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Exploring the use of time-sensitive sound quality metrics and related quantities for detecting crackle

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Crackling signals cannot be identified using any sound level or quality metric that relies solely on the long-term spectrum as input. In order to identify sound quality metrics that might succeed in modeling human perception of crackling and non-crackling sounds, a set of metrics sensitive to temporal properties of signals is applied to a set of signals with equivalent spectra but exhibiting varying degrees of crackle. Several methods for altering signals including some that remove crackling sound quality from an acoustic signal were drawn from previous work [Swift, Gee, Neilsen, 2014, Swift, Gee, Neilsen, 2017]. In this paper, an additional alteration which can partially remove crackle—randomizing the Fourier phase of a crackling signal in the frequency domain in selected frequency ranges—is considered. Variables from time-varying sound quality metrics such as loudness and sharpness, as well as roughness to signals exhibiting varying degrees of crackle are explored and relationships between them that can be exploited to identify crackling sounds are identified. Time-sensitive sound quality metrics can be used to discriminate between crackling and non-crackling signals and may help inform discussions of human perception of high-performance jet noise.

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1. INTRODUCTION

Crackle, as initially described by Ffowcs Williams[1] in 1975, is among the more interesting sound qualities associated with jet noise. It is also purported to be one of the more annoying and more challenging to quantify. This difficulty exists because, as Ffowcs Williams puts it, "'Crackle' cannot be characterized by the normal spectral description of noise."[1] Put more generally, no metric that depends solely upon the power spectrum of a waveform is capable of conclusively determining whether a given sound sample crackles. Gee *et al.*[2] have shown that signals with and without a crackling sound quality can share the same long-term power spectrum and, thus, all metric values that derive from the long-term power spectrum. These metrics include Zwicker[3] or ANSI S3.4-2007[4] stationary loudness, stationary sharpness,[7] all letter-weighted levels, or third-octave based calculation systems such as PNdB.

This limitation of long-term spectrum-only metrics has led to proposals to consider the use of time-varying sound quality metrics as possible descriptors of crackle.[2,5] These metrics include time-varying loudness and sharpness, as well as roughness and fluctuation. These metrics evaluate the characteristics of the waveform through time and, in some cases, attempt to simulate more complex aspects of hearing and human perception. A brief description of each follows.

Time-varying loudness calculation methods have been developed by Zwicker (ISO/DIS 532-1:2016),[3] as well as by Glasberg and Moore.[6] These metrics evaluate the energy passing through the auditory system as a function of time and include stages to model some spectral and temporal aspects of the hearing system, such as masking.

Sharpness evaluates the relative spectral contributions of high- and low-frequency components within a sound; the presence of greater relative loudness contributions from high-frequency components increases sharpness. Sharpness can be calculated within either a stationary or time-varying loudness metric by taking a weighted moment of the specific loudness output.[7] DIN 45692, the German standard for sharpness, calls for S_{50}, the sharpness exceeded fifty percent of the time, to be used to practically quantify the sharpness in narrowband noise signals which contain natural temporal fluctuations.[7] This, then, summarizes an intrinsically time-varying quantity.

Roughness and fluctuation each deal with explicitly time-varying aspects of the sound. Roughness describes the sound quality produced by modulation of sounds at frequencies high enough—15-300 Hz—that the modulation peaks cannot easily be individually resolved, but where the resultant non-smooth texture or timbral quality is still apparent. Fluctuation, on the other hand, deals with slower—and more easily tracked—loudness fluctuations modulated below about 20 Hz.[8] Some overlap has been noted between the applicable ranges of the two sensations.

An additional benefit of using these particular sound quality metrics is their potential utility in predicting annoyance produced by acoustic signals. Work by Aures,[9] popularized in Fastl and Zwicker,[8] discusses the possibility of predicting sensory pleasantness—the opposite of annoyance—based on a composite metric including loudness, sharpness, roughness, fluctuation and tonality. Neither tonality nor fluctuation are considered here, but the other three metrics are evaluated for a set of crackling and non-crackling signals. This enables us to consider the question of what sound qualities may be interacting or combining together to form the crackle percept. Crackle is reported to be an annoying aspect of the sound quality of high performance jets[1] and determining which perceptual dimensions may contribute to this experience might be useful in guiding efforts to attenuate the resultant annoyance.

In order to investigate which basic sound qualities might relate to crackle, the response of sound quality metrics to signals with and without a crackling quality is investigated. The methods used to obtain these signals were reported previously in Swift *et al.*,[10,11] and the .wav files associated with the signals themselves were published in Swift *et al.*[11] In this paper, we consider these signals as well as signals produced by modifying the Fourier phase of the set of components above a given cutoff frequency. We report the results of time behavior-sensitive sound quality metrics (in contrast to the average-spectrum-only inputs reported previously[2]) to crackling and non-crackling waveforms. Differences in metric responses between these two classes of sounds are highlighted as well as the possibility of developing a metric that specifically identifies the crackle percept.

2. SOUND ALTERATION METHODS

Because classification into crackling or non-crackling signals has often involved evaluation of the skewness of the pressure waveform or its derivative, transformations that selectively affect one of these two variables are of special interest. A transformation technique developed by Swift *et al.*[10,11] was used to create a custom nonlinear transformation that preserved continuity and maintained the locations of increasing and decreasing intervals but changed the distribution of the underlying variable to follow a truncated Gaussian distribution. This transformation was used to deliberately reduce the skewness of either the pressure waveform ($T\{p\}$) or its derivative ($T\{dp/dt\}$). When this technique was applied to the distribution of the derivative, it resulted in the removal of crackle, while applying the transformation to the pressure waveform preserved the original crackling sound quality. An additional alteration method involved interpolating points into acoustic shocks in order to “slow” the rate of rise or increase the rise time of the shocks. In prior work by Swift *et al.*[10] (in which codes for executing these alterations are made available), this alteration was shown to reduce derivative skewness and eliminate the crackling sound quality of the signal.

In previous work, we have used complete randomization of the Fourier phase as a means of producing a waveform with the same long-term spectrum but with a non-crackling sound quality.[2,10] In this work, this alteration technique is again used. However, we also introduce a variation of this technique in which only frequency components above a particular frequency are randomized. This is termed “partial re-phasing”. This technique makes it possible to incrementally change the sound quality within a family of signals with identical power spectra from clearly crackling to smooth noise by degrees. These incremental differences can then be evaluated in terms of the responses elicited in sound quality metrics and the observed subjective qualities of the waveform.

3. SOUND QUALITY METRICS

Sound quality metrics provide an objective model of particular qualities of the sounds and may help identify especially salient aspects of these signals for further study. Metrics employed in this study include Glasberg and Moore time-varying loudness,[6] sharpness[7] (implemented within Glasberg loudness), spectral variance (a sharpness supplemental metric proposed by Marui and Martens[12]) and roughness (following the general outline of Daniel and Weber’s roughness model,[13] but with alterations to allow it to be implemented in a modified Glasberg time-varying loudness metric). The loudness metric implementation was validated using the stationary signal results in ANSI S3.4-2007.[4] The sharpness metric implementation was tested by comparison with the published results in Fastl and Zwicker[8] for narrowband and high-pass broadband sounds. The roughness metric was tested against the published results in Fastl and Zwicker, as well as some of the results from Daniel and Weber.[8,13]

In order to understand why these particular metrics are used, it is important to know more about the characteristics of crackling signals and how they relate to the sensitivities of the metrics. Sounds exhibiting crackle contain large numbers of acoustic shocks, which appear to exert an important influence on the subjective sound quality.[10,11] Acoustic shocks in crackling waveforms tend to contain a greater concentration of energy—particularly high-frequency energy—than other portions of the waveform. This concentration of energy in time is expected to directly elicit responses from these metrics. The increased concentration of energy at the shocks leads to spikes in loudness concurrent with their passage. The concentration of high-frequency energy relative to low-frequency energy leads, additionally, to spikes in sharpness during shock passage. The shock passage frequency—the approximate number of shocks per second in a signal—tends to fall in the range of 50-200 Hz, well within the range of modulation frequencies—15-300 Hz—to which roughness is sensitive.[8] Fluctuation tends to respond to lower modulation rates—less than 20 Hz—than those prominent in crackling signals. Because of the correspondences between the behavior of crackle-containing signals and the characteristics to which each metric responds, aspects of time-varying loudness and sharpness, as well as roughness, can be reasonably expected to respond to the differences between crackling and non-crackling signals and are calculated in this study, while fluctuation is not expected to respond and is not investigated.

A number of the measures that are considered in this paper use the Glasberg instantaneous loudness values without further temporal summation. This is unusual because the instantaneous loudness is not normally considered to be available to conscious perception as loudness. Although this information may not be available to the listener *as loudness*, aspects of it may be available for conscious perception as a textural or timbral quality. This possibility was suggested in Swift.[5] The idea that this information might be available as loudness attracted just criticism from Rennies,[14] who rightly indicated that a model taking into account special onset effects might perform more effectively in predicting the loudness perceived in such sounds. With this limitation in mind, several measures based on the instantaneous loudness are used in this paper, not as indicators of loudness per se but as possible indications of a crackling timbre or sound quality.

4. RESULTS AND DISCUSSION

The waveforms from Swift *et al.*[11] were evaluated using a collection of sound quality and statistical metrics. These signals include three that crackle—the original crackling jet waveform, a copy which was differentiated and "leaky" integrated and a pressure-transformed copy ($T\{p\}$)—as well as three signals which have had crackle removed: a copy which was derivative-transformed ($T\{dp/dt\}$), a copy where the shocks were slowed and a copy which has had its phase entirely randomized. Additional signals were produced using the partial re-phasing technique described above. These signals have component Fourier phases randomized above cutoff frequencies of $f_c = 4000$, 7000 and 10000 Hz. These values were chosen because all result in sound qualities that are subjectively distinguishable (in informal tests by the first author) from the extreme cases of crackle removal (last three signals) and clear crackle (first three signals) as well as from each other. Thus, varying degrees of crackle are present in these waveforms, with the highest cutoff frequency corresponding with the greatest degree of subjectively observed crackle among these three and the lowest cutoff frequency being associated with the least crackle. The number of cases selected was limited by the desire to keep the plots from becoming overcrowded. The varying degrees of crackle present in the waveforms enable comparisons between the responses of the metrics, the subjective sound quality and physical statistical measures of the waveforms. The responses of the sound quality metrics to the jet noise signal and its modified daughter signals are shown in Figure 1.

In this figure, results of loudness (N, upper left), sharpness (S, upper right), spectral variance ($S.V.$, lower left) and roughness (R, lower right) measures are shown. Beginning with the loudness, the difference between the mean (μ) and maximum (Max) instantaneous loudness (N_i) is larger for crackling than for non-crackling signals. The standard deviation (σ) of N_i is also larger for crackling than for non-crackling signals. The same is true, although to a lesser degree, of the short-term loudness N_s. Considering next the sharpness results, differences in both S_{50} and μ_S are seen between crackling and non-crackling signals, with lower μ_S values seen in the crackling signals than would be expected in the more typical non-crackling signals or when considering sharpness based on the long-term spectrum. σ_S also consistently shows larger values for crackling signals. The spectral variance does not show the degree of consistent discrimination that would be desired of a crackle indicator. However, it was designed as a supplemental rather than a direct sharpness measure, so its applicability to this problem was inherently uncertain and its inclusion experimental. Roughness clearly discriminates between crackling and non-crackling signals.

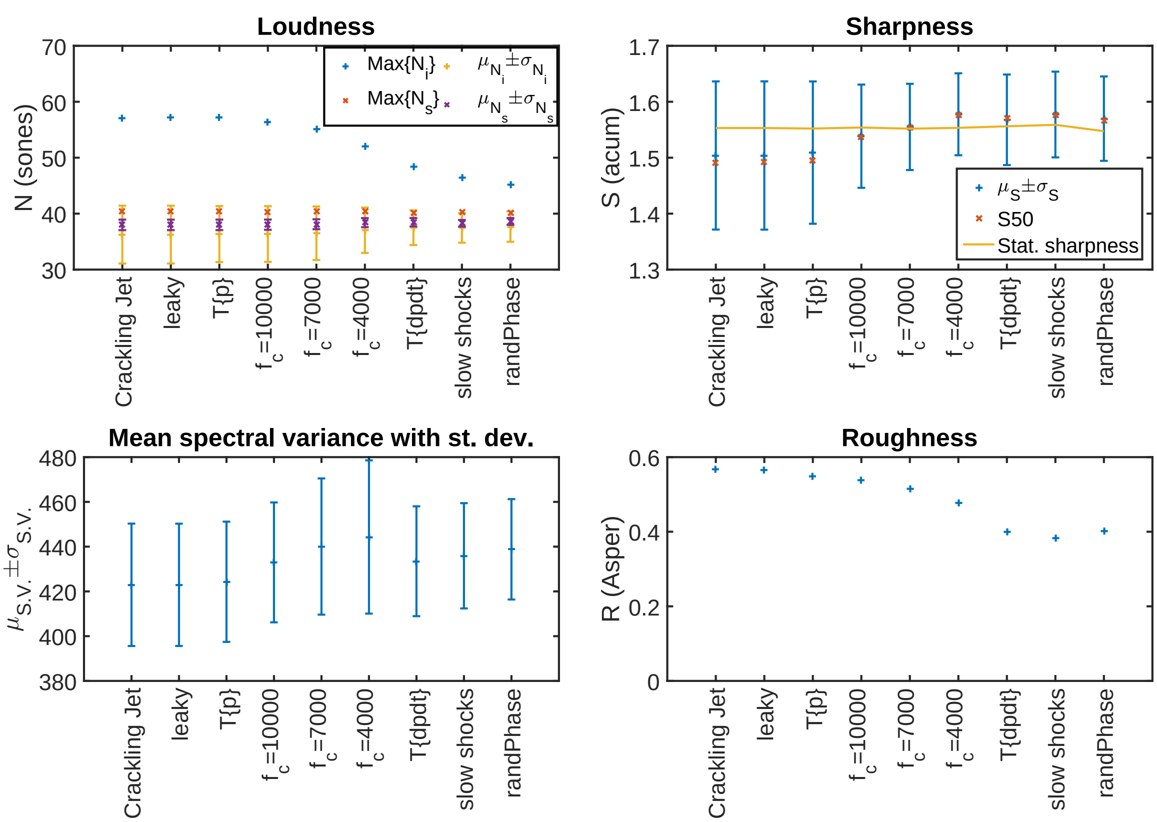

Figure 1: Metric results for the original (crackling) jet noise waveforms and altered waveforms based on modifications of the jet noise waveform.

It ought to be noted at this point that the long-term spectra of all of the test sounds are the same, so none of the differences seen in these plots are the consequence of long-term spectral phenomena, but are instead due to the specific temporal behavior of the waveforms.

In the loudness and sharpness measures, a general pattern is evident, in which the amount of variation (typically quantified as standard deviation, σ) relative to the mean quantity, μ, is larger in crackling than non-crackling signals. This nondimensionalized quantity is often referred to as the coefficient of variation ($c_v = \sigma/\mu$). For example, the c_v of the instantaneous loudness was greater (0.1426 for the crackling jet waveform and 0.0722 for the re-phased waveform) in crackling than in non-crackling signals. The same was true of the c_v of the sharpness (0.0881 for the crackling jet waveform and 0.0480 for the re-phased waveform). For reference, just-noticeable difference (JND) values around 5 percent for loudness and 2-3 percent for sharpness have been noted in tests on sounds for earthmoving equipment.[15] Thus, these differences would likely be noticeable in a more sound with slower temporal behavior. Thus, the c_v of the instantaneous loudness and sharpness appear to provide a plausible identifier of a crackling sound quality. The use of these variables as direct quantifiers of the crackle percept is complicated by the fact that they use the instantaneous variables without temporal summation.

Mean and median sharpness both display some discriminating ability. Neither S_{50} nor μ_S would function well as an independent measure because sharpness can be directly affected by spectral changes, but either could be normalized by the sharpness of the average spectrum to achieve an independent measure. The average sharpness of the crackling signals is reduced relative to the sharpness calculated from the average spectrum because the combination of the compressive nonlinearity of the hearing system with the temporal concentration of high-frequency energy at the shocks inefficiently allocates high-frequency energy in crackling signals, resulting in a decreased mean value. This effect, however, is relatively small (around 3-4 percent difference between crackling and non-crackling signals) and is not likely to be as effective as the approach using the c_v.

Roughness also showed a particularly interesting ability to discriminate between crackling and non-crackling signals. The just-noticeable difference for roughness is around 17 percent,[13] and the range of roughness values here spans around two and a half JNDs, an easily recognizable degree of distinction. Roughness is explicitly dependent on the presence of time-varying behavior and so is, on some level, a more intuitive candidate for quantifying an aspect of crackling sound quality than some of the other metrics. It therefore seems worthwhile to evaluate why roughness was responsive to the distinctions between crackling and non-crackling signals, both to establish the usefulness of the metric for this application and also to inform the discussion of how crackle might be more perfectly quantified based on its unique characteristics.

The roughness metric used in this work is embedded in a time-varying loudness metric that provided a number of useful precursor variables and processes. The first stage in the time-varying loudness and roughness calculation process, the spectrum through time, or running spectrum (as it is described in Glasberg and Moore's 2002 paper[6] describing the calculating of time-varying loudness), provides an initial point of interest. In the crackling jet waveform, the passage of shocks results in significant high-frequency spikes, which appear as light horizontal lines in the left top panel of Figure 2. The non-crackling signal, on the other hand (upper right panel), has less time-coordinated arrangement of spectral energy. It also tends to have slightly less dipping in the spectrum. The same amount of energy is present in both cases; however, it is more concentrated and temporally coordinated in the crackling case.

These differences are further reflected in the excitation pattern through time, shown in the lower portion of Figure 2. Here, the increased concentration of energy into discrete temporal events in the crackling signal (left) is even more apparent, especially in the higher-frequency regime, where significantly deeper dips in excitation occur in between shocks and the horizontal bands of energy corresponding to the shocks become increasingly apparent.

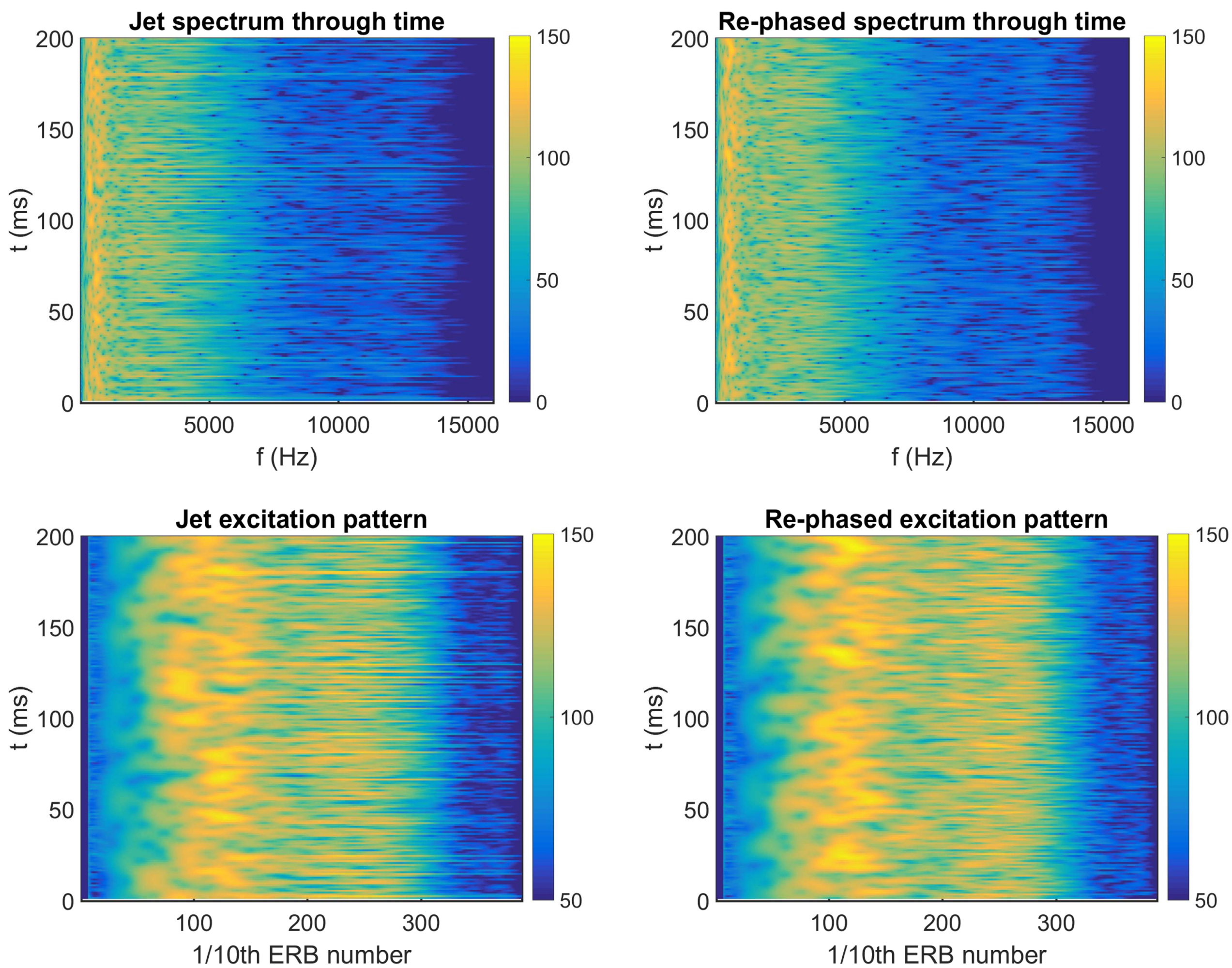

Figure 2: Running spectra and excitation pattern associated with a crackling (jet waveform) and non-crackling signal (re-phased waveform).

The increased coordination of energy in the higher frequencies leads to greater correlation across critical bands, one of the variables accounted for in the calculation of roughness shown in Figure 3 (upper left). The increased depth of the dips in the excitation pattern in between the shocks leads to increased values of generalized modulation depth (upper right), another roughness precursor variable. These two effects lead to significantly increased specific roughness values (lower left and right) in the high frequencies for the crackling signals versus the non-crackling signals. Thus the roughness metric's differential response is directly related to known physical characteristics of the crackling and non-crackling signals.

In addition to the relatively common sound quality measures considered above, statistical measures based on the instantaneous loudness (N_i) and instantaneous sharpness (S_i) time series were

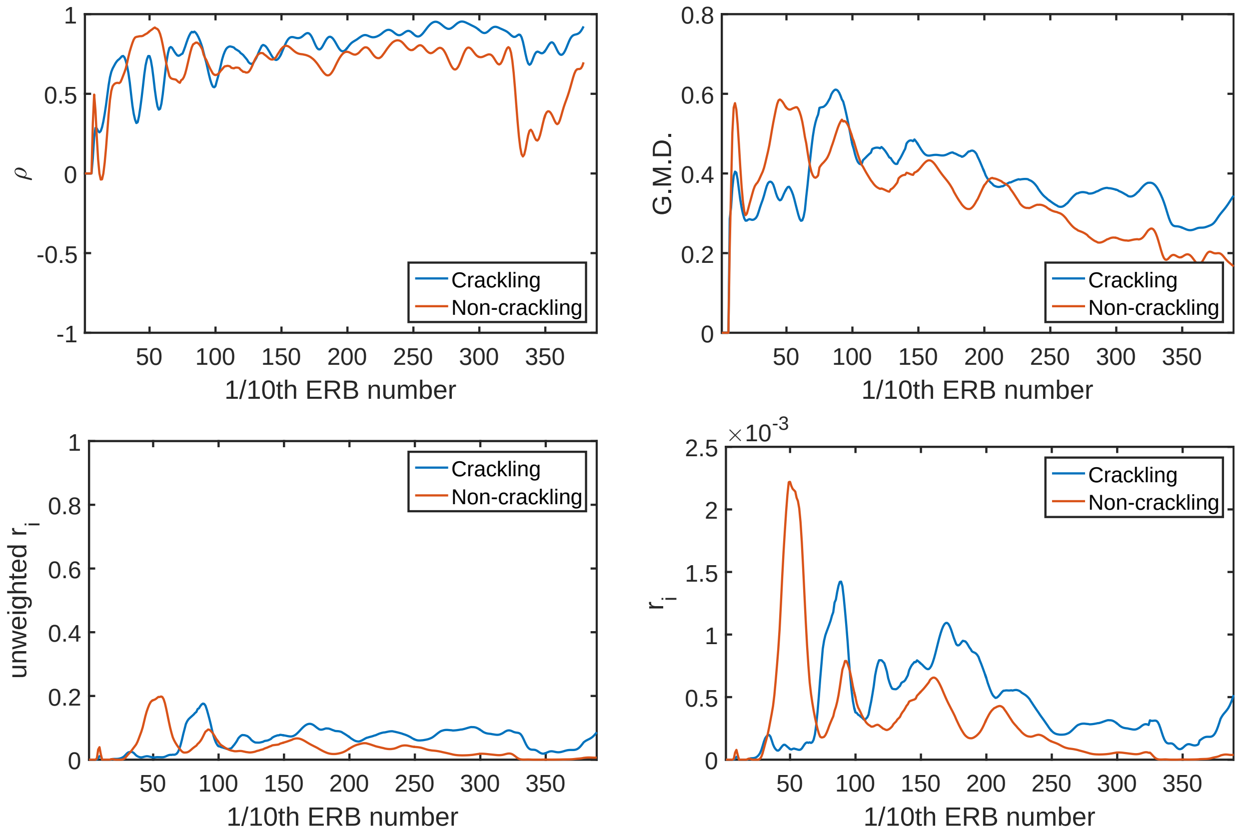

Figure 3: Roughness variables compared between a crackling and non-crackling example case. Note: due to calibration variables that exist at various stages of the calculation (including after the variables shown), these are best regarded as relative rather than absolute values.

considered as possible crackle predictors. The results of these tests are shown in the left panel of Figure 4, where it can be seen that, in the crackling signals, the sharpness and the loudness are more correlated than in the non-crackling signals. Furthermore, this correlation is always positive in the crackling signals whereas a negative correlation sometimes occurs in the signals where crackle has been removed or attenuated. The distributions $\mathrm{PDF}\{N_i\}$, $\mathrm{PDF}\{S_i\}$ and $\mathrm{PDF}\{N_iS_i\}$ are also plotted in Figure 5, and their skewness values are plotted for comparison in the right panel of Figure 4. The skewness values $\mathrm{Sk}\{N_i\}$, $\mathrm{Sk}\{S_i\}$ and $\mathrm{Sk}\{N_iS_i\}$ all show a potentially useful ability to distinguish between the crackling and non-crackling signals in this test.

Considering the distributions of these variables shown in Figure 5, there appears to be a significant difference in the shape of $\mathrm{PDF}\{N_i\}$, $\mathrm{PDF}\{S_i\}$ and $\mathrm{PDF}\{N_iS_i\}$ associated with crackling and non-crackling waveforms. The non-crackling waveforms tend to have approximately Gaussian distributions of instantaneous loudness, instantaneous sharpness and their product. The crackling sounds have skewed distributions of all three variables. The three sounds which have had crackle partially removed through partial re-phasing (dotted lines with triangles) appear to follow intermediate distributions. The long tail seen in all three variables in the crackling signals is a direct physical consequence of the acoustic shocks which are the cause of the crackling sound quality. Thus the distribution of these variables is a direct result of waveform features that produce

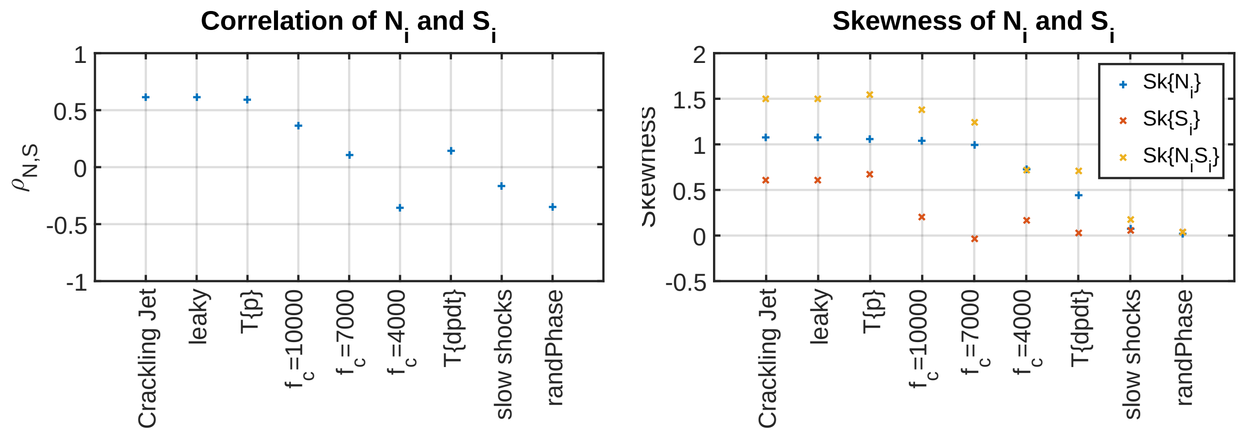

Figure 4: Correlation between the instantaneous loudness and the instantaneous sharpness measures. Skewness of the instantaneous loudness and sharpness distributions as well as that of their product.

the sound quality in question. The asymmetry seen in the distributions associated with crackling sounds provides a ready means of quantifying this tail through use of the skewness values reported in Figure 4, and provides a solid rationale for the use of these variables as crackle quantifiers.

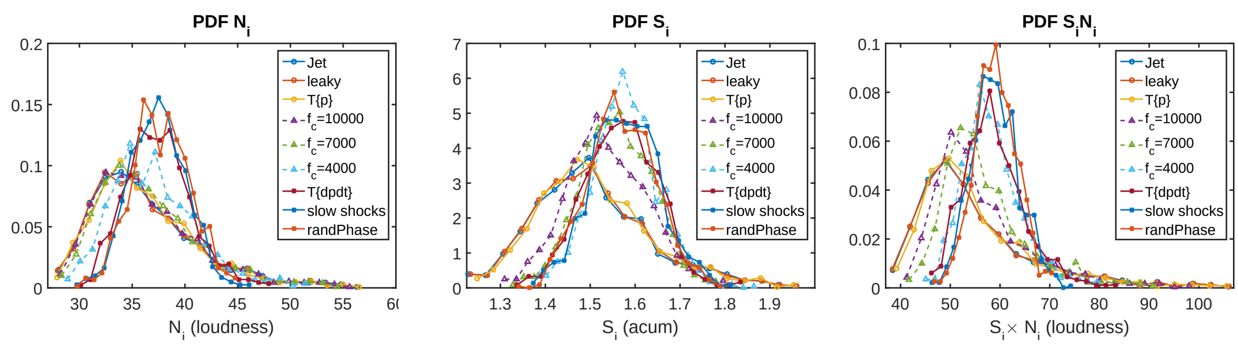

Figure 5: Probability density functions for the instantaneous loudness and the instantaneous sharpness of the modifed signals as well as their product.

Several of the metrics which were examined showed good ability to discriminate crackling from non-crackling signals. These metrics included roughness, c_v of loudness, c_v of sharpness, as well as the correlation between N_i and S_i and the skewness of N_i, S_i and N_iS_i. Looking at these metrics, roughness naturally includes much of the information that the loudness fluctuation variable provides, so there is a certain amount of redundancy in including both variables. It does not, however, include the information regarding the relationship of instantaneous loudness and sharpness variables, their correlation and distribution. It is also notable that the differences seen in roughness were seen in the high rather than the low frequencies. In order to attempt to consider these possible influences on crackle perception, a sharpness weighting function was introduced into the roughness metric, producing a “sharp roughness” or “serration” metric. The responses of this modified metric to the test sounds are shown in Figure 6. This metric discriminates well between crackling and non-crackling signals and also seems to reflect the qualitative gradations which exist between these signals. However, this is not, unlike roughness, an established sound quality metric and so does not carry with it the benefit of a ready psychoacoustic interpretation. Whether this metric consistently reflects some aspect of human experience with these sounds must necessarily await subject tests with a wide variety of sound to confirm.

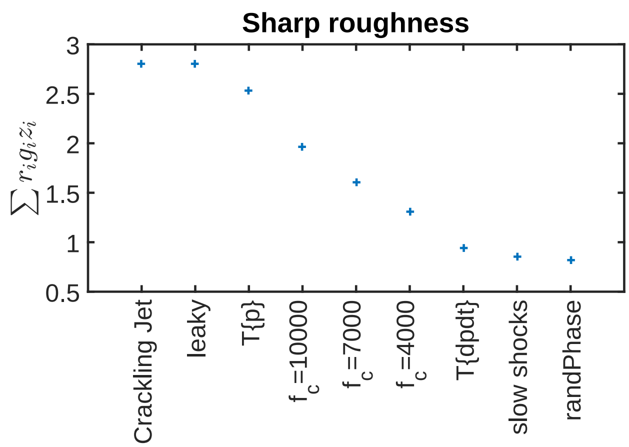

Figure 6: Sharpness-weighted roughness or "serration" of crackling and non-crackling signals.

The skewness and kurtosis of the derivative of the acoustic pressure, physical statistical measures related to the shock content in the waveforms, are shown in Figure 7 because of the association of such variables with crackling sound quality.[10,11] The derivative skewness and kurtosis associated with the partially re-phased waveforms decreases in approximately the expected manner with decreasing f_c. One notable feature of the intermediate waveforms is that, while they still display some degree of crackle, their derivative skewness is considerably less than 5, which has been seen as a potential point of demarcation for the presence of significant shock content and as a predictor of a crackling sound quality.[10,11] This result suggests that an elevated derivative value does predict a crackling sound quality, but also reveals a need to determine what range of values in the derivative skewness correspond to various subjective degrees of crackle.

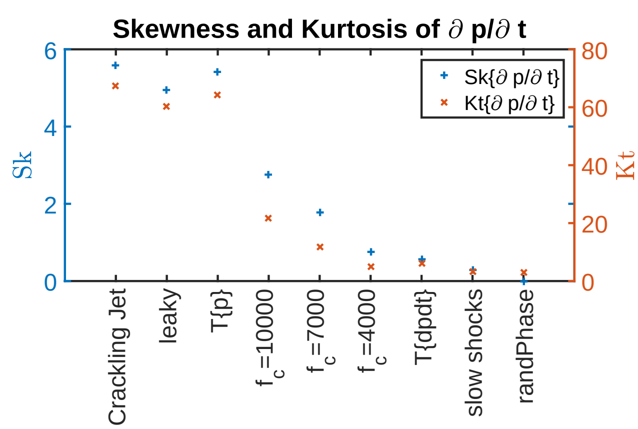

Figure 7: Skewness and kurtosis of the derivative of each signal.

The responses of sound quality metrics to crackling and non-crackling signals seen in this paper seem to be consistent with the allegation of Ffowcs Williams that crackling sound quality results in additional annoyance beyond what one would predict using a purely spectral representation of the sound.[1] Roughness, sharpness and loudness are known as positive contributors to annoyance.[8] Roughness is clearly elevated in the crackling signals. The same events that produce the roughness also involve coordinated spikes in the sharpness; however, it is not entirely clear how this might affect the resultant annoyance. The compressive nonlinearity of the hearing system leads to decreased average loudness and sharpness when energy is temporally concentrated at the shocks. Although the average sharpness in the crackling signals is decreased, the contrast between the elevated sharpness at the shocks and the perceptual spaces between them is increased. The same relationship occurs with loudness. Concentration of energy in shocks results in both decreased average levels and increased foreground-background contrast between the shocks and intermediate intervals. Would the decrease of the average loudness and sharpness lead to decreased annoyance, or would the greater contrast between the peak values at the shocks and the background increase the annoyance? A further question, elicited by the observation of Rennies[14] previously mentioned, is how a metric that is designed to account for onset effects in a sound might differentially respond to these signals, which share a common power spectrum. Should the presence of crackle result in an increase or a decrease in subjective loudness? These are questions which must await subject tests before they can be satisfactorily answered.

5. CONCLUSIONS AND FUTURE WORK

Copies of a crackling jet noise have been successfully modified in order to produce a series of waveforms which exhibit varying degrees of crackling sound quality. These waveforms have been evaluated using sound quality metrics assessing loudness, sharpness and roughness. In addition, physical statistical metrics have been evaluated for these signals. The responses of these metrics (which have been considered as predictors of annoyance in the psychoacoustics literature) may help inform investigations into which aspects of crackling sound quality might result in increases in subjectively measured annoyance. However, it is not yet clear whether the crackle percept can be entirely expressed as some combination of the more elemental sound quality metrics here examined. Roughness showed a significant independent ability to discriminate between crackling and non-crackling waveforms. In addition, measures based on correlation between or distribution of the instantaneous loudness and sharpness showed good discrimination between crackling and non-crackling waveforms. The coefficient of variation of the instantaneous loudness and sharpness also showed good discriminative properties. A "serration" metric, in which sharpness-weighted roughness is evaluated, showed a relatively strong ability to discriminate between crackling and non-crackling signals.

While further investigation is certainly needed in order to determine if this or any of the metrics considered in this paper can adequately quantify the presence of the crackle percept, this work has demonstrated a clear ability of measures derived from time-varying sound quality metrics to distinguish between crackling and non-crackling signals with equal long-term spectra. It has thus opened the door to further discussion on this point and for the development of metrics designed to specifically identify the presence of crackle produced by high-performance jets. Ultimately, any metric that might be proposed as a quantifier of crackling sound quality requires validation using jury studies in connection with a jet noise database. In addition, this study has shown that the threshold $\mathrm{Sk}\{\partial p/\partial t\}$ value for a crackling sound quality may be lower than previously thought,[10,11] with a signal with $\mathrm{Sk}\{\partial p/\partial t\} \approx 3$ exhibiting fairly clear crackle. This too should be a subject of further examination using jury studies.

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