DIFFERENCES IN THE NON LINEAR PROPAGATION OF CRACKLE AND SCREECH

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Model scale jet experiments showed differences in the nonlinear properties for crackle and screech events in the farfield. Although crackle arises from turbulent mixing and screech forms part of the shock associated noise their nonlinear propagation processes are entirely different. Far-field crackle showed higher skewness than high amplitude screech skewness. Crackle was dominated by greater 'bunching' and faster decay than screech which is self sustaining with fresh energy being supplied by cyclic feedback loop. From investigating the farfield probability distribution resulting from nonlinear propagation it is for the first time possible to clearly distinguish the differences between screech and crackle. Surprisingly although screech is considered as a highly nonlinear event its waveform derivative skewness behaves very differently. Results showed significant rise in the derivative skewness for crackle whereas its corresponding screech derivative skewness had dropped considerably. The study concludes that crackle can quantified by skewness only when its skewness derivative is larger than its waveform, which should be larger then the threshold value of ± 0.3.

Keywords: jet noise, crackle, screech, nonlinear propagation

1. Introduction

Aircraft noise is generated by a number of different sources though the dominant one is still the main engines. Jet noise from high powered turbojet engines used in military aircrafts are extremely noisy. Exposure to such noise levels can be detrimental to human health effects, particularly increased blood pressure and contribute to hearing loss.

The study of supersonic screech and crackle noise in military jets and rockets are of much interest as they are very intense. Supersonic screech is a discernible component of the Broad band shock associated noise and was first investigated systematically by Powell [1] in 1953. He showed that screech is controlled by a feedback loop for an imperfectly expanded jet where the disturbances at nozzle exit are convected downstream and eventually interacts with shock waves in the shear layer to produce a violent discreet tones. Screech is important not only due to concerns about sonic fatigue failure of aircraft structures but also to understand its nonlinear propagation outside the flow dominating all other noises. Many researchers [2], [3], [4], [5], [6] and others have studied screech as it can cause sonic fatigue failure and hence has been greatly investigated for designing advanced aircraft.

Crackle noise in high speed military jets and rockets exhibiting random bursts of compression sound waves has remained somewhat of an enigma as it involves high exhaust velocities resulting in sporadic emissions with very short life span when until now only skewness has been used to measure it. The roar of crackle is dependent on the intensity of shock like waves present in the waveform. Its source has been much debated since it is said to account for 30% of the annoyance of noise [7] radiated from jet engines. There has been until now no theory based on fundamental principles to estimate its absolute noise levels other than from its skewness. The perceived effect of this impulsive and distinctive crackle was first studied by Ffowcs Williams et al [7] for Rolls Royce Olympus 593. They defined the onset of crackle when the sharp pressure transients in the time domain get distorted enough that its skewness peaks to 0.3. Several other researchers have attempted in studying crackle such as Gee et al [8] who simulated crackle waveforms and showed the importance of its skewness derivative. Schlierens of Krothapalli et al [9] for hot jet showed crackle whereas Martens [11] used chevrons to reduce crackle. Baars et al [10] studied the spectral contents of crackle and Avital et al[12] had crackle using wave packet model of jet large scale structures.

In an earlier experimental study for laboratory scale model of untreated jets Punekar et al [13] had experimentally investigated screech tones and the associated non-linearity in the near and far fields at $M_j = 1.3$, M_j being the jet exit Mach number. They also had [14] for $M_j = 1.3$ crackle which was mildly heard as a mixture of incoherent sound . In these studies which was worth noting was the noise radiation of the farfields in the upstream and downstream angles. The skewness of the pressure in upstream shock associated noise for screech was of almost the same order of magnitude as the skewness of crackle found in the downstream Mach direction. But the skewness of the pressure derivative for screech was far much lower compared to skewness of crackle derivative. This skewness behaviour was a notable feature discussed in Punekar [15] which lead to the present study for untreated jets but with even higher Mach number of $M_j = 2$. It was expected that higher Mach number would lead to more non-linearity in the wave forms. The study was intended to investigate if the same differences in skewness would be present between crackle and screech and if so to study their nonlinear properties by investigating their near field and far field waveform distributions and spectra.

2. Model scale acoustic measurements

Jet noise measurements for a converging diverging nozzle of diameter $D = 3cm$ for near and farfield distances are made in this study for an underexpanded jet at $M_j = 2$. Acoustic signals were sampled at $140kHz$ over $0.5sec$ each with details of test section available in Punekar [14] . A schematic of the jet model facility with microphones in the farfield of 40 nozzle diameters is shown in fig. 1.

For near-field 5 equally spaced microphones mounted on a high precision traverse downstream of nozzle exit from 5 nozzle diameters placed at the rim of jet centreline. They were traversed horizontally or vertically at several observer polar angles. Microphone need not be pointed at the nozzle exit at this close distance as the source noises are non compact. For farfield 10 microphones from 15^0 (inlet to the axis) up 90^0 (sideline) are mounted to capture all acoustic noise radiation. Following Krothapalli et al's [9] description of the Mach direction at 39^0 for cold jet at $M_j = 2$ where they had crackle the present microphone was positioned at 40^0 for any crackle. The remaining microphones were placed from upstream at 90^0 to capture screech and along all other radial directions as shown in fig. 1.

3. Near-field and farfield measuremtents

Figure 2 (a) (see caption) is the near-field and far field fully evolved spectra for crackle shown in Mach direction of 40^0. It shows a dramatic increase in the high frequency content of crackle which shows crackle has both low and high frequencies. The farfield crackle in figure (see captions) shows considerable reduction in the intensity of about 19dB in high frequencies. Figure also shows the far-field spectra is in agreement with Tam's[6] empirical F spectra for the turbulent mixing region.

Figure 2 (b) shows the near field and far field fully evolved spectra for screech taken at upstream angle of 90^0. Nearfield shows undeveloped screech tones where as farfield screech frequencies at 3.6kHz and its harmonic at 7.38kHz are observed agreeing with Powell's [1] formula. The farfield is in agreement with Tam's [6] empirical G spectra as shown.

The near-field screech and crackle were heard clearly as a loud tone and distinct bursts when played back. The perception of these measured playback records when heard for the near-field and far-field were almost identical in their crackle. Fig 3 shows the farfield pressure waveforms for screech and crackle where the average amplitude for screech was about a 1/3rd higher than crackle. The cyclic nature of screech waveform due to its feedback mechanism is shown in the figure (see caption). The amplitude decrease of crackle is due to having undergone more 'bunching' process from nonlinear energy transfer. The reduced number of crackle waves compared to screech is shown in the same figure below for shorter trace of time.

4. Comparison of crackle with screech and their skewness

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

It was expected that skewness of screech should be more than crackle considering its large amplitude nonlinear propagation. Shown in Fig.4(a) are the near-field probability distribution functions measured along the verge of the jet centreline at $5D$, taken at 40^0 70^0 and 90^0 showing all having a Gaussian curve. Far-field skewness values for all radial angles are shown in Fig.4(b) where skewness for screech and crackle are high and almost similar around 0.65. More noteworthy is the 90^0 skewness for screech derivative of 0.23 where skewness for crackle has shot up to 0.73. Skewness derivative of screech is lower than it waveform skewness and further is far less then skewness derivative of crackle as shown in fig.4(b). These results were tested for a wide range of data by repeating the measurements and each time the same skewness values were found. The trend for Nonlinear processes was earlier believed to be that skewness of waveform derivative is larger than the waveform skewness, but in case of screech this trend is violated.

It is deduced from the above that the nonlinear propagation of crackle causes the skewness of its pressure derivative to be more then the skewness of its pressure. This is an important find which is new indicating that the nonlinear propagation processes are very different for screech and crackle.

In the PhD thesis [15] the author derived analytic solutions of simulated near-field Gaussian waveforms which continued to remain Gaussian when nonlinearly propagated until the average shock formation distance was reached. The near-field measurements presented here seem to follow the above analytic results when near-field screech and crackle remained Gaussian.

5. Conclusion

Accurate and detailed measurements were made in QMUL jet facility at $M_j = 2$ for both near and farfield noise radiation. It was found the nearfield waveforms were Gaussian and when played back were heard as a mixture of crackle and screech.

The nonlinear propagation for screech and crackle are entirely different in the far-field where screech has higher amplitude than crackle. Crackle undergoes more ’bunching’ with faster decay rate due to merging of the small waves by the larger ones. Thus far-field crackle becomes highly skewed in both pressure and its derivative when sharp crackle spikes burst from nonlinear propagation. Screech’s gradients are not steep enough to cause this rapid decay and fall in amplitude. Nevertheless their nonlinear properties are entirely different. It is concluded here that although far field screech waveform is highly skew its pressure derivative somehow recovers from further asymmetry. This behaviour of skewness of the pressure derivative for screech is new and not been mentioned in any literature as far as we are aware. Crackle on the other hand can be quantified only when skewness of its pressure derivative becomes higher then its pressure, far beyond the threshold of 0.3. This increase in skewness of derivative for crackle is of vital importance also not been mentioned in literature as far as we are aware. Its importance for crackle has been mentioned by Gee [8] but not its dramatic increase. The farfield crackle was heard similar to that of a supersonic aircraft flying overhead unmistakably identical.

The current model-scale laboratory jets measurements are made under clean conditions due to which an amplifying effect of crackle was heard whereas in a full scale engine which are heated and unclean the noise passing through atmosphere with different densities and wind speeds gets damped. A rough comparison with full scale engine is shown where due to large dissipation from model jet diverges in the high frequencies. It is suggested that high levels of crackle found in the near-field can lead to severe vibrations on the nearby components of the aircraft causing fatigue.

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References and links

1. Powell A., ‘On the mechanism of choked jet noise ,’ Proc. Roy. Phys. Soc. London, Sect. (1953) A66, pp 1039.

2. Raman, G., ‘Supersonic Jet Screech: Half century from Powell to the Present.’ J Sound & vibration (1999) 225(3),pp 543-571.

3. Westley R., Lilley G M., ’An investigation of the noise "eld from a small jet and methods for its reduction.’ Rep. No. 53, College of Aeronautics, Cran,eld (England). 1952.

4. Kaji S., and Nishijima N., ’Pressure field around a rectangular supersonic jet in screech.’ American Institute of Aeronautics and Astro- nautics Journal 334, 1990.

5. Merle C R., ’ Sur la fre’quencies des sondes e’mises par un jet d’air &a grand vitesse. ’Academy of Science Paris 243, 490 493. 1956.

6. Tam C. K. W., Golebiowski M.,Seiner J.,‘On the two components of turbulent mixing noise from supersonic jets,’ AIAA Meeting Papers on Disc, May 1996 A9630830, NAG1-1776, AIAA Paper 96-1716.

7. Ffowcs Williams J. E., Simson, J., and Virchis, V. J., Crackle : An Annoying Component of Jet Noise,’ Journal of Fluid Mechanics, Vol. 71, No. 2(1975) pp 251-271

8. Gee K., Sparrow V.W.,‘On the Perception of Crackle in High-Amplitude Jet Noise,’ AIAA Journal, Vol. 45, No. 3 (2007)pp 593-598.

9. Krothapalli, A., Venkatakrishnan, L., and Lourenco, L., ‘Crackle: A Dominant Component of Supersonic Jet Mixing Noise,’ AIAA Paper 2000-2024, pp 1-8

10. Baars W., and Tinney C., ‘Temporal and spectral quantification of the crackle component in supersonic jet noise,’ Springer-Verlag Berlin Heidelberg 2014.

11. Martens S., Spyropoulos, J. T., Nagel, Z. 2011 ‘The effect of chevrons on crackle: Engine and Scale model results,’ Proc. ASME Turbo Expo. GT2011-46417.

12. Avital E.J., Musafir R.E., and Korakianitis T., ‘Nonlinear Propagation of Sound Emitted by High Speed Wave Packets, Journal of Computational Acoustics,’ 21, (3) 1-21 2013.

13. Punekar J.N., Avital E.J., ‘Nonlinear Propagation of screech,’. The Journal of the Acoustical Society of America, vol. 123, issue 5, p. 3249.

14. Punekar J., Avital E.J., Li X., ‘Crackle: measurements and analysis of supersonic jet noise,’ (2012) Asian Joint Conference on Propulsion and Power.

15. Punekar J.N., ‘Numerical simulation of nonlinear random noise,’ PhD thesis , University of Southampton 1996.

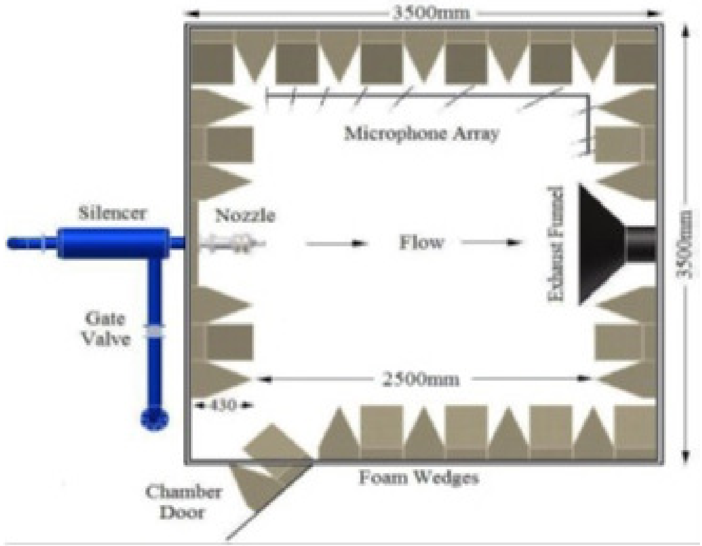


Figure 1: Schematic representation of QMUL acoustic chamber with farfield microphone arrays at all polar angles

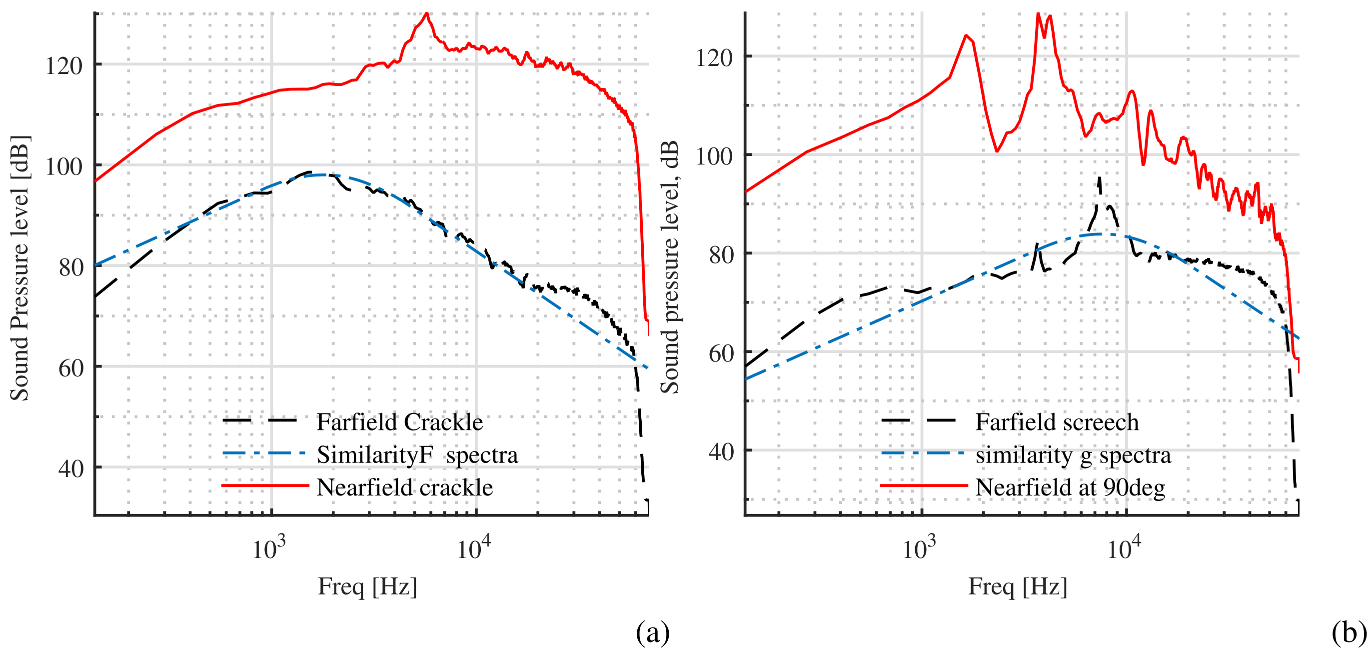


Figure 2: '(Color online)' (a) Spectral contents of near-field and far-field crackle (- -). Far-field following Tam's F spectra (-.-) for downstream mixing noise. $M_j = 2$. (b) (Color online)' (a) Spectral contents of near-field and far-field screech (- -). Far-field following Tam's G spectra (-.-) for upstream shock associated noise.$M_j = 2$.

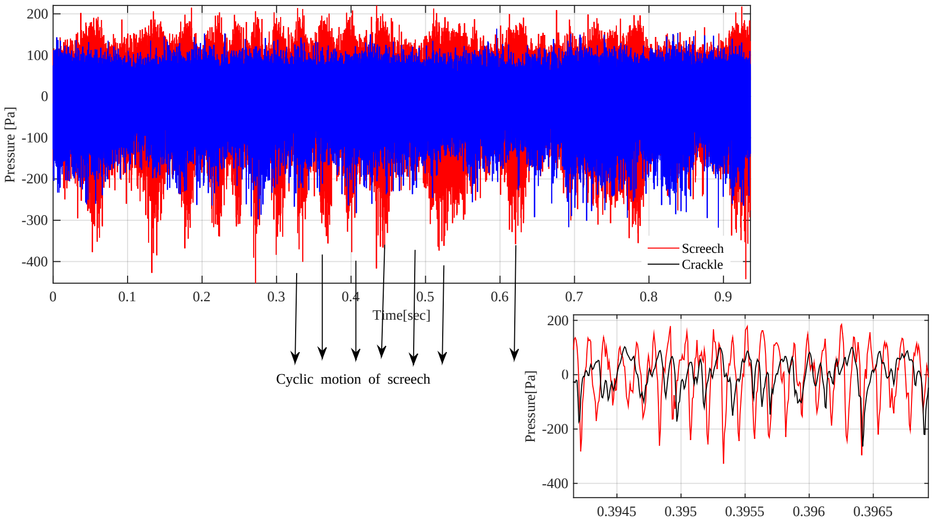
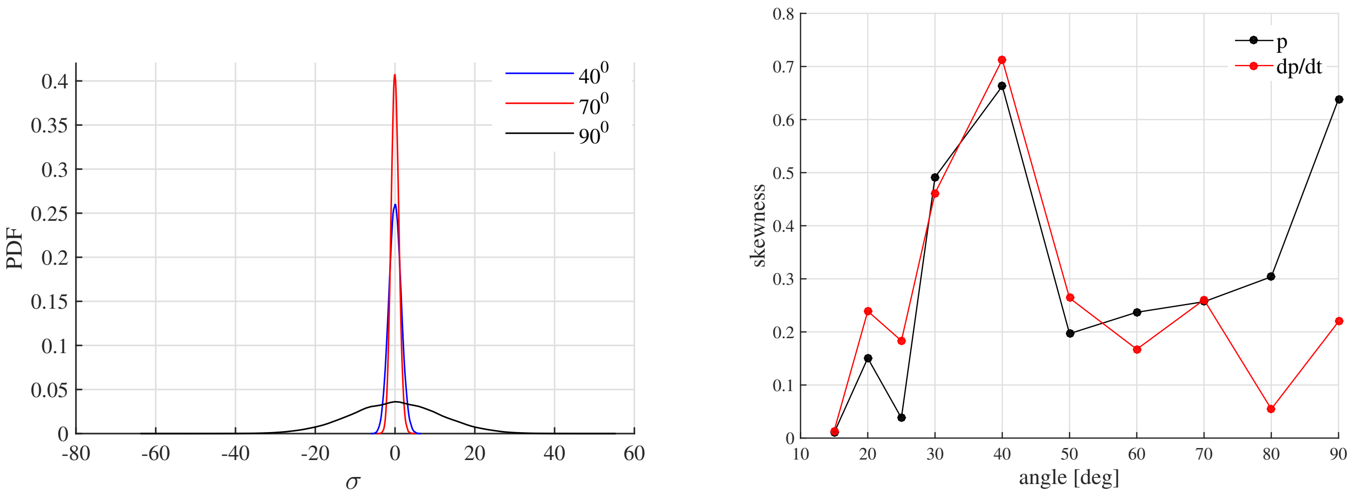


Figure 3: ‘(Color online)’ Screech and Crackle waveforms in far-field showing decreased amplitude for crackle. $M_j = 2$. Also below is a magnification a small time trace of the crackle and screech waveforms overlaid showing reduction in crackle



(a) (b)

Figure 4: ‘(Color online)’ (a) Nearfield probability distribution function for pressure when microphones at traversing distance pointed at 40^0 70^0 and 90^0 showing Gaussian curves. (b) Farfield Skewness at various angles for pressure and its derivative .