On the potential limitations of conventional sound metrics in quantifying perception of nonlinearly propagated noise

Kent L. Gee and S. Hales Swift
Department of Physics and Astronomy, N319 ESC, Brigham Young University, Provo, Utah 84602
kentgee@byu.edu; hales.swift@gmail.com

Victor W. Sparrow
Graduate Program in Acoustics, 201 Applied Science Building, The Pennsylvania State University, University Park, Pennsylvania 16802
vws1@psu.edu

Kenneth J. Plotkin
Wyle Laboratories, 2001 Jefferson Davis Highway, Suite 701, Arlington, Virginia 22202
kplotkin@wylelabs.com

J. Micah Downing
Blue Ridge Research and Consulting, LLC, 13 1/2 West Walnut Street, Asheville, North Carolina 28801
micah.downing@blueridgeresearch.com

Abstract: The use of conventional metrics to quantify the perception of nonlinearly propagated noise has been studied. Gaussian noise waveforms have been numerically propagated both linearly and nonlinearly, and from the resulting waveforms, several metrics are calculated. These metrics are overall, A-, C-, and D-weighted sound pressure levels, perceived noise level, Stevens Mark VII perceived loudness, Zwicker loudness, and sharpness. Informal listening demonstrations indicate that perceived differences in annoyance between linearly and nonlinearly propagated waveforms are substantial. Because the metrics studied seem inadequate in representing the perceived differences, rigorous subjective testing is encouraged to properly quantify and understand these differences.

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1. Introduction

The effects of noise radiated by high-performance jet aircraft on nearby communities and the environment is a research question that has been studied in a variety of contexts. One relevant issue related to the noise impact of these aircraft is the possible influence of nonlinear propagation effects. Pernet and Payne,[1] who performed experiments on nonlinear noise traveling in a long tube, were motivated by anomalous propagation effects previously observed in jet noise studies. Webster and Blackstock[2] later conducted outdoor experiments with high-amplitude noise propagation and offered evidence that nonlinearity also affected the propagation of noise from high-performance aircraft. More recent studies have provided verification that nonlinearity can significantly impact high-amplitude jet noise propagation (e.g., see Ref. 3) and efforts are underway to incorporate nonlinear effects in noise analysis models for these aircraft.[4]

The nonlinear propagation of a high-amplitude noise waveform may be described in the context of either the time or frequency domain. In the time domain, nonlinearity causes steepening of the high-amplitude portions of the waveform and the possible coalescence of acoustic shocks.[5] In the frequency domain, these time domain effects correspond to a spectral broadening as cascading sum- and difference-frequency generation occurs. These effects could significantly alter the perception of a waveform from that predicted by linear propagation. Crighton[6] further contextualized the potential impact of nonlinear jet noise propagation when he pointed out that a nonlinear transfer of energy to high frequencies could impact calculations of noise metrics that penalize these frequencies.

The purpose of this letter is to begin to address the issue of the perception of nonlinear effects in the atmospheric propagation of broadband noise with the intent of motivating additional improvement in environmental impact modeling for high-performance aircraft noise. Specifically, two questions are addressed. First, if nonlinear effects are important in high-amplitude noise propagation, does perception of the noise change as a result of nonlinear propagation? Second, do common metrics adequately account for any change in perception due to nonlinearity?

In this letter, results are presented from a study in which a waveform with a shaped broadband spectrum has been numerically propagated both linearly and nonlinearly. The resultant waveforms may be heard by the reader. From the linearly and nonlinearly predicted waveforms, several single-number metrics commonly used in the environmental noise and sound quality communities have been calculated. The metrics calculated are overall, A-, C-, and D-weighted sound pressure level, perceived noise level, Stevens Mark VII perceived loudness, Zwicker loudness, and sharpness. Although the list is by no means exhaustive, the results demonstrate a possible shortcoming of traditional metrics when used to quantify the readily perceived difference between the nonlinearly and linearly propagated waveforms.

2. Metrics considered

The metric that is most commonly used to calculate the perceptual impact of an acoustic source is A-weighted sound pressure level, L_A. However, because the A-weighting curve is based on the 40-phon equal loudness contour and observed jet noise levels are often much greater than 40 phon, C-weighted sound pressure level (L_C), which is based on the 90-phon contour, has also been calculated. Another weighting that has been used specifically for aircraft noise is D-weighting, which is based on work by Kryter[7] and emphasizes annoyance or noisiness caused by high-frequency energy in the range of 1–12 kHz. Although D-weighting was formally standardized,[8] that standard has since been withdrawn and the weighting is not frequently used now. However, because of its intended application to aircraft noise and its particular emphasis on high-frequency content, which could be important for the perception of nonlinear effects, D-weighted sound pressure level (L_D) has also been calculated in this study. In addition, ordinary (nonweighted) overall sound pressure level, L, has also been calculated.

An additional metric that has been calculated is perceived noise level (PNL), which is also based on Kryter's work with the perception of noisiness.[9,10] (PNL) is currently used by the Federal Aviation Administration as part of the calculation of effective perceived noise level (EPNL), the standard metric for noise certification of commercial aircraft. PNL, rather than EPNL, has been calculated because the latter metric is intended for transient waveforms measured from flyovers.

Two other metrics calculated are Stevens Mark VII (Ref. 11) perceived loudness (PL) and Zwicker loudness[12] (ZL). Mark VII perceived loudness calculates the loudness in third-octave bands according to estimated inverses of the equal loudness contours. The loudness for each band is then summed with additional weight being given to the loudest band. Zwicker loudness calculates the specific loudness in each critical band and then sums them to find the total loudness. Both PL and ZL have been used extensively to assess loudness and annoyance in various sonic boom studies.[13]

The final metric that is calculated is sharpness (S), which is a psychoacoustical quality that increases according to the relative amount of high-frequency energy in a signal. Sharpness is viewed as a negative indicator of sensory pleasantness; thus sharp sounds are frequently felt to be more annoying or unpleasant. Although there are different proposed methods for calculation of sharpness,[14–17] the method selected for this study is that of Zwicker and Fastl,[14] who calculate sharpness based on a weighted sum of specific loudness.

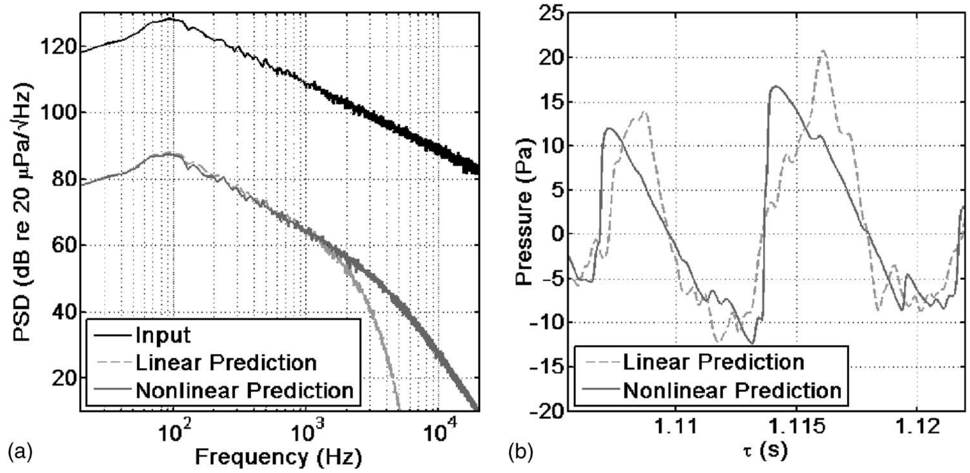

Fig. 1. (a) Input power spectral density at 10 m and predicted power spectral densities at 1000 m. (b) Short segments of the nonlinearly and linearly predicted waveforms at 1000 m as a function of retarded time, τ. Note the shock-like steepness of the nonlinearly predicted waveform at approximately 1.107 and 1.114 s.

Before proceeding, it is important to note that some of these metrics (L, L_A, L_C, PL, and ZL) are intended to quantify the subjective impression of loudness while the remaining metrics (L_D, PNL, and S) are designed to correlate with annoyance or perceived noisiness. However, loudness is a significant contributor to overall annoyance and L_A, PL, and ZL are often used to quantify the overall perceptual impact of sounds. The merits and shortcomings of many of these metrics (e.g., L_A) have been frequently discussed and debated for various applications and an extensive list of references could be given. However, for the purposes of this investigation, all the metrics have been placed on equal footing in their presumed ability to quantify an overall impression of a noise waveform, regardless of their original intent to quantify loudness or noisiness.

3. Test case description and results

3.1 Test case description

For this study, an initially Gaussian waveform with a shaped broadband spectrum has been numerically propagated with a model[18] that solves the generalized Burgers equation (GBE),[19] a widely used nonlinear model equation. The particular GBE used in this research accounts for the phenomena of quadratic nonlinearity, atmospheric absorption and dispersion, and spherical spreading. Free-field linear propagation of the waveform has also been carried out by simply removing the nonlinear term from the GBE. The shape of the power spectral density (PSD) for the input waveform, shown in Fig. 1(a), has been chosen to have a 6 dB/octave slope below the peak frequency of approximately 100 Hz and a −6 dB/octave slope above the peak frequency in order to simulate a jet mixing noise spectrum. The overall sound pressure level for the input waveform is $L=150$ dB re 20 μPa at an assumed input distance of 10 m, a reasonable level for a military jet aircraft.[20]

The input waveform, which consists of 524,288 points sampled at 200 kHz, has been propagated with both the nonlinear and linear numerical models out to a distance of 1000 m. Uniform atmospheric conditions of 1 atm, 20 °C, and 50% have been assumed for ambient pressure, temperature, and relative humidity. The calculated PSD (with a frequency resolution of 12 Hz) for each of the predicted waveforms is also shown in Fig. 1(a), where a nonlinear transfer of energy to high frequencies at the expense of the energy in peak-frequency region partially mitigates the expected roll-off due to ordinary linear atmospheric absorption. The high-frequency energy transfer is also evident in a comparison of short segments of the numeri-

Table 1. Calculated metrics and difference for the nonlinearly and linearly predicted waveforms. L denotes overall sound pressure level and the subscripts signify the type of weighting applied. PNL, PL, ZL, and S, respectively, represent perceived noise level, Stevens Mark VII perceived loudness, Zwicker loudness, and sharpness.

	L (dB)	L_A (dB A)	L_C (dB C)	L_D (dB D)	PNL (PN dB)	PL (PL dB)	ZL (phon)	S (acum)
Nonlinear	108.4	98.0	107.4	104.1	111.4	102.5	105.5	1.01
Linear	109.0	97.9	107.9	104.0	110.2	101.5	103.9	0.72
Difference	−0.6	0.1	−0.5	0.1	1.2	1.0	1.6	0.29

cally propagated waveforms, which are displayed in Fig. 1(b). The relatively steep portions of the nonlinearly predicted waveform compared to the linear waveform are the source of the additional high-frequency energy in the nonlinearly predicted PSD in Fig. 1(a).

3.2 Waveform playback

A critical aspect of this letter is the ability to listen to the input and output waveforms, which have been resampled at 44.1 kHz for convenience. As a reference, the shaped Gaussian input waveform may be heard by clicking on the link to Mm. 1. The linearly and nonlinearly predicted waveforms may be heard in Mm. 2 and Mm. 3, respectively. Note that the effect of spherical spreading has been removed from the predicted waveforms so that these and the input waveform may be heard and compared for a single audio playback level.

Mm. 1. Input.wav (225 kB). Shaped Gaussian waveform used as an input to the numerical models.

Mm. 2. Linear.wav (225 kB). Linearly predicted waveform at 1000 m.

Mm. 3. Nonlinear.wav (225 kB). Nonlinearly predicted waveform at 1000 m.

Playback of these three waveforms reveals two noteworthy points. First, the lowpass-filter effect of atmospheric absorption is heard when the linearly predicted waveform in Mm. 2 is compared to the input waveform in Mm. 1. Second, the perceptual impact of nonlinear propagation may be clearly heard by comparing Mm. 3 with the linear waveform in Mm 2. There is a staccato-like, impulsive quality of the nonlinearly propagated waveform that is also present in some far-field jet noise recordings and appears to be related to the presence of shock-like structures in the waveform.[21] In informal listening demonstrations carried out by the authors, the nonlinear waveform is usually perceived to be somewhat louder but significantly more annoying than the linear waveform, although these are admittedly subjective statements that should eventually be quantified by rigorous jury testing. However, because there appears to be a considerable difference in perception between the nonlinearly and linearly propagated waveforms, regardless of subjective descriptors used, a study of which metrics also exhibit significant difference between the waveforms has been performed.

4. Metric calculations and discussion

The metrics described previously in Sec. II have been calculated for the linearly and nonlinearly predicted waveforms and are displayed in Table 1. Also shown in Table 1 is the difference between the nonlinear and linear predictions for each of the metrics. The result for overall sound pressure level, L, indicates that the nonlinear spectrum has slightly less energy than the linear spectrum. This result is generally expected for atmospheric nonlinear propagation because energy is transferred to higher frequencies where absorption coefficients are greater. Although the difference in L for this test case (0.6 dB) is likely negligible, one could potentially argue that nonlinear effects might cause an aircraft to be perceived as quieter than for ordinary linear propagation as a consequence of the additional energy losses. Of course, L does not account for the nonuniform response of the ear and so calculation of the other metrics better addresses this issue.

Table 1 also shows the calculated results for the weighted sound pressure levels, L_A, L_C, and L_D, and the more sophisticated measures, PNL, PL, and ZL. Because of its greater weighting of low frequencies, L_C gives an almost identical difference between nonlinear and linear propagation as L. The other weighted sound pressure levels, L_A and L_D, only show differences of 0.1 dB and therefore indicate that the nonlinear and linear waveforms should be perceived essentially the same. Finally, PNL, PL, and ZL, all exhibit somewhat greater differences between the nonlinearly and linearly predicted waveforms (1.2 PN dB, 1.0 PL dB and 1.6 phon, respectively) and suggest that the nonlinear waveform should be perceived as slightly more annoying or louder. However, these differences are still relatively small and appear to be insufficient to accurately represent the perceived difference between the two waveforms.

The final metric shown in Table 1 is that of sharpness, S. Because the unit of S, the acum, is intended to vary linearly with perception of sharpness, the nonlinear waveform's sharpness is approximately 40% greater than that of the linear waveform. This difference could likely be perceived as significant. However, before sharpness is considered to be a candidate quantifier of nonlinearly propagated noise, there is another shortcoming of S (and, in fact, of all the metrics) that should be discussed.

A fundamental difficulty with sharpness and the other metrics calculated is that they rely solely on averaged power spectral calculations. Because phase is neglected, these metrics do not uniquely characterize perception of a waveform. Although phase is typically ignored when quantifying perception of noise, formation of an acoustic shock through nonlinear propagation requires a specific phase relationship between Fourier spectral components of a complex waveform. If this phase relationship is altered, so are the time waveform and the perception of an acoustic shock. In other words, if the shock-like structures are critical to the overall perception of the nonlinearly propagated waveform, modification of the Fourier phase spectrum of the waveform could significantly alter how it is perceived.

To illustrate this point, the Fourier phase spectrum for the nonlinearly propagated waveform in Mm. 3 has been randomized with uniform probability. This process results in a time waveform that has a Gaussian probability density function but possesses the same PSD as the original nonlinearly propagated waveform. This phase-modified waveform may be heard in Mm. 4 and is perceived to be different than the original nonlinearly propagated waveform. Because each of the metrics discussed, including sharpness, responds identically to Mm. 3 and Mm. 4, none can completely quantify the perceptual impact of nonlinear propagation.

Mm. 4. Phase-modified Nonlinear.wav (225 kB). Nonlinearly predicted waveform at 1000 m with its Fourier phase randomized.

One final point of discussion regards the "staccato-like impulsive" quality of the nonlinearly propagated waveform in Mm. 3. For the traditional classification of impulsive sounds (explosions, sonic booms, gunfire, etc.), an annoyance penalty is given when assessing perceptual impact due to their short duration and high intensity.[22] If the nonlinearly propagated waveform can be treated as conventional impulsive noise, then there is already a standardized protocol for addressing its perception. However, the nonlinear noise phenomenon differs from traditional impulsive noise because the pressure fluctuations are part of a steady-state noise signal and not a sudden deviation from ambient levels (as occurs in an explosion). In addition, nonlinearity actually causes the pressure excursions in the nontransient nonlinearly propagated waveform to be of lower amplitude than the linearly propagated waveform [see Fig. 1(b)], which does not possess an impulsive quality. Finally, the perceptual difference between the nonlinearly propagated waveform in Mm. 3 and the phase randomized version in Mm. 4 is clear, but conflicts with the conclusion of Fidell *et al.* that phase randomization of impulsive sounds does not alter perception of noisiness.[23] Additional research is therefore needed to better quantify the perception of the unique phenomenon of nonlinearly propagated noise.

5. Conclusion

This letter has sought to increase awareness regarding the potential limitations of various noise and sound quality metrics when used to quantify perception of nonlinearly propagated noise. Both the waveforms and the metric comparisons have direct implications regarding environmental impact assessment of high-performance jet aircraft. Playback of the waveforms indicates that nonlinear propagation could cause these aircraft to be perceived as more annoying than predicted by models that assume ordinary linear propagation. However, this perceptual difference may not be observed with conventional single number metrics because the weighted sound pressure levels, perceived noise level, Stevens Mark VII loudness, and Zwicker loudness do not appear to adequately penalize the annoyance caused by the high-frequency energy present in the nonlinear waveform. Although the sound quality metric, sharpness, does indicate some appreciable perceived difference between nonlinearly and linearly predicted waveforms, the neglect of phase information important to nonlinear propagation limits its utility as a viable metric for this application.

It is clear that additional research regarding the perceptual impact of nonlinearly propagated noise is needed. Although the multimedia content of this letter makes possible informal listening demonstrations, rigorous subjective testing is required to quantify perceived differences between nonlinearly and linearly propagated noise. Subjective testing could result in the formulation of an alternative metric and thereby improve environmental impact assessments of high-power jet aircraft.

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