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An Analysis of Model Scale Data Transformation to Full Scale Flight Using Chevron Nozzles

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Abstract

Ground-based model scale aeroacoustic data is frequently used to predict the results of flight tests while saving time and money. The value of a model scale test is therefore dependent on how well the data can be transformed to the full scale conditions. In the spring of 2000, a model scale test was conducted to prove the value of chevron nozzles as a noise reduction device for turbojet applications. The chevron nozzle reduced noise by 2 EPNdB at an engine pressure ratio of 2.3 compared to that of the standard conic nozzle. This result led to a full scale flyover test in the spring of 2001 to verify these results. The flyover test confirmed the 2 EPNdB reduction predicted by the model scale test one year earlier. However, further analysis of the data revealed that the spectra and directivity, both on an OASPL and PNL basis, do not agree in either shape or absolute level. This paper explores these differences in an effort to improve the data transformation from model scale to full scale.

1 Introduction

In the spring of 2000, a test of chevron nozzles as a noise reduction device for supersonic turbojet engines was conducted in the Nozzle Acoustic Test Rig (NATR) located at the Aero-Acoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center. The test results indicated that the chevrons reduced the noise level by 2.5 EPNdB. This significant reduction led to a fly-over test which was conducted with the NASA Learjet 25 in March of 2001. The flyover test confirmed the 2 EPNdB reduction which was measured in the model scale test. Further comparison between the model data and the Learjet data, however, showed many shortfalls in the process of transforming model scale data to full scale fly-over data. This paper seeks to identify areas of the data transformation which need to be improved and to verify that model scale tests are a valid method for predicting full scale noise reduction.

2 Nozzle Acoustic Test Rig Model Data

A test was conducted in the spring of 2000 in the Nozzle Acoustic Test Rig (NATR) located in the Aero-Acoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center to test chevron nozzles as a noise reduction concept. The NATR is a 53-in.-diameter free jet capable of speeds up to Mach 0.35. A jet exhaust simulator rig is located at the free jet exit to provide a core jet flow which can reach 1425 degrees F with a maximum nozzle pressure ratio of 4.5 and mass flow rates up to 9.0 lbs/s (cold). The rig is instrumented with pressure sensors, thermocouples, and mass flow measuring devices. The data from these instruments is sent to a central computer which records all the information for each data point. Two nozzles were used during the test: the conic baseline nozzle (figure 1) and a 12 chevron nozzle (figure 2). Nozzle pressure ratios (NPR) between 2.0 and 2.5 were tested. The 12 chevron nozzle at a maximum NPR of 2.3 was also used for the flight test and, therefore, the data presented here are at those conditions to maximize the jet noise while minimizing the effects of fan and airframe noise. This will allow the best comparision of model and flight data. Acoustic data were acquired by 24 microphones located on a arc at a radius of 50 feet from the nozzle, covering angles from 45 degrees to 165 degrees at 5 degree increments. Data were recorded at two sample rates, 18 kHz and 240 kHz. Each sample rate was processed separately and combined in one-third octave bands at the end. This method allowed processing third-octave spectra from 200 Hz to 80 kHz.

Once the data were acquired, it was transformed to full scale flight conditions. First the time domain was transformed to frequency domain and background noise was subtracted. Second, the spectra were corrected for microphone spectral characteristics based on factory documentation (both free-field and acutator response). Next the data was corrected for the shear layer of the free jet that the sound must traverse to reach the microphone. This is a critical step in the processing as it has a direct effect on the sound directivity. As the sound moves through the shear layer it is refracted, changing the location where it will be received. In order to correct for this, a source location is assumed and the angle of refraction calculated from the free jet Mach number. This angle is used with the assumed source to calculate the angle at which the sound was actually emitted (angle of emission). Now the measured data is shifted to reflect the angle of emission and not the angle at which the sound was actually received (figure 3)[1].

One difficulty is assuming the correct source distribution. The simplest source location model assumes that all sources are located at the nozzle exit. For the chevron nozzles, the nozzle exit was defined at the chevron tips. Another source location method assumes sources are distributed along the jet axis as a function of frequency. Figure 4 shows the results of both the point source model and the distributed source model for the baseline nozzle and figure 5 shows these results for the chevron nozzle. Table 2 shows the impact of source distribution model on EPNL (more than 1 EPNdB difference with the chevron nozzle). In addition, each figure compares the results to the actual flight data. In both the baseline and chevron nozzles, the distributed source model more accurately predicts the full scale data by raising the peak noise level and increasing the rate noise level decreases as a function of frequency when compared to the point source data. Therefore, the distributed source model was used for all the NATR

model scale data processing in this report. However, more research is still needed into source location to improve the results from model scale testing. After the shear layer correction, the data was converted to a one-foot-lossless condition accounting for spherical spreading and atmospheric attenuation losses[2]. The data was transformed to full scale by linearly scaling the frequency and adding $20log_{10}(linear\,scale\,factor)$ (where linear scale factor is the ratio of nozzle areas). Again using spherical spreading and atmospheric conditions the data were transformed, using the flight test conditions, a flyover altitude of 500 feet, and an aircraft speed of Mach 0.30 to a sideline observer location. The frequency was corrected for the Doppler shift that occurs during flight. Finally, the processed narrow-band spectra is integrated to third-octave spectra to match the flight test data systems. At this point, each microphone location during the model scale test now represents an aircraft location during the fly-over test.

After processing, the data is analyzed in various ways. First, the sound pressure level (SPL) is plotted as a function of frequency at the peak emitted PNL noise location, approximate emission angle 140 degrees (figure 6) and at the location when the aircraft is at the 90 degree emission angle (figure 7). Remember, although the origin of the data is a static model scale test the processing has transformed each static microphone into an equivalent aircraft location. At both aircraft locations the spectra shows chevrons reduce the low frequency noise by up to 5 dB. However, they also slightly increase noise levels at frequencies above 2 kHz by shifting the noise peak from 300 Hz to 3 kHz. The high frequency penalty, however, is more than compensated by the low frequency reductions. This is illustrated in both figure 8, which shows the OASPL as a function of angle, and in figure 9, which shows the PNL as a function of time. The chevrons on an OASPL basis show a reduction of 4 dB at approaching (low) angles, 4.5 dB at peak, and 3.5 dB at departing (high) angles. On a PNL basis, the chevrons make little difference as the aircraft is approaching but reduce the peak by almost 2 dB and shorten the peak duration by approximately 0.5 seconds. This combination reduces the EPNL from 112.0 dB for the baseline nozzle to 110.0 dB for the chevron nozzle. The model scale testing at the NATR, therefore, validates chevron nozzles as a noise reduction concept.

3 Learjet Fly-over Data

The original model scale tests performed at the NATR gave significant motivation for further development of the chevron nozzle. Therefore, a full scale fly-over test was performed on NASA Learjet 25 from March 26 to March 29, 2001. The tests were conducted at Estrella Sailport near Phoenix, Arizona. The aircraft crew was based out of Sky Harbor Airport and the acoustic acquistion personnel at Estrella consisted of Wyle Laboratory personnel from NASA Langley Research Center; members of the acoustics group at Honeywell Engines, Systems, and Services; and observers from NASA Glenn Research Center. Two ground based microphone arrays were independently operated my Wyle and Honeywell; this report uses the data from Wyle which is corroborated by the Honeywell data.

Three nozzles were tested each with an area of 100 in^2: a round baseline nozzle (figure 10), a 6 chevron nozzle (figure 11), and a 12 chevron nozzle (figure 12). On the chevron nozzles the area was determined at the midpoint of the chevron. The baseline nozzle was mounted on one engine and the chevron nozzle was mounted on the other engine. The engines were alternated on each pass, with one engine set to idle and the other at the desired engine pressure ratio (EPR), to give a back to back comparison between the two nozzles. Table 1 shows all the aircraft and engine operating conditions for each run. The maximum EPR achievable was 2.3 and the fly-over altitude for all runs was 500 feet. Altitude, airspeed and EPR were called out by the pilots and written into a spreadsheet. The pilots also called to start and end the data recording based on their location to fixed landmarks. The noise was measured using a 20 microphone array which was laid out in three lines; two 6 microphone sideline arrays (one on each side of the flight path at 1000 feet distance) and an 8 microphone linear array directly under the flight path (figure 13). Each one-half inch Bruel and Kjaer microphone was taped to a steel plate which was placed on the ground (figure 14). Atmospheric data were recorded on the ground and at various altitudes using weather balloons. Acoustic data were recorded every 0.25 seconds and averaged with time offsets to give one channel per point. The data were not changed based on atmospheric conditions and were transformed from time domain to frequency domain for analysis.

Figure 15 shows the EPNL for all EPRs recorded for the baseline, 6 and 12 chevron nozzles. At the 2.3 EPR there was a 2 EPNdB benefit from the chevrons. At the 1.8 EPR the 12 chevron still showed roughly 1 EPNdB benefit; but the 6 chevron nozzle showed a slight penalty. At the lowest, 1.6 EPR, the 12 chevron showed no advantage or penalty while the 6 chevron nozzle showed a 2.5 EPNdB penalty. Model scale data were only available for the 12 chevron nozzle and, therefore, only the 12 chevron nozzle is presented.

Due to differences in data starting location and lack of an aircraft positioning system (a differential GPS system was installed but not functional at the time of the test), the Learjet data had to be transformed to a common origin. Simultaneously, this origin must agree with the NATR origin to allow full scale verses transformed model scale comparisons. The common origin then gave one point in space and time shared by each set of data allowing all other points to be calculated. The task of finding the common origin was achieved by selecting a jet noise dominated one-third octave band (250 Hz) and plotting one-third octave SPL against time for this band. These plots, shown in figures 16 and 17, were used to align the noise peaks from the two data sets, creating a common location at a point in time. The position of the aircraft was then calculated relative to that common location using the speed and altitude of the aircraft (called out by the pilots) and the known time difference between data points. This is not an exact method and some small differences in peak alignment exists for various plot types. Note that the scaled NATR data has a higher amplitude at nearly all angles compared to the Learjet data, showing deficiencies in the model data processing at this important jet noise dominated one-third octave band.

The Learjet fly-over data were analyzed in several ways. First, figure 18 shows the one-third octave SPL as a function of frequency for the baseline and 12 chevron nozzle at the location of peak PNL. In this plot, the chevron nozzle reduces the noise by 1 to 1.5 dB from 150 Hz to 1500 Hz and shows almost identical results above 1500 Hz. At the 90 degree emission angle (figure 19), the chevron nozzle shows reductions of 3 to 5 dB up to 2 kHz with smaller reductions above 2 kHz. This reduction is again shown in figure 20 which illustrates OASPL as a function of angle. The chevron nozzle reduces the OASPL by approximately 1 dB for angles up to the peak and by approximately 2 dB from the peak throughout the roll off. On a PNL basis the chevrons have no effect on the noise levels as the aircraft approaches, which is expected given that jet noise is aft-dominated. The chevrons do, however, reduce the peak noise level by approximately 2.5 dB and shorten the time between the 10 dB down limits in the EPNL calculation (figure 21). This results in a reduction of 2.1 EPNdB, from 113.5 dB for the baseline nozzle to 111.4 for the chevron nozzle, validating the use of chevron nozzles for noise reduction on a turbojet engine.

4 Comparison of Learjet and NATR Data

Model scale tests are used to predict the results of a full scale test while incurring less cost. For this to be effective, the model scale data must be accurately transformed to the full scale conditions. Techniques are always being developed to make the jump from model to full scale and this is an opportunity to evaluate some of these techniques. If EPNL is compared (table 2), the results are very good. However, a more detailed study of the data shows several significant differences in the model and full scale results.

The data sets were compared using the same methods used to compared the baseline and chevron nozzles for each set individually: spectra at peak noise location, spectra at the overhead position, OASPL as a function of angle, PNL as a function of time, and EPNL. Ideally, each NATR point would scale up to exactly match the Learjet point. This does not happen for three primary reasons. First, the Learjet has noise sources, such as fan noise, that are not present in the NATR data. Second, there are some deficiencies in the transformation of the NATR data to full scale flight, particularly the free-jet shear layer correction source location model (see figures 4 and 5). Finally, differences in alignment between aircraft position and NATR transformed position result in some small shifts in point location. Each of these factors will appear in the spectra, OASPL, and PNL comparison.

When the aircraft is at the 90 degree emission angle, the baseline nozzle on the Learjet has a higher peak amplitude than does the NATR baseline nozzle (figure 22). In

addition, the Learjet spectrum decreases at a faster rate than the NATR data following the peak. Similarly, the Learjet chevron nozzle has a higher peak and more rapid decrease as a function of frequency than the NATR chevron nozzle (figure 23). At the peak PNL noise location for the baseline nozzle (figure 24), the NATR spectrum is higher at low frequencies and lower at high frequencies than the Learjet spectrum. This could be a result of the shear layer correction applied to the NATR data or a small error in the position alignment between the two data sets. With the chevron nozzle, the noise from the NATR is lower between 250 Hz and 4 kHz by up to 10 dB. This might indicate an excess noise source in the Learjet data in that frequency range.

Plotting OASPL against angle for the baseline nozzle on the Learjet and on the NATR (figure 25) shows a shift of the NATR data by approximately 5 degrees, putting its peak earlier than that of the Learjet data. The peak noise level is slightly lower on the NATR data. Again, both factors are probably due to the combination of shear layer correction and position alignment based on the example of shear layer correction (figure 4) and the changes source models had on the overall levels of OASPL as a function of angle. The shape of each line matches reasonably well. With the chevron nozzle (figure 26), the peak of the NATR data is shifted slightly downstream by approximately 3 degrees and the peak is lower by almost 4 dB relative to the baseline nozzle results. The change in peak amplitude is most likely due to the same excess noise source shown in the spectra at the peak PNL location (figure 27) and the shift is probably accounted for by the shear layer correction.

Finally, the PNL against time for the baseline nozzle (figure 28) shows a 2 EPNdB difference at the peak. It also shows the NATR PNL decreases at a slower rate as a function of time than does the Learjet. This difference in shape is again attributed to the shear layer correction. The chevron nozzles (figure 29) behave in the same manner. The noise difference at the peak time is now 3.5 EPNdB for the chevron nozzle. The NATR data peaks 0.5 to 1 second earlier than dose the Learjet data. It would appear possible to shift the NATR data to align its peak with the Learjet data; however, the non-linear transform to time makes it impossible to improve the current alignment. This suggests that a systematic error, such as the shear layer correction source model, is the primary factor in the differences between the two data sets. After integrating the PNL data into an EPNL value (table 2), the baseline nozzle on the Learjet gives a value of 113.5 EPNdB compared to 111.4 EPNdB for the chevron nozzle. This is an improvement of 2.1 EPNdB. On the NATR, the baseline nozzle has an EPNL of 112.1 EPNdB compared to 110.0 EPNdB for the chevron nozzle. This represents a benefit of 2.1 EPNdB, exactly the difference measured on the Learjet. Certainly the reduction predicted by the model is not expected to exactly match the result measured on the aircraft given the differences in spectra and directivity. The fact that is does match, however, indicates that the transformation from model scale to full scale contains some consistent errors that compensate for each other when the data is integrated into an EPNL.

5 Conclusion

Transforming model scale data to full scale flight data is a tricky business. Each step introduces the possibility for errors. In particular, the choice of a source distribution model for model free jet correction was shown to greatly impact the results (figures 4 and 5). In addition, the aircraft flight data has other noise sources such as fan noise that must be sorted out from the pure jet noise of the model scale rig. The results in this test showed some of these problems. The data were not always aligned perfectly between the Learjet and the NATR. The source location model chosen for the model scale data still left the peak noise level on the transformed data below the flight test data and caused the data to decrease at a slower rate than the actual flight data. However, when the final EPNL number was computed, the noise reduction predicted by the model was almost exactly the reduction measured on the full scale fly-over. This combination of circumstances clearly indicates two things. First, more research is required to properly predict the full scale spectra and directivity, on both an OASPL and a PNL basis. Second, model scale test are a viable, comparatively low cost, option for predicting overall noise reduction for various concepts.

References

[1] Ahuja, K.K, Tester, B.J. Tanna, H.K., "The Free Jet as a Simulator of Forward Velocity Effects on Jet Noise", NASA Contractor Report-3056, October 1978.

[2] H.E. Bass, L.C. Sutherland, A.J. Zuckerwar, D.T. Blackstock, and D.M. Hester, "Atmospheric absorption of sound: Further developments", Journal of the Acoustic Society of America, 97(1):680-683, January 1995.

Engine Pressure Ratio (EPR)	Airframe Condition
2.3	Flaps and gear deployed
2.2	Flaps and gear deployed
2.0	Flaps and gear deployed
1.8	Flaps and gear deployed
1.6	Flaps deployed only

Table 1: Airframe condition at each EPR. The airframe condition was varied to hold a constant aircraft speed while flying each EPR.

	Learjet	NATR-point source model	NATR-distributed source model
Baseline Nozzle	113.5 EPNdB	111.4 EPNdB	112.1 EPNdB
Chevron Nozzle	111.4 EPNdB	108.8 EPNdB	110.0 EPNdB
Reduction	2.1 EPNdB	2.6 EPNdB	2.1 EPNdB

Table 2: EPNLs for the Learjet and the NATR using the point source distribution and the distributed source distribution in the shear layer correction with the noise reduction generated by the chevron nozzle. All EPNLs were calculated using an aircraft speed of Mach 0.3.

Figure 1: The baseline model scale nozzle.

Figure 2: The 12 chevron model scale nozzle. Note that nozzle area was determined at the midpoint of the chevron.

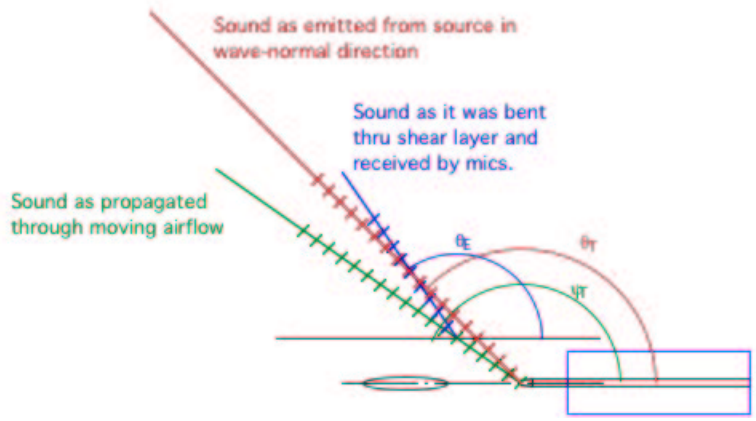

Figure 3: Shear layer correction transforms the measured sound angle (blue) to the angle from which the sound was emitted (red).

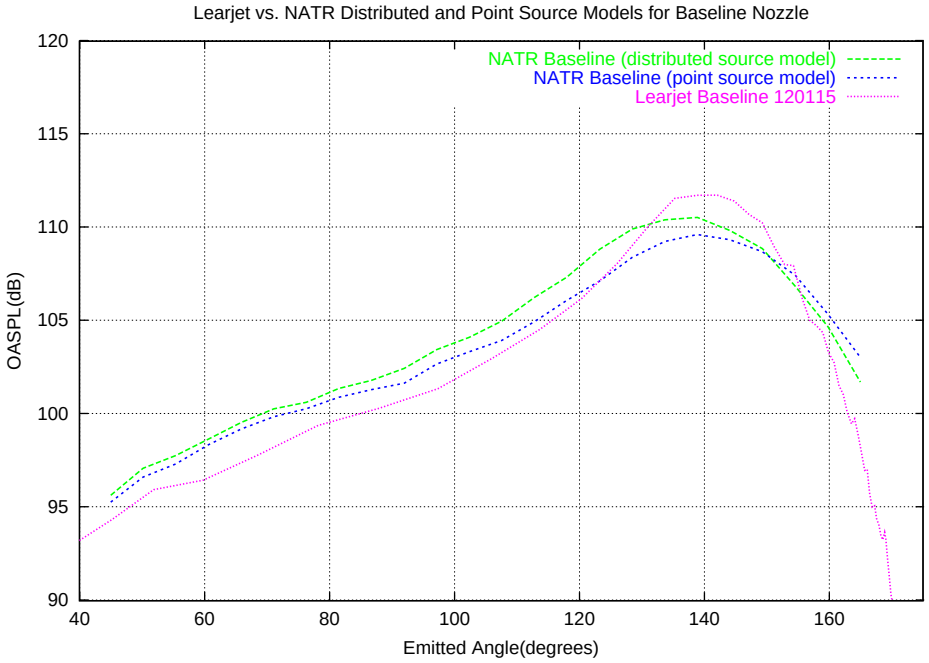

Figure 4: Results of using a point source model and a distributed source model for the shear layer correction, compared to actual flight data for the baseline nozzle. The data is presented as a function of emitted angle. Using the distributed source model increases the peak level and the rate of decrease as a function of angle compared to the point source model. The distributed source model, therefore, more accurately predicts the actual flight data.

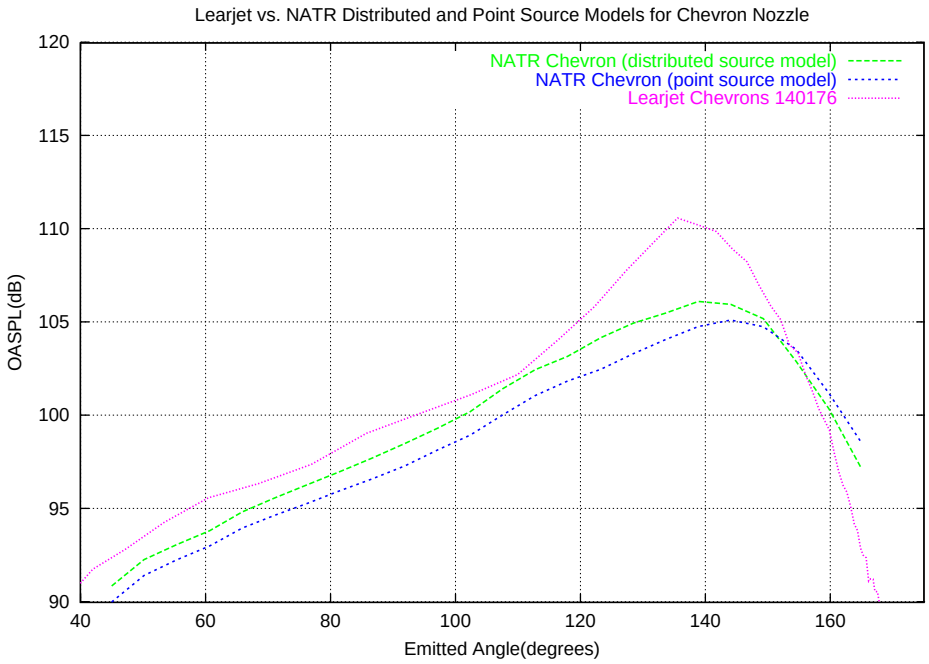

Figure 5: Results of using a point source model and a distributed source model for the shear layer correction when compared to actual flight data for the chevron nozzle. As in figure 4, the distributed source model raises the peak level and increases the rate of decrease as a funciton of angle compared to the point source model. These changes more accurately predict the results shown in the actual flight data.

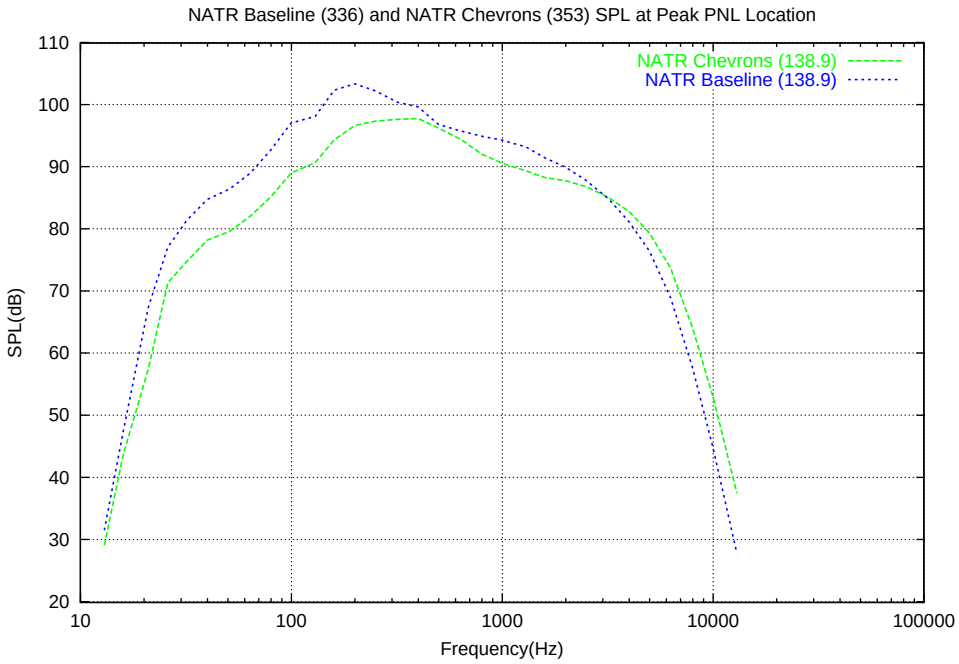

Figure 6: One-third octave SPL as a function of frequency for the NATR baseline and chevron nozzles at the location of peak PNL (approximately 140 degrees). The model data has been scaled to match the Learjet nozzle area (100 in^2) and fly-over altitude (500 ft). The chevrons show a reduction in low frequency noise but have a slight increase in the high frequency noise.

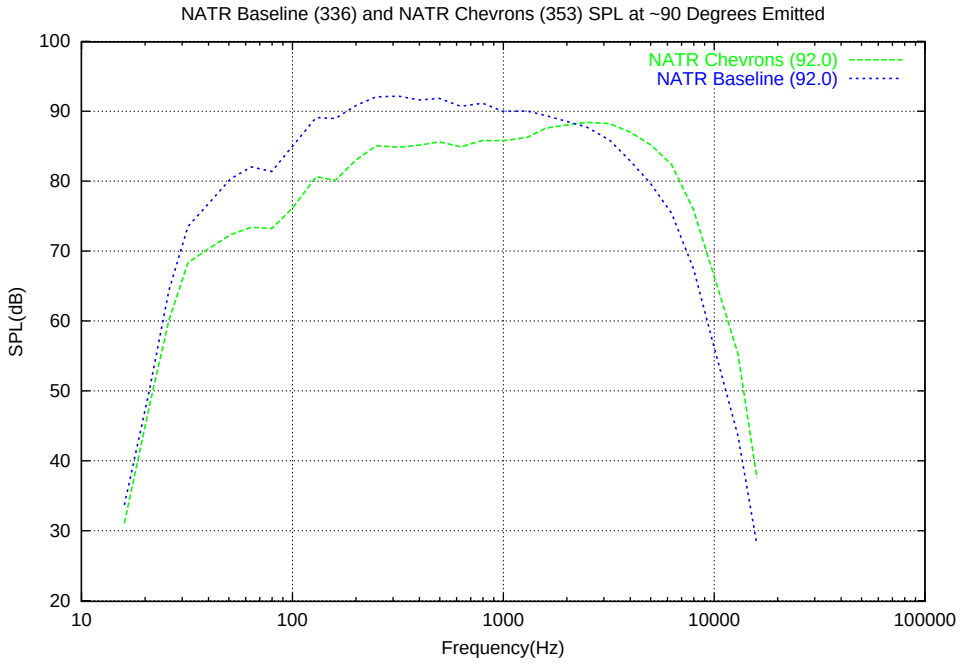

Figure 7: One-third octave SPL as a function of frequency for the NATR baseline and chevron nozzles. The model data has been scaled to match the Learjet nozzle area (100 in^2) and fly-over altitude (500 ft). The aircraft is directly overhead (90 degrees emitted) at this point in the simulated fly-over.

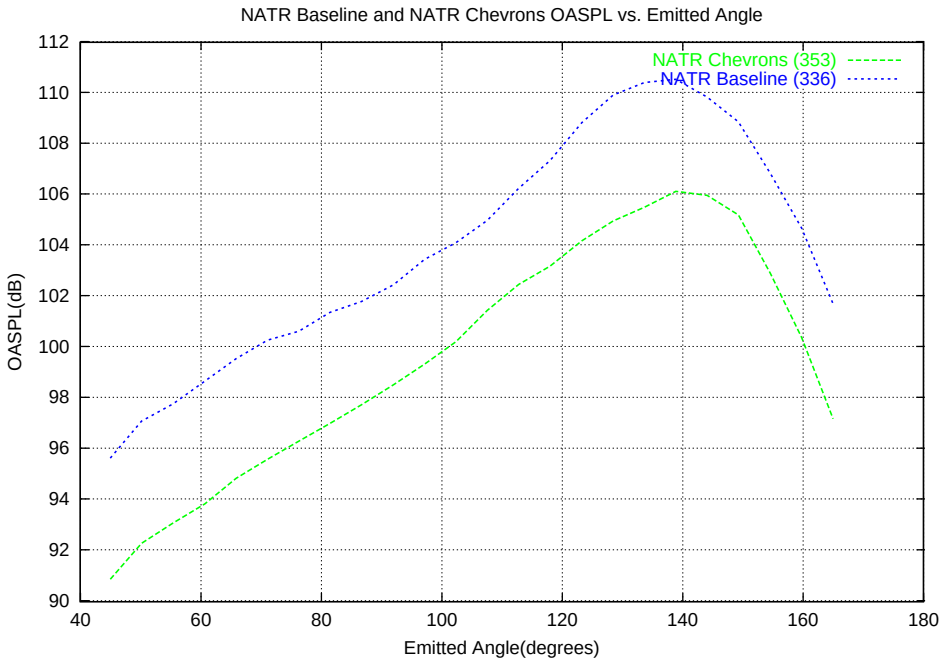

Figure 8: OASPL as a function of emitted angle for the NATR baseline and chevron nozzles scaled to Learjet nozzle size and fly-over altitude.

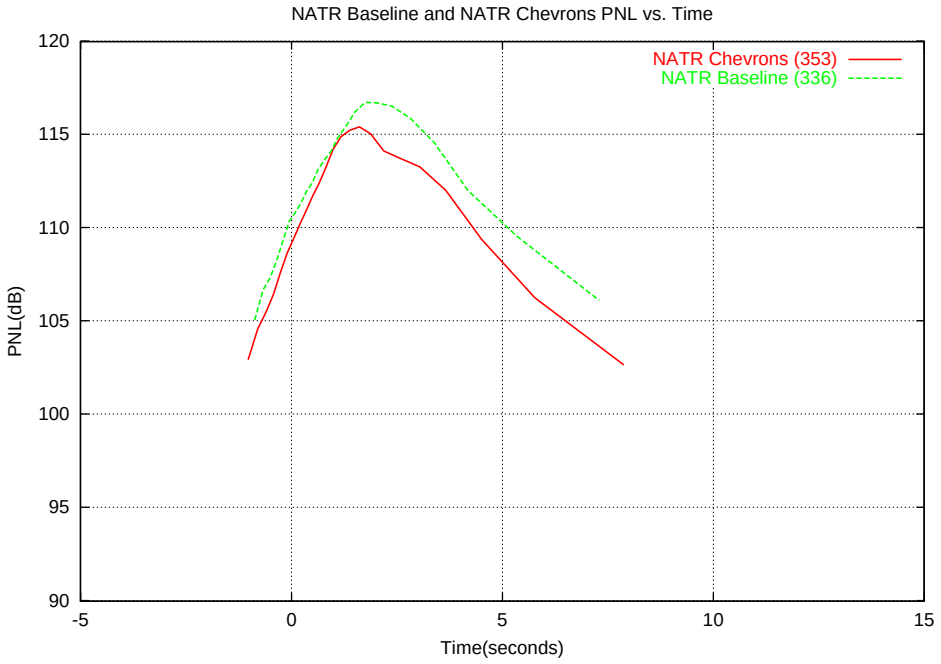

Figure 9: PNL as a function of time for the NATR baseline and chevron nozzles. Note that the flight transformation was done with a aircraft speed of Mach 0.30 in both cases to form the common time base.

Figure 10: The baseline nozzle mounted on the Learjet.

Figure 11: The six chevron nozzle mounted on the Learjet.

Figure 12: The 12 chevron nozzle mounted on the Learjet.

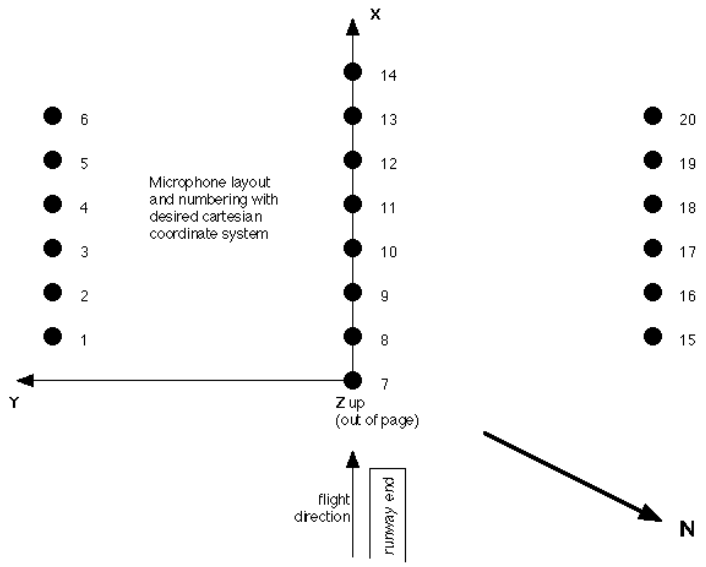

Figure 13: The microphone layout used for the Learjet fly-over test.

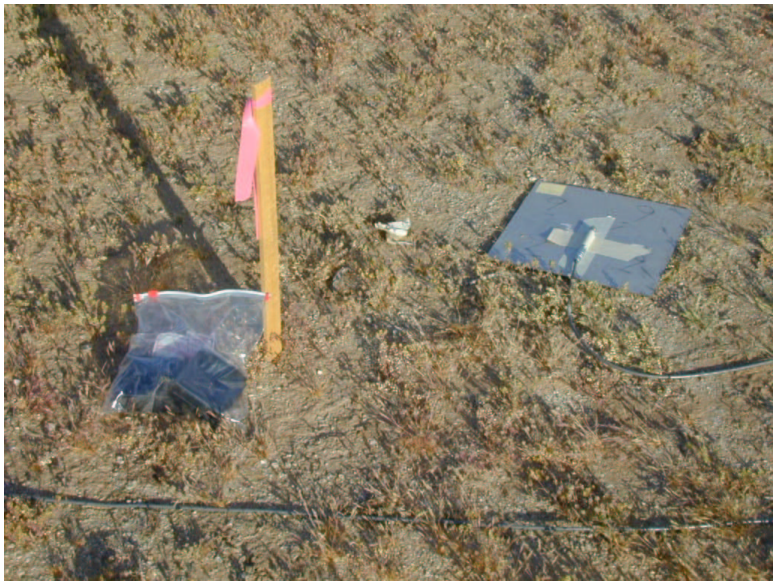

Figure 14: Each microphone was taped to a steel plate and placed on the ground. One-half inch Bruel and Kjaer microphones were used at all locations.

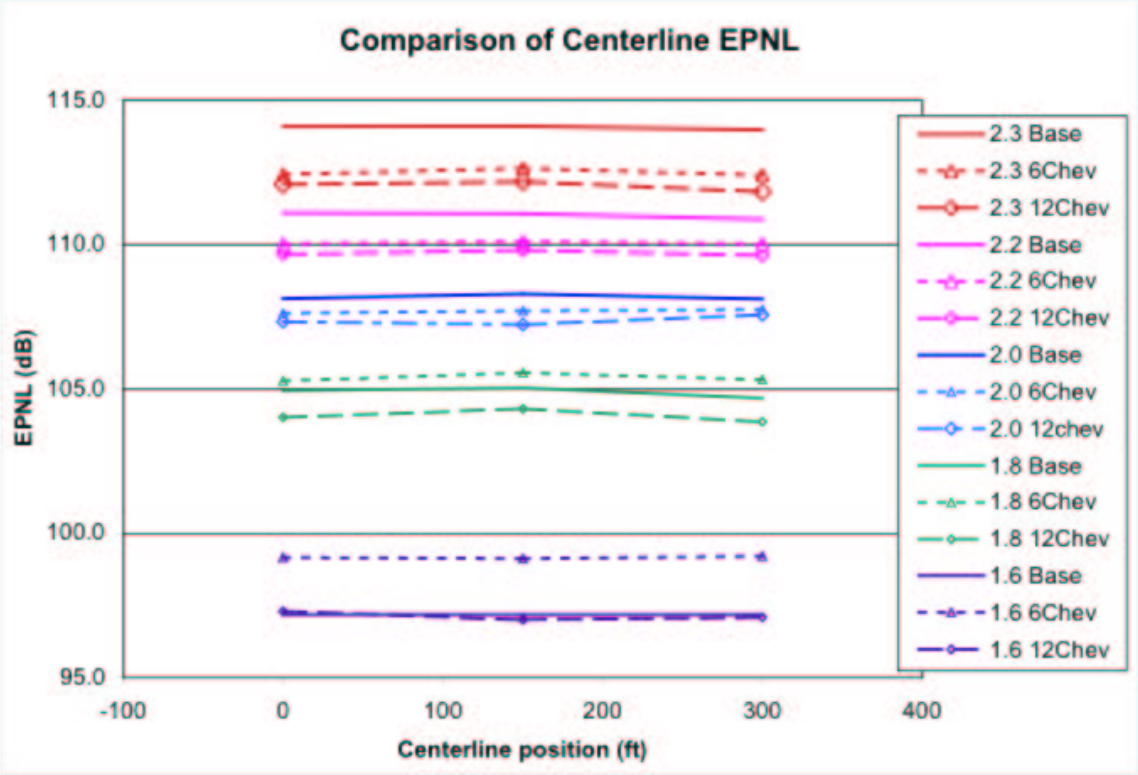

Figure 15: EPNL for all EPRs acquired during the Learjet test.

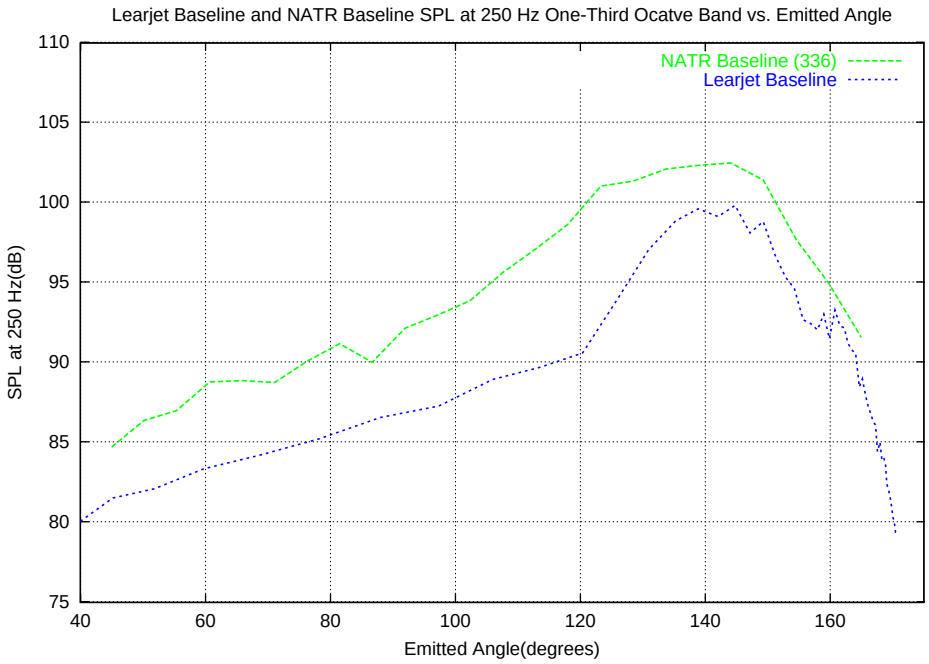

Figure 16: SPL at the 250 Hz one-third octave band plotted against emission angle for the NATR and the Learjet baseline nozzles. The peak emission angle for this band was used to create a common origin for the two data sets.

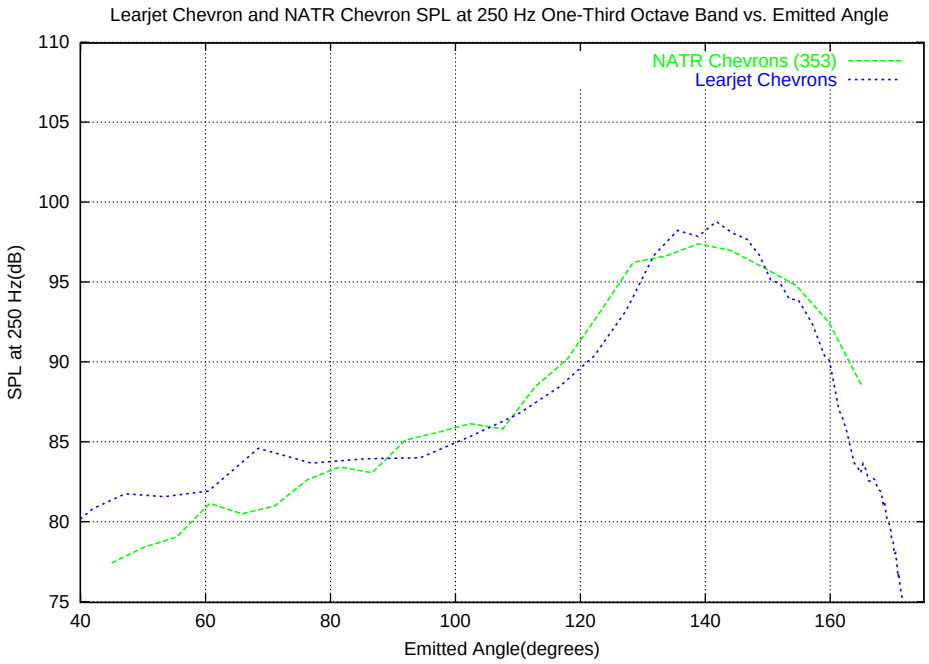

Figure 17: SPL, at the 250 Hz one-third octave band, plotted against angle for the NATR and the Learjet chevron nozzles. The peak of this band was used to create a common origin for the two data sets.

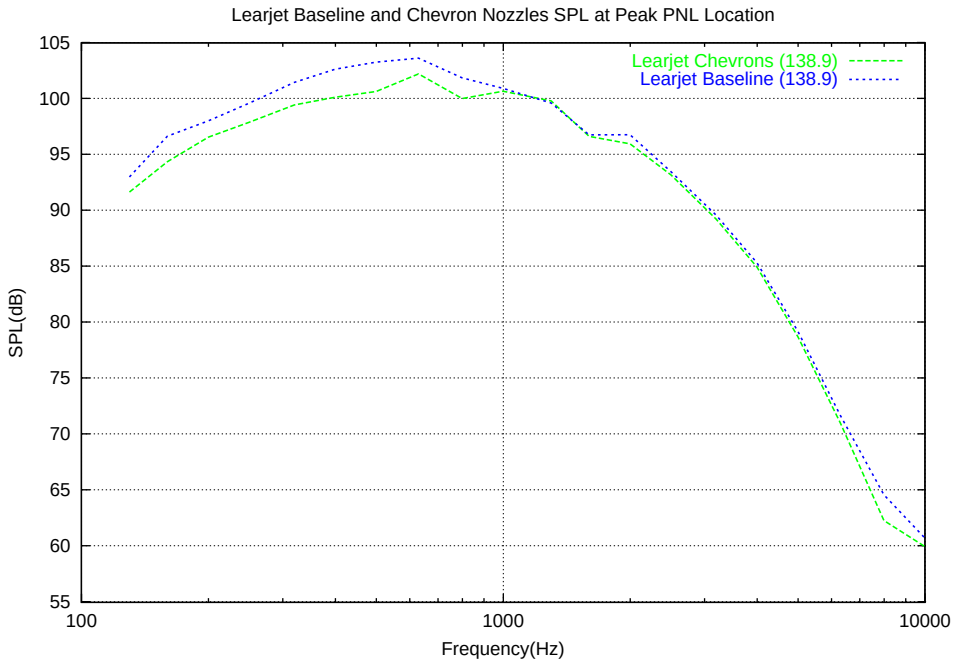

Figure 18: One-third octave SPL as a function of frequency for the Learjet baseline (blue) and chevron (green) nozzles. The aircraft is at the peak PNL noise location (approximately 138 degrees departing).

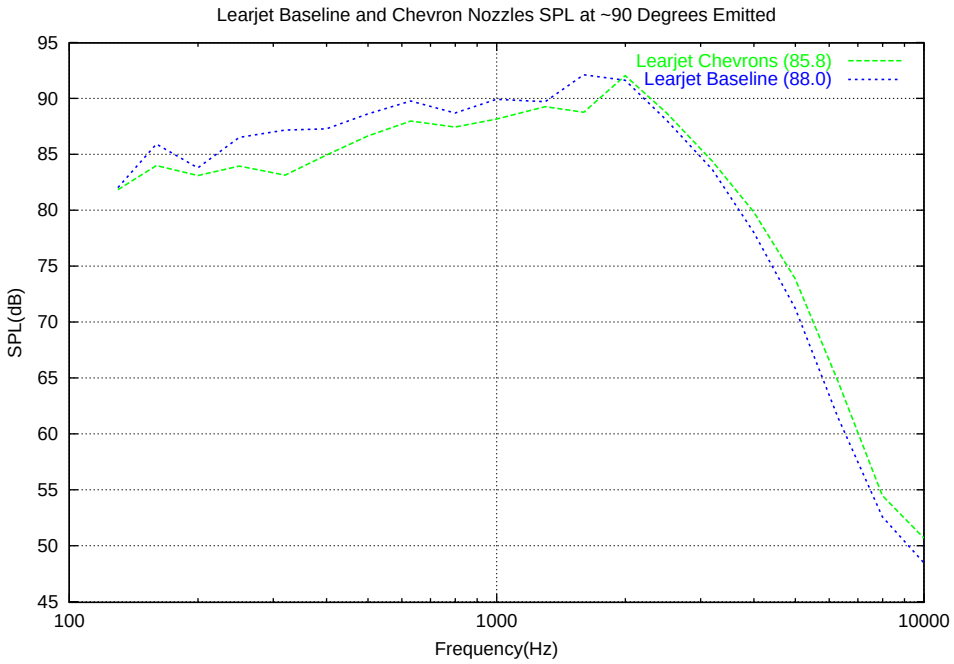

Figure 19: One-third octave SPL as a function of frequency for the Learjet baseline (blue) and chevron (green) nozzles. The data were recorded when the aircraft was almost directly overhead.

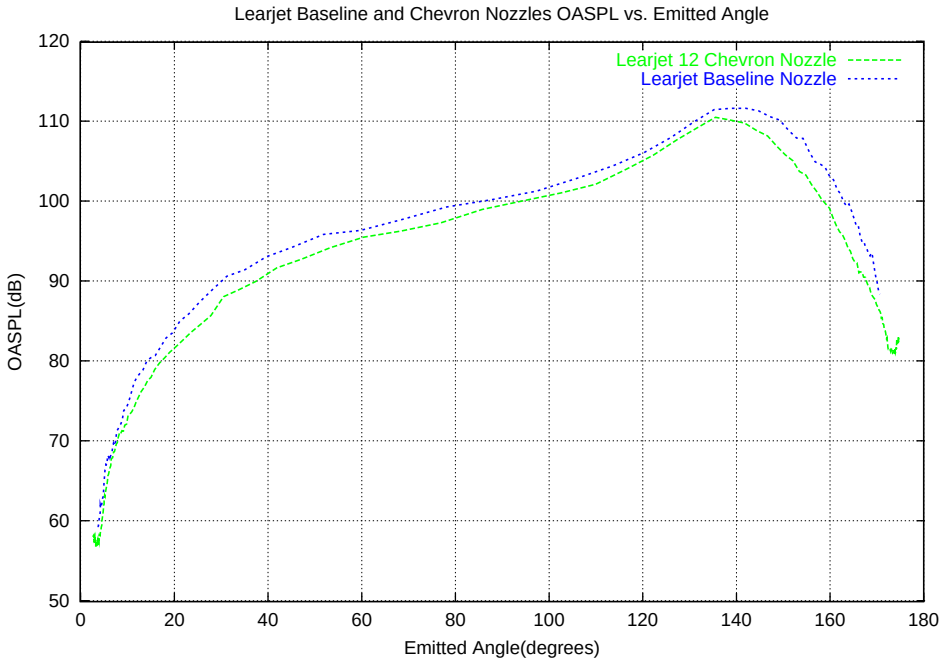

Figure 20: OASPL as a function of emission angle for the Learjet baseline (blue) and chevron (green) nozzles.

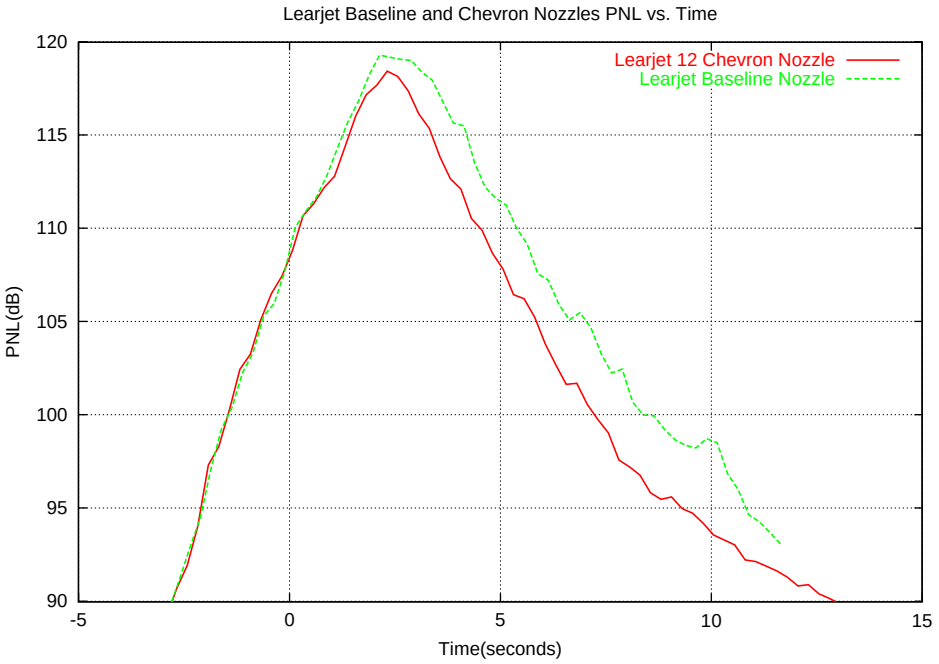

Figure 21: PNL as a function of time for the Learjet baseline (green) and chevron (red) nozzles.

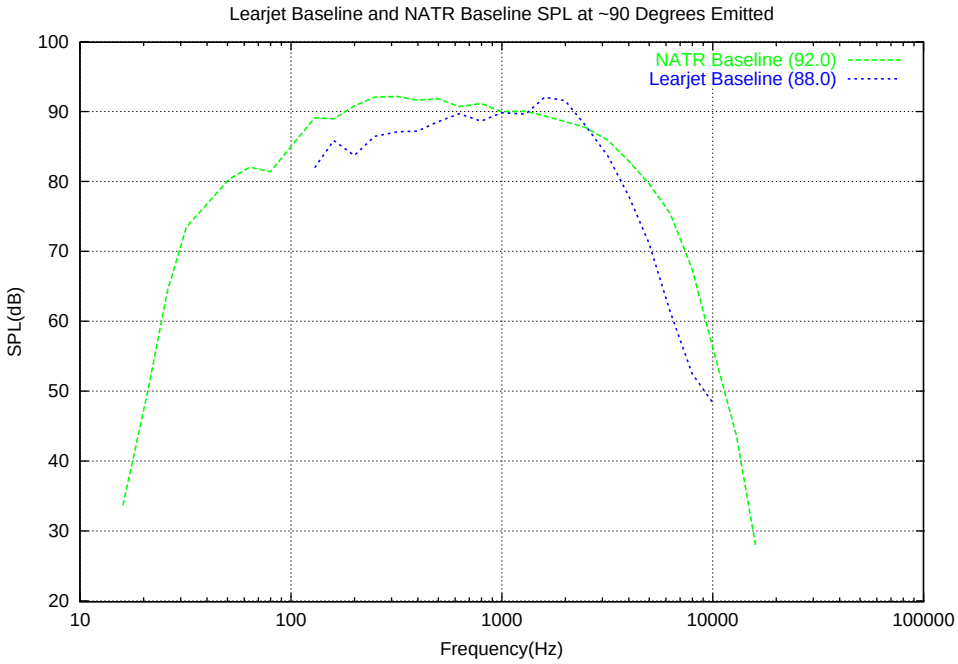

Figure 22: One-third octave SPL for the NATR (green) and the Learjet (blue) baseline nozzles when the aircraft is almost directly overhead.

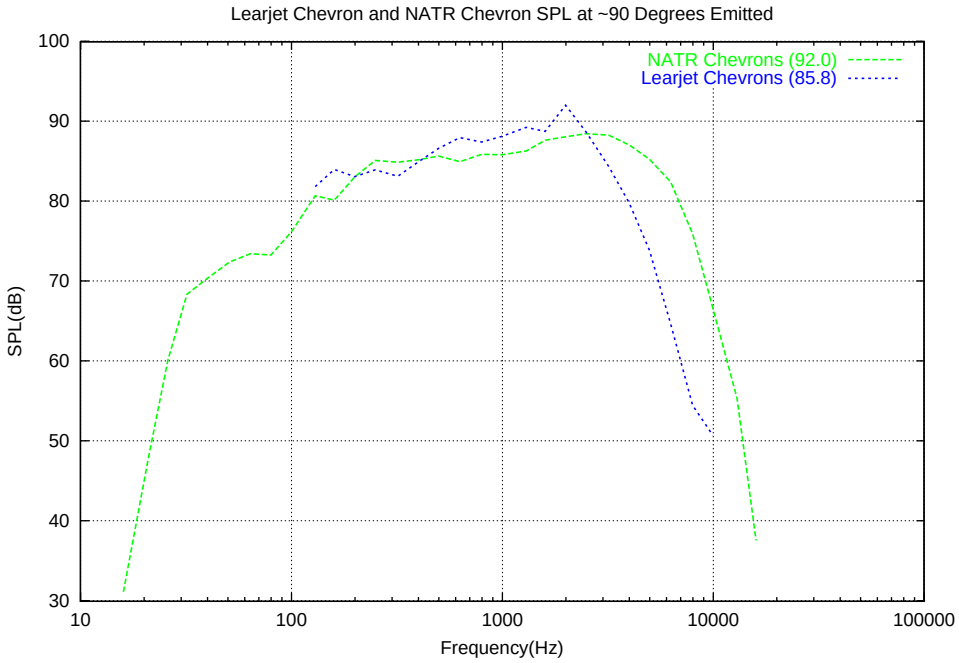

Figure 23: One-third octave SPL for the NATR (green) and the Learjet (blue) chevron nozzles when the aircraft is almost directly overhead.

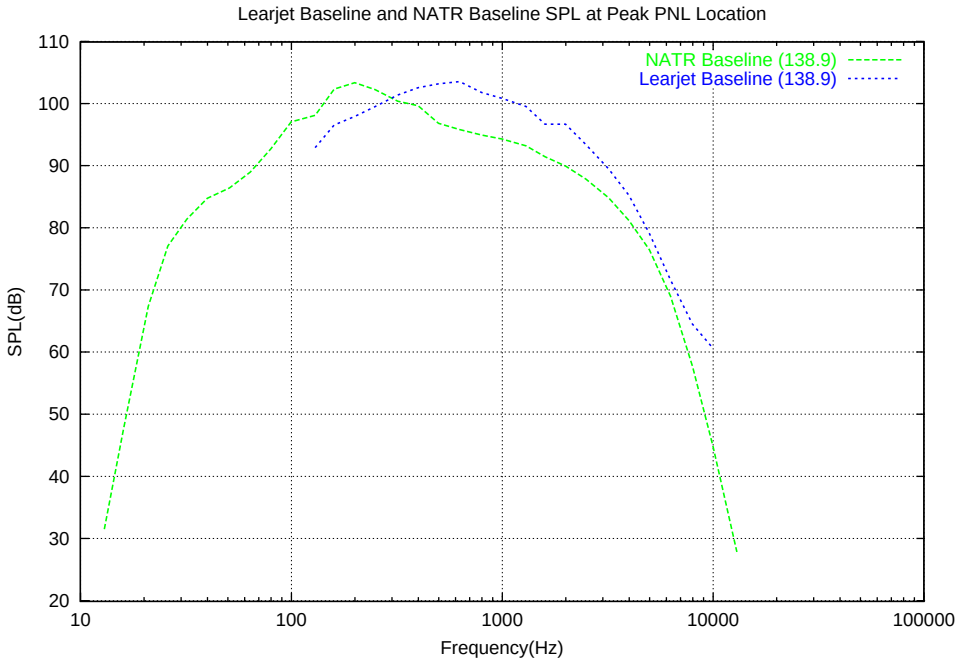

Figure 24: One-third octave SPL for the NATR (green) and the Learjet (blue) baseline nozzles at the peak noise location.

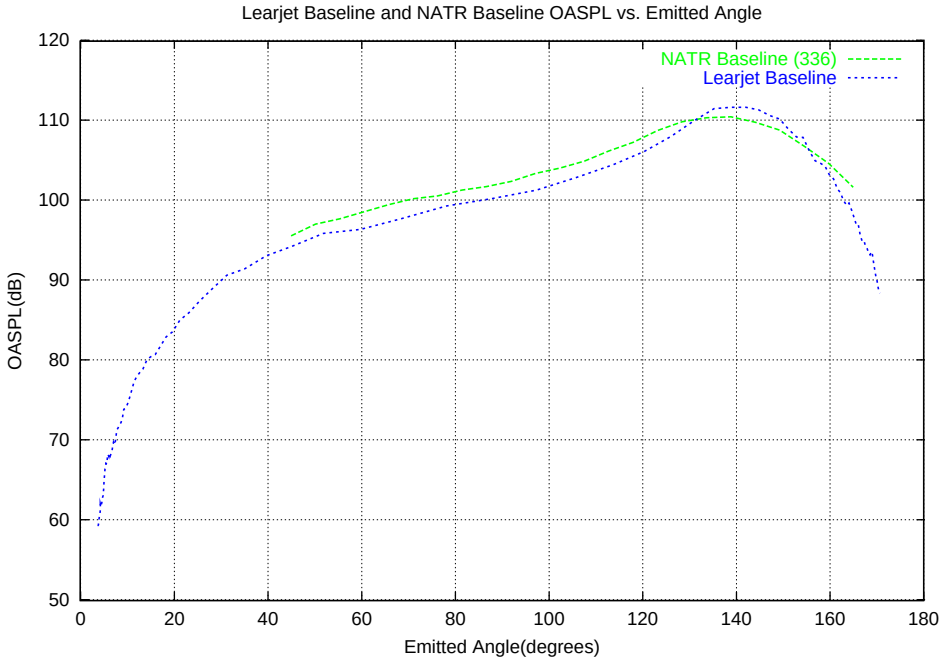

Figure 25: OASPL as a function of angle for the NATR and Learjet baseline nozzles.

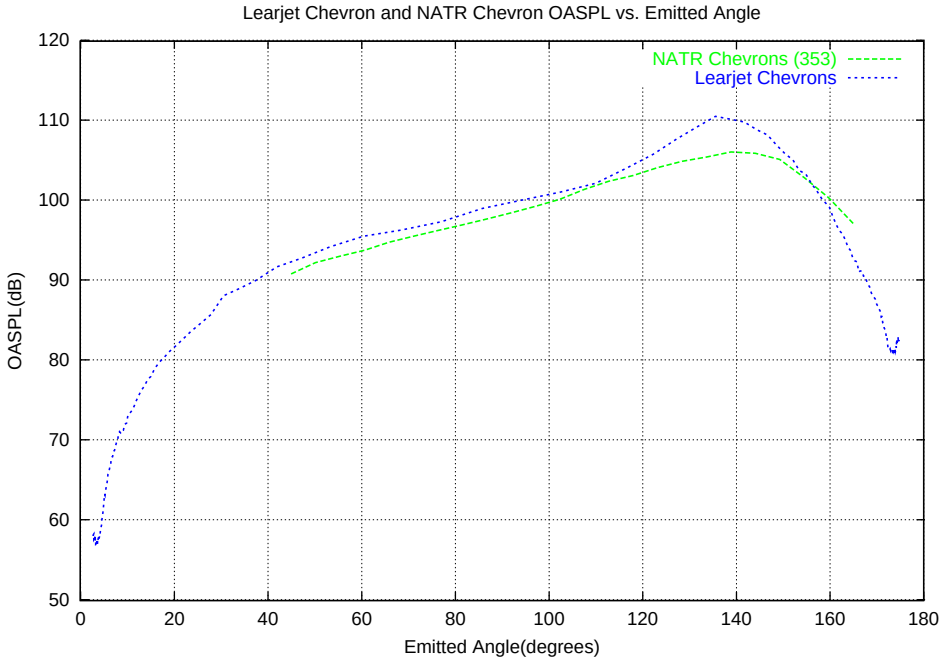

Figure 26: OASPL as a function of angle for the NATR and Learjet chevron nozzles.

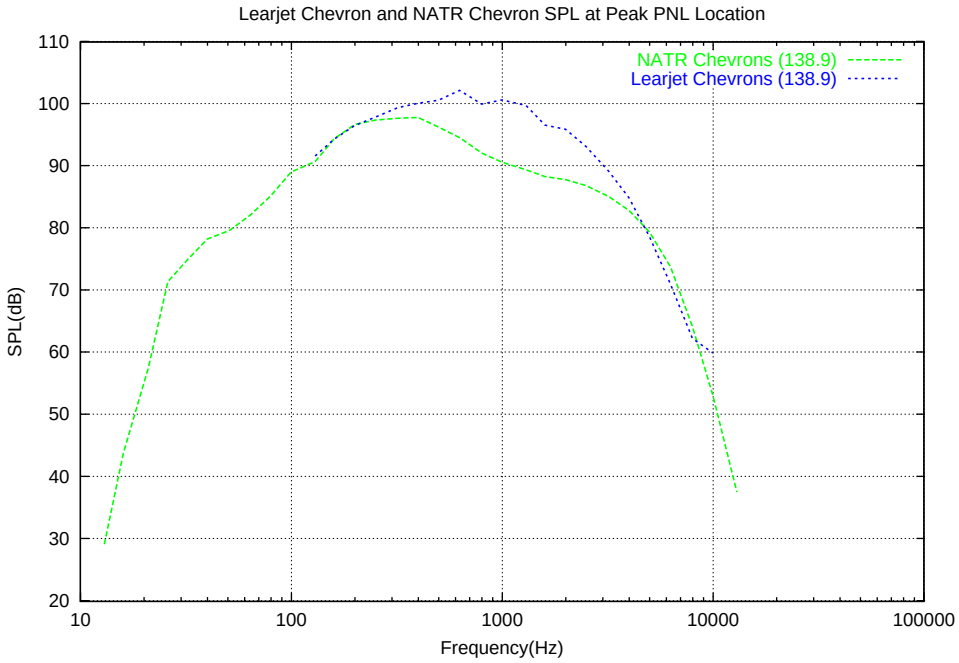

Figure 27: One-third octave SPL for the NATR (green) and the Learjet (blue) chevron nozzles at the peak noise location.

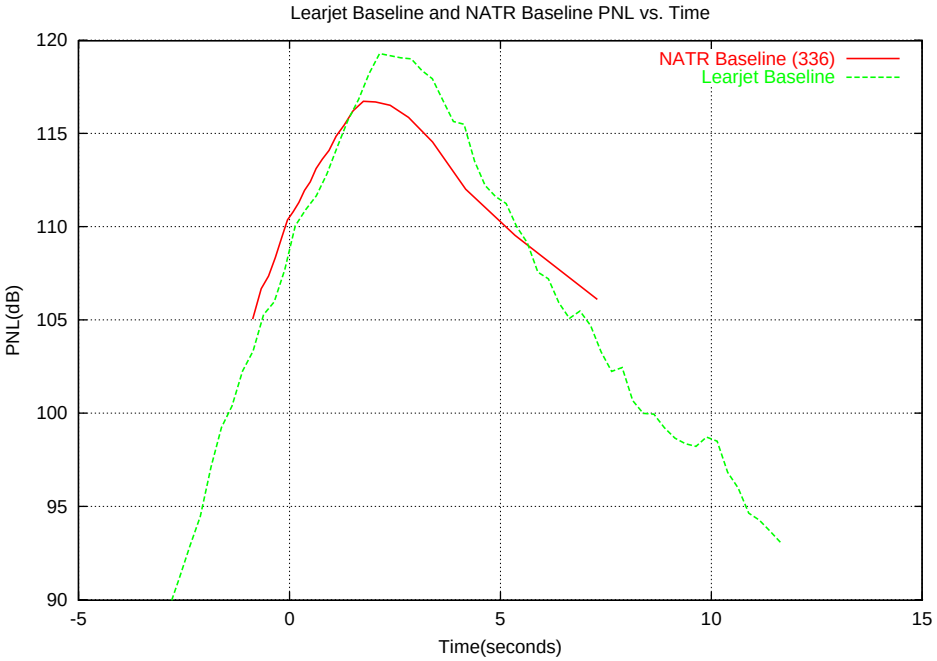

Figure 28: PNL as a function of time for the NATR and Learjet baseline nozzles.

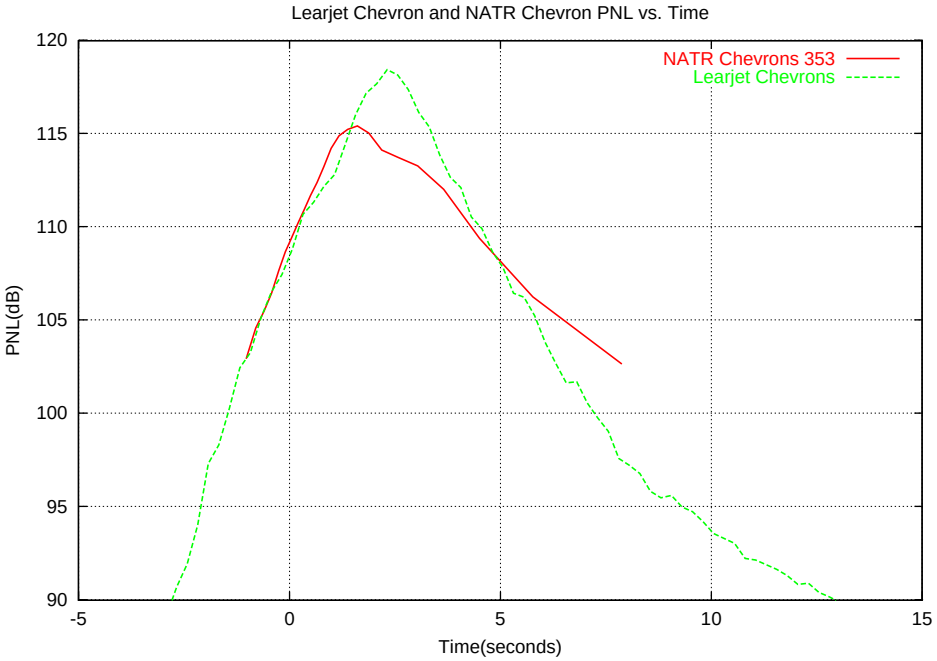

Figure 29: PNL as a function of time for the NATR and the Learjet chevron nozzles.

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13. ABSTRACT ***(Maximum 200 words)***

Ground-based model scale aeroacoustic data is frequently used to predict the results of flight tests while saving time and money. The value of a model scale test is therefore dependent on how well the data can be transformed to the full scale conditions. In the spring of 2000, a model scale test was conducted to prove the value of chevron nozzles as a noise reduction device for turbojet applications. The chevron nozzle reduced noise by 2 EPNdB at an engine pressure ratio of 2.3 compared to that of the standard conic nozzle. This result led to a full scale flyover test in the spring of 2001 to verify these results. The flyover test confirmed the 2 EPNdB reduction predicted by the model scale test one year earlier. However, further analysis of the data revealed that the spectra and directivity, both on an OASPL and PNL basis, do not agree in either shape or absolute level. This paper explores these differences in an effort to improve the data transformation from model scale to full scale.

14. SUBJECT TERMS

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