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THE EFFECT OF CHEVRONS ON CRACKLE – ENGINE AND SCALE MODEL RESULTS

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ABSTRACT

GE and the USN continue to work together to find and develop practical techniques to reduce jet noise on tactical aircraft such as the F/A-18 E/F/G. Noise is an important issue for the Navy because of the harsh acoustic environment induced during operations of these aircraft on aircraft carriers and the impact to communities around Naval Air Bases and training sites.

The noise generated by these systems is predominantly the noise generated by the exhaust plume due to the low bypass ratio of the engine and very high exhaust jet velocities. The main components of this jet noise are the jet mixing, shock and crackle noise. The present paper reports on progress, following Reference [1] with the F/A-18 E/F/G jet noise reduction program, which is currently focused on the USN *near term* goal of up to 3 dB reduction in the peak directivity direction. This goal also includes the reduction of the shock and crackle noise components. These goals are currently being pursued with nozzle plume mixing enhancement employing mechanical chevrons. These chevrons can be incorporated in the production version as a redesign of the F414 nozzle seals and do not involve the introduction of additional parts to the nozzle.

This paper focuses on the effect of chevrons on the crackle noise component both in full scale on the F404 engine, and in small scale on the F414 engine nozzle in the twin configuration.

The paper aims to make the case that this effect, which was first observed during ground engine testing of prototype chevrons, is a beneficial one in reducing/eliminating crackle which continues to be prevalent in high performance tactical aircraft engines today.

NOMENCLATURE

AB - Afterburner
dB - decibel
dBA – A-Weighted dB
DNS - Direct Numerical Simulation
F/A – Fighter/Attack
GE – General Electric
IRP – Intermediate Requested Power (or mil power)
JBD – Jet Blast Deflector
LES – Large Eddy Simulation
NAVAIR – Naval Air Systems Command
NPR – Nozzle Pressure Ratio
SPL – Sound Pressure Level
USN – United States Navy

INTRODUCTION

High-performance tactical aircraft launches from USN carriers have to take place in the confined spaces of the carrier decks, mostly in front of Jet Blast Deflectors (JBD) and always in the presence of launch personnel (Figure 1). Although they are a remarkable engineering achievement, they generate a significant amount of near-field jet noise as a by-product. Jet noise is also an issue during the arrested landings of these aircraft on the carrier deck, where they have to land at high power in case they miss the arresting cables and have to go around for another landing attempt (Figure 2). Near field jet noise is also an issue for the pilot of the trailing aircraft in the tactical aircraft mid-air refueling procedure (Figure 3), one of the few cases where the aft-propagating peak jet noise enters the cockpit adversely affecting pilot communication.

Figure 1 Tactical aircraft carrier launch noise issues
USN Public release photo 031103-N-2838C-510.

Figure 2 Tactical aircraft carrier landing noise issues.
USN Public release photo 0040926-N-7732W-065.

Figure 3 Tactical aircraft midair refueling noise issues
USN Public release photo 080402-N-2984R-660.

A close up of a tactical aircraft in after-burner preparing for carrier launch is shown in Figure 4. The picture illustrates the potential core of the hot supersonic jet and its proximity to the carrier deck and to the JBD. Compared to commercial transports or even fighter takeoffs from land bases, the physics of the carrier launch procedure are complex, leading to even more complex aeroacoustics. As an introduction, the much simpler aeroacoustics of a single hot supersonic jet in the absence of JBD and ground effects will be reviewed next.

Figure 4 Visualization of jet plume at launch of tactical aircraft **USN Public release photo 090125-N-2610F-397.**

The aeroacoustics of hot supersonic jets involve very high noise amplitudes, broadband noise spectra, and rich directivities (Figure 5). The major noise source for these jets are the large turbulent eddies that radiate noise in the aft direction (typically about 135-145 degrees) and at low frequencies. A minor noise source for these jets is the noise from the shock cells that is radiated in the forward direction and at high frequencies. Another minor noise source for supersonic jets is the high frequency noise from the small turbulent eddies near the nozzle exit that radiate noise in the forward angles and at high frequencies.

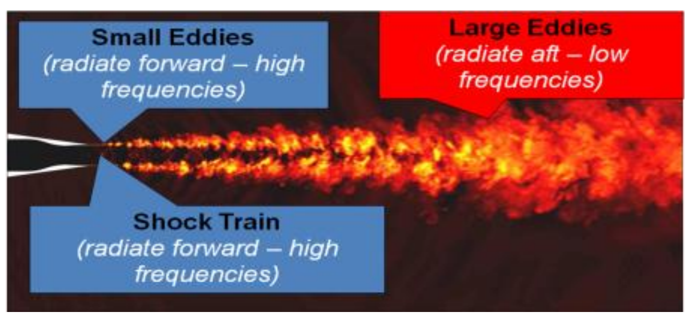

Figure 5 Aeroacoustics of hot supersonic jets.

The relative noise amplitudes of typical high thrust to weight, low bypass tactical aircraft engines is illustrated in Figure 6 as a function of frequency. It should be noted that fan noise, which is significant in commercial transports high by-pass ratio engines, is totally dominated by the jet noise. The major component of afterburner noise has been found to be aerodynamic in nature due to the jet velocity and not due to the combustion process.

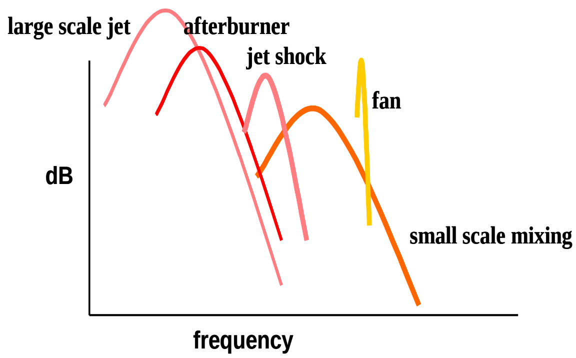

Figure 6 Typical tactical aircraft noise sources relative amplitudes.

It is our current understanding that the large scale structures are coherent (i.e. orderly, not random) and that they are generated by the jet shear layer instability waves. They propagate supersonically and dominate the jet mixing noise at low frequencies (Figure 7). The Small Scale turbulent structures affect the instability waves which control the growth of the jet shear layers, and also contribute to jet mixing noise at high frequencies.

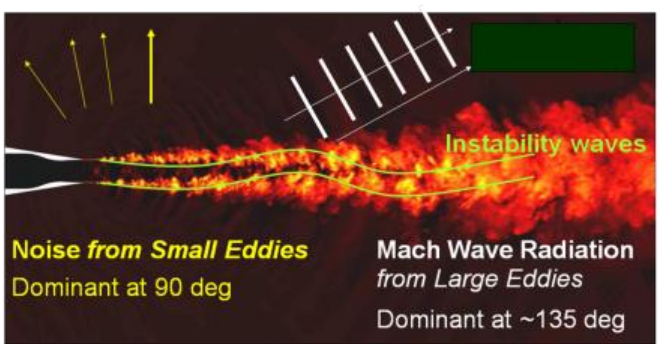

Figure 7 The two components of supersonic jet mixing noise.

The Large Scale coherent structures propagate supersonically and interact with the shock cells in imperfectly expanded jets to produce shock noise at high frequencies, as illustrated in Figure 8. Crackle noise can be observed in References [4,5,6] in pressure-time charts as a series of strong compressions and slow decays at high frequencies (Figure 9). Both shock and crackle noise are very annoying to outside observers when they occur.

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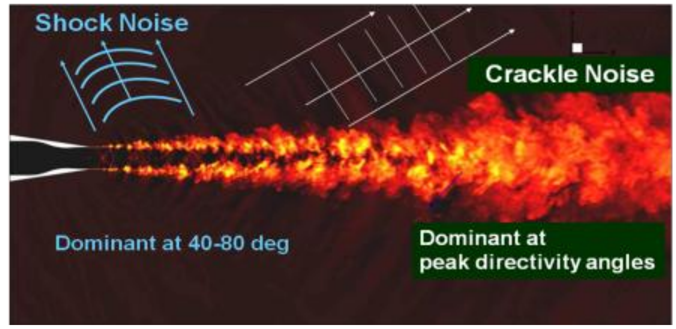

Figure 8 Shock and Crackle noise components of supersonic jets.

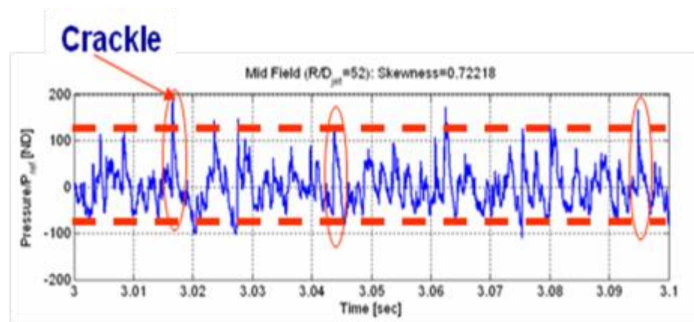

Figure 9 Crackle waveform of a typical tactical aircraft engine [6].

The formal tie-in of crackle to the Large Scale coherent structures is currently an open problem and the subject of ongoing research. But it is intriguing that both crackle and eddy Mach waves result in peak noise at the same aft angles, although crackle is observed, only at high engine power settings while eddy Mach waves are present throughout the supersonic jet regime. Furthermore, because shock noise, like crackle, is observed in the high end of the spectrum, a plausible conjecture is that crackle is produced by shocklets attached to the large eddies of hot supersonic jets, like those observed in the Direct Numerical Simulation (DNS) of decaying compressible turbulence in Reference [7], and experimentally in small scale for a Mach 2 flow in Reference [8]. If that conjecture is proven, then it would follow that crackle is an *orderly* "occurrence of distinct bursts of strong narrow positive pressure transients," not *random,* as posited in Reference [5]. But it would also confirm the conclusion in Reference [5] that "crackle spikes observed there are formed within, or in the very near vicinity of, the turbulent jet flow."

Another fundamental question regarding crackle that needs to be answered is why some high Mach jets crackle and some do not? Although this is currently an open problem, it might be worthwhile to pursue the framework proposed in Reference [9] for the universal phenomenon of crackling noise in physical systems like earthquakes on faults, superconductors and superfluids, magnets, etc., (jet crackle was not considered).

According to Reference [9], "crackling noise arises when a system responds to changing external conditions through discrete, impulsive events spanning a broad range of sizes." The objectives then for future research on jet crackle would be, first, to determine the necessary external conditions for a hot, supersonic jet that will make it crackle as it responds in a series of discrete shock wavelets spanning a broad range of length and time scales in the overall flow and, second, to derive the law(s) governing crackling noise of jets.

A visualization of sound waves radiated from an over-expanded hot supersonic jet at Temperature ratio of 1.74 and jet Mach number of 1.35 is shown in Figure 10. It was obtained by performing a Large Eddy Simulation (LES) coupled to a Ffowcs-Williams Hawkins methodology by Cascade Technologies, Palo Alto, CA. They also provided the instantaneous LES temperature field of a Mach 1.5 jet shown in (Figures 5, 7 and 8 [private communication]).

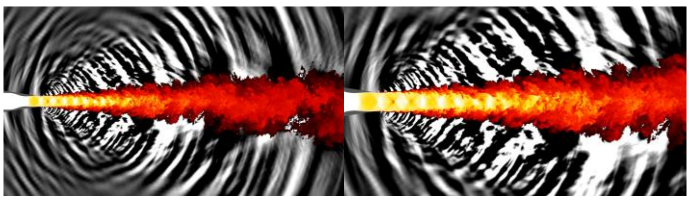

Figure 10 LES of an over-expanded jet; Tr=1.74, Mjet= 1.35.

It is clear from the previous discussion, that even though the questions on crackle are not yet settled, the Large Scale coherent structures play a central role in all noise generation mechanisms of interest of hot supersonic jets. It should be noted that the Screech noise component is not of much interest in the aeroacoustics of hot supersonic jets in full scale, except when it occurs in twin jets. Screech issues with the F-15 and B-1 were resolved during the development phase of these programs.

The present paper reports on progress, following Reference [1] with the F/A-18 E/F/G jet noise reduction program, which is currently focused on the USN *near term* goal of up to 3 dB reduction in the peak directivity direction. This goal also includes the reduction of the shock and crackle noise components. These goals are currently being pursued with nozzle plume mixing enhancement employing mechanical chevrons. These chevrons can be incorporated in the production version as a redesign of the F414 nozzle seals and do not involve the introduction of additional parts to the nozzle. This paper focuses on the effect of chevrons on the crackle noise component both in full scale on the F404 engine, and in small scale on the F414 engine nozzle in the twin configuration.

TEST DESCRIPTIONS

The data used in this paper to show the effects of chevrons on crackle are taken from both a full scale F404 static engine test and an approximately 1/6th scale model test of the twin exhaust nozzle configuration of the F414 powered F/18-E/F tactical aircraft. The F404 engine powers the F/18 A/B/C/D aircraft and is has a very similar nozzle design as the F414. More details of the engine test can be found in Reference [1]. Figure 11 shows a photo of the F404 on the static engine test stand, the microphones are in an inverted ground plane set-up on a 134 ft. arc measured from the nozzle exit centerline. Figure 12 shows a photo of the microphone set-up. Figure 13 shows a close-up of the F404 exhaust in the chevron configuration. The chevrons are an extension to the 12 nozzle inner seals and have proven to be a feasible retrofit to provide noise reduction with acceptable system trades.

Figure 11 Photo of F404 Engine on Test Stand During Test.

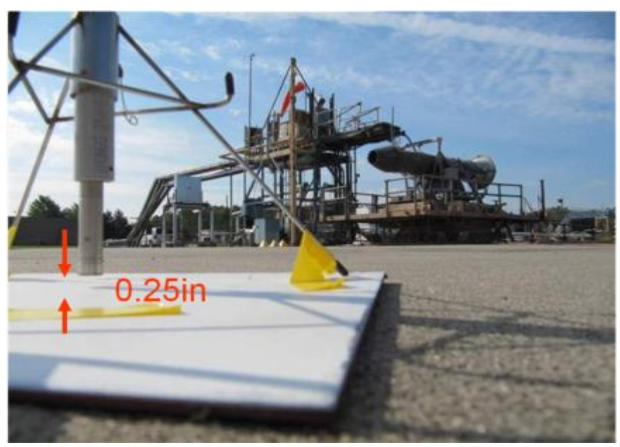

Figure 12 Photo of the microphone set-up.

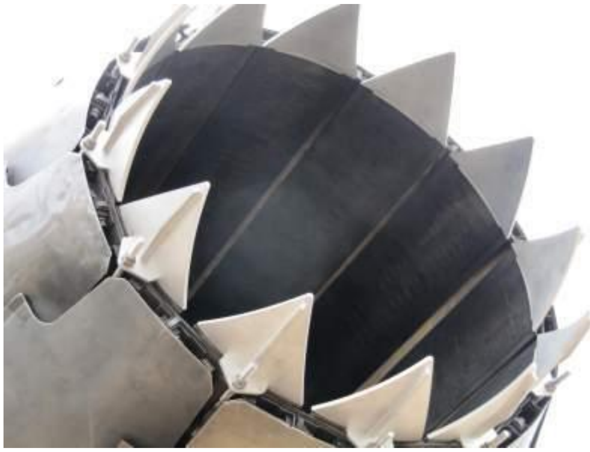

Figure 13 Close-up Photo of Engine Exhaust Nozzle and Chevrons.

Figure 14 shows a photo of the 1/6th scale model of the twin nozzle exhaust from the F414 nozzle mounted in GE Aviation's anechoic jet noise facility located in Evendale OH. More details of the facility are provided in Reference [2]. Figure 15 shows another photo of the model mounted in the facility with the far field microphone array approximately 22 ft. from the centerline of the twin nozzles, seen in the background. This array is mounted on a tower that can move in an arc around the model. Figure 16 shows a photo, again, of the scale model mounted in the facility with a near field microphone array installed, approximately 16.5 in from the center of the model. This array testing was conducted jointly with ASE Holdings and more information can be found in Reference [3]. The data for the near and far field arrays was taken approximately simultaneously with the arrays aligned through the centerline of the twin nozzles, but on opposite sides of the model, as shown in Figure 17.

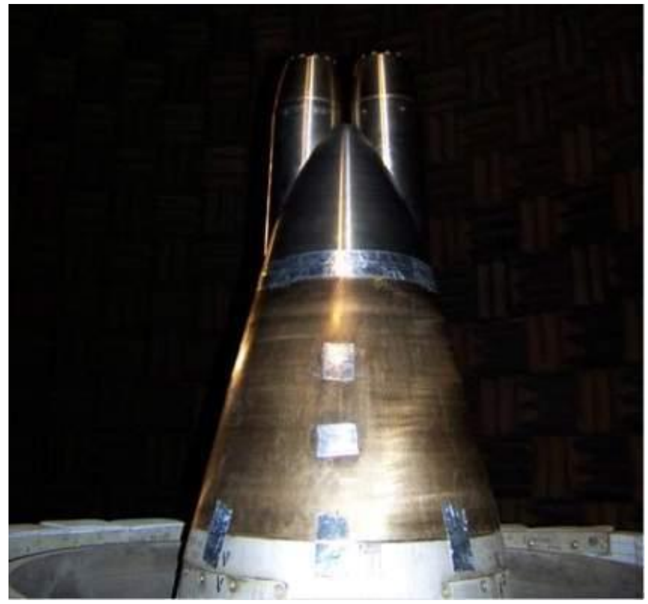

Figure 14 Photo of Twin Nozzle Simulation of Installed F414 Configuration.

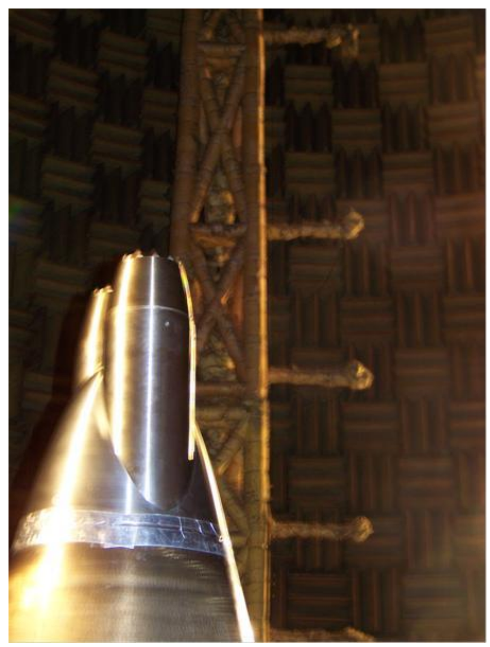

Figure 15 Photo of Twin Nozzle and Farfield Microphone Array in the Background.

Figure 16 Photo of Twin Nozzle and Nearfield Array.

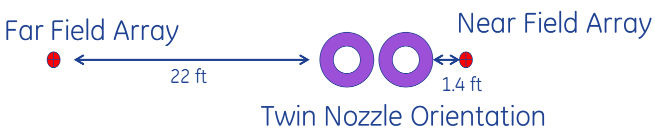

Figure 17 Schematic of Near and Far Field Arrays Relatives to the Twin Nozzle Orientation.

ACOUSTIC DATA

The data from the two tests to be shown include standard acoustic data, dBA directivity and sound pressure level (SPL). For both tests the data is only corrected to a standard day, this means the scale model data has not been scaled and the frequency ranges will differ between the two tests. This is because the focus will be on the time series and skewness calculations, which generally are not scaled in any way. Representative time data will be shown as will the skew of the time series.

ENGINE TEST RESULTS

Figure 18 shows the dBA directivity measured at 134 ft. for the IRP and AB engine conditions. The directivity angle is measured relative to the engine inlet, so the 0 deg microphone would be directly in front of the engine. These plots show the relative difference in peak level between the two conditions, which have approximately similar nozzle pressure ratios, but the AB condition has a much higher total temperature. It is also apparent that the chevrons provide a significant noise reduction over most of the directivity.

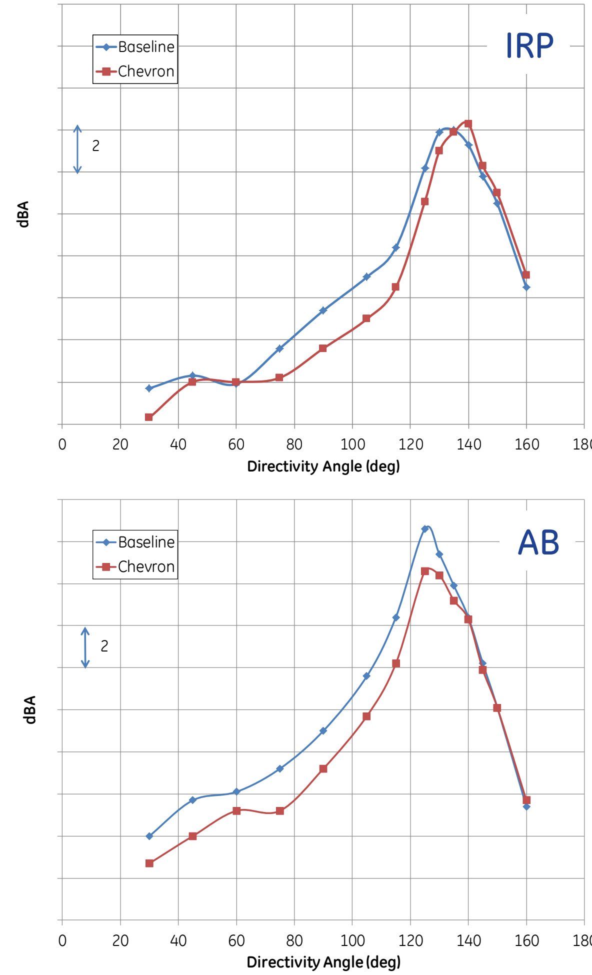

Figure 18 dBA Directivity from Engine Test at 134 ft., for IRP and AB Engine Conditions.

Figure 19 shows the SPL spectra at 75 deg, an upstream location for the same conditions. Again, the difference in relative amplitude for the two conditions is evident. The peak at 1,000 Hz is from the broadband shock associated noise and the chevrons are seen to provide a noise reduction at frequencies above this peak.

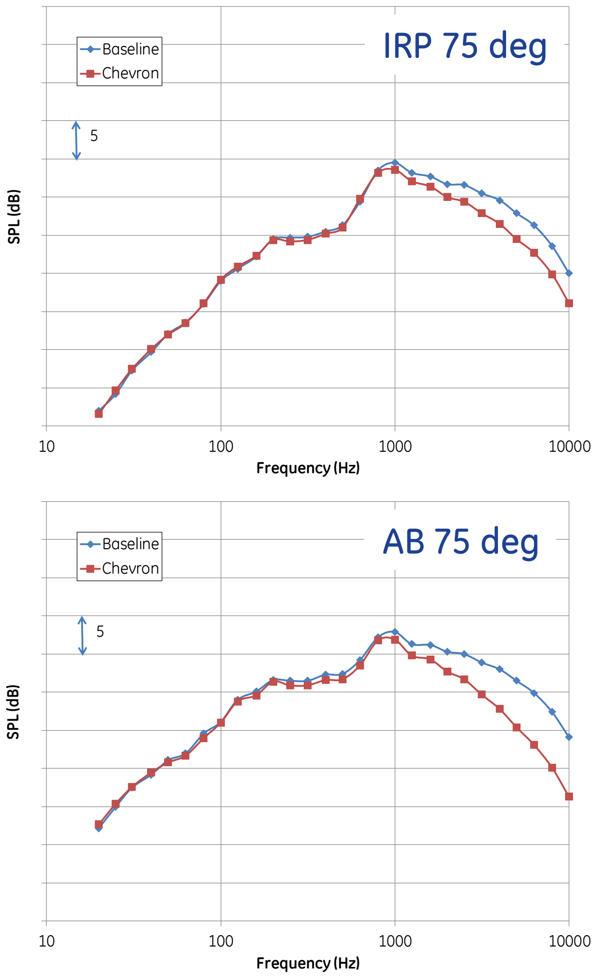

Figure 19 SPL Spectra from Engine Test at 134 ft., for IRP and AB Engine Conditions at 75 deg.

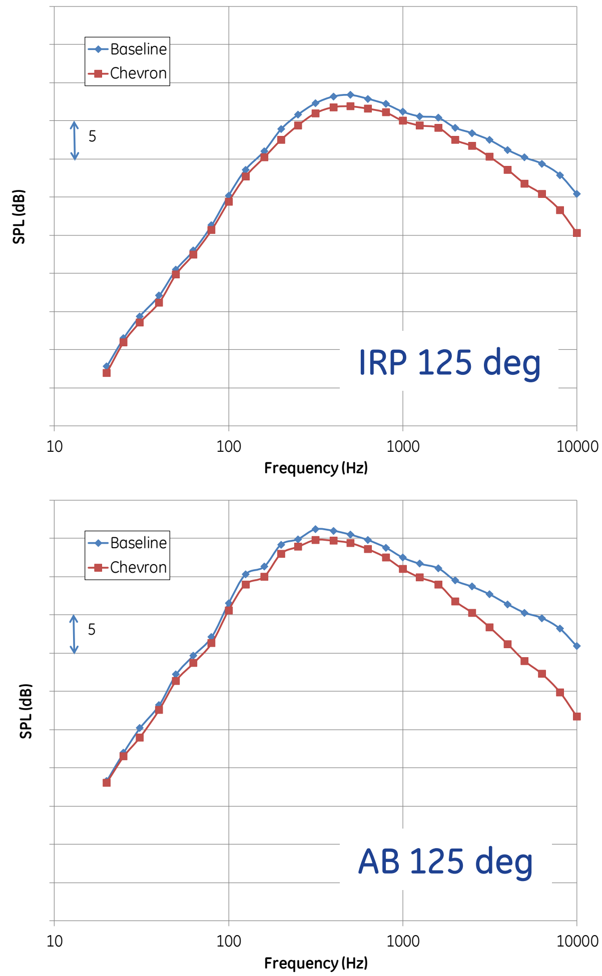

Figure 20 SPL Spectra from Engine Test at 134 ft., for IRP and AB Engine Conditions at 125 deg.

Figure 20 shows the SPL spectra at 125 deg, a downstream location for the same conditions. At this location there is no evidence of broadband shock associated noise. At this location the chevrons provide noise reduction over a fairly wide range of frequencies.

Next, the data pertaining to crackle will be presented and discussed. Figure 21 shows a representative portion of the pressure time signal from the 75 deg microphone at the IRP and AB engine conditions. These signals look fairly representative of this type of signal and overall the chevron signal seems to have a lower amplitude than the baseline signal. Also, the amplitude of the AB signal is higher than the IRP as would be expected.

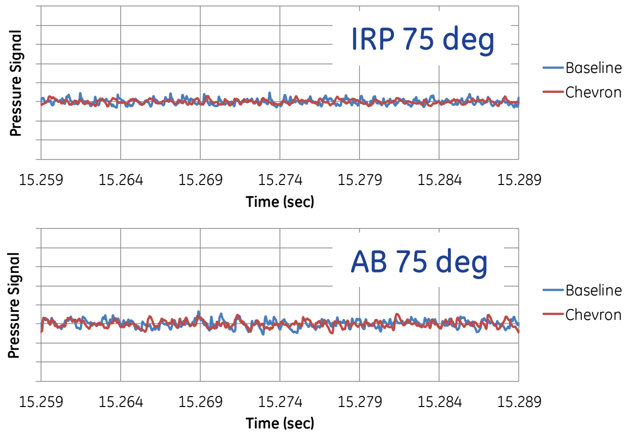

Figure 21 Pressure Signal Time Series from Engine Test at 134 ft., for IRP and AB Engine Conditions at 75 deg.

Figure 22 shows the same thing at the 125 deg microphone location. At this downstream location the amplitude is much higher than the upstream location as would be expected from Figure 18. These signals now also look very similar to those shown in Reference [4]. The signals, especially for the AB case, show a number of high amplitude excursions and very steep shock-like characteristics, typically seen as evidence of crackle.

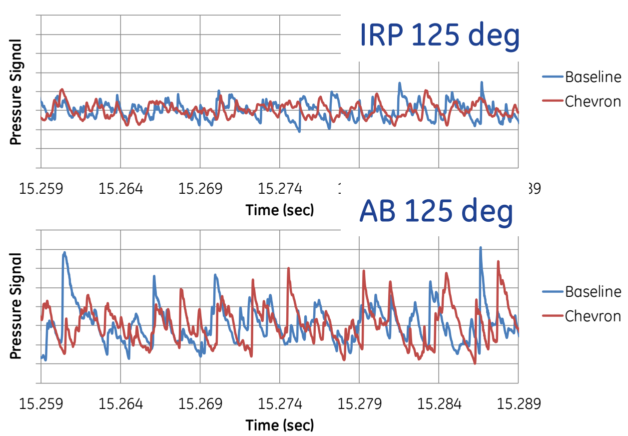

Figure 22 Pressure Signal Time Series from Engine Test at 134 ft., for IRP and AB Engine Conditions at 125 deg.

Figure 23 shows the skewness of the pressure time signal for the two engine conditions for all of the directivity angles. A couple of observations can be made based on this. One is that this would indicate crackle is likely present in both of the baseline cases based on the work in Reference [5] that crackle occurs at skewness levels greater than 0.4 and does not occur at skewness levels less than 0.3. The other very important observation is that the chevrons appear very effective at reducing the characteristics in the pressure field that can result in higher skewness levels and could potentially eliminate crackle if such a clear limit is real. It is also very interesting to observe how similar the directivity shapes and chevron deltas are between the skewness directivity and the dBA directivity, previously shown in Figure 18.

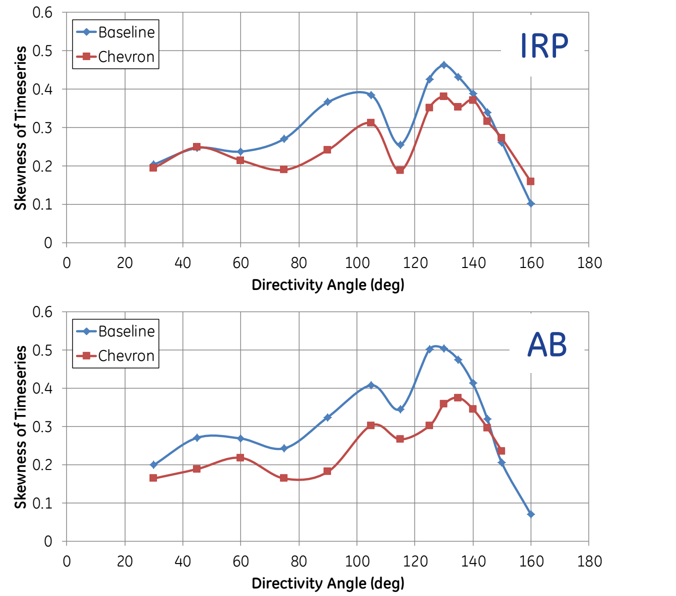

Figure 23 Skewness of pressure signal from Engine Test at 134 ft., for IRP and AB Engine Conditions.

SCALE MODEL TEST RESULTS

Now, similar information will be presented from the 1/6th scale model test as those in the previous section from the engine test. A couple of differences need to be noted here. First, this is a twin nozzle configuration not a single nozzle as in the engine test. However, the scale model test was also performed with a single nozzle configuration and all of the trends were similar. Second, in the scale model facility, AB temperatures cannot be simulated so all of the data will be shown for a constant high temperature, close to that of the IRP engine condition. However, three nozzle pressure ratios will be presented to show some variations with conditions. Third, the acoustic data plots will correspond to the far field microphone array but the time series and skewness data will be from the near field array. The analysis of the far field microphones showed very low levels of the skewness, with no evidence of crackle.

Figure 24 shows the dBA directivity for the three nozzle pressure ratios. These conditions all result in overexpanded nozzle conditions, with the nozzle pressure ratio of 4.5 nearing a theoretical perfectly expanded condition. Due to the design of the throat and divergent section of these realistic nozzles there will always be shocks generated. Another note about these scale models is that they do simulate the flap and seal configuration of the engine test with a faceted design in the azimuthal direction, so they are a true representation of the engine exhaust geometry. Again, the relative change in the peak amplitude can be seen as the nozzle pressure ratio changes. The directivity shape is similar to that of the engine shown in Figure 18.

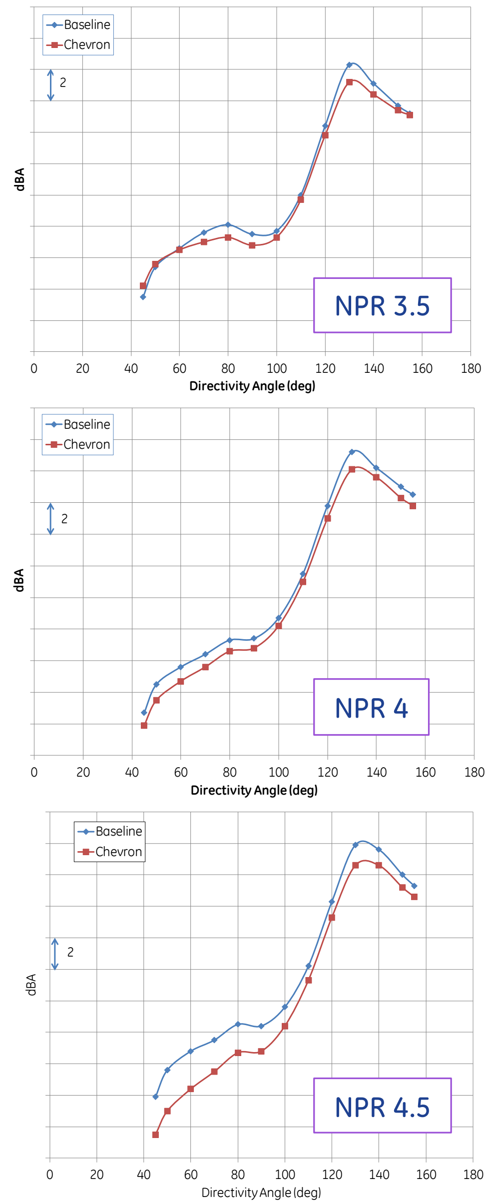

Figure 24 dBA Directivity from Scale Model Test at 22 ft., for Three Nozzle Pressure Ratios.

Figure 25 shows the SPL spectra for the same three conditions at 70 deg, an upstream angle. The peak at 3,150 Hz for the NPR 3.5 case is the broadband shock associated noise, and this condition actually has the highest amplitude at this angle since it is furthest from a pressure balanced condition. For all three conditions the chevrons offer some noise reduction compared to the engine data at a similar angle, Figure 19. The shapes are similar, although the engine spectra seem to have more high frequency acoustic content.

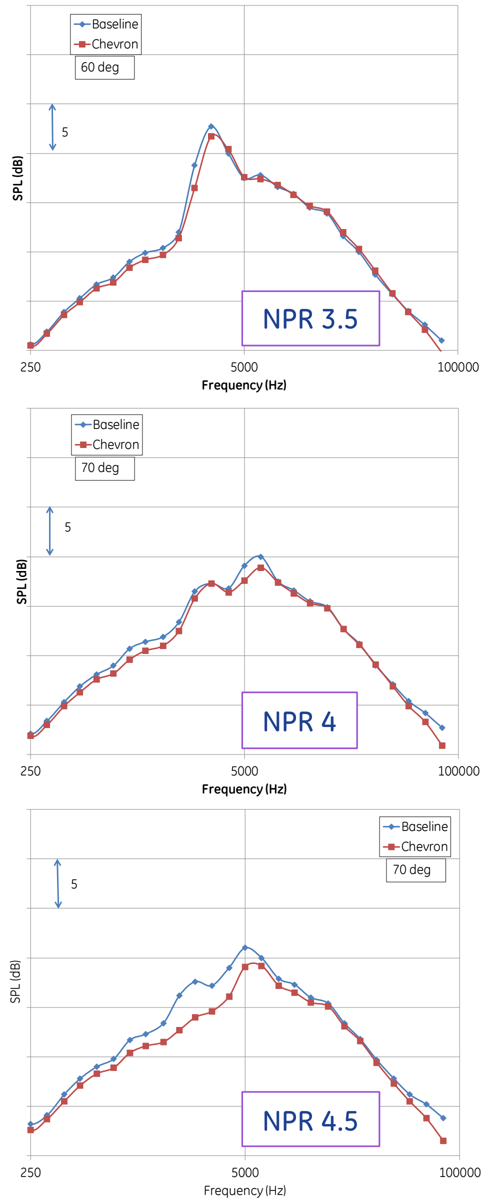

Figure 25 SPL Spectra from Scale Model Test at 22 ft. for Three Nozzle Pressure Ratios.

Figure 26 shows the SPL spectra for the same three conditions at 130 deg, a downstream angle. The chevrons provide a noise benefit over much of the frequency range and the benefit can be seen to increase with increasing nozzle pressure ratio, this is again an effect of the flow condition being overexpanded and the chevrons becoming more effective as the pressure matched condition is approached. The spectral shape is again similar to that of the engine, but again the shape of the high frequency roll-off for the engine is different.

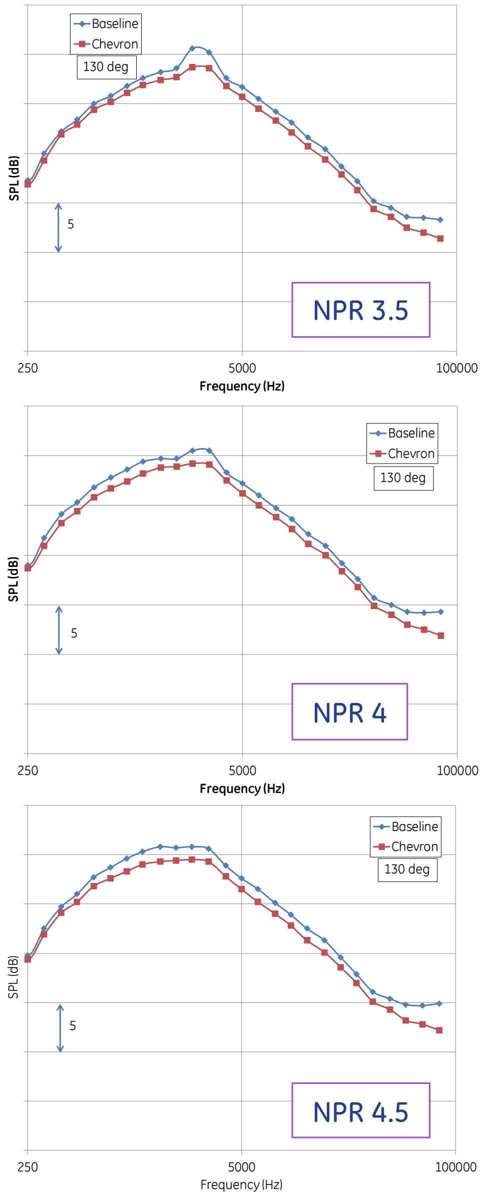

Figure 26 SPL Spectra from Scale Model Test at 22 ft. for Three Nozzle Pressure Ratios at 130 deg.

Figure 27 shows a representative pressure time signal for the three conditions from the nearfield array at an angle of 123 deg. The near field array starts just downstream of the nozzle exit so there are no upstream measurements. The signal generally increases in amplitude with increasing nozzle pressure ratio. Starting at a nozzle pressure ratio of 4 amplitude excursions and shock like features become evident. One surprising observation is that the chevron configuration signal is the same as or higher amplitude than the baseline configuration. This is not the case in the far field measurements shown previously and is also not the case when the data is projected to the far field as shown in Reference [3]. One explanation for this may be that since this measurement is taken in the hydrodynamic near field this may be the fluid dynamic signature of the chevron which either does not propagate as acoustic energy or is at a high enough frequency it is significantly attenuated through the atmosphere.

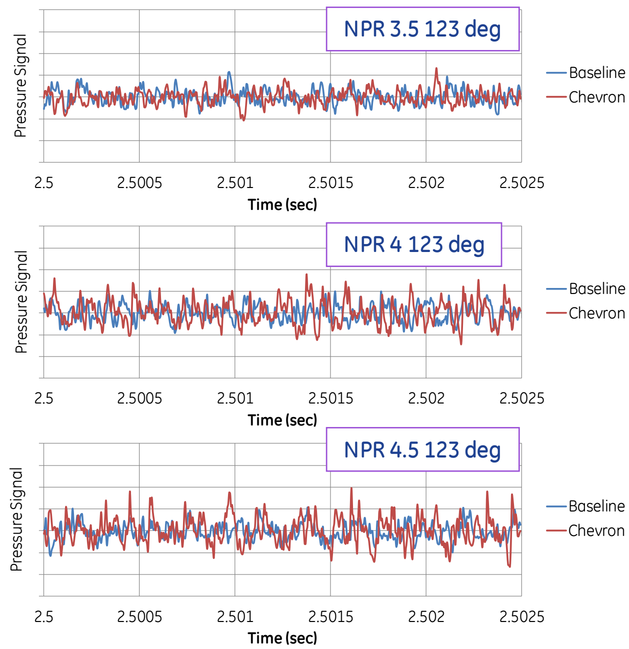

Figure 27 Pressure Signals from Scale Model Test at 16.5 in for Three Nozzle Pressure Ratios at 123 deg.

Figure 28 shows a representative pressure time signal for the three conditions from the near field array at an angle of 146 deg. At these locations the signals show characteristics indicating crackle is present with much lower frequency content than the previous location. Now, at least for the two higher nozzle pressure ratios the chevron signal is lower than the baseline signal in general. These signals would indicate high levels of skewness and potential crackle.

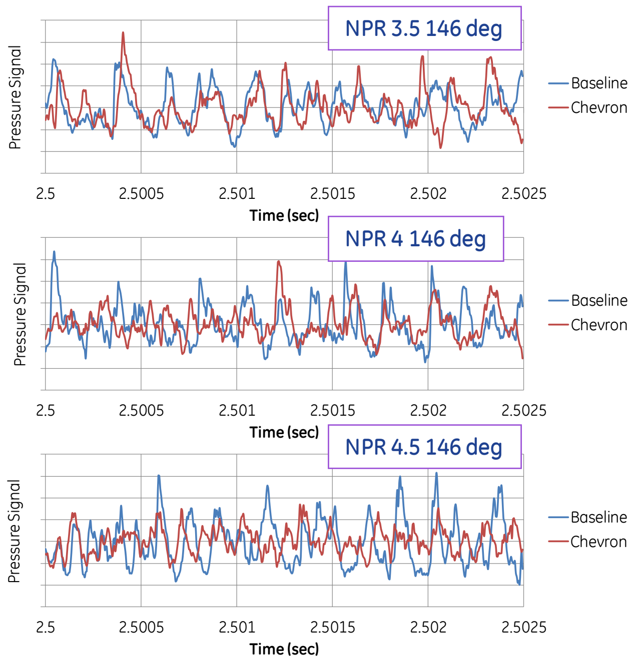

Figure 28 Pressure Signals from Scale Model Test at 16.5 in for Three Nozzle Pressure Ratios at 146 deg.

Figure 29 shows the skewness for the three nozzle pressure ratios. As was intimated from the time series data at angles lower than approximately 140 deg it is questionable whether crackle is present, and the chevron configuration consistently has a higher level. Above 140 deg crackle would be expected to be found and the chevron again shows a significant reduction as was seen in the far field measurements.

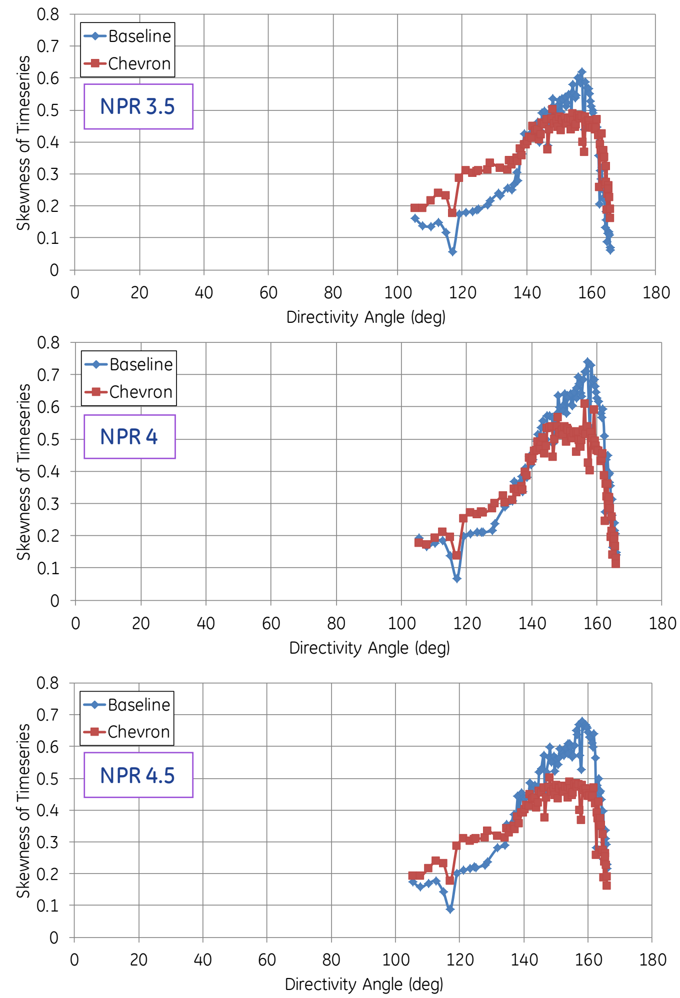

Figure 29 Skewness of pressure signal from Scale Model Test at 16.5 in for Three Nozzle Pressure Ratios.

DISCUSSION

Data has been presented from both full scale engine testing and 1/6th scale model testing of realistic nozzles at different conditions and with and without chevrons to look at the effect of chevrons on the jet noise component called crackle. In the engine data the parameters indicative of crackle (from literature, time series characteristics and skewness levels of the time series) indicate crackle is present at IRP and AB engine conditions. Chevrons appear to have the potential to reduce the skewness to levels below which crackle is observed. The trends in the skewness also looked remarkably similar to that of the dBA directivity, in terms of shape and the effect of chevrons.

Scale model data also supported these observations. Although, very near field measurements showed chevron configurations with a higher skewness level when the time series had a rich high frequency content that was not seen in the far field.

However, the far field data did not have skewness levels anywhere near those indicative of crackle. More investigation into scale model measurements made at different distances need to be performed to understand this better.

ACKNOWLEDGEMENTS

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