Toward high-quality X-59 sonic thump measurements

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ABSTRACT

Brigham Young University has been investigating best practices for recommendation to NASA in upcoming X-59 sonic thump measurements. This preparatory work has focused both on obtaining high-fidelity data and standardizing signal analysis techniques for sonic thumps. Included in the research are topics such as whether to use a ground-based or elevated microphone, how to use low-noise microphones and still recover high-fidelity data at low frequencies, and estimating the uncertainty in a given measurement due to local atmospheric turbulence effects. Also included is a study of windowing techniques, zero padding, and the removal of high-frequency ambient noise contamination.

1. INTRODUCTION

In coming years, NASA will fly the X-59 shaped low-boom supersonic aircraft (see Figure *1*) over several different communities to assess resident annoyance.[1] This testing campaign will feature acoustic recordings concurrent with community surveys, so that objective noise metric values can be associated with each survey response. These acoustic measurements are the primary concern of this paper.

The sonic booms produced by the X-59 are anticipated to be much quieter than booms from conventional supersonic aircraft and hence are sometimes given the nickname "sonic thumps." Although this is great for community noise levels, it makes the acoustic recordings more challenging. Factors like ambient noise and microphone choice become more important in lower signal-to-noise ratio (SNR) environments. Anticipating some of these challenges, Brigham Young University (BYU) has been working with researchers at the NASA Langley Research Center for the past several years to develop recommendations for measurement and signal processing techniques related to sonic boom measurements.[2-6]

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Figure 1. A depiction of the X-59 in flight. [Credit: Lockheed Martin (image cropped)].

A summary of these results was presented at the 183rd meeting of the Acoustical Society of America,[7] and a detailed Proceedings of Meetings on Acoustics (POMA) article will soon be published that will cover further details of this research, pointing to other publications as appropriate. The summaries given in the current paper are succinct topical overviews.

2. WINDOWING

Many sonic boom metrics are calculated directly from spectra. One of the important aspects to consider when performing a fast Fourier transform (FFT)-based spectral analysis is the time-domain window to apply to the data. Windowing is typically required with FFT analysis to taper the waveform endpoints to zero, thus reducing high-frequency energy leakage. In the case of windowing a transient sonic boom waveform, if the window is too steep (as a rectangular window would be), then the near-discontinuity produced in the waveform can also cause its own leakage, thereby artificially increasing high-frequency spectral levels. However, if the window ramp is too long, then the sonic boom might become artificially attenuated, also corrupting the data. Therefore, the analyst must use a window that is both long enough to eliminate artificial discontinuities but not so long as to destroy the acoustic data. Our analyses have shown that a Tukey (or tapered-cosine) window is effective, provided the tapered portion of the window does not impinge on the main sonic boom waveform.

3. ZERO PADDING

When calculating a one-third octave (OTO) band spectrum, it is common to integrate the results of an FFT analysis to determine the levels for each OTO band. However, when the FFT is short, such as a 650-ms sonic boom recording,[14] the FFT frequency resolution is sparse. The result is that lower-frequency OTO bands (< 10 Hz) start to show jagged, nonphysical behavior because there is insufficient data to accurately estimate levels in those bands. Examples of this behavior can be found throughout Reference 2. A solution to this problem is to use a longer recording, which will increase the FFT frequency resolution. To artificially extend a 650-ms sonic boom recording, it is recommended to add a minimum of four seconds of zero padding before the FFT is performed, but after the window is applied. This results in a frequency resolution of less than 0.25 Hz, smoothing the low-frequency OTO band spectrum down to at least 1 Hz, producing a more physical spectrum.

4. DIGITAL POLE-SHIFT FILTERING

An important choice when making sonic boom recordings is the microphone. Microphones that are able to measure the low-frequency content in a sonic boom waveform tend also to have low sensitivity, such as the GRAS 47AC (8 mV/Pa) or PCB 378A07 (5 mV/Pa). Although these microphones are able to accurately measure the low frequencies that are crucial to accurate waveform representation, their low sensitivities translate directly into greater self-noise and a higher noise floor. However, what if the low-frequency response of a higher-sensitivity microphone could be corrected to recover the low-frequency content? This is the goal behind digital pole-shift filtering, as discussed in References 3 and 8. This enables one to use a higher-sensitivity microphone such as a GRAS 40AE (50 mV/Pa) for its lower noise floor and then correct the low-frequency response.

5. GROUND-BASED VS ELEVATED MICROPHONES

Although elevating a microphone above the ground provides some level of weatherproofing, it results in multipath interference due to ground reflections. Even relatively small elevations of 0.46 m (18 in) can result in spectral nulls at key frequencies for human perception metrics. Therefore, it is recommended to place the microphone as near to the ground as possible to avoid these effects.[4,6,9] These ground-based microphones can often still provide high levels of weather-robustness.[6,10]

6. ATMOSPHERIC TURBULENCE

The lower portions of the atmosphere are more turbulent than higher layers and constitute what is known as the atmospheric boundary layer (ABL). Because every sonic boom ray travels along a slightly different path through the ABL, microphones within a few tens of meters can measure notably different waveforms.[4] This causes uncertainty regarding the mean metric levels around a given location. The uncertainty is metric-dependent and is often on the order of several decibels. Although researchers have investigated how many microphones may be needed and how far apart they should be spaced, this remains an area of open research.[11,13] Analysis of field measurements related to atmospheric turbulence[4] determined that, although more research is needed, dispersing multiple microphones over several tens of meters at each measurement site is recommended to help ascertain metric level uncertainty due to atmospheric turbulence during sonic boom measurements.

7. AMBIENT NOISE REMOVAL

Another aspect of outdoor measurements, especially in urban environments, is ambient noise. Previous studies have shown that the ambient noise often dominates the signal at frequencies greater than a few hundred hertz.[14] Unfortunately, these are the most important frequencies for the sonic boom metrics, which means that sonic boom metrics are susceptible to high-frequency ambient noise contamination. Therefore, a method is needed for effectively removing the ambient noise from the recordings before calculating metric values. This problem has been investigated by researchers in the past.[14-17] An alternate method has been developed that successfully removes ambient noise from sonic boom measurements and returns a usable waveform.[17] The method relies on estimating the SNR from ambient noise levels immediately prior to the boom and then applying a sixth-order Butterworth-magnitude filter with a corner frequency equal to the first OTO band center frequency with SNR less than 3 dB. For some noise metrics, this simple method tends to outperform other methods for simulations involving predicted low-boom waveforms and real-world ambient noise, when post-boom noise is ignored.

8. SUMMARY OF RECOMMENDATIONS

Recent analyses of outdoor sonic boom measurements and simulations have resulted in several recommendations for NASA X-59 testing and analysis. Overviews of the different parts of the research have been given in this paper and cover best practices for measurement setup and signal processing. The primary recommendations from this work are:

- Use a time-domain Tukey window before performing an FFT analysis on a sonic boom waveform. The window ramp portions should not impinge on the sonic boom waveform.
- For smooth one-third-octave band spectra down to at least 1 Hz, apply a minimum of four seconds of zero padding to a 650-ms recording[14] after applying the window but before the FFT analysis.
- Use a high-sensitivity microphone with a low noise floor and then apply digital pole-shift filtering to recover the lowest frequencies in the signal. This avoids the high noise floor associated with low-sensitivity microphones while still being able to estimate the signal energy at low frequencies.
- Use ground-based microphones instead of elevated microphones. This will reduce the impact of multipath interference on measured spectra and metric levels.
- Use multiple microphones spaced apart from each other at a given measurement station to estimate the uncertainty in metric values due to atmospheric turbulence. Further field research is needed to determine the proper spacing.
- Remove ambient noise from the metric calculations to reduce bias in the metric values. The noise filtering technique is a promising method, which also returns a usable filtered waveform with less visible ambient noise contamination.

A more detailed discussion of this research will be available in the future through the link in Reference 7.

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