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Evaluation of time-varying loudness for quantifying perception of nonlinearly propagated noise

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ABSTRACT

There are several factors that affect the prediction of the noise impact of military jet aircraft. These range from physical effects, e.g., nonlinear propagation of high-amplitude sounds, to auditory system effects, which include temporal summation and masking. An effort to characterize the perceptual impact of jet noise waveforms has led to a preliminary investigation of the suitability of time-varying loudness for quantifying the subjective impact of a shock-containing noise signal. The short-term loudness (which includes hearing's temporal effects) of the waveform shows some variation in loudness; however, it does not appear to exhibit as much variation as is commonly perceived in informal listening tests. On the other hand, examination of the instantaneous loudness shows that the loudness appears to be concentrated in discrete moments in the signal rather than distributed as in a typical steady sound—a better qualitative match to what is heard when listening to the waveform. Also, there appears to be a strong correlation between the instantaneous loudness and the derivative of the waveform, which suggests that the acoustic shocks are the major contributor to the loudness of the signal. Possible functional relationships between the instantaneous loudness and the derivative of the waveform are discussed. These lead to a possible explanation of certain statistical indicators of crackle-like elements or qualities within a signal.

1. INTRODUCTION

The effects of noise radiated by high-performance jets have been examined in a number of contexts. Several interesting aspects of these unique signals relate to the role of nonlinear effects in their propagation. Nonlinear processes affect the waveform in several ways. In the time domain, high pressure portions of the wave advance relative to low pressure portions of the wave causing steepening. This steepening of the waveform leads to the formation of acoustic shocks. These shocks become a dominant feature of the waveform as other features are gradually smoothed out through atmospheric absorption (see Fig. 1). The processes of steepening and shock formation also bring about the nonlinear transfer of energy from the peak frequency region to the higher frequencies.

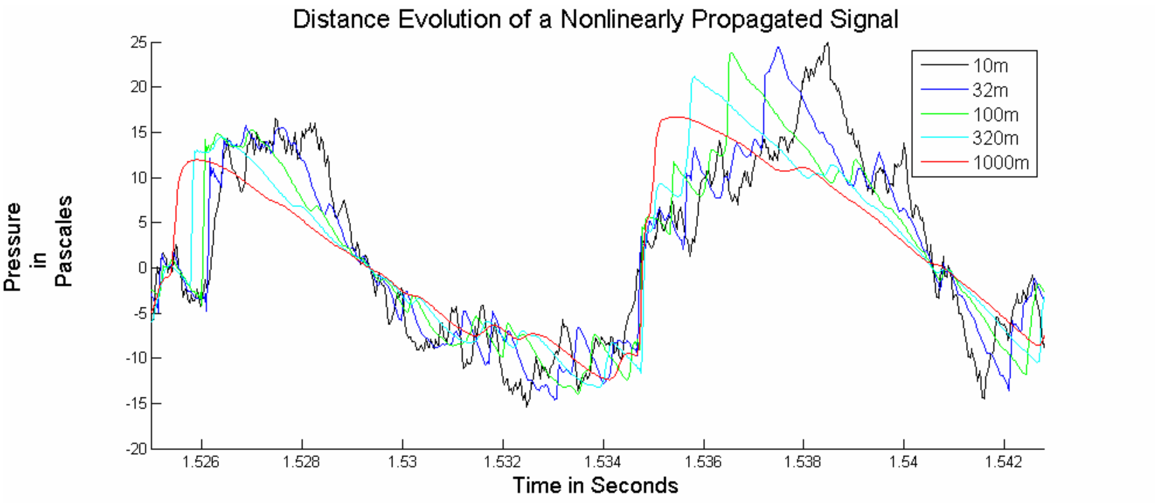

Figure 1: Distance evolution of a nonlinearly propagated signal

Steepening, and the resulting transfer of energy to high frequencies in a nonlinearly propagated waveform can result in a unique perceptual phenomenon that is qualitatively similar to what has generally been understood as a jet noise source phenomenon known as “crackle.[1]” An example of the differences between nonlinear and linear propagation may be heard by clicking on the hyperlinks found in reference 2. Recent work by Gee et al. suggests that crackle is likely related to the presence of acoustic shocks, as evidenced by highly skewed probability density functions (pdf) of the time derivative of the pressure waveform.[3] In this paper, we pursue the view that a crackle-like quality may result from the development of shocks during nonlinear propagation. Further, these shocks seem to be audible as discrete loudness events, leading to the percussive quality of the waveform, and are both the dominant characteristic of and loudness contributor in the nonlinear signal.

Because the nonlinearly propagated waveform can have significantly greater energy at high frequencies (relative to linear propagation), it has been speculated that it may be possible to describe the effects of nonlinear propagation and thus the perceptual impact of jet noise waveforms using metrics sensitive to high-frequency content. Indeed sharpness, a sound quality metric, as well as other metrics which specifically address high-frequency content, do respond to the spectral differences. However, like sharpness, none of the purely spectrum-based metrics are able to differentiate between a nonlinearly propagated signal and a phase-randomized signal with the same spectrum despite the fact that these two signals are perceived quite differently.[2] Thus, while still relevant, none of these spectrum-only metrics is able to capture certain unique and important aspects of the way informal listeners typically perceive nonlinearly propagated sounds. Accordingly, a signal with equivalent spectrum but random phase becomes an important test case in determining whether the metric is responsive to certain defining attributes of a nonlinear signal and will thus be of interest in this study.

This shortcoming of metrics that examine only the bulk spectrum has led to interest in the use of time-varying loudness to characterize perception of nonlinearly propagated signals. Loudness is generally calculated for stationary signals by taking in the spectrum of some sound of interest, filtered so as to represent passage through the various stages of the auditory system up to the basilar membrane.[4] At this point, the excitation pattern of the basilar membrane is calculated, and used to determine the specific loudness in each equivalent rectangular bandwidth, which is then summed to obtain the total loudness.

When dealing with non-stationary or time-varying signals, the ear exhibits some temporal behavior that needs to be considered when determining the loudness. Notable among these are temporal masking and summation. The first describes a circumstance wherein it is difficult to perceive the loudness of a quieter sound shortly after a loud sound. The second refers to the integrator-like behavior of the ear wherein, for a sound of consistent level, a certain period of time is required before the loudness closely approaches its asymptotic value. These behaviors and their respective effects may be condensed and summarized by saying that an increase in loudness may be perceived more rapidly than a decrease in loudness (see Fig. 3). This behavior is represented in time-varying loudness as described by Moore and Glasberg.[5] It is thus hoped that by employing a protocol representative of the temporal behavior of the ear that we may be able to obtain a more accurate representation of the loudness of this unusual class of signals.

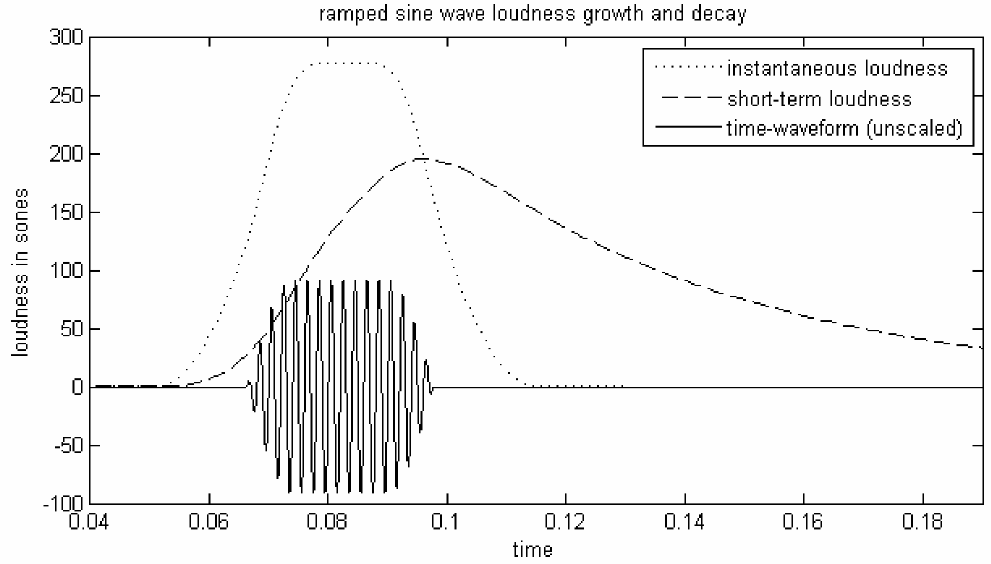

Figure 2: The characteristic growth and decay of loudness for a brief sine pulse as a function of time

2. METHODS

For this paper, nonlinear propagation of a shaped random noise spectrum was simulated using a numerical implementation of the Generalized Burgers Equation,[6] which includes atmospheric effects such as absorption as well as nonlinear effects up to quadratic order. The details of the process used to create the waveforms were identical to those in reference 2 and readers are referred there for details. Additionally the waveforms are embedded there as wave files and so may be experienced qualitatively as well. The propagation was carried out to a simulated distance of 1000 m so that spherical spreading reduced the sound to a level where human perception is a tenable research question—closer, the sound remains far too intense.

A time-varying loudness model was built in Matlab based on Moore and Glasberg's method[5] using a Matlab implementation of ANSI S3.4-2005 to convert between the running spectrum, the excitation pattern, and the instantaneous loudness.

A “rephased” signal was created by randomizing the Fourier phase of the nonlinearly propagated signal and holding the power spectrum constant. The short-term loudness and instantaneous loudness of this signal were then calculated using both the TVL metric and the derivative method. This waveform may also be heard via a hyperlink in reference 2.

3. METRIC RESULTS AND DISCUSSION

Since previous work by Gee et al.[3] suggests that crackle-like qualities may be linked with the skewness of the probability density function of the derivative, the probability density function seems a good place to begin our discussion. The derivatives of the two waveforms were found, and the probability density functions calculated. The pdf of the derivative (hereafter called the Dpdf) of the nonlinear sample was found to be skewed, suggesting that this may be a crackling or “crackle-like” waveform. The Dpdf of the rephased sample was found not to be skewed, suggesting that randomization of the Fourier phase has eliminated the shocks and with it the crackle-like quality (see Fig. 4).

The instantaneous loudness of the waveforms was calculated and compared to the associated values of the derivative. A scatter plot of the values of the instantaneous loudness and the derivative was created with the instantaneous loudness as the ordinate and the derivative as the abscissa for the nonlinearly propagated sample. An approximate lower bound line and a trend line were superimposed on the data (see Fig. 3). Since the loudness at the shocks (or peaks in the derivative) is primarily influenced by the steepness of the shocks, the “function line” in the graph was chosen to show average values at the peaks in the derivative with other features making limited contributions characteristic of the nonlinear waveform. It should be noted that nearby shocks can still contribute to the loudness even when the shock is not centered in the windows, thus the large values on the left of the graph. However, the shape of the data suggests that large values of the derivative (corresponding to acoustic shocks) lead to large values of the instantaneous loudness. It should also be noted that the converse—large values of the instantaneous loudness imply centering at large values of the derivative is false as may be observed from the left portion of the graph.

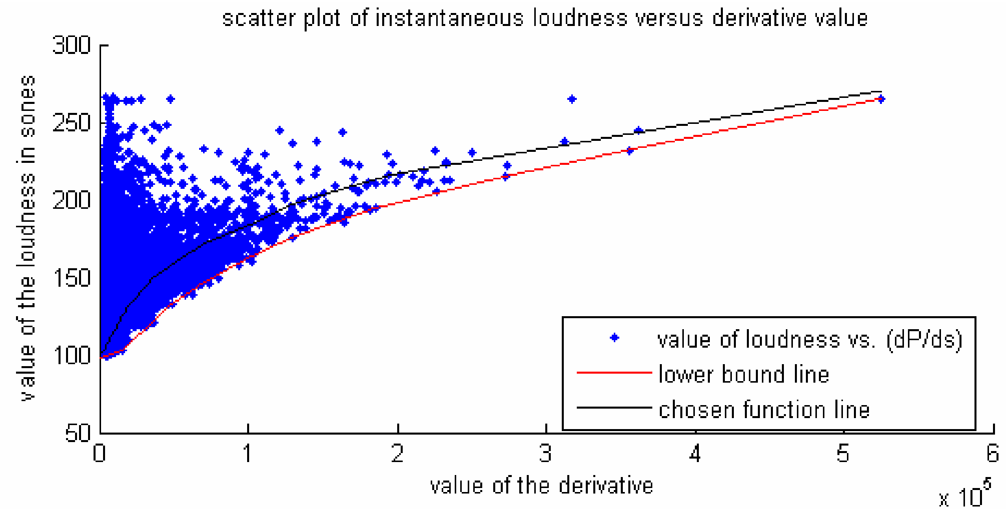

Figure 3: Scatter plot showing the loudness of points in relation to the value of the derivative with lower bound line and trend line for the nonlinearly propagated signal

Accordingly, one might expect the features of the Dpdf of the waveform to influence the statistics of the instantaneous loudness, which, indeed, seems to be the case. The pdf of the instantaneous loudness of each waveform shows skewness properties similar to the Dpdf, In effect, what this means is that the loudness of the nonlinearly propagated waveform is concentrated in discrete events (shocks) in a background of relative quiet. This may then provide a qualitative explanation of the results of Gee et al., that is, skewness of the Dpdf implies the presence of discrete loudness events in a background of relative quiet, which then suggests, qualitatively, a crackling or crackle-like signal.

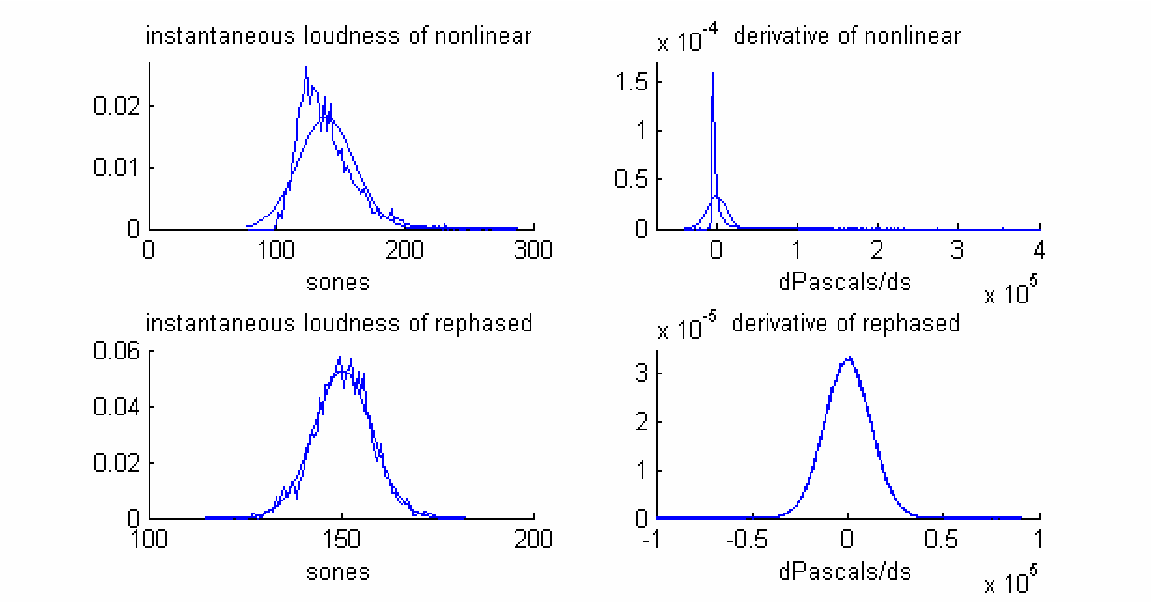

Figure 4: Plots of the probability density functions of the derivative and loudness of the nonlinearly propagated signal and a rephased signal with same spectrum, overlain with a Gaussian distribution of same mean and standard deviation for comparison

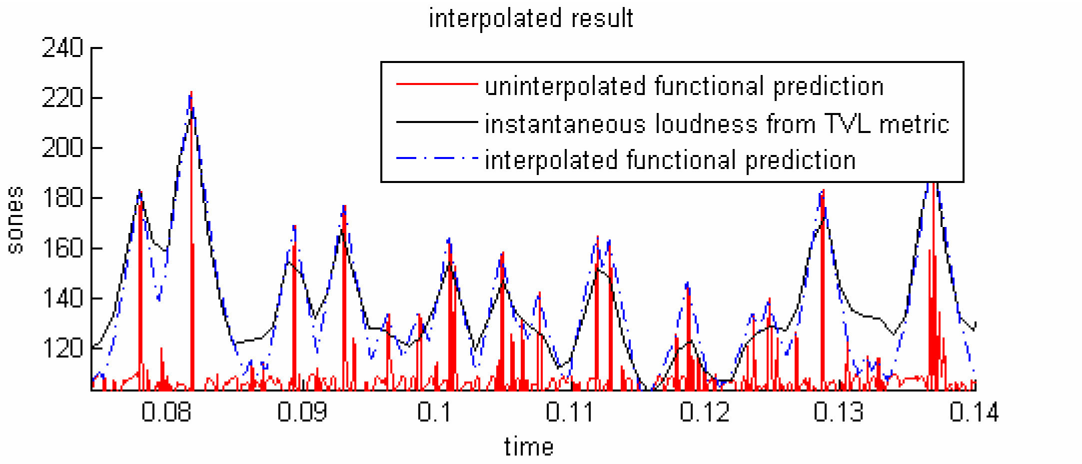

Figure 5: Comparison of predictions of instantaneous loudness of the nonlinearly propagated signal by TVL metric and interpolated derivative method

Using a functional relationship similar to that described earlier, as implemented in a Matlab routine, the instantaneous loudness was predicted using only the magnitude of the derivative and some time-domain interpolation to find values in between the peaks. The interpolation was necessary because while the derivative is an instantaneous feature, the excitation of the ear takes a certain amount of time to build (even for "instantaneous loudness")—longer for lower frequencies and less time for higher.[5] Thus, the interpolation employed is similar in shape to the windows used in computing the running spectrum. From this, the short-term loudness of the nonlinear signal was also calculated and found to be very accurate (usually within 1 phon of the predicted value), as is seen in Fig. 6. The rephased signal follows a slightly different trend because of the greater density of features contributing to the loudness in the signal. In the nonlinear signal the loudness is concentrated in the shocks and reduced elsewhere. In the rephased signal the loudness is less discrete and more distributed. Thus, multiple features will contribute simultaneously to a greater degree, and a somewhat different trend line is needed as well as, possibly, a more sophisticated interpolation method. As a result, the rephased class of signals is somewhat less susceptible to this method. If such a method were to be used for this signal, the statistics of the signal—the Dpdf and such—may need to be among the input variables considered in determining a trend-line. Likely the increased feature density would correspond to an increase in the "DC offset" of the function curve. For signals of known shock density and magnitude, however, it appears that the relationship is fairly effective and dramatically reduces computation effort and complexity.

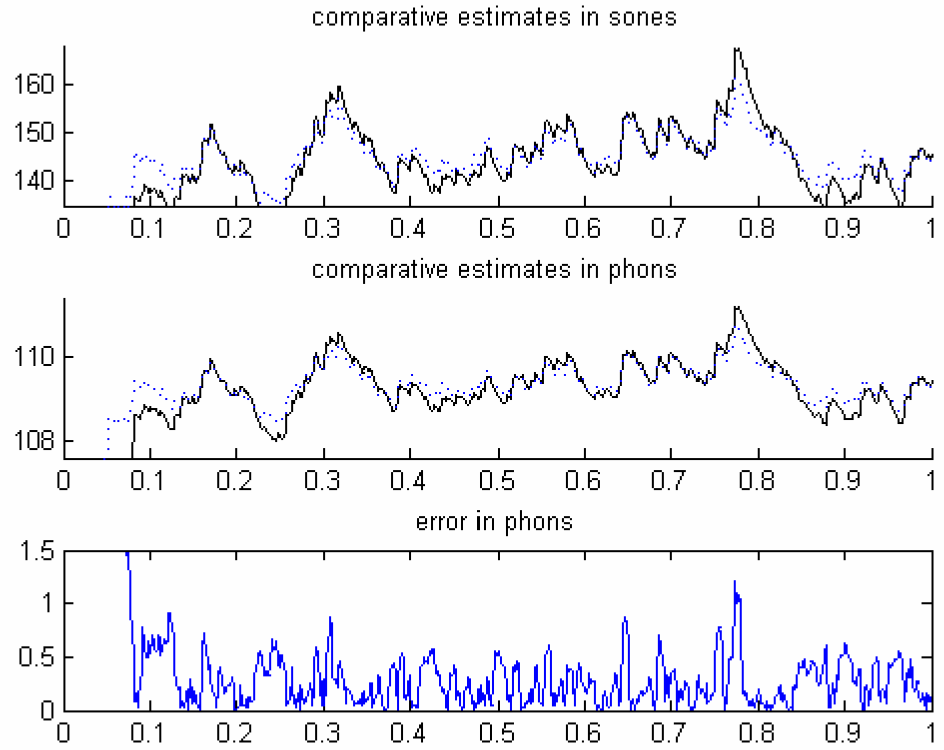

Figure 6: Comparison of short-term loudness predicted by TVL and derivative method for the nonlinearly propagated signal, derivative method results shown with dotted lines

There is one problem with this use of the instantaneous loudness, however, and that is that the instantaneous loudness is not supposed to be a variable available for conscious perception, but is believed to require further processing and summation at higher levels of the cognitive process before being perceived as loudness.[5] Thus, the shocks should, possibly, not be audible to the listeners or at least should not seem to be more than a few sones above the average as shown in this plot (see Fig. 6, middle, where the variation is only about three phons on the interval). However, as they do seem to be audible and their presence dramatically influences the quality of the sound, a further explanation is needed. Recent research by Mossbridge and Wright,[7] as well as earlier research by Formby et al.,[8] suggests that it may be possible for the attack coefficients to grow larger with larger signal bandwidth. Since shocks have a broad spectrum, this could allow the loudness to approach the values of the shocks more quickly than otherwise. At present, summation coefficients for TVL are allowed to change between an attack and a decay value depending on whether the incoming instantaneous loudness is greater than or less than the current short term loudness. Thus it may be valid for them to change more for extreme differences in level, however, this is only speculation and understandably, psychoacoustic data for these levels and conditions is lacking. Additionally, research by Gockel et al. suggests that the presence of cosine phase may influence the perception of loudness of tone complexes.[9] Shocks do indeed possess a unique phase relationship, though different from the one investigated in Ref. 9 and this does seem to influence the perception of loudness in the signals as well as their quality, and so may need to be taken into account in future models. Furthermore, their work suggests that phase may impact temporal (forward) masking. This may further impact the way the loudness decays and may thus affect the overall levels predicted as well as the general shape of the short-term loudness.

4. CONCLUSIONS AND FUTURE WORK

In conclusion, the link between derivative values and instantaneous loudness has been shown. This suggests a possible explanation of the crackle-like quality of nonlinearly propagated signals. Though a propagation phenomenon, nonlinear propagation leads to sounds qualitatively quite similar to the sound characterized as crackle and points to the potential value of studying crackling signals from the paradigms employed in this paper as well as those employed by Gee et al.[3] Particularly, it may be of interest to examine other known crackling signals using the pdf of the instantaneous loudness to see how it compares with the Dpdf, which has been previously studied, as an indicator of crackle-like behavior. Using the derivative method may be a valid way of assessing the potential presence and loudness impact of shocks in jet noise. However, for all these possible avenues, subjective testing becomes necessary in order to evaluate how well listeners' and metrics' reactions compare to one another.

It may be of further interest to evaluate these signals using other sound quality metrics such as roughness to determine how they respond and learn if any of these may prove more indicative of the presence of crackle-like attributes or other qualities that are found to be more descriptive of these unique and interesting signals. It may also be of interest to determine if some of the other sound quality metrics may be calculated from the output results of time-varying loudness or the derivative statistics.

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