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Experimental investigation of nonlinear properties of crackle and screech in supersonic jets

J. N. Punekar,[1,a)] E. Avital,[1] and X. Li[2]
[1]*School of Materials and Engineering, Queen Mary University of London, Mile End, London, E1 4NS, United Kingdom*
[2]*School of Energy and Power Engineering, Beihang University, Xueyuan Road 37, Beijing, 100191, China*
jyopun@yahoo.co.uk, e.avital@qmul.ac.uk, lixd@buaa.edu.cn

Abstract: Supersonic crackle, an irritable component of aircraft jet noise, was investigated using model scale measurements. Near-field results showed Gaussian distribution but far-field had high skewness and even higher in its derivative. Skewness, a measure of asymmetry in the waveform, was compared to screech arising from shock associated noise which was also high but in contrast to crackle its skewness derivative had dropped to a much smaller value than its waveform. Both crackle and screech are nonlinear but their nonlinear properties are entirely different. Crackle is quantified when its derivative skewness becomes larger than its waveform skewness which should exceed 0.3.

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1. Introduction

The study of crackle noise in high speed military jets and rockets exhibiting sudden random bursts of sound has remained somewhat of an enigma as it involves high exhaust velocities. It is a phenomenon of a jet with sharp loud rasping noise that is most annoying dependent on the intensity of shock like waves present in the waveform with a very short life span. Until now, only skewness, a measure of asymmetry of the waveform, has been used to define it. Its bursts are dependent on the intensity of shock-like waves present in the waveform. It has been difficult to measure the perceived effect of this impulsive and distinctive sound, i.e., crackle when it was first studied by Ffowcs Williams *et al.*[1] for the Rolls Royce Olympus 593. Its source has been much debated since it is said to account for 30% of the annoyance of noise[1] radiated from supersonic jet engines. To date, there has been no theory based on fundamental principles to estimate its absolute noise levels other than from its skewness. The onset of crackle has been defined as when the sharp pressure transients in the time domain get distorted enough that its skewness peaks to 0.3 and above.

The third moment of the fluctuation pressure is the skewness, $S_k(p')$, where p' is the pressure fluctuation, a measure of the asymmetry in the positive and negative parts of the wave distribution caused by nonlinear steepening given by $S_k(p) = (p')^3/\sigma^3$, where σ is the standard deviation.

Gee and Sparrow[2] emphasised the importance of the skewness of pressure derivative to quantify crackle using simulated waveforms that have crackle similar to the F22 Raptor. Krothapalli *et al.*[3] measured crackle of a supersonic hot jet for a full scale engine and obtained Schlieren pictures in the far-field. Baars and Tinney[4] studied the high frequency spectral contents caused by crackle for unheated jets along the Eddy Mach direction and Baars *et al.*[5] estimated shock formation distance and Goldberg numbers for diverging waves from a lab scale model. More recently methods of interpreting autocorrelations for jet noise have been discussed by Harker *et al.*[7] and Mora *et al.*[6] simulated high crackle noise at specific ranges when noise is exhausted over a parallel flat surface.

Martens *et al.*[8] reported that chevrons are beneficial in reducing crackle for high performance tactical aircraft engines. Avital *et al.*[9] considered wave packets to model the jet large scale structures when they found nonlinear propagation caused skewness in far-field crackle. In an earlier experimental study of a laboratory cold jet for $M_j = 1.3$ by Punekar *et al.*,[10] M_j being the design Mach number, crackle was mildly heard as a mixture of incoherent sounds. Their far-field skewness in the

[a)]Author to whom correspondence should be addressed.

downstream Mach direction was always higher in its pressure derivative than in the skewness of the pressure waveform from nonlinear propagation. Punekar and Avital[11] also experimentally investigated screech nonlinear propagation into the far-field which had shown no rise in skewness in its waveform derivatives.

High amplitude screech harmonic is a component of the broadband shock associated noise in the upstream angle. Screech as a nonlinear phenomenon in the upstream angle has been studied by many researchers, e.g., Refs. 13–16 to name a few. Its intense sound generation is concerned with sonic fatigue failure to aircraft structures and hence greatly investigated for designing advanced aircrafts.

To understand the differences in the pressure excursions from nonlinearities between crackle and screech it was decided to study them for a higher design Mach number of $M_j = 2$ and to know if their near-fields and far-fields can cause sonic fatigue to aircrafts.

2. Model scale acoustic measurements

Jet noise measurements were made for a converging diverging nozzle of diameter $D = 3\,\text{cm}$ for near and far-field distances. Acoustic signals sampled at 140 kHz over 0.5 s each with details of test section available in Ref. 10. Near-field measurements were made with a highly controlled array of five equally spaced microphones traversing at increments of 7.5 mm horizontally and 15 mm vertically along the downstream of nozzle exit. For the far-field, microphones were radially placed from downstream 15° (inlet to the axis) to 90° (sideway) of the nozzle to capture all acoustic radiation. Following the description of Krothapalli *et al.*[3] of the Mach direction at 39° for a cold jet at $M_j = 2$, where they had intense crackle the present measurements included a data analysis at 40° and in addition at 90° for sideway screech.

2.1 Near-field measurements

All measurements were made for under-expanded jet at $M_j = 2$. Figure 1(a) shows a near-field fully evolved spectra captured by microphone traverse pointing in direction of 40°. There is a dramatic increase in high frequency content arising from clusters of high amplitude noise at the source which when played back sounded like a mixture of incoherent spiky noises similar to crackle. Near-field spectra of Fig. 1(c) shows the formation of screech tones arising from shock associated noise when the traverse pointed upstream towards 90°. Nevertheless, all near-field waveform distribution and their time derivative taken at several positions including above 40° and 90° relative to the jet axis remained Gaussian in nature. Their probability functions are shown in Fig. 2(a) and discussed in Sec. 3.1.

Previously, Punekar derived analytic solutions of simulated near-field Gaussian waveforms which continued to remain statistically Gaussian when nonlinearly propagated until the average shock formation distance was reached in her Ph.D. thesis.[12] The measurements presented here seem to somewhat follow the above analytic results when the near-field remained Gaussian, but the waveforms crackled intensely as in a nonlinear event. The near-field symmetry indicate nonlinear N waves that are generated in the far-field of interest are from nonlinear propagation only. The symmetric waveform generation is explained to some extent in that the convective Mach number of the bulk nonlinear turbulent motion may still not have reached unity in the near-field of the mixing region. Once this exceeds unity, alteration in the distribution will occur producing stronger waves that allow them to propagate nonlinearly into the far-field.

2.2 Far-field measurements

Figure 1(a) is also the far-field spectra for crackle at 40° at a distance $40D$ from the nozzle. The empirical F similarity spectra of Tam *et al.*[17] for large turbulent structures in the downstream direction follows. Crackle is present in the low frequency range of 1 to 2.5 kHz appearing as a humped peak along with high frequencies above 3 kHz. It seems to be an agglomeration of low frequencies having high frequency edges. The far-field spectra shows a rapid reduction of 19 dB in high frequencies and a shift towards low frequencies due to the intense "bunching" described by Lighthill[18] in the waveforms when larger waves take over the smaller. Figure 1(b) shows that the low amplitude waveform for crackle along with the high amplitude periodic clusters of screech are obvious due to the resonance feedback cyclic motion. Nonlinear distortion has resulted in steepening of crackle towards the negative side as shown in Fig. 1(b), which has been magnified for visibility. It shows a reduced number of waves for crackle with an overall amplitude of a thirde less than screech. The magnified figure for crackle also shows sharp pressure excursions bursting intermittently, which in high

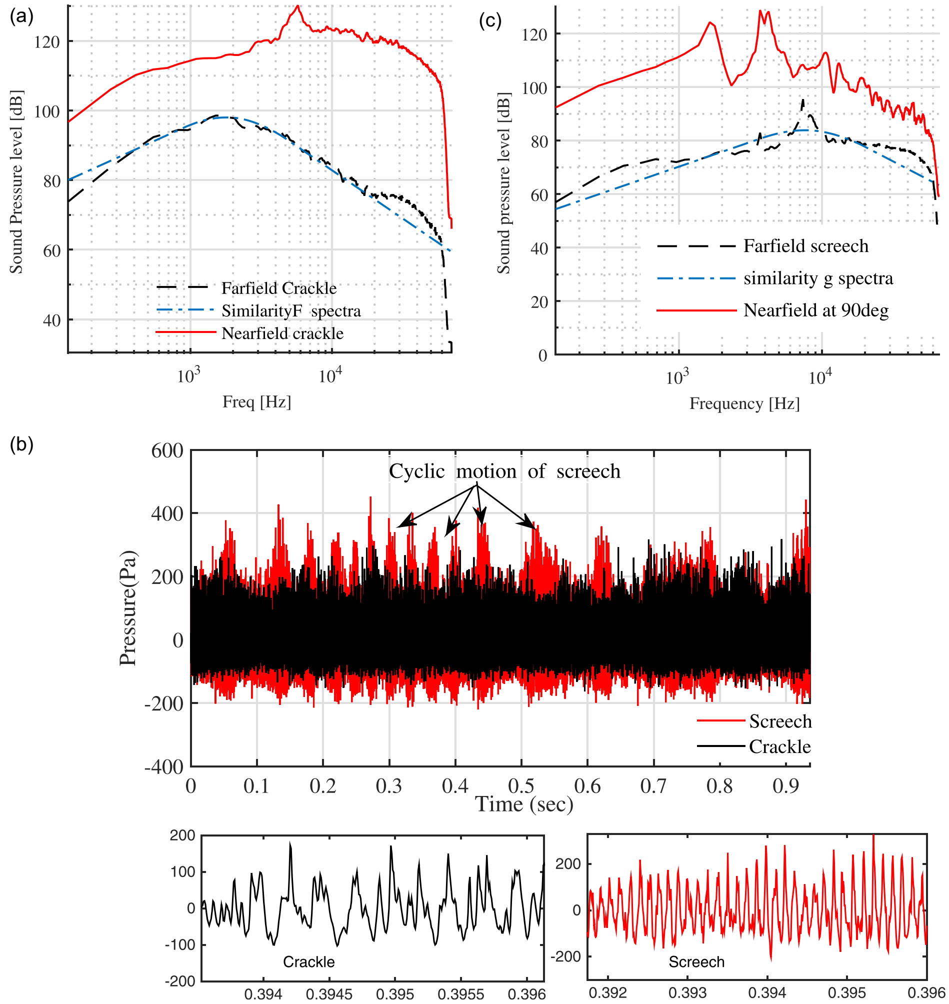

Fig. 1. (Color online) (a) Spectral contents of near-field and far-field crackle. Far-field following Tam's F spectra for mixing noise at downstream angle of 40°. (b) Far-field screech and crackle waveforms showing reduction in crackle amplitude. Underneath are their magnified short time traces. (c) Spectral contents of near-field and far-field screech. Far-field following Tam's G spectra for upstream shock associated noise at 90°. $M_j = 2$ for all figures.

frequencies results in loss of energy from dissipation. Both crackle and screech show the presence of shock waves with steep fronts but with varying speeds. The wave fronts reach their peak due to nonlinear propagation when they burst and disintegrate, each one having their individual lifespan.

The compressions of the pressure transients shown in Fig. 1(b) for crackle are of the order 140 Pa (≈ 0.0015 atmos) having positive narrow pulses whose peaks are being formed as quickly as 1/10 of a millisecond.

Figure 1(b) for screech shows decreased screech obliqueness resulting in lower skewness of its derivative and is discussed in Sec. 3.1. Screech shock waves avoid becoming further oblique due to fresh energy being provided from the feedback loop of the upstream-propagating acoustic waves.

Shown in Fig. 1(c) are the far-field spectral contents of the upstream screech tones at 90° due to shock associated noise, showing agreement with the asymptotic G formula of Tam *et al.*[17] The screech frequencies are at 3.69 KHz fundamentally, with harmonics at 7.38 KHz. The far-field spectral content of screech is increased at high frequencies. It seems that dissipation of energy for screech is largely in the vicinity of the shock wave compared to crackle where dissipation is dominated by larger waves engulfing the smaller ones.

3. Probability distribution functions (PDFs)

Probability distribution curves are used as an informal way to check the for differences in the skewness of crackle and screech. The PDF of near-field waveform towards Mach angle 40° and sideway screech were found to be within the Gaussian limit as shown in Fig. 2(a).

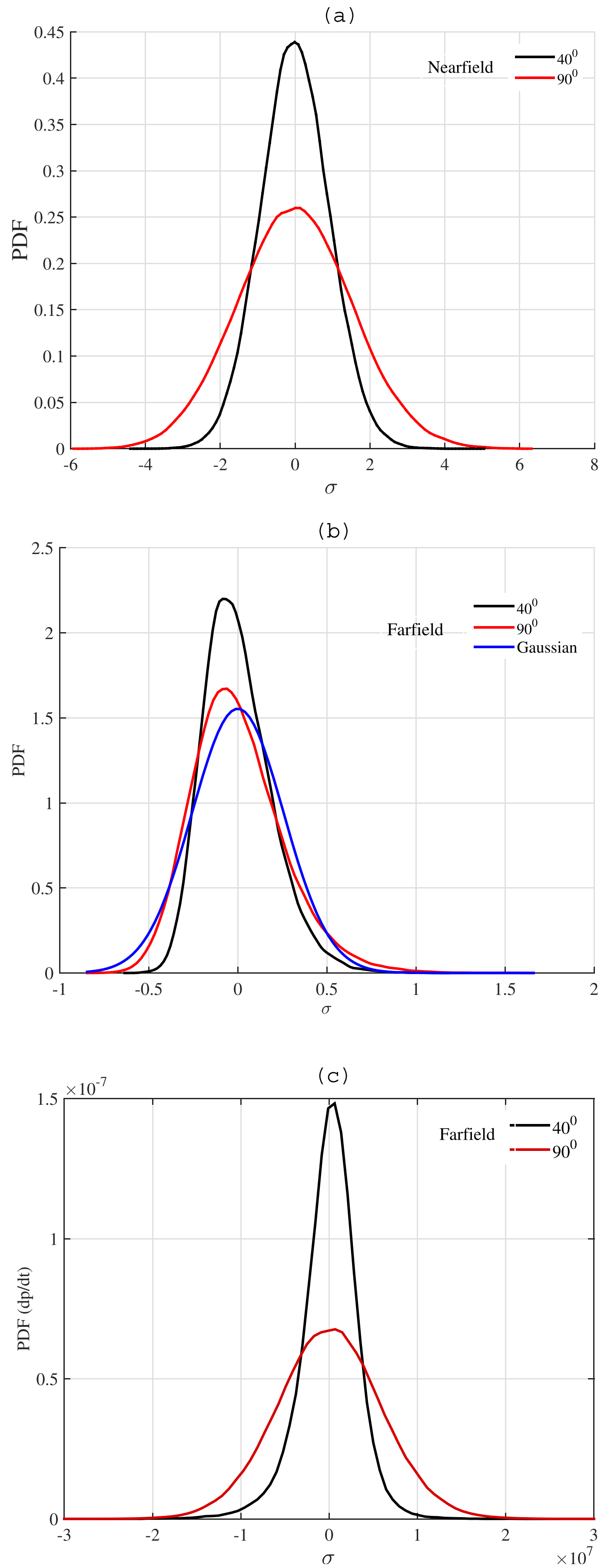

Fig. 2. (Color online) (a) Near-field PDF of crackle and screech taken with microphones at traversing along downstream angle 40° and upstream 90°, close to nozzle exit. (b) Far-field PDF for crackle and screech and (c) far-field PDF of their derivatives.

Figure 2(b) shows the far-field PDF for crackle and screech showing both diverging from the Gaussian mean. Divergence from each other is more evident towards the negative tails. These tails illustrate the non-linearity in the crackle and screech contents, but also the difference between the two, showing that crackle's energy is less distributed in the negative tail than in the screech. The tails for crackle represent a lower probability with lesser energy than screech. The PDFs of the gradients in Fig. 2(c) show crackle is further diverging from screech by having less energy inside the tails. On the other hand, the PDF for screech derivative has reorganised itself to become an almost Gaussian normal distribution, becvause its waveform is not subjected to further steepening caused by the screech feedback loop. This physical mechanism of the screech PDF reorganising from a non-Guassian to near Gaussian in its derivative is new and has not been reported in any literature to date.

3.1 Skewness $S_k(p)$ comparison for crackle and screech and their skewness derivative $S_k(dp/dt)$

As mentioned earlier, previous studies at $M_j = 1.3$ for screech had $S_k(p) > 0.3$,[11] similar to the threshold for crackle $S_k(p) \geq 0.3$ given by Ffowcs Williams *et al.*[1] Since the PDFs described above could not sufficiently display the unique physical nature and differences in crackle and screech, $S_k(p)$ and $S_k(dp/dt)$ were calculated for the present measurements.

For the far-field it was expected that $S_k(p)$ of screech should be more than crackle considering its large amplitude nonlinear propagation. Results showed far-field skewness $S_k(p) \approx 0.65$ for screech and crackle were almost equal as shown in Fig. 3(a). Also noteworthy is the drop in $S_k(dp/dt) = 0.22$ to lower than its waveform $S_k(p) \approx 0.64$, far less than $S_k(dp/dt) = 0.71$ for crackle at 40°. To date, it was believed that $S_k(dp/dt)$ of any nonlinear process was larger than its waveform, but in the case of screech observed here, this trend is violated. $S_k(dp/dt)$ for screech drops to a value even lower than the specified threshold skewness of 0.3 for crackle.

The above results seem to establish that a supersonic jet crackles only when $S_k(dp/dt) > S_k(p)$ but not so for a screeching jet, even though both phenomena are highly nonlinear. This is an important finding using skewness to further support that nonlinear propagation processes are entirely different in the 2 events.

Measurements were repeated for the same condition to check if there were any defects in the microphone calibration. No flaws in microphones or any procedures could be found. The Strouhal number for screech tone is 0.34 as shown in Fig. 3(b) while screech measured by Norum and Seiner[16] was at 0.35. The figure also shows that crackle has a Strouhal number in the range of 0.15–0.25.

3.2 Spectral comparison with full scale

Figure 3(c) shows the far-field spectral contents for crackle from the present measurements to Martens *et al.*[8] full scale engine measurements. This is a rough comparison since the data had to be digitised from the plots so it does not accurately show the inconsistency in the high frequencies. Although the overall shape and levels of the curve agree reasonably well over a broad range of frequencies, the full scale engine's high frequencies amplitudes are much higher than the lab jet amplitudes. This can be attributed to the small scale of the lab jet, which for the same Strouhal number as the full scale engines, produces higher frequencies that are more affected by dissipation as they propagate.

4. Conclusion

Model scale measurements at the QMUL jet facility for under-expanded $M_j = 2$ gave crackle noise radiation with low frequency impulsive noise with sharp high frequency edges along the downstream angle of 40°. Measurements were also made for high frequency screech tone along the sideline 90° whose nonlinear properties were compared with that of crackle. Near-field measurements made in detail were not free of crackle or screech even though they had symmetric probability distribution. Symmetric crackle waveforms indicate that nonlinear N waves are generated from nonlinear acoustic propagation over distances of interest in the far-field and not directly by supersonic jet itself that Ffowcs Williams *et al.*[1] described. Crackle was distinctly heard for both near-field and far-field, similar to that of a supersonic aircraft flying overhead that seemed unmistakably identical. As for screech tone, which generally is not heard in a real engine being shrouded by combustion and clog, its study here for model scale revealed a new understanding of its nonlinear phenomena.

Far-field measurements showed higher skewness in the crackle's pressure time derivative higher than in its waveform as an outcome of excessive nonlinear

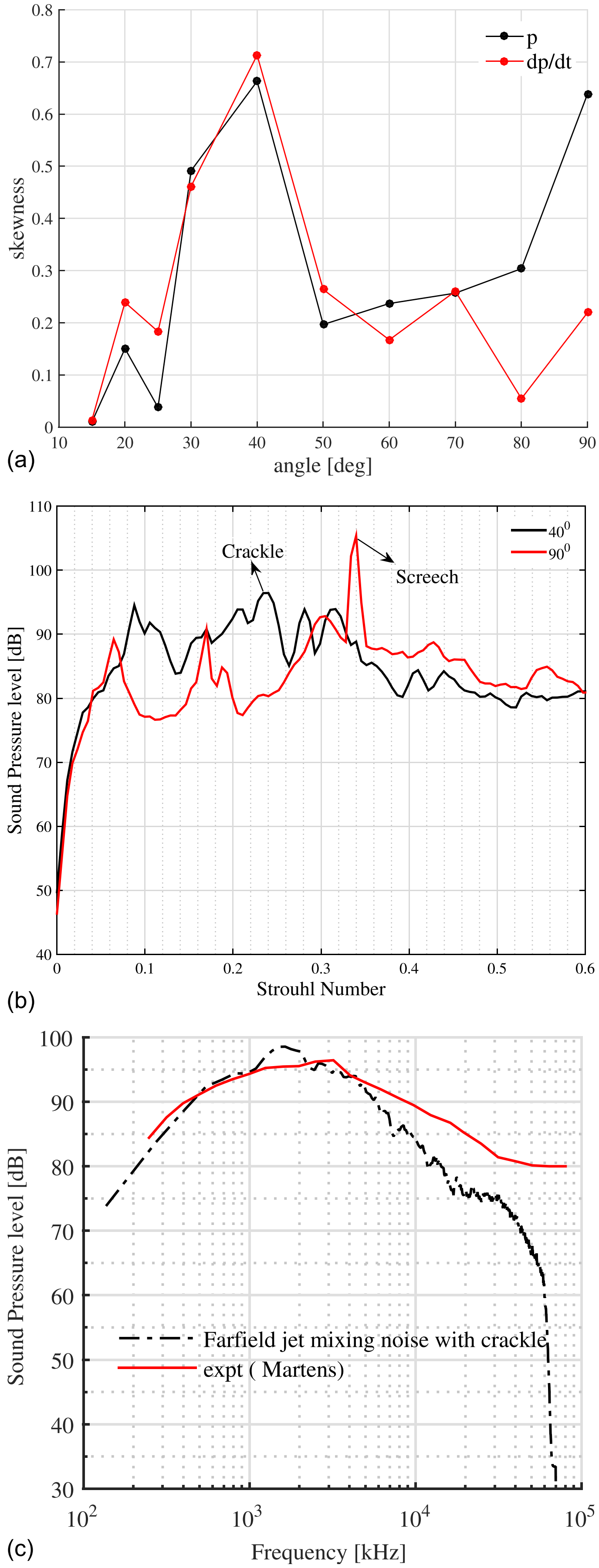

Fig. 3. (Color online) (a) Far-field $S_k(p)$ and $S_k(dp/dt)$ angular variation at distance of $40D$ from nozzle exit. (b) Far-field Strouhal number of 0.34 for screech at 90° and for crackle between 0.15 to 0.25 at 40°, respectively. (c) Comparison of crackle from the present model scale with full-scale engine.

"bunching" resulting in reduced amplitude. Far-field screech was also found to be highly skewed, but not its skewness derivative, which had surprisingly dropped to an almost near Gaussian distribution. Results also showed screech had more waves and its amplitude did not fall rapidly like crackle. This behaviour of screech derivative skewness not peaking further to high values is most likely an outcome of fresh energy being provided from a continual resonant feedback at the nozzle lip. Thus, the nonlinear effects are entirely different in both cases where crackle has faster decay than screech. Thus, to quantify far-field crackle, its skewness waveform derivative should be more than the skewness of its waveform, which should in turn exceed the given threshold of 0.3. This increase in the crackle pressure skewness derivative is of vital importance and has not been mentioned in the literature so far, although its applicability has been narrated by Gee and Sparrow.[2]

The current model-scale laboratory jet measurements were made under clean conditions due to which an amplifying effect of crackle and screech was heard. In a full scale engine which is heated and unclean, the noise passing through atmosphere with different densities and wind speeds gets damped. It is suggested that high levels of crackle and screech found in the near-field may lead to severe vibrations on the nearby components of the aircraft causing fatigue. Further studies under other jet conditions and quantification of the source length leading to estimates of the near sound field penetration into the surroundings will be communicated separately.

Acknowledgments

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