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Technical Notes

Evaluating Two Definitions of Perceived Level for Sonic Booms

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I. Introduction

TO IMPROVE assessments of human response to noise, Stevens [1] developed the Mark VII loudness calculation procedure, which accounts for the behavior of the human auditory system. Mark VII gives the perceived level (PL) of loudness in decibels (PLdB). Although originally developed for continuous noise, PL has been adapted for estimating human annoyance from sonic booms [2–4]. As a result, PL has been widely adopted to describe both sonic boom predictions [5–8] and measurements [9–11]. Because of its demonstrated effectiveness, the target loudness for NASA's X-59 low-boom aircraft is defined using Stevens Mark VII PLdB [12].

To simplify the PL calculation, Higgins and colleagues [13–15] derived an empirical equation based on sonic boom rise time and peak overpressure. While earlier studies included PL calculated with the Mark VII and Higgins methods as separate metrics [16], the Higgins method has recently been used in place of Mark VII in research designing low boom supersonic transport (SST) aircraft [17,18] and in SST trajectory planning [19]. This Note presents and discusses discrepancies between PL values calculated using the Higgins and Mark VII methods for different types of sonic booms.

The procedure for calculating Mark VII PL proceeds as follows. First, the user begins with a sound pressure level (SPL) spectrum in 1/1- or 1/3-octave bands. The SPL spectrum can be directly calculated for steady-state signals. For impulsive stimuli, however, the sound exposure spectrum is calculated and then converted to an equivalent SPL spectrum. To obtain the equivalent SPL spectrum, the sound exposure spectrum is first divided by 70 ms, the critical time of human the auditory system [20,21]. It is assumed that most of the energy is contained in the two pulses at the front and rear of the waveform, the waveform is symmetric, and the separation between the two pulses is greater than the auditory critical time. This results in the pulses being heard as two distinct events of equal loudness. However, loudness calculated directly from the sound exposure spectrum would combine the energy of both pulses. To avoid this, the SPL is reduced by 3 dB [21]. The resulting SPL spectrum is then used in the PL calculation. Each band in the SPL spectrum is assigned a loudness value in sones using a set of equal-loudness contours with a reference frequency of 3150 Hz. The shape of each equal-loudness contour changes as level increases. At high levels, the contours flatten out, weighting high and low frequencies similarly. The mathematical expression of the contours given in Ref. [22] is used for the transformation to equivalent loudness. Next, each band is added together to determine the total loudness, with extra weight given to the loudest band. After summing, the total perceived loudness in sones is converted to PLdB. This procedure, shown on the left in Fig. 1, is implemented for sonic booms in Refs. [23,24].

In contrast, the Higgins approach calculates the perceived level as

$$\mathrm{PL\,(PLdB)} = 55 + 20\log_{10}\left(\frac{\Delta P}{\tau}\right) \tag{1}$$

where ΔP is the overpressure in pounds per square foot and τ is the rise time in seconds. This simplified calculation, shown on the right in Fig. 1, highlights the importance of boom rise time in perceived loudness. References [14,15] compare values computed with Eq. (1) against those obtained using Mark VII for simulated outdoor booms, and the results are shown in Fig. 2. Subplot a) compares the PL values calculated with both approaches. Subplot b) shows the difference in PL values and illustrates expected agreement when using the Higgins approach. The solid lines represent the mean difference for

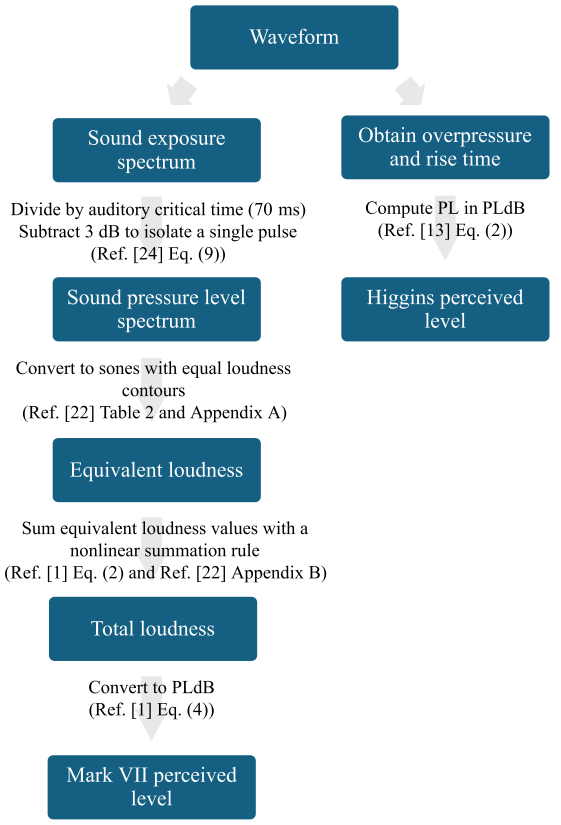


Fig. 1 Flowchart of PL calculation procedures. The Mark VII method is shown on the left, and the Higgins method is shown on the right. The equations and tables used in the calculation are referenced, and Ref. [24] details each step in the Mark VII procedure.

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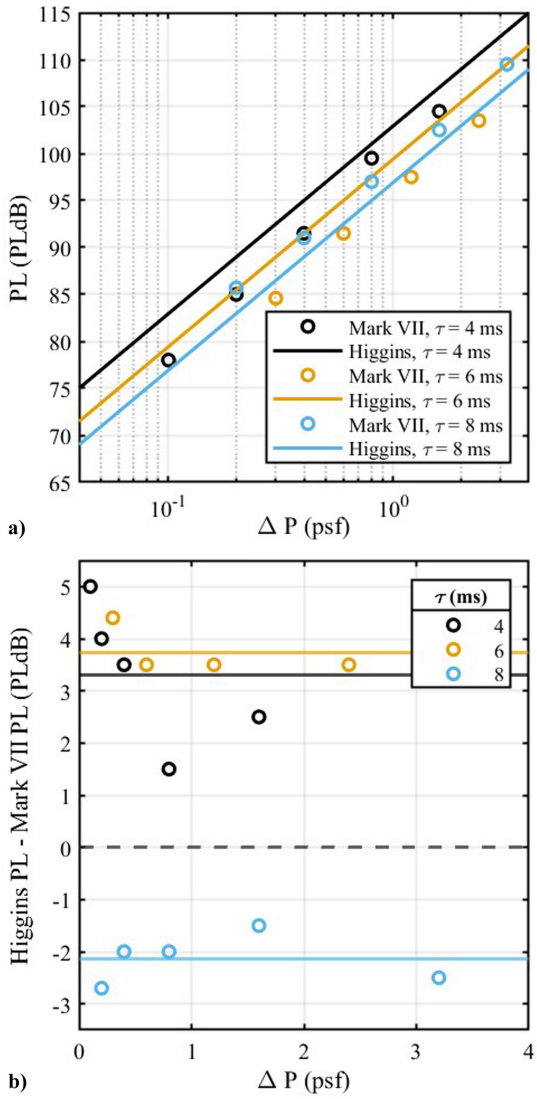


Fig. 2 a) Comparison of PL values from the Mark VII and Higgins methods. b) Difference between the Higgins and Mark VII PL values. The solid, horizontal lines represent the mean PL difference for the corresponding rise time. Produced using data from Ref. [14].

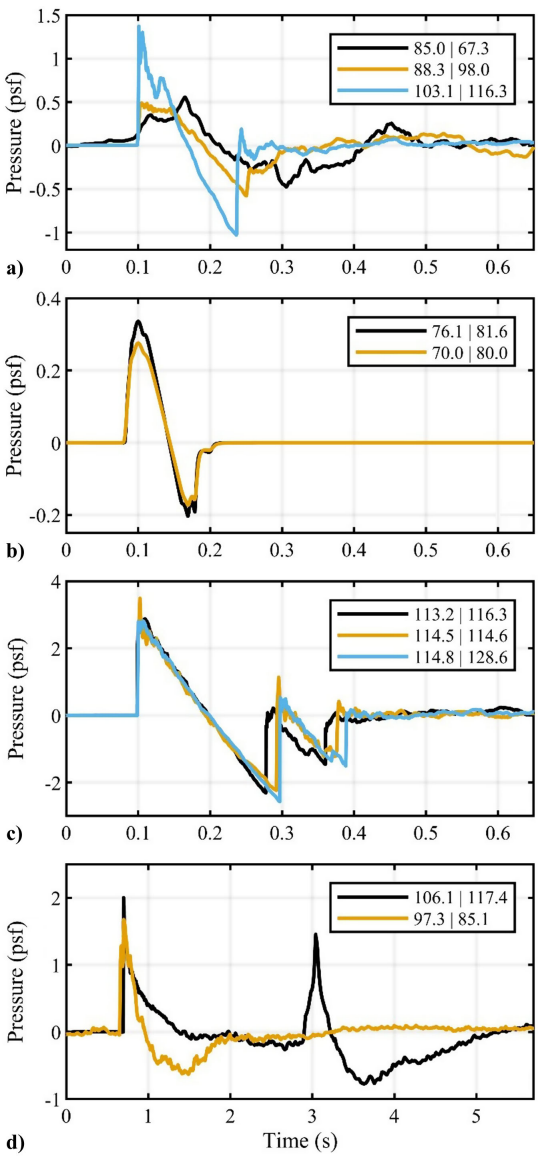


Fig. 3 Sonic boom waveforms from a) traditional aircraft, b) simulated low-booms, c) reusable rocket booster flyback, and d) rocket launch-ascent. PL (PLdB) according to the Mark VII and Higgins methods are compared in the legend following the format "Mark VII | Higgins."

each rise time. For the 14 sonic booms considered by Higgins, the mean absolute error was 3.0 PLdB. In Fig. 2, the Higgins method tends to overestimate the PL for waveforms with $\tau = 6$ and 4 ms and underestimate the PL for waveforms with $\tau = 8$ ms.

If the Higgins simplified calculation procedure is to be used, further validation studies ought to be performed to verify that the calculation agrees with the Mark VII procedure beyond Higgins' initial test cases. Using a variety of measured and simulated sonic boom waveforms, this Note demonstrates that, in general, the Higgins simplification in Eq. (1) does not agree with the Mark VII calculation for PL. In Sec. II, four waveform types are considered, including sonic booms from traditional aircraft, low-boom simulations, rocket booster flyback, and rocket launch-ascent. Following this, the PL values calculated via the Mark VII and Higgins procedures are compared. Overall, the two methods do not agree sufficiently to justify using the Higgins procedure as a proxy for the Mark VII calculation.

II. Results

To determine the general effectiveness of the Higgins simplified procedure, several different sonic boom waveform shapes are considered here. A few examples from each waveform category are shown in Fig. 3. In subplot a), measured sonic booms from traditional supersonic aircraft are shown. The measurements were made during the NASA Carpet Determination In Entirety Measurement III campaign [11]. In the legend, the PL values calculated according to the Mark VII and Higgins methods are shown, respectively. Notice that the differences between the two metric calculations can vary substantially between waveforms. In subplot b), a pair of simulated low-boom waveforms is shown. These waveforms are taken from the NASA C609 dataset [5] and represent an earlier design iteration of the X-59 [25]. The low-boom waveforms have longer rise times and lower amplitudes than N-waves. Subplot c) then contains measured SpaceX Falcon 9 flyback sonic booms, which are unique because of their three-shock structure [26–28]. And lastly, subplot d) contains measured rocket launch-ascent sonic booms [29], with their unique Friedlander-like waveform shape and long durations [30], sometimes with multiple arrivals.

Figure 4 contains the metric calculations for the full datasets. Subplot a) shows the two PL calculation methods plotted against each other, with each waveform category indicated with a different color. The two methods do not produce equal results. If they both produced equal values, then all data points would lie along the dashed line. To better visualize the differences, subplot b) shows the difference between Higgins PL and Mark VII PL relative to the Mark VII result.

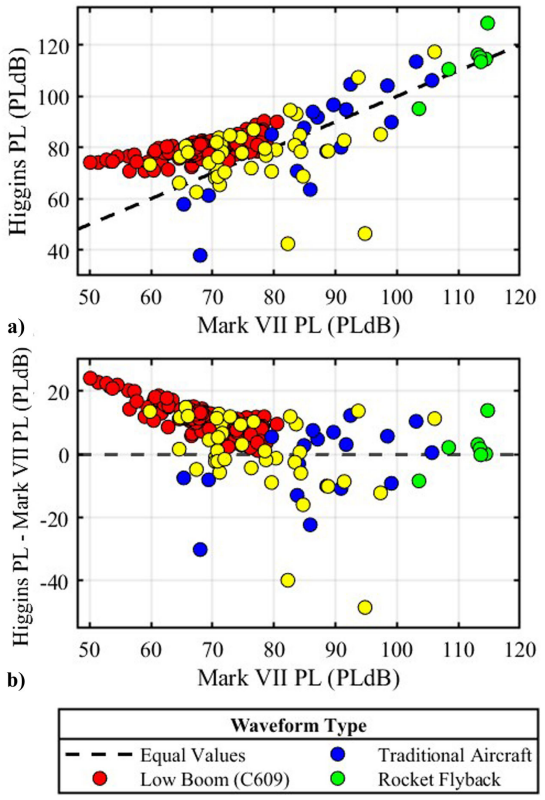


Fig. 4 a) Comparison of PL values computed with the Higgins and Mark VII methods, with each waveform category indicated using a different color. The dashed line indicates equivalent PL values for both methods. b) Higgins PL relative to Mark VII PL.

For nearly half (48%) of the waveforms, the Higgins PL estimates disagree with Mark VII PL by more than ±9 PLdB, greater than a factor of two in loudness [1]. Additionally, there are several notable outliers; the Higgins PL estimates disagree by more than ±20 PLdB for 11 waveforms. This is the case for seven simulated low-boom waveforms, two aircraft waveforms, and two rocket launch-ascent waveforms.

The aircraft and rocket launch-ascent waveforms with large PL discrepancies in Fig. 4 have unusually large rise times. While there are a variety of rise time definitions, the most common is the time for the pressure to increase from 10 to 90% of the maximum overpressure [31]. Higgins and Sanlorenzo [14], however, define rise time as the time required to reach the peak pressure. To be consistent with Higgins' definition of rise time, this analysis uses an equivalent 0–100% rise time obtained by dividing the 10–90% rise time by 0.8. Beyond differences in definition, rise time can be an insufficient descriptor of sonic boom waveforms [32], particularly for signatures that have turbulent spiking, higher-level ambient environments, or multiple boom arrivals. In the outlying aircraft waveforms, both of which were recorded during supersonic cruise, a secondary peak exceeded the amplitude of the primary shock, leading to artificially extended rise times. The two nearly 40-PLdB underpredicted rocket launch-ascent waveforms have multiple arrivals that follow a similar pattern.

While there are no clear trends for the over- or under-estimates of PL for traditional aircraft, rocket flyback, or rocket ascent sonic booms, there is a clear trend for the simulated low-boom results, which is of critical importance if Eq. (1) is to be used for SST design. The Higgins calculation consistently overestimates the PL of these simulated, quieter booms. For the quietest booms, this overestimation exceeds 20 PLdB. It is unclear whether this pattern is expected from all low-boom waveforms or is somehow unique to the C609 dataset. Overall, the disagreement between the Higgins simplified method and the Mark VII PL calculation for these four sonic boom shapes indicates that the Higgins simplified method is not sufficient.

III. Conclusions

A standardized approach to calculating PL is essential to eliminating potential discrepancies relevant to supersonic aircraft design. The Higgins method for calculating PL does not agree with the Stevens Mark VII PL for a variety of measured and simulated waveform shapes. For nearly half of the traditional aircraft, simulated low-booms, reusable rocket booster flyback, and rocket launch-ascent sonic booms considered, PL values calculated with both methods disagree by over 9 PLdB, more than a doubling of loudness. The Higgins approach overestimates the PL of the simulated low-boom waveforms, while differences in PL values do not follow a clear pattern for the other waveform shapes. Because of these discrepancies, the Mark VII procedure is recommended whenever calculating PL for a sonic boom. The procedure is described in Ref. [1], and more details about the implementation and algorithms are described in Refs. [22–24,33]. Additionally, NASA has publicly released code to calculate PL for sonic booms according to the Mark VII procedure [34].

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