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Subjective rating of the jet noise crackle percept

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Abstract: Results of the first formal perceptual study of jet crackle are presented. Prior studies examined noise waveform properties believed to be linked to the jet crackle percept from a physics perspective or using signal processing and informal subjective evaluation. This investigation involves 31 listeners that rated 15 jet noise waveforms with a category subdivision scaling test. Results reveal a strong log-linear correlation between the pressure waveform time derivative's skewness and crackle rating. A regression analysis establishes practical derivative skewness bounds for a five-point categorical crackle scale and results in the suggested definition of the *crepit* as the unit of crackliness.

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1. Introduction

The supersonic jet noise phenomenon, crackle, has been called an annoying[1] and dominant[2] characteristic of the total perceived noise. The description of Ffowcs Williams *et al.*[1] of crackle included phrases such as "sudden spasmodic bursts," "rasping fricative sound," and "startling staccato of cracks and bangs." In the past four decades, experimental and computational studies have sought to better quantify different aspects of crackle, including attempts to uncover physical[3–7] and perceptual[8–10] origins and characteristics.[11–15] However, in these prior studies, the crackle percept has only been identified using informal listening by researchers. This letter describes the first analysis of the jet crackle percept via a formal jury-based listening test.

Most prior crackle studies have acknowledged acoustic shocks as being the source of the crackle percept but have differed in how to quantify the phenomenon and, therefore, in some of the physical conclusions and choice of appropriate metrics. Following the study of Ffowcs Williams *et al.*, many studies have quantified crackle using the skewness of the pressure waveform distribution. However, Gee *et al.*[8] suggested that the statistics of the pressure waveform derivative were a more appropriate measure of crackle because they were sensitive to the rapid pressure changes associated with a shock. Swift *et al.*[10] have further demonstrated that positive pressure skewness is neither a necessary nor a sufficient condition for a waveform to crackle, and that the skewness of the pressure waveform time derivative (hereafter referred to as derivative skewness) is a better measure of the crackle percept.

This initial correlation of the derivative skewness with the crackle percept and its possible use as a crackle metric has paralleled investigations into the characteristics of derivative skewness in laboratory[11,13,14] and full-scale[15] supersonic jet noise and its behavior for nonlinear acoustic propagation. Of particular significance is the investigation by Reichman *et al.*,[16] whose analytical and numerical study showed that a derivative skewness value of five corresponded to significant shock formation, provided that the sampling rate was approximately 100 times the spectral peak frequency. This finding helps to provide a direct link between the physical acoustics of shock formation and the psychoacoustics of crackle perception, as described in this letter.

Whereas prior studies have investigated crackle from a physics perspective or examined metric suitability using signal processing and informal subjective evaluation, this letter describes results of a formal jury-based listening test designed to rate crackle in jet noise. The results show a much stronger correlation between perceived crackle and derivative skewness than pressure skewness. The results also establish initial derivative skewness bounds for a five-point categorical crackle scale.

2. Methods

Many of the crackle rating methods are described in Ref. 17 but are summarized here for clarity. The overall philosophy for crackle rating tests stemmed from an internal

Table 1. Crackle categories and descriptors, based on an informal listening study of over 3600 F-35 noise waveforms. The descriptors were used to label the rating test categories, which were subdivided according to the rating scale.

Category	Category description	Rating scale
1	Smooth noise; no crackle	0–10
2	Rough noise; no crackle	10–20
3	Sporadic (intermittent) crackle	20–30
4	Continuous crackle	30–40
5	Intense crackle	40–50

study where a student listened to over 3600 recordings from a ground run-up measurement of the F-35A and B noise at different engine power settings[18] and placed them in one of five categories, according to crackle content. Although the initial goal was to simply connect modern high-fidelity recordings to informal descriptors of Ffowcs Williams *et al.*:[1] "did not crackle," "crackled distinctly," and an unnamed intermediate crackling condition, this exercise led to the development of five categories that seemed satisfactory to researchers in describing perceptually distinct regimes of jet crackle. These categories are listed in Table 1. Thus, the goals of the subject rating study were to (a) correlate two physical waveform measures (derivative skewness and pressure skewness) with perceived crackle and (b) obtain rating criteria for the different perceived crackle conditions.

Waveforms for the crackle rating test were selected from the F-35A run-up measurement using two criteria. First, only data from a 305-m radius measurement arc were used. This was done because near-field personnel would wear some form of hearing protection (thus altering perception) and because the present motivation for understanding crackle is more directed toward community annoyance. Second, the waveforms were selected to effectively span the range of recorded values of derivative skewness. Preliminary tests suggested a logarithmic spacing for the derivative skewness. Selected 3-s waveforms ranged from 50% (low power) to 150% (maximum afterburner) engine thrust request across the full angular aperture. The waveforms were resampled to 51.2 kHz, which was convenient for audio playback, while still meeting derivative skewness sampling requirements.[16] Note that waveform derivative estimates were obtained using a first-order forward difference and the skewness calculation for each 3-s pressure waveform and its derivative was performed using the sample skewness.

The key characteristics of the 15 selected waveforms are displayed in Fig. 1: the derivative skewness, $\mathrm{Sk}\{\partial p/\partial t\}$, versus the pressure skewness, $\mathrm{Sk}\{p\}$, for each waveform are represented logarithmically to show their non-negligible correlation. This correlation is unsurprising; prior studies[15,18] have shown that although the two quantities do not peak in the same direction, their maxima span broad, overlapping angular regions aft of the aircraft and near the maximum directivity angle. Also shown in Fig. 1 are amplitude-normalized, 20-ms segments and associated derivatives for the waveforms with maximum and minimum derivative skewness. The waveform colors indicate the corresponding data point on the derivative versus pressure skewness graph. A comparison of Figs. 1(e) (maximum $\mathrm{Sk}\{\partial p/\partial t\}$) and 1(c) (minimum $\mathrm{Sk}\{\partial p/\partial t\}$) shows the

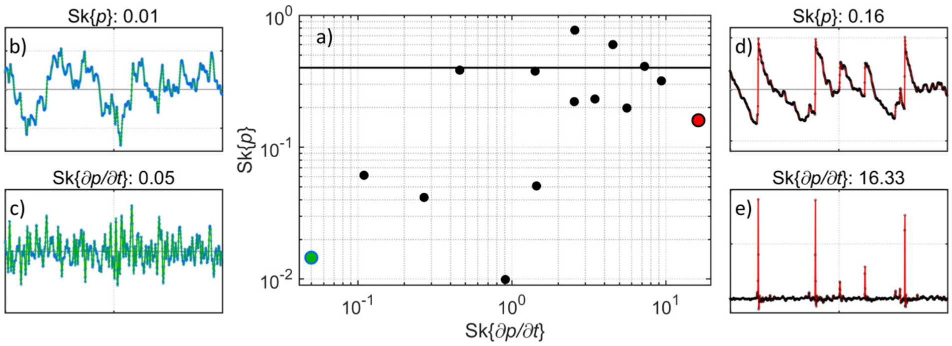

Fig. 1. (Color online) (a) Derivative skewness versus pressure skewness for the 15 waveforms used in the listening study. The historical $\mathrm{Sk}\{p\} = 0.4$ distinct crackle threshold is shown. (b) A 20-ms, amplitude-normalized segment of the waveform with minimum derivative skewness, and (c) its normalized time derivative. (d) and (e) Same as (b) and (c) but for the waveform with maximum derivative skewness.

acoustic shocks evident in Fig. 1(d) result in large derivative values not present for the minimum derivative skewness case. (Spectra and some probability density functions for the selected waveforms are shown in Ref. 17.)

Although the waveforms for the listening study were selected to span the derivative skewness space, they also represent a large range of pressure skewness values from effectively zero to appreciably greater than $\mathrm{Sk}\{p\} = 0.4$, the original Ffowcs Williams *et al.* criterion for "distinct" crackle [solid line in Fig. 1(a)]. Three of the 15 waveforms are above the criterion, nine have $\mathrm{Sk}\{p\} < 0.3$ the threshold below which Ffowcs Williams *et al.* indicated no crackle should be present, and the remaining three fall within the intermediate range, $0.3 < \mathrm{Sk}\{p\} < 0.4$, that can only be interpreted as the range in which crackle was marginally or occasionally present. It should be noted, however, that because the Ffowcs Williams *et al.* study was based on informal judgments without error bars, their $\mathrm{Sk}\{p\} = 0.4$ distinct crackle criterion could apply to the two waveforms in Fig. 1(a) with $\mathrm{Sk}\{p\} = 0.38$. These two data points are interesting, however, because they are also appreciably below the $\mathrm{Sk}\{\partial p/\partial t\} \approx 5$ threshold[15,16] that identifies a waveform as having significant shock content. Figure 1 shows other cases that could distinguish between the two statistical measures of crackle discussed by Gee *et al.*[15] For example, the waveform with maximum pressure skewness (0.77) only has $\mathrm{Sk}\{\partial p/\partial t\} = 2.57$. Conversely, the waveform with maximum derivative skewness (16.3) has $\mathrm{Sk}\{p\} = 0.16$. Despite the weak physical correlation between pressure and derivative skewness, one measure is likely to be a perceptually superior crackle descriptor; relevant prior signal processing studies[8,10] with informal listening tests suggest derivative skewness is the more appropriate measure.

To formally relate waveform metrics to the crackle percept, a jury-based listening test was conducted. Given the numbered crackle categories in Table 1, plus the possible ability of a listener to perceive differences in crackle within a given category, the crackle scaling test was designed using a category subdivision procedure as described by Hellbrück[19] and implemented by, e.g., Ellermeier *et al.*[20] To allow listeners to distinguish crackle gradations within the five categories in Table 1, a numerical scale was adopted between 0 and 50 such that the range for each category spanned 0–10, 10–20, etc.

The listening study, which was approved by the Brigham Young University Institutional Review Board, was conducted with 31 participants (16 males/15 females). Participants ranged between 18 and 47 years old, and were university students and staff. Each listener was given a free-field audiometric screening with pure tones between 125 Hz and 8 kHz to ensure hearing thresholds were within 20 dB of those given in ISO 389-7:2005. The study was conducted in an anechoic (>80 Hz) chamber with interior working dimensions of 8.71 m × 5.66 m × 5.74 m. A Dragonfly® 24-bit external audio interface and Mackie® HR824mk2 studio monitor, which was tested to have a flat on-axis response (±2 dB) from 40 to 20 000 Hz, were used for high-fidelity waveform playback at a distance of ~2 m from the listener. A detailed description of the pretest procedures is provided in Ref. 17.

During the test, the 15 waveforms were normalized for equal loudness (23.4 ± 0.6 sones), which resulted in a mean listening level of 62 ± 1 dBA. The seated listener rated each waveform by adjusting a slider bar to rate the crackle perceived.[17] Along the slider, the locations of the different categories in Table 1 were labeled with their descriptions, with subdivisions represented by tick marks. During the test, the sound clips were presented in a random order on the screen for each of the 31 listeners, so as to reduce average ordering bias. In addition, each listener had access to all 15 waveforms and could replay each one as many times as desired, and in any order, to globally adjust ratings as needed.

3. Results and analysis

The listeners' crackle ratings reveal expected trends. Figure 2 presents the 31 listeners' crackle scaling for the 15 waveforms, versus skewness measures represented logarithmically. In Fig. 2(a), crackle rating as a function of $\log_{10}(\mathrm{Sk}\{\partial p/\partial t\})$ is displayed as the mean ± standard error, whereas Fig. 2(b) contains the crackle rating as a function of $\log_{10}(\mathrm{Sk}\{p\})$. In both cases, the logarithmic scaling was convenient because the log-linear representation permits a straightforward linear regression. In Fig. 2(a), the linear regression fit and tight 95% confidence bounds are shown. The goodness-of-fit for derivative skewness is high, with $R^2 = 0.933$ indicating 93% of the data variance is explained by the log-linear model.

Comparison of the pressure skewness vs crackle rating in Fig. 2(b) exposes large differences. While there is a rough log-linear trend, the data are highly scattered

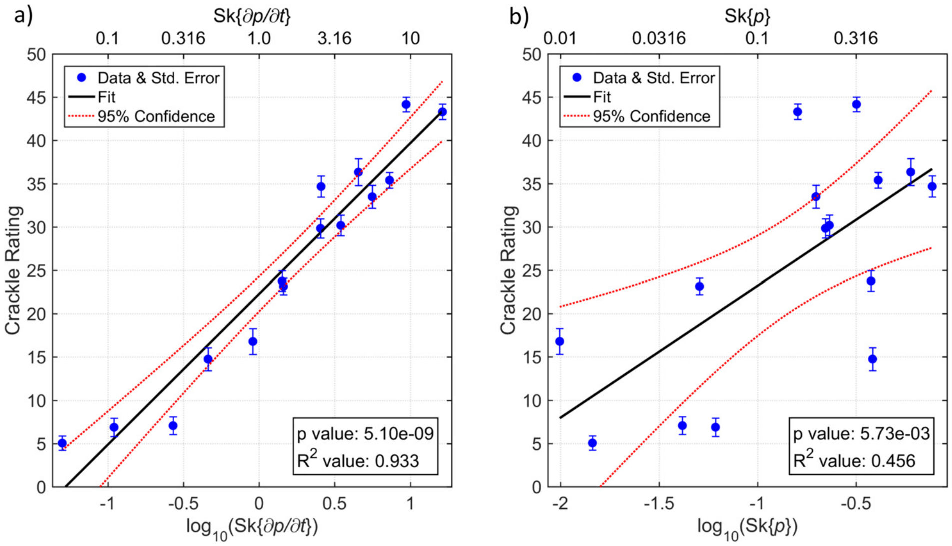

Fig. 2. (Color online) Results of crackle rating study plotted as a function of the logarithm of (a) derivative skewness and (b) pressure skewness.

around the linear regression with a resultant $R^2 = 0.456$, signifying that the linear model explains less than 46% of the data scatter. It is further worthwhile to note specific cases. Consider first the maximum pressure skewness waveform ($\mathrm{Sk}\{p\} = 0.77$); its mean crackle rating of 34.7 (continuous crackle) is significantly below the ratings of the two waveforms with maximum derivative skewness, both of which were rated as greater than 43 (intense crackle). One of these, which had maximum derivative skewness but a pressure skewness of only 0.16 (see Fig. 1), is one of the two data points farthest from the pressure skewness model's confidence bounds. The other largest outlier has $\mathrm{Sk}\{p\} = 0.38$, on the edge of the "distinct crackle" criterion of Ffowcs Williams *et al.*, but only had a mean crackle rating of 14.8, within category 2, "rough noise, no crackle." The failure of the regression fit to predict these cases confirms prior signal processing-based analyses[8,10] that jointly indicated pressure skewness is neither a necessary nor sufficient condition for the perception of crackle.

Despite the failure of pressure skewness as a predictor of the crackle percept, the results offers partial redemption for the original crackle study,[1] thereby increasing the utility of other pressure skewness-related jet noise investigations. For the regression line in Fig. 2(b), the 0.4 skewness criterion occurs at a crackle rating of 32.4, which is, in fact, located above the lower edge of the continuous crackle category. Thus, there is a greater likelihood of crackle being perceived for waveforms having high pressure skewness, because of its weak physical correlation with derivative skewness. Said another way, despite their lack of psychoacoustic interdependence, the weak correlation between the crackle percept and pressure skewness appears to stem from the overlapping occurrence of high pressure and derivative skewness in the jet noise field. This is confirmed via a linear multivariate regression including both $\log_{10}(\mathrm{Sk}\{\partial p/\partial t\})$ and $\log_{10}(\mathrm{Sk}\{p\})$; with $\log_{10}(\mathrm{Sk}\{\partial p/\partial t\})$ included in the regression with $\log_{10}(\mathrm{Sk}\{p\})$, the p-value for $\log_{10}(\mathrm{Sk}\{p\})$ increases from 0.0057 to 0.18, above the 0.05 value for statistical significance.

The present analysis concludes with a more in-depth treatment of derivative skewness and crackle scaling. The primary result of this study, represented in Fig. 2(a), shows that perceptual scaling of jet crackle is strongly correlated with $\log_{10}(\mathrm{Sk}\{\partial p/\partial t\})$. The linear regression analysis can be used to develop lower bounds for each of the crackle categories in Table 1. The crackle rating model in Fig. 2(a), written as

$$\mathrm{Rating} = 22.3 + 17.4\log_{10}(\mathrm{Sk}\{\partial p/\partial t\}), \tag{1}$$

explains 93% of the variance in crackle percept, but the linear regression has a possible shortcoming in that it cannot explain the saturation of the crackle percept that should occur at the extremes of categories 1 and 5. For example, there is evidence in Fig. 2(a) that the "smooth noise" percept has reached its asymptote for $\mathrm{Sk}\{\partial p/\partial t\} \lesssim 0.3$. If the first two data points are left out of the regression, the resulting regression model, $\mathrm{Rating}_{>0.3}$, is

$$\mathrm{Rating}_{>0.3} = 20.4 + 20.8\log_{10}(\mathrm{Sk}\{\partial p/\partial t\}), \tag{2}$$

Table 2. Lower bounds in derivative skewness for different crackle categories, as estimated by two log-linear regression models, and a simple intermediate approximation.

Category	Description	Lower bound from Eq. (1)	Lower bound from Eq. (2)	Approximate lower bound
2	Rough noise; no crackle	>0.20	>0.32	>0.3
3	Sporadic crackle	>0.74	>0.96	>1
4	Continuous crackle	>2.77	>2.89	>3
5	Intense crackle	>10.4	>8.76	>9

which causes the crackle percept to increase more quickly than in Eq. (1). Equation (2) yields $R^2 = 0.942$, a slight improvement over Eq. (1). From Fig. 2(a), it is also likely that the crackle percept for intense crackle is beginning to saturate around $\mathrm{Sk}\{\partial p/\partial t\} \approx 10$, and the final data point is evidence of that behavior. However, an additional regression analysis that contained only the 12 middle data points did not further improve R^2, so determination of the upper asymptote in crackle percept is left for future studies.

By using the category rating boundaries (10, 20, etc.) with Eqs. (1) and (2), a table of derivative skewness thresholds for different crackle categories can be created. The lower derivative skewness bounds for crackle categories 2–5, derived by using both regression models, are shown in Table 2. There is also an "approximate bound" column that represents a rounded version of the results from Eq. (2). This approximate bound seems to be worthwhile for a few reasons. First, the extreme low and high derivative skewness regimes have not been rigorously explored. Second, a derivative skewness estimate can be affected[16] by sampling rate, peak frequency, and measurement noise. Finally, there is value in easy-to-remember guidelines with few significant digits. In any case, the approximate bounds established here are not drastically different from either of the more exact models.

The regression models and thresholds for crackle categories in Table 2 can be tied back to prior physics-based studies of $\mathrm{Sk}\{\partial p/\partial t\}$. Reichman *et al.*[16] had identified $\mathrm{Sk}\{\partial p/\partial t\} \approx 5$ as a threshold for significant shock formation in noise, which results in a crackle rating of about 35 using either regression model. Thus, the presence of significant shocks corresponds to a definite perception of at least continuous crackle. However, what of the lower boundary for the continuous crackle category, $\mathrm{Sk}\{\partial p/\partial t\} > 3$? Experimental results[21] for nonlinearly propagating noise show a rapid change in the growth rate of derivative skewness at $\mathrm{Sk}\{\partial p/\partial t\} \approx 3$, which occurs[16] when a large number of shocks are forming. Thus, a threshold of 3 appears to have both physical and perceptual significance, as an approximate lower bound of the presence of shocks in noise and of continuous crackle.

The results in Fig. 2(a) and in Eqs. (1) and (2) have been used to develop bounds for the crackle percept in terms of derivative skewness, but the high correlation also suggests an absolute magnitude scaling for the crackle percept. Although further research is required to determine key features such as the number of just-noticeable-differences, it is helpful to begin to standardize vocabulary regarding the crackle sound quality. To disambiguate crackle perception from various physical phenomena previously described as "crackle," we suggest that models of crackle perception predict a sound's "crackliness," adding to other sound quality models that predict loudness, sharpness, roughness, or impulsiveness. The suggested unit for crackliness is the *crepit* (Cr), from the Latin verb *crepitāre*, which means "to produce a rapid succession of sharp noises," i.e., "to crackle" or "to rattle." Regarding this experiment, crackliness could range simply from 1 to 5 Cr, according to the clearly distinguishable perceptual categories. However, future testing may show that crackliness scaling should be more finely resolved based on increasing shock content and possibly other physical variables (peak frequency, spectral shape, and shock rate) not yet examined.

4. Concluding discussion

The formal jury-based listening test of jet crackle fills a need within the supersonic jet noise research community. As anticipated, the skewness of the pressure time derivative correlates much more strongly with the crackle percept than the historical measure, the pressure skewness. The log-linear relationship between derivative skewness and crackle rating and the accompanying regression analysis has resulted in approximate derivative skewness bounds for five distinct crackle categories. The results of this study also help place in context prior jet noise investigations that reported values of derivative skewness and/or pressure skewness.

Although this investigation has confirmed that pressure skewness is not a meaningful, independent measure of crackle perception, the results also motivate numerous additional studies. In addition to repeating this study with a larger set of waveforms, future studies should include the effect of playback level, peak frequency, and spectral shape and bandwidth on the crackle percept, and the use of other physical and sound quality metrics to investigate not only crackliness, but annoyance, loudness, and other perceptual dimensions. These studies will help further understand perception of this supersonic jet noise phenomenon.

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