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Crackle is a perceptual aspect of noise caused by impulsive acoustic shocks and observed in noise from supersonic jets, including those from military aircraft and rockets. Overall and long-term spectral noise metrics do not account for the unique perception of crackle. Listening tests were designed to better understand perception of crackle and examine its relationship to physical noise metrics, such as skewness of the first time derivative of the pressure waveform, hereafter derivative skewness. It is hypothesized that as derivative skewness increases, the perception of crackle tends to increase. Two listening tests were conducted with 31 subjects to examine their perception of crackle. In the first test, subjects compared and ordered crackle-containing sounds. In the second test, category scaling was employed with subjects rating the crackle content with category labels: 1) smooth noise with no crackle, 2) rough noise with no crackle, 3) sporadic or intermittent crackle, 4) continuous crackle, and 5) intense crackle. Both the order and rating tests confirm there is a high correlation between perception of crackle and derivative skewness. These insights will help inform community noise models, allowing them to incorporate annoyance due to jet crackle.

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1. INTRODUCTION

If you've ever witnessed a rocket launch, seen a jet take off from an aircraft carrier, or experienced a high-speed flyby of tactical military aircraft at an airshow, you have heard what is called crackle. Crackle is an impulsive aspect of jet noise that has been linked to acoustic shocks.[1–4] Crackle was described in 1975 by Ffowcs Williams *et al.*:[5]

> "sudden spasmodic bursts of a rasping fricative sound not dissimilar to that made by the irregular tearing of paper. Some observers liken it to the sound of an electric arc welder or of a badly connected loud speaker; others liken it to the spitting of water added to extremely hot fat. It is a startling staccato of cracks and bangs, and its onomatope, 'crackle', conveys a subjectively accurate impression."

Current metrics for community noise assessments of jet noise do not account for the unique perception of crackle, due to it being perceived as louder and more annoying than other noises with similar levels.

To better understand perception of crackle and examine its perceptual impact to physical noise metrics, IRB-approved listening tests were conducted. Fifteen waveforms were selected for the study that span a wide range of engine operating conditions and measurement angles. Listeners participated in both a random access (ordering) test and category subdivision scaling (rating) test for 15 waveforms measured 305 m (1000 ft) from a tied-down F-35A. The results of the first formal, jury-based listening test are reported and the strong correlation between the perception of crackle and the skewness of the probability density function (PDF) of the time-derivative of the pressure waveform—referred to as derivative skewness—is established.

2. METHODS

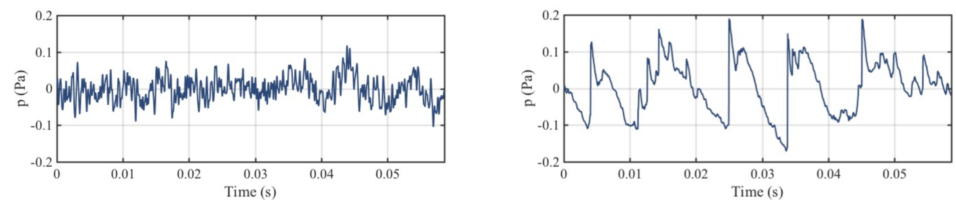
Preparation for the listening study required several inter-related components. A metric that had shown promise in informal listening studies[1,2,4] for predicting crackle perception was identified: the derivative skewness. Fifteen sound samples were selected for the study that spanned the range of derivative skewness values exhibited by waveforms measured at 305 m (1000 ft) from a tied-down F-35A operating at multiple engine conditions. Other preparation included selecting the types of comparative listening tests, determining the playback method, and developing the GUI interfaces for the ordering and ratings tests. These methods for designing the listening test are described in this section, followed by an outline of the testing procedures.

A. DERIVATIVE SKEWNESS

Previous research at BYU found that one quantity in particular appears to be highly correlated with the presence of acoustic shocks in a waveform.[1,6–10] This metric, referred to here as derivative skewness or dSk, is calculated by taking the first time derivative of a pressure waveform and calculating the third central moment. A positive derivative skewness exists when the PDF of the derivative data is positively skewed compared to a Gaussian distribution.

Informal listening studies found that the derivative skewness is linked to the perception of crackle. Reference [4] reported that positive skewness of the pressure waveform (pressure skewness) does not provide enough information to determine if a waveform will crackle and recommended instead skewness of the pressure waveform derivative. Recently, Swift *et. al*[11] examined the relationship between other sound quality metrics as well as derivative skewness for jet noise waveforms modified in ways that influence the shock content and showed that high positive derivative skewness was present in the sounds the authors perceived as crackling. These informal listening studies led to the selection of derivative skewness as the metric that guided the selection of the sound samples for the listening study.

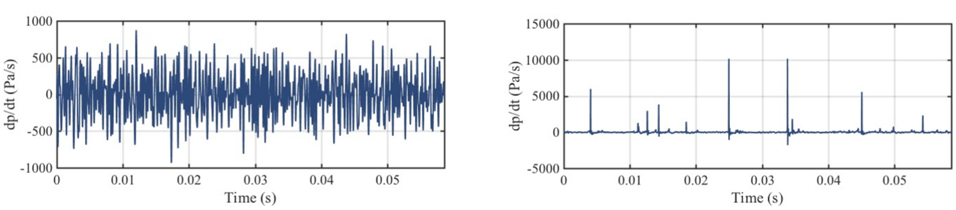
To understand the relationship between crackle and derivative skewness, a comparison is presented of two waveform snippets—one perceived as crackling and one that is not. In Fig. 1, 60 ms of each signal, normalized to have equal loudness, are displayed. The two signals were recorded at the same time and radial distance, merely at different locations with respect to the angle from an F-35A. The crackle containing signal in Fig. 1b has significantly larger abrupt increases in pressure than the noncrackling signal in Fig. 1a. These rapid rises in pressure indicate acoustic shocks are present at 305 m (1000 ft) from the aircraft, which have formed during nonlinear propagation of the high amplitude sound.[10] As the sound propagates nonlinearly, the waveforms steepen and large shocks form as the sound travels.[1,6,7,9] The goal of the formal listening study is to verify that the presence of these shocks are correlated with perception of crackle.



(a) No crackle. ***(b) Crackle.***

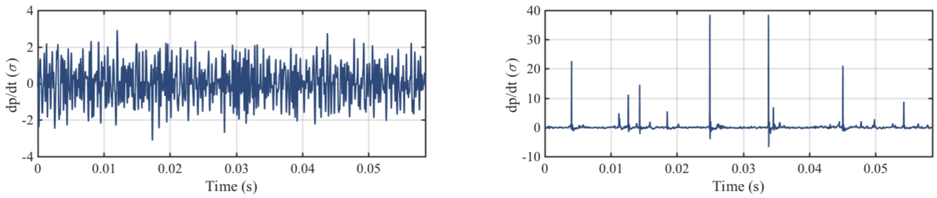
Figure 1: Pressure waveforms for two, normalized, resampled, jet noise recordings: The signal in (a) has no perceived crackle and (b) has intense crackle.

Shock presence is easier to identify by observing the time derivative. The next pair of plots in Fig. 2 shows dp/dt, the time derivatives of the pressure waveforms in Fig. 2, calculated as a first-order forward difference using the MATLAB **diff** command. The derivatives (diff divided by the time) of the noncrackling signal (Fig. 2a) have small values, while the acoustic shocks in the crackling signal have extremely large derivatives (Fig. 2b). When the derivative signals in Fig. 2 are scaled by the standard deviation, σ, of their respective PDFs as in Fig. 3, the extremely large derivatives in the crackle containing sound (Fig. 3b) are even more obvious. These scaled derivative are used to illustrate the relationship between the acoustic shocks and derivative skewness.



(a) No crackle. ***(b) Crackle.***

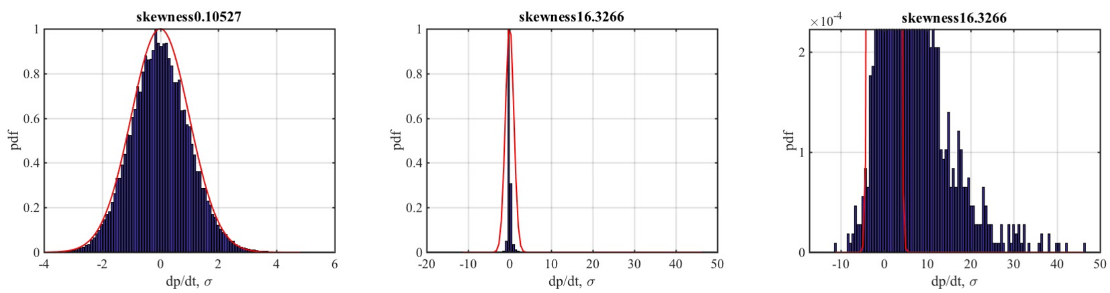
Figure 2: Pressure-time derivatives for two jet noise recordings, with varying shock content.



(a) No crackle. *(b) Crackle.*

Figure 3: Pressure time derivatives scaled by standard deviation of each signal, σ.

The statistical properties of each derivative signal are seen by plotting the PDF, as in Fig. 4. A PDF is used to specify the likelihood of a random variable falling within a particular range of values. If there is no skewness or bias in the data, the PDF is a normal, or Gaussian, distribution. The PDF of the time derivatives of the non-crackling jet noise waveform (Fig. 4a) shows a roughly Gaussian distribution, whereas the PDF from the crackling waveform's derivatives (Fig. 4b) shows a high skewness to the right compared to a Gaussian distribution (red line) with the same σ as the derivative PDF. This very asymmetric PDF has very large positive outliers, which can be seen upon zooming in as in (Fig. 4c), and is indicative of a positively skewed derivative PDF caused by the presence of large acoustic shocks.



(a) No crackle. *(b) Crackle.* *(c) Crackle (enlarged).*

Figure 4: Probability density functions for time derivatives of (a) the non-crackling signal (Fig. 3a) with an approximately Gaussian distribution and (b) the crackling signal (Fig. 3b) with a significant positive skewness. Part (c) contains a zoomed in version of (b). The red line in each is a Gaussian distribution with the same standard deviation, σ, as the displayed PDF.

B. F-35A WAVEFORM SELECTION

Derivative skewness is postulated to be be highly correlated with the perception of crackle in jet noise. This hypothesis is the basis for the formal, jury-based listening study. Sound samples for the study were selected from waveforms recorded across a 305 m (1000 ft) radius arc from a tied-down F-35A aircraft as its engine was operated at a range of engine thrust requests (ETR). An example of the spatial variation in overall sound pressure level (OASPL) produced by the F-35A is displayed in Fig. 5.

Fifteen sound samples were selected for the listening test. It was estimated that each sound sample should be 3 sec long. The original 30 sec recordings were divided into 3 sec segments,

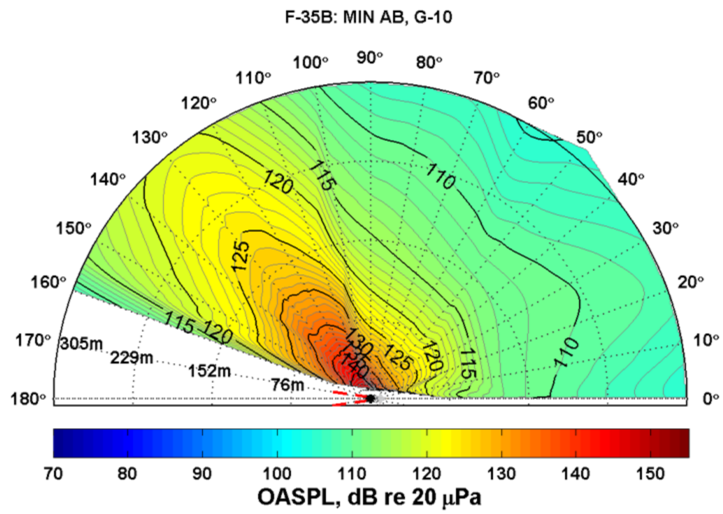


Figure 5: Overall sound pressure level (OASPL) map from an F-35 operated at 130 %ETR[12]. The F-35 is at center (Used with permission from Ref. [12]).

and a variety of physical metrics were calculated for each one. In selecting the sound samples for the listening study, importance was placed on spanning derivative skewness values, from trivial to high values, on a logarithmic scale, and choosing 3 sec samples that were representative (both quantitatively and qualitatively) of the 30 sec recordings. Characteristics of the 15 selected, 3 sec sound samples are given in Table 1: the peak frequency of the time-averaged spectrum, original sampling frequency, location of the recording as the angle relative to the nose of the aircraft, ETR, OASPL, and dSk of the original signal. A summary of the ETR and angles of the selected sound samples as a function of dSk are shown in Fig. 6. The one-third octave band levels of the selected sounds are shown in Fig. 7. The general spectral shape does not exhibit a relationship with the dSk values (listed in the legend), except that the spectra with high dSk tend to have more high-frequency energy than spectra with low dSk.

The selected sound samples were modified to ease playback during the listening study. The first task was to make each one sound equally loud so they could be played at approximately the same safe listening level. Waveform scaling was performed such that each delivered signal had an approximate loudness of 23.4 ± 0.6 sones at a mean listening level of 62 ± 1 dBA. In addition, the 15 selected sounds were resampled to 51.2 kHz for ease of playback on audio systems. This resampling still meets the sampling requirement of Reichman *et al.*[9] for obtaining good estimates of the derivative skewness. The dervative skewness values for the resampled waveforms are also shown in Table 1. The difference between the original and resampled dSk values increases as derivative skewness increases because the 51.2 kHz sampling frequency limits the maximum possible value of dp/dt. The resampled dSk values are used in the figures.

C. LISTENING STUDY DESIGN

In addition to waveform selection, decisions needed to be made regarding the playback method and the types of perceptual tests to be conducted. We used a KEMAR manikin[13] to determine ideal playback method. Sounds were played over headphones and through a loudspeaker and the

Table 1: Characteristics of the fifteen 3 sec sound samples used in the listening study: peak frequency, original sampling frequency, inlet angle of the measurement location, engine thrust request, original overall sound pressure level before normalization for equal loudness, derivative skewness as recorded at original sampling frequency, and derivative skewness after the signal was resampled to 51.2 kHz.

peak f (Hz)	fs (kHz)	Angle θ	ETR (%)	OASPL (dB)	original dSk	dSk @ 51.2 kHz
22	51.2	160	150	105	0.05	0.05
100	96	60	50	89	0.10	0.11
64	51.2	90	50	92	0.27	0.27
720	96	60	75	98	0.47	0.47
117	51.2	160	50	105	0.91	0.91
34	96	70	150	108	1.44	1.42
75	192	150	50	109	1.45	1.46
91	51.2	160	75	110	2.55	2.55
766	96	70	100	107	2.64	2.58
359	96	30	100	106	3.54	3.49
550	51.2	90	130	113	4.53	4.53
61	51.2	155	130	115	5.62	5.62
75	51.2	110	150	116	7.26	7.26
80	192	120	130	121	10.3	9.38
86	192	125	150	121	19.0	16.3

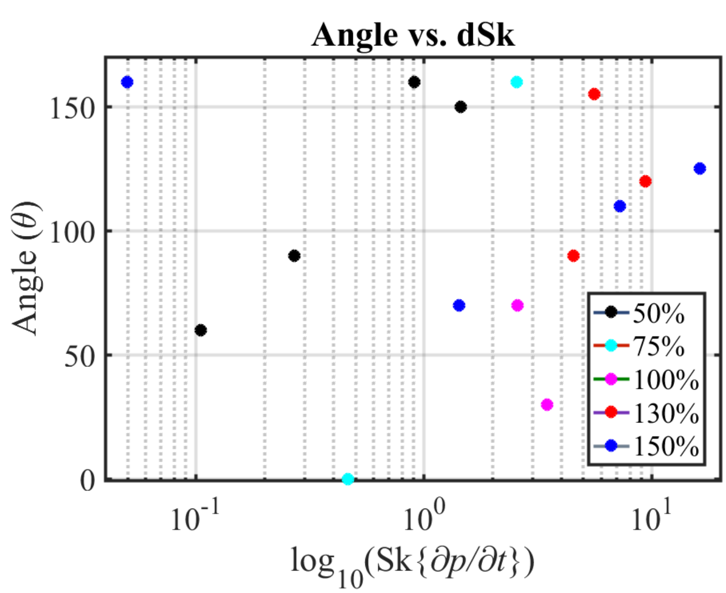


Figure 6: Inlet angle, ETR, and derivative skewness of the 15 selected, 3 second sound samples, with ETR indicated by color.

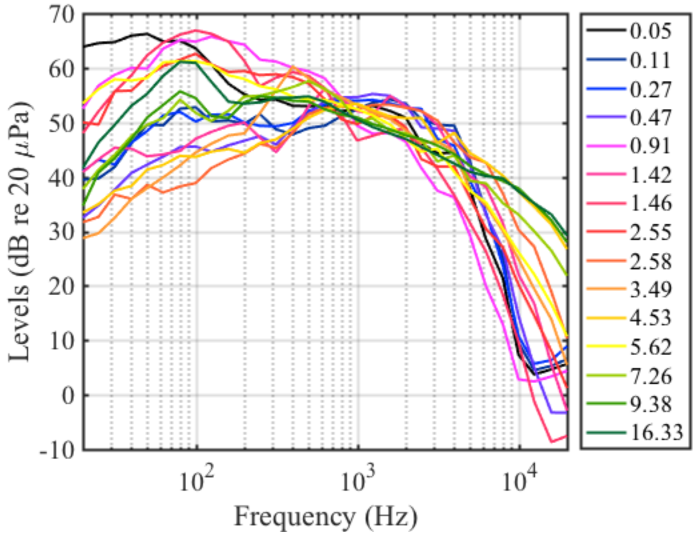


Figure 7: One-third octave band levels for the fifteen, 3 sec sound samples, after they were normalized to be equally loud and resampled to 51.2 kHz. The derivative skewness for each is shown in the legend.

recording from KEMAR's ears were analyzed. The loudspeaker playback method in the anechoic chamber proved to simulate a free-field listening environment, without needing adjustments. After researching multiple options for designing perceptual listening tests, two distinct test variants were selected and implemented: a random access or ordering test, and a category subdivision scaling or rating test.

Random access is a comparative ordering test where the listener performs multiple paired comparisons simultaneously and chooses an order based on some perceptual quality.[14] In this case, the perceptual feature considered was the amount of crackle a signal contains. A screenshot of the user interface designed for the ordering test is shown in Fig. 8. The 15 sound samples were first all on the left side of the interface labeled in alphabetic order A to O. The assignment of the letters to the 15 samples was random for each listener. Listeners used the interface to first playback the sounds and then sort them in ascending crackle order. They used a touch screen tablet to drag and drop the sounds from the left to their desired order on the right. The listener could play the sounds as many times as needed until satisfied with their ordering. By the end of this test, all 15 sounds were on the right ordered from least to greatest (top to bottom) amount of perceived crackle.

Category subdivision scaling is a rating test where the listener ranks a sound they hear on a scale within different descriptive categories.[14–16] Category subdivision scaling is similar to a Likert scale with various distinguishable levels but different in the resulting data; this categorical scaling test is put on a continuous measure scale so the test response is equated to a value on a 0-50 point scale. An example is given in Ellermeier *et al.*[16] showing how subjects listened to a sound and then rated it by placing a slider anywhere along the categorical scale. For the present study, we selected five descriptive categories to span the range of F-35 jet noise sounds: 1) smooth noise; no crackle, 2) rough noise; no crackle, 3) sporadic or intermittent crackle, 4) continuous crackle, and 5) intense crackle. These categories are listed in the GUI test interface shown in Fig. 9. After listening to the sound, the listener moved the slider to the spot they felt described the crackle content of

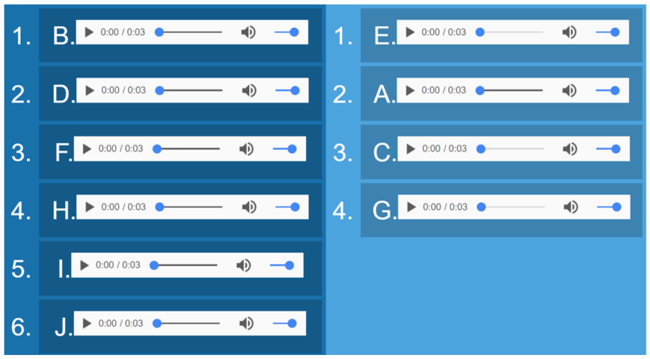


Figure 8: Screenshot of user interface for the random access (ordering) test. At the beginning of the test, all 15 sound samples are on the left. Subjects tap on sounds for playback and then drag and drop them to the right side, placing them in order from least to greatest (top to bottom) amount of perceived crackle.

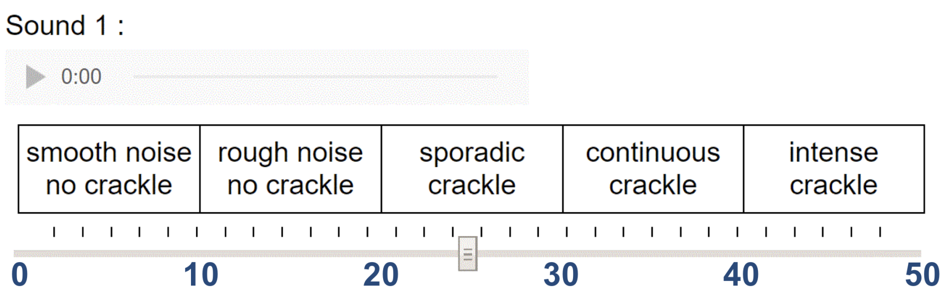


Figure 9: Screenshot of user interface for the category subdivision scaling (rating) test. After listening to the sound, participants subjects rated their perception of crackle by moving the slider bar anywhere along the continuum. (Numbers were not seen by listener but indicate how the results were quantified.)

each signal. All sounds were presented on the screen, and participants could listen to the sounds repeatedly until satisfied with their responses. To record the final ratings, the positions of the slider bars were equated with a 0-50 scale, with 10 points in each descriptive category. The numbers, shown in Fig. 9, were not presented to the listeners but show how their responses were quantified.

D. LISTENING STUDY PROCEDURE

The listening study protocol approved by the Institutional Review Board of Brigham Young University (BYU) is now provided. Participants were recruited from BYU employees and students, and each signed informed consent documents. A loudspeaker was calibrated to play back the waveforms at a mean listening level of 62 ± 1 dBA. When a listener arrived, they were shown into the anechoic chamber ($>$ 80 Hz) and seated in a chair 2m away from a Mackie® HR824mk2 studio monitor, as shown in Fig. 10. The sounds were sent to the loudspeaker through a Dragonfly® 24-bit external audio interface resulting in a flat response ($\pm$ 2 dB) from 40 Hz to 20,000 Hz.

A hearing screening was performed on each participant, to ensure normal hearing. A series of test tones ranging from 125 - 8000 Hz were played at varying loudness levels in accordance with

Figure 10: Listening test setup in BYU's anechoic chamber.

the ISO 389-7:2005 standard for free field hearing thresholds.[17] Allowed deviation from the free field normal thresholds defined in the standard was 20 dB. Subjects raised their hand when a test tone was heard.

A listening test administrator read an IRB-approved script to guide the subject through the various test procedures. Listeners first completed the Random Access (ordering) test and then the Category Scaling (rating) test. A break was offered in between the two tests. All 31 subjects passed the hearing screening and completed both listening tests successfully.

No pretest training was provided, but a description of crackle (as quoted in the introduction)[5] was placed as a reference at the top of the testing interface. Because subjects heard the signals in the first test, it can be considered a pre-listening experience for the second test. However, no feedback was provided during or after either test. Each listener was presented with the sounds in a different random order for each of the two tests. During both tests, subjects could listen to each sound as many times as desired.

3. RESULTS

The jury-based formal listening study was completed by 31 participants, ages 18-47 yrs, with 16 males and 15 females. Results of the ordering test and rating test are presented using box and whisker plots in order of increasing derivative skewness, as listed in Table 1.

During the first test, the participants ordered the sounds in ascending order from least to greatest perceived crackle. A trend emerges across the ordering results, shown as box and whisker plots in Fig. 11. As dSk of a signal increases, its placement in the ordered list tends to increase. Sounds with the smallest dSk value are placed closer to the top of the ordered list. Many sounds with similar dSk value have significant overlap in the boxes, i.e., they were ordered similarly by different participants. One noticeable exception is the sounds with nearly the same dSk values (2.55 and 2.58, respectively) in Fig. 11 show little overlap with one another, likely due to differences in the peak frequency (see Table 1). Overall, the trend of increasing dSk to boost the perceived crackle is visible.

During the second test, the participants rated the sounds based on the amount of crackle per-

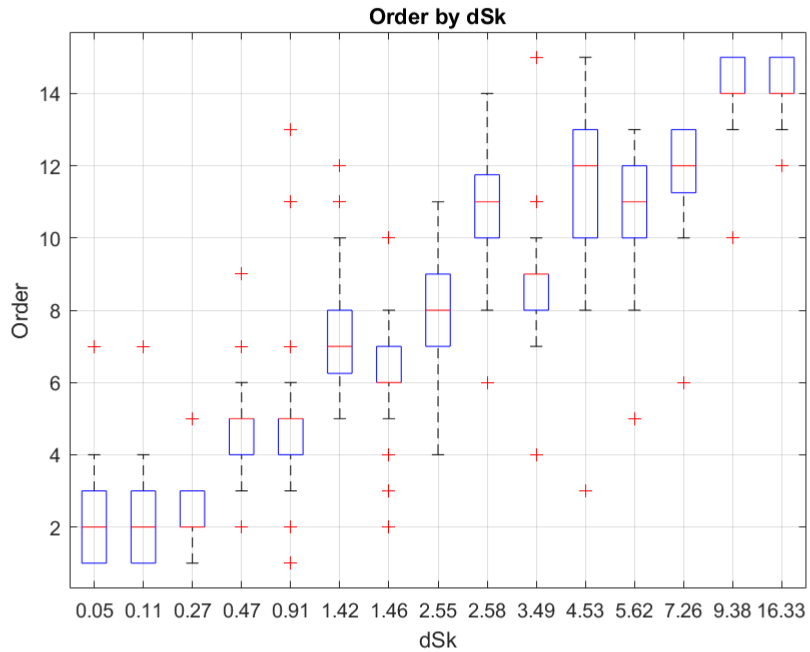


Figure 11: Box and whisker plots of 31 ordering test results ordered by dSk value. The central red line indicates the median, and the bottom and top edges of the blue box indicate the 25th and 75th percentiles, respectively. The whiskers cover a length 1.5 times the interquartile range (middle 50%), and responses beyond this range are outliers, which are denoted by the '+' symbol.

ceived in each signal according to subdivisions among five crackle categories: 1) Smooth noise no crackle, 2) Rough noise no crackle, 3) Intermittent or sporadic crackle, 4) Continuous crackle, 5) Intense crackle. The listener ratings were converted to a 50 point scale, and the results are summarized in Fig. 12. A similar trend is evident as in the ordering test in Fig. 11: Sounds with similar dSk are generally rated similarly. In particular, the first three (lowest dSk) are rated similarly with significant overlap of the distributions, as are the last two (highest dSk). This overlap suggests saturation or asymptotic behavior at the ends, with low values of dSk corresponding to smooth noise no crackle and high dSk to intense crackle.

4. ANALYSIS

The mean ratings for the 15 sounds along with standard error bars are plotted as a function of log(dSk) in Fig. 13a. The standard error of the mean is employed instead of the more commonly used standard deviation. Put simply, the standard error of the sample mean is an estimate of how far the sample mean is likely to be from the population mean, whereas the standard deviation of the sample is the degree to which individual points within the sample differ from the sample mean. The solid black line in Fig. 13a is the log-linear regression fit for the mean ratings. The statistics of this fit show a low p-value of 5e-9 and an R-squared value of 0.93. The red dotted lines represent 95% confidence bounds of a linear regression fit, and most mean ratings fall within these boundaries. Further analysis of the linear regression is provided in Gee *et al.*[18]

In addition to the striking relationship between dSk and the crackle rating, the comparison of

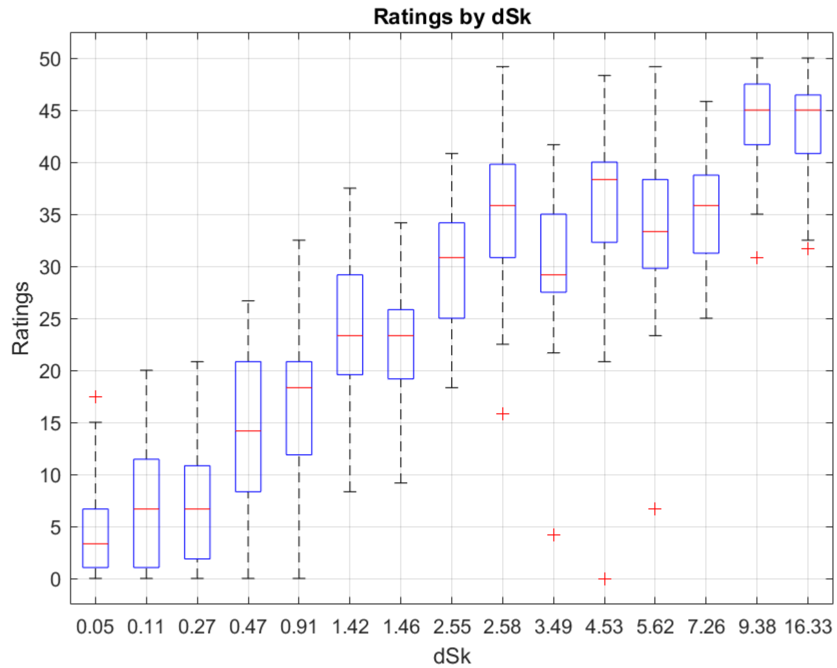


Figure 12: Box and whisker plots of 31 rating test results ordered by dSk value. Similar to Fig. 11

the rating and ordering test results shows consistency between the two studies. The mean rating and ordering of the 15 sounds are plotted in Fig. 13 along with error bars indicating standard error in each value. From this comparison, several groupings appear. The three sounds that have mean ratings less than 10 (solidly in the smooth noise, no crackle category) were consistently ordered to have the least crackle, although the exact order among the three varied among participants. The two signals with mean ratings near 45 (the intense crackle category) were ordered to have the most crackle, however, listeners were split on which one of the two should be ordered as having the greatest amount of crackle. In between these two, possibly asymptotic, regions, there may be additional groupings of comparable crackle or possibly a continuum over which the perceived crackle increases.

5. CONCLUSIONS AND FUTURE WORK

The first formal, jury-based listening test on the perception of crackle in jet noise has been conducted at Brigham Young University. A strong correlation has been found between an increase in the perception of crackle and an increase in the skewness of the time-derivative of the pressure waveforms. The correlation between crackle perception and this derivative skewness was observed in the results of both the category subdivision (rating) test and the random access (ordering) tests. Further analysis of these results will be reported in Gee *et al.*[18] This study has laid the ground work for additional formal listening studies to explore further the perception of crackle with the goal of creating an adjustment to community noise models to include the impact of annoyance due to jet crackle.

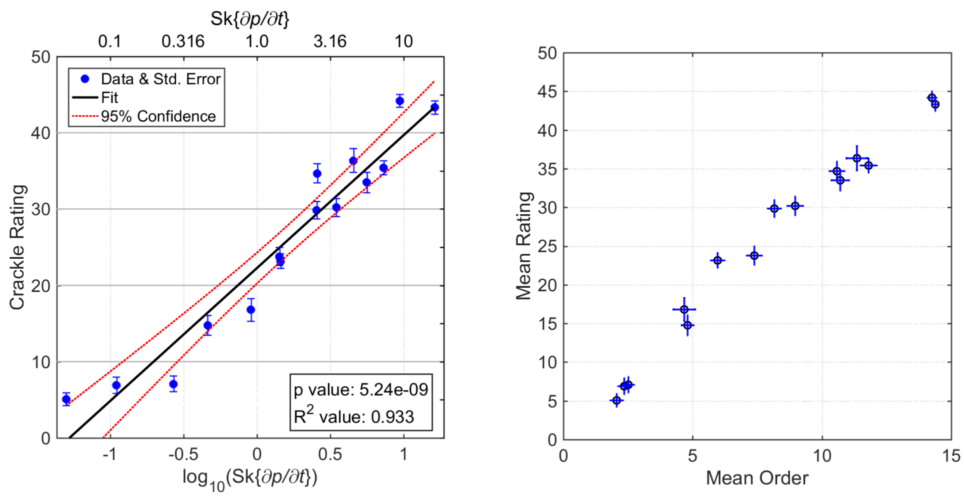


Figure 13: (a) Mean and standard error for the crackle ratings as a function of the log of the derivative skewness, along with the regression fit (black line) and the 95% confidence bounds (red lines). (b) Comparison of the mean rating and the mean ordering with standard error bars in both quantities.

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