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A temporal and spectral quantification of the 'crackle' component in supersonic jet noise

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OUTLINE – The high-intensity noise generated by a shock-free and unheated Mach 3 jet is investigated experimentally. Unlike subsonic jets, the noise produced by a supersonic jet flow can be categorized into three distinct mechanisms (Tam 1995, An. Rev.): turbulent mixing noise, broadband shock associated noise and screech tones. It has been postulated for quite some time that turbulent mixing noise consists of two components. The first, most distinguishable component is generated by the convective motion of large turbulent structures or instability waves that pass along the potential core region of the flow. This is the source of Mach wave radiation that is observed in the Mach cone. The second component is associated with the fine-scale turbulence within the shear layer. The full paper will focus on a subtle noise component embedded in the mixing noise, known as *crackle*. Although crackle is often perceived as the most dominant and most annoying component of supersonic jet noise, it is surprising that only a limited number of studies have focused on it. The most extensive work dates from the 1970's, when Ffowcs Williams *et al.* (1975, JFM) investigated crackle emitting from a full-scale static engine.

One of the major challenges in studying crackle are the issues of perception, some of these are addressed in the work of Gee *et al.* (2007, AIAA J). Various observers may perceive an acoustic waveform as crackle-free, while others do not. And, when it is perceived, what is the degree of crackle? This issue is aggravated by the fact that there is no unique measure of crackle to assess its presence in an acoustic measurement. Moreover, conventional Fourier-based spectral representations are insensitive due to the fact that (1) the temporal characteristics are not time-preserved in the ensemble averaging, and since (2) crackle causes a wide (almost broadband) low amplitude energy footprint.

In the full paper, a novel study will be presented that aims on quantifying crackle in a temporal and spectral sense and is concisely described below. Temporal pressure waveforms are acquired on a grid in the x,r-plane of a perfectly expanded Mach 3 jet. Theoretical computations of the shock formation distance relative to the viscous absorption length ensure that *cumulative* nonlinear effects (waveform distortion with distance) do occur for this scaled jet. However, given the restrictions of the anechoic chamber, no major cumulative waveform distortions were captured in the measurement range. On the other hand, crackle is categorized as a *local* cumulative effect, since its waveform signatures are formed almost instantaneously, close to the source.

QUANTIFYING CRACKLE – Instances of crackle in the acoustic pressure signals are observed as shock-type structures, as are shown in Fig. 1(top). The sharp rises in pressure, followed by a more gradual lower amplitude expansion are responsible for the crackling sound.

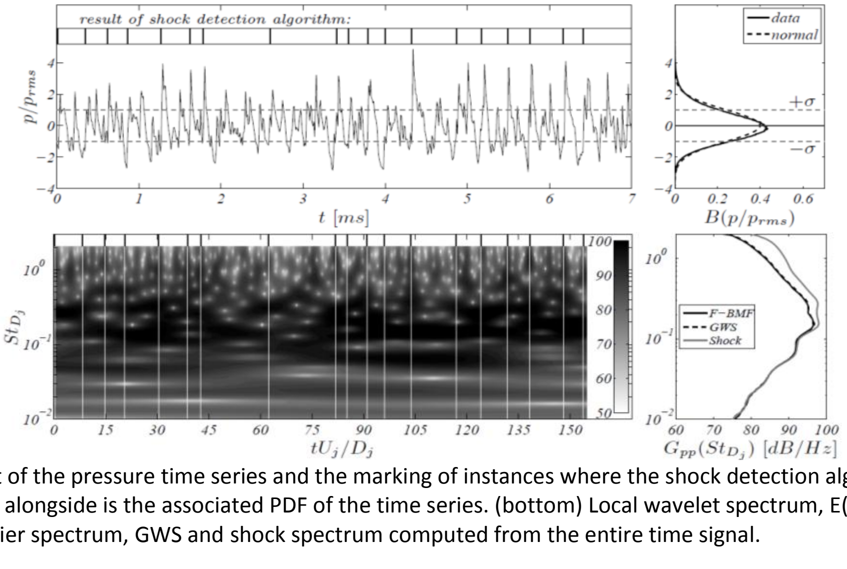

Figure 1, (top) Part of the pressure time series and the marking of instances where the shock detection algorithm identified crackle signatures, alongside is the associated PDF of the time series. (bottom) Local wavelet spectrum, E(f,t) in *dB/Hz*, and alongside the Fourier spectrum, GWS and shock spectrum computed from the entire time signal.

A 'shock detection algorithm' was developed and applied to the data to identify the temporal occurrences of crackle at each position in the x,r-grid. For the signal shown, the instances when structures were identified are marked at the top of the figure by the vertical lines. To gain spectral information, while still preserving the temporal information of the signal, a time-frequency analysis is then performed following the wavelet transform technique (Farge 1995, An. Rev.). The result is shown at the bottom of Fig. 1, where the time-signal is decomposed in time (x-axis), frequency (y-axis), and spectral amplitude (contour). At the instances of crackle, the sharp pressure rises reveal itself as an energy increase at the higher frequencies. This is visualized on the right hand side, where the global wavelet spectrum (GWS, essentially the Fourier spectrum for this steady acoustic pressure signal) is compared with the spectrum associated with the instances of crackle. The latter one is referred to as the 'shock' spectrum. The full paper includes a discussion of the spectral features and presents how they vary with spatial position in the x,r-plane of the jet.

With the results of the shock detection algorithm, a contour of the average number of crackle structures per unit time can be created and is shown in Fig. 2. As can be seen, the contour levels follow spherically spreading lines that approximately emanate from a point on the jet axis just aft of the potential core. Furthermore, most shocks are identified along the 45° radial that coincides with the computed Mach cone angle for this particular jet. Adjacent, the temporal characteristics of the crackle signatures are quantified by PDF's of the intermittence (the time in between two subsequent crackle signatures), which are shown in Fig. 3. The first study that is known to the authors looking into time-series, thus the passage of shock type Mach wave radiation signatures, was the work by Laufer *et al.* (1976, AIAA J.).

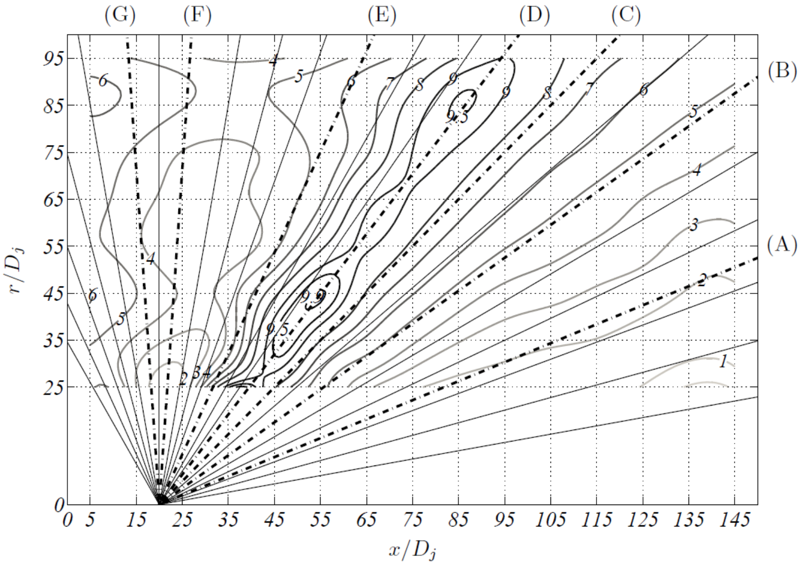

Figure 2, Contours of the average number of shocks per second. The maximum number of shocks is 1835 shocks/sec at position (x,r)/Dj = (55,45).

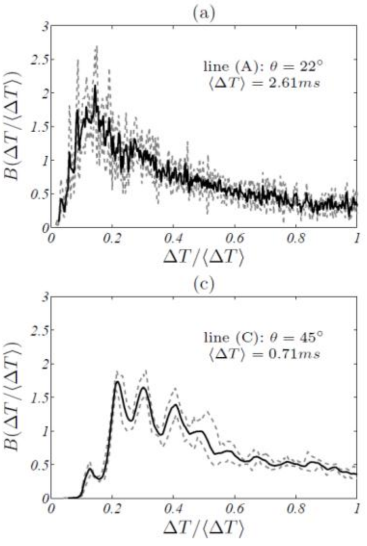

Figure 3, PDFs of the 1^{st}-order intermittence of the crackle instances.

FULL PAPER OBJECTIVES – The final paper will include an extensive description of the shock detection algorithm and the wavelet transform techniques, that are the two primary techniques applied to the temporal acoustic pressure waveforms. Also the more conventional metrics such as the skewness of the pressure signal and pressure derivative will be addressed. The strength of the analyses is explained by considering one signal, where after the techniques are applied to positions in the x,r-plane of the jet to reveal the topology of crackle signatures. It is concluded that crackle is indeed solely present in the Mach cone and that the signatures are most intense at the Mach angle, where Mach wave radiation dominates. The temporal characteristics will be related to a so-called 'scissoring mechanism' of the shock type structures that are propagating out to the far-field. The 'scissoring' refers to the motion of the curved spatial wave fronts relative to each other when they are emitted from various positions along the shear layer and have various degrees of curvature. Finally, the perception of crackle in relation to the human ear will be addressed, as that will eventually determine the level of discomfort experienced by persons working in the close vicinity of full-scale jets.

Keywords: **Supersonic jet noise, crackle, nonlinear acoustics, time-frequency analysis.**