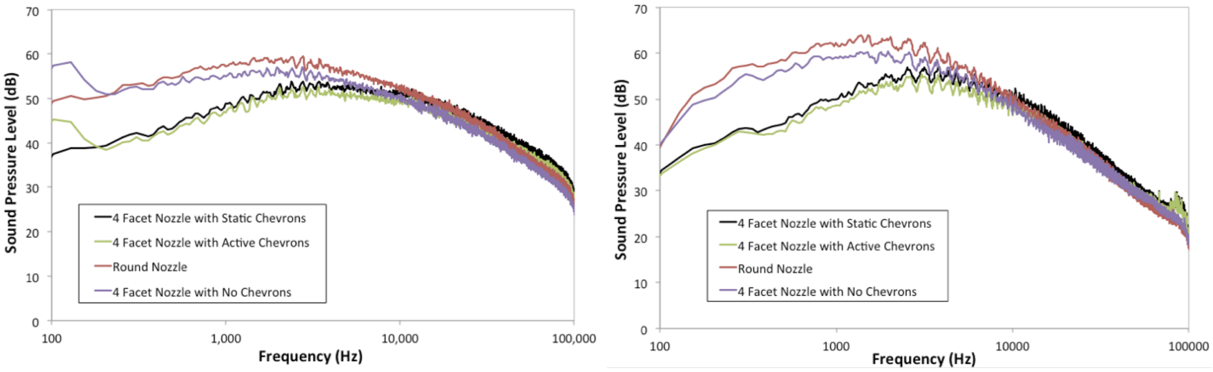


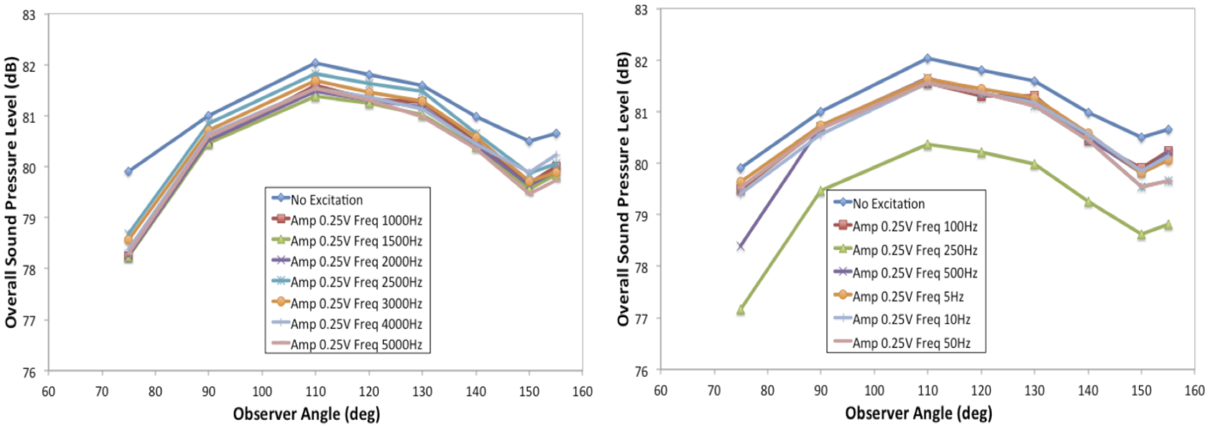
Figure 6: OASPL directivity of the faceted nozzles with static chevrons for a Mach 0.5 jet.



(a) 90 degrees

(b) 150 degrees

Figure 7: SPL spectra of the four-faceted nozzle with active chevrons for a Mach 0.5 jet.



(a) High Frequencies

(b) Low Frequencies

Figure 8: OASPL directivity of the four-faceted nozzle with active chevrons for a Mach 0.5 jet.