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1pNSb3. Do recent findings on jet noise answer aspects of the Schultz curve?

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Recent research efforts on nonlinear propagation from high performance jet aircraft have revealed an interesting challenge to predicting community response. This challenge focuses on receiver perception of these unique acoustical signals, which contain acoustical shocks that appear to increase their relative loudness and/or noisiness. This current finding suggests a need for an improved description of a receiver perception of the loudness of these signals in order to improve the assessment of noise impacts from these aircraft. Looking backwards, an interesting question emerges: did the earlier low bypass jet engines on commercial and transport aircraft also include these acoustical shocks? If they did contain these features, then the perceptual differences observed between aircraft and other transportation noise sources may be partially explained.

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INTRODUCTION

In 1978, Schultz[1] analyzed responses to social surveys regarding transportation noise in order to develop a curve of "percent highly annoyed" people versus day-night level. In 1991, Fidell *et al*.[2] showed that the "Schultz curve" still provided a reasonable fit to additional transportation noise data sets, but neither study distinguished between different forms of transportation. However, when Miedema and Vos[3] separated the survey data into different curves according to the type of transportation noise (aircraft, traffic, and railway), the aircraft noise yielded a significantly greater percentage of responders highly annoyed for a given day-night level. Although there might be several contributing factors, including the nature of the survey questions themselves,[4] this paper offers a possible explanation for the increased annoyance for aircraft noise as a function of level. At the heart of our explanation is the nature of engines in the legacy aircraft included in the surveys and a perceptual phenomenon known as jet "crackle."[5]

At the start of commercial jet service, the engines were low bypass engines, which generate higher noise levels than more modern high bypass ratio engines. The public's concerns with the original engine noise levels led the Federal Aviation Administration to develop regulations for allowable aircraft source noise, which are contained in FAR Part 36, published in 1969. Although this regulation has gradually led to quieter commercial aircraft, it was not until 1976 when operating aircraft had to meet the initial noise limit standards. At this time, aircraft meeting the noise limit standards were identified as Stage 2. It is important to note that the regulations were not implemented until after the social surveys utilized by Schultz and many of the surveys analyzed by Fidell *et al*. and Miedema and Vos. Consequently, there is a question as to the applicability of surveys mostly performed with Stage 2 aircraft, when the current commercial fleet consists of hush-kit retrofitted Stage 2 and newer Stage 3 and 4 aircraft with lower noise levels.

While the high noise levels produced by older aircraft likely contribute to the annoyance experienced by the survey participants, there was likely another reason that, for the same day-night level, aircraft noise was judged to be more annoying than rail or traffic noise. A phenomenon associated with high-power jets, known as "crackle," was first studied in the 1970's. It was characterized by Ffowcs Williams *et al*.[5] and described as an annoying component of the noise that is largely indiscernible in the power spectrum. Consequently, traditional level and loudness-based metrics used to calculate noise perception do not distinguish between crackling and non-crackling waveforms.[6] Recent studies have related crackle to the presence of acoustic shocks in the waveform,[7,8] which form during the course of nonlinear propagation.[9,10]

Although there is currently no metric to quantify the *perception* of crackle, various techniques have been used to examine acoustical nonlinearities and the presence of acoustic shocks. These include bispectral analysis[11-13] and other indicators of shock strength.[14-16] Employed in this study are two techniques that have been used in previous jet and rocket noise studies and whose behavior for high and low-amplitude noise is at least qualitatively understood. One method utilizes the skewness of the time waveform derivative, which was introduced by McInerny[17] and has been used to study nonlinear effects and shocks in jet[18,10] and rocket noise.[15,19] The other analysis method is a spectral indicator developed by Morfey and Howell[20] during their efforts to model the nonlinear evolution of the jet noise power spectrum. It involves calculating the quadspectrum between the pressure waveform and the square of the pressure waveform, which then reveals nonlinear energy transfer between frequency bands. Related indicators have been used in various studies of jet, rocket, and other noise.[21-24,13,18]

These two analysis methods have been applied to three recordings of jet noise – from the Concorde, the Boeing 727, and the Boeing 757. The high-power Rolls Royce Olympus 593 engine used on the Concorde was the subject of a previous crackle study[5] and provides a sort of benchmark for the other aircraft recording calculations. The Boeing 727, produced between 1964 and 1984, was a very common Stage 2 aircraft, representative of what would have been part of the social surveys. On the other hand, the Boeing 757 (produced 1982-2004) typifies current Stage 3 aircraft with much quieter high bypass-ratio engines. Evidence of shock formation/crackle in the 727 waveform, but *not* in the 757 recording, indicates the presence of different characteristics in the older aircraft and could point to a cause for the increase in annoyance versus level for aircraft, as discussed by Miedema and Vos.[3]

DATA ANALYSIS

As described previously, two methods for analyzing a waveform for evidence of nonlinear propagation are applied to recordings from the Concorde, the 727, and 757. The joint use of these methods is more conclusive because the skewness analysis operates directly in the time domain for shock content identification and the quadspectral indicator is a frequency-domain measure that identifies frequency bands of nonlinear energy transfer. The skewness is the normalized third central moment of the probability density function (PDF) of the waveform and is a measure of the PDF's asymmetry.[7] For a Gaussian PDF, which is symmetric about its mean value, the skewness is zero. A positive skewness of a waveform indicates the presence of relatively large amplitude positive outliers. Similarly, because the time derivative of an acoustic shock-containing waveform contains large positive values (because of the short rise times of the shocks), a positive "derivative skewness" can be used as an indicator of nonlinear steepening and shock formation.

The "Morfey-Howell" nonlinearity indicator is a dimensionless spectral measure that involves the normalized quadspectrum between the acoustic pressure waveform and the *square* of the acoustic pressure waveform.[20] Their "*Q/S*" spectrum is calculated as

$$Q/S = \frac{Q_{p^2p}(f)}{S_{pp}(f)p_{\mathrm{rms}}}, \tag{1}$$

where

$$Q_{p^2p}(f) = \mathrm{Im}\{\mathcal{F}[p^2(t)]\mathcal{F}^*[p(t)]\}, \tag{2}$$

$\mathcal{F}$ is the Fourier transform, and p_{rms} is the root-mean-square pressure of the time waveform. As calculated here, the Q/S spectrum is positive for frequencies that are losing energy due to nonlinear effects and negative for frequencies that are gaining energy. Previous calculations[21] for the F/A-18E showed that at high engine powers, there was a clearly defined energy loss ($Q/S > 0$) at lower frequencies and an energy gain ($Q/S < 0$) at high frequencies. On the other hand, at low engine power (idle), there was no obvious trend in Q/S, and it appeared to fluctuate randomly about zero. Examination of Q/S and the derivative skewness calculated from the three aircraft recordings can provide insights into potential nonlinear characteristics of the noise not readily observable from ordinary level-based and spectral analyses.

The first waveform analyzed is that from the Concorde. Because Ffowcs Williams *et al.* found significant crackle and shock-like characteristics in noise from the Olympus 593 engine, it is expected that, when applied to the Concorde recordings, the above metrics will deviate from linear, Gaussian behavior. A histogram (a non-normalized estimate of the PDF) of the waveform derivative, and a zoomed-in version of the same, are shown in Fig. 1. The waveform derivative's histogram is asymmetric with a skewness of 2.9, which is significantly non-Gaussian and indicative of the presence of short rise times associated with nonlinearly steepened waveforms. Also shown in the lower part of Fig. 1 is Q/S. Below approximately 1.5 kHz, the quadspectrum is mostly positive, whereas above 2.5 kHz, the spectrum is negative. This trend indicates nonlinear energy transfer from the lower to the higher frequency regions. Both analysis techniques support the idea that the crackle present in the Concorde data is tied to nonlinearity and shock formation.[5]

A similar analysis is performed for Boeing 727 data in Fig. 2. The data are less skewed (skewness = 1.2), and the quadspectral indicator is only negative at very high frequencies. These indicate the presence of nonlinearity, but to a lesser extent than for the Concorde. Thus, the crackle perceived in the 727 recording is expected to be less than for the Concorde. Auralization of the waveforms confirms this. These older two aircraft have different waveform characteristics from the newer Boeing 757, whose data are shown in Fig. 3. The Boeing 757 analyses reveal a waveform with Gaussian behavior (derivative skewness is less than 0.01) and a Q/S with no distinct frequency regions of positive or negative values. Thus, the newer aircraft has a very different acoustical signature than the older Boeing 727, which was similar to those aircraft used to generate the Schultz curves.

SUMMARY

The analysis using statistical and spectral indicators has shown evidence of nonlinear effects in the Concorde and Boeing 727 waveforms, but not in the recording of the Boeing 757 aircraft. This finding is significant because nonlinearity has been tied to crackle and potentially an increase in perceived annoyance. The crackle present in older commercial jet engines could help to explain why Miedema and Vos[3] found a difference in annoyance between aircraft noise and other forms of transportation in the Schultz survey,[1,2] which consisted primarily of older aircraft. However, at the present, this is conjecture and suggests only that additional surveys might be performed with Stage 3 and Stage 4 aircraft to see if the annoyance-versus-level bias persists with the present fleet of commercial aircraft. This could result in an adjustment of the Schultz curve and, possibly, a better collapse of annoyance with day-night level across the various forms of transportation.

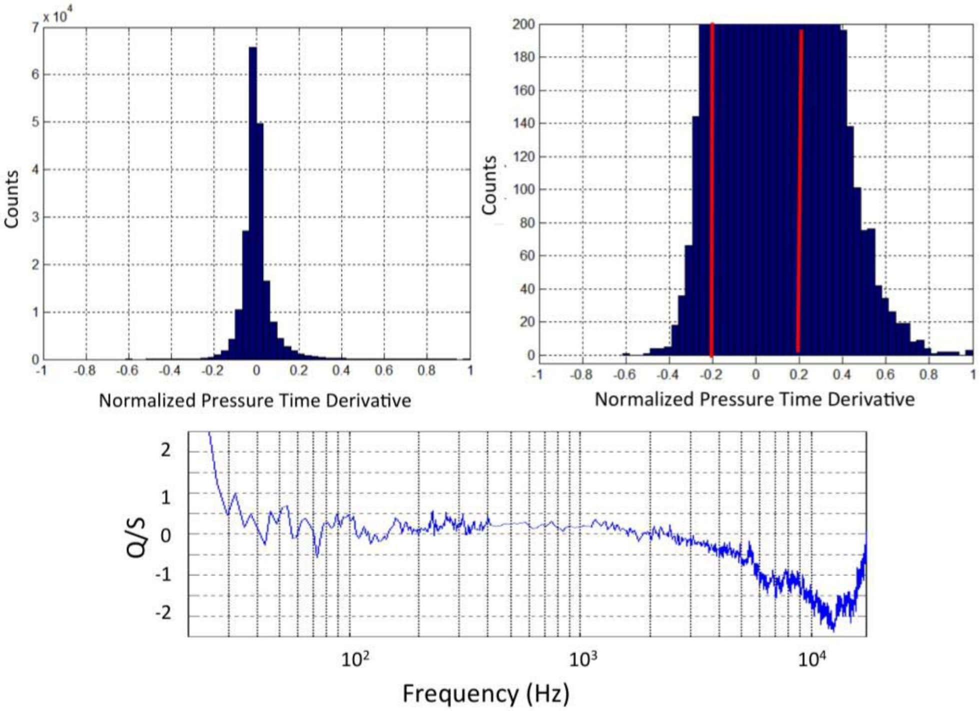

FIGURE 1. Nonlinearity analysis of a recording of the Concorde. (Upper) Histograms of the normalized time derivative of the pressure waveform, with a zoomed-in version on the right. (Lower) The Morfey-Howell Q/S nonlinearity indicator.

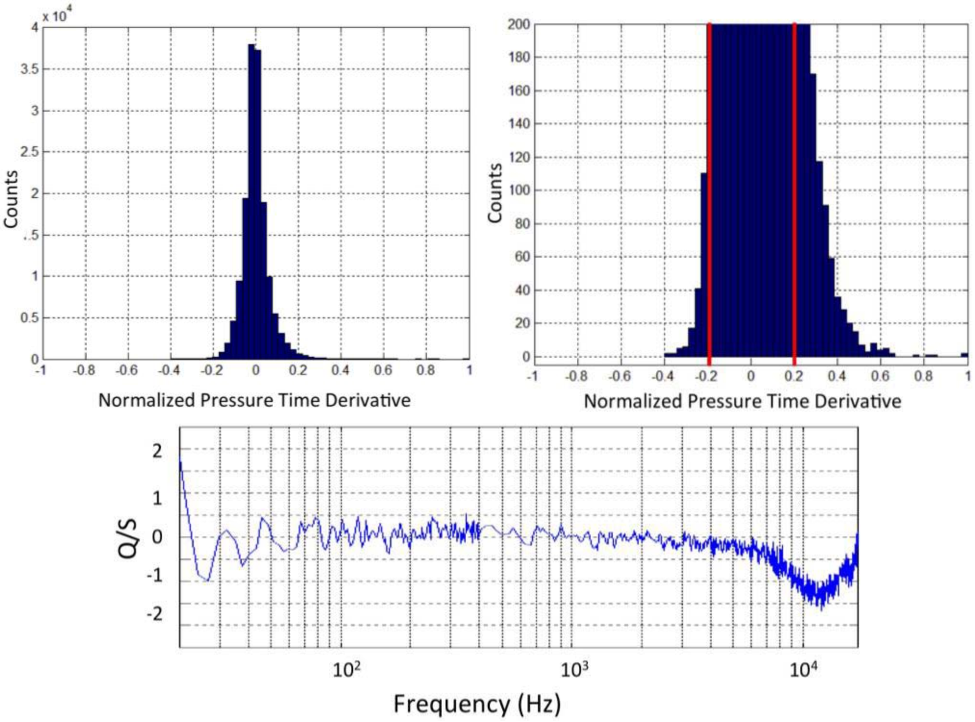

FIGURE 2. Nonlinearity analysis of a recording of a Boeing 727. (Upper) Histograms of the normalized time derivative of the pressure waveform, with a zoomed-in version on the right. (Lower) The Morfey-Howell Q/S nonlinearity indicator.

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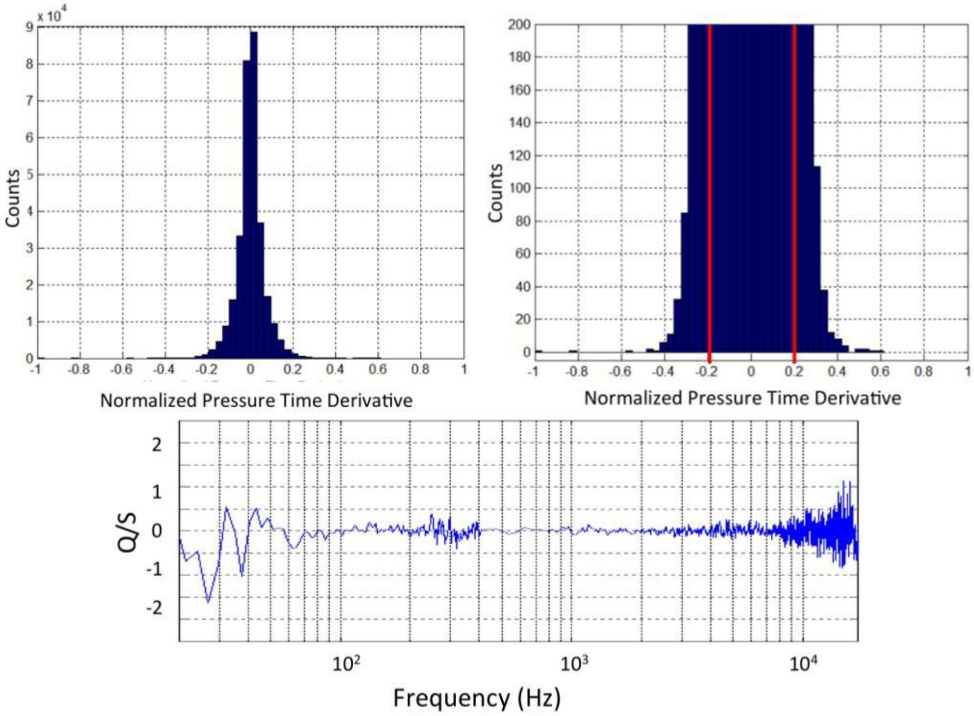

FIGURE 3. Nonlinearity analysis of a recording of a Boeing 757. (Upper) Histograms of the normalized time derivative of the pressure waveform, with a zoomed-in version on the right. (Lower) The Morfey-Howell Q/S nonlinearity indicator.

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