

Abstract

The economic viability of a supersonic commercial transport airplane would be much enhanced if it could fly supersonically over land. Efforts to design an airplane to produce a minimized sonic boom at the ground require knowledge of the impact of sonic booms on people. Loudness, being a fundamental and well-understood characteristic of human hearing, was chosen as a means of quantifying the magnitude of sonic boom impact on people. This paper describes in detail a procedure that can be used to calculate the loudness of sonic booms. The procedure is applied to a wide range of sonic booms, both classical N-waves and a variety of other shapes of booms. The loudness of N-waves is controlled by overpressure and the associated rise time. The loudness of shaped booms is highly dependent on the characteristics of the initial shock. A comparison of the calculated loudness values indicates that shaped booms may have significantly reduced loudness relative to N-waves having the same peak overpressure. This result implies that a supersonic transport designed to yield minimized sonic booms may be substantially more acceptable than an unconstrained design.

Introduction

The National Aeronautics and Space Administration (NASA), in conjunction with major aerospace companies, is investigating the technical and economic feasibility of a new generation of supersonic transport airplanes. The first phase of this investigation is aimed primarily at addressing critical environmental concerns about atmospheric impact, airport noise, and sonic boom. The possibility that engine emissions might cause major perturbations to stratospheric chemistry, leading to depletion of the ozone layer, must be explored thoroughly and resolved before serious consideration can be given to the development of a supersonic transport. Public acceptance of such a transport will also depend on its ability to meet airport noise level standards currently applied to newly designed subsonic transports. In addition, this NASA/industry program aims to establish either that supersonic flight over land with acceptably low levels of sonic boom can be assured or that design for subsonic cruise over land will not unduly compromise the economic viability of the aircraft.

Considerable effort is being devoted to an examination of the feasibility of designing and operating a supersonic transport that will yield a sonic boom acceptable to the affected population. Current supersonic airplanes produce a sonic boom at ground level that is generally referred to as an N-wave. Such a pressure disturbance is characterized by a rapid rise to a maximum positive overpressure, which is followed by a relatively slow decay to a below-ambient pressure, and then an abrupt

return to atmospheric pressure. Theoretical analyses suggest that precise tailoring of the volume and lift distributions of a supersonic airplane can yield a sonic boom at ground level that differs from the conventional N-wave. Therefore, appropriate methods are required to assess sonic boom impact in order to guide the design and operating conditions of the airplane. There is no consensus within the regulatory and scientific communities regarding the appropriate metric for sonic boom assessment. Loudness, being a fundamental and well-understood characteristic of human hearing, was chosen for this study as a means of quantifying the magnitude of sonic booms.

The purpose of this paper is to describe in detail a procedure that can be used to calculate the loudness of sonic booms. This procedure is based largely on an approach described by Johnson and Robinson (ref. 1). Their approach utilized a loudness calculation procedure that had a low frequency limit of 50 Hz. Since the dominant acoustic energy of sonic booms is well below this frequency, they proposed an ad hoc method to incorporate this low frequency energy. The procedure proposed in this paper utilizes a more recent loudness calculation procedure that extends the frequency limit to 1 Hz. The procedure is applied to a wide range of sonic booms, and particular emphasis is given to an examination of the loudness of sonic booms that differ in shape from the classical N-wave. Finally, estimates are made of the loudness of sonic booms as they would be heard indoors, based on the measured noise reduction provided by typical dwellings.

Symbols

A, B	first and second pressures, respectively, shown in figure 3, N/m^2
D	$= T_1 + T_2$
$F(\omega)$	Fourier transform
f	frequency, Hz
i	$= \sqrt{-1}$
P	peak overpressure (see fig. 1), N/m^2
p	pressure, N/m^2
T_1, T_2, T_3	time parameters shown in figures 1 and 3
t	time, sec
W_A	A-weighting
W_C	C-weighting
τ	rise time, sec
ω	frequency, radians

Loudness Calculation Procedure

Several approaches have been proposed for assessing the impact of sonic booms on people (refs. 1–3). The American National Standards Institute (ref. 2) has adopted the C-weighted sound pressure level. The choice of C-weighting, which emphasizes low frequencies relative to other noise impact metrics such as A-weighting or Perceived Noise Level, is an attempt to incorporate the effects of structural vibrations and the resulting rattling of objects. The A-weighted sound pressure level has been proposed by Brown and Haglund (ref. 3) so that sonic booms can be assessed by the same method commonly used for subsonic airplane flyover noise. Since the purpose of this paper is to examine human response to relatively small differences in sonic boom signatures, a more sophisticated loudness calculation procedure has been adopted. The appendix contains convenient methods for the calculation of A- and C-weighted sound pressure levels for sonic booms.

The following sections describe the steps required to calculate the loudness of sonic booms. The approach requires the pressure time history of the sonic boom signature as input. This time history is transformed into the frequency domain and then converted into an effective one-third octave band sound pressure level spectrum. The loudness of the sonic boom is then calculated by using this spectrum.

Energy Spectrum of Sonic Booms

N-wave sonic booms. Several investigators (refs. 1 and 4–7) have derived expressions for the spectrum of an N-wave sonic boom. Using the nomenclature given in the pressure function of figure 1 gives the Fourier transform

$$F(\omega) = \int_{-T_2}^{T_2} p(t) e^{-i\omega t} dt$$

which is found to be

$$F(\omega) = \frac{i2P(T_2 \sin \omega T_1 - T_1 \sin \omega T_2)}{\omega^2 T_1 (T_2 - T_1)} \quad (1)$$

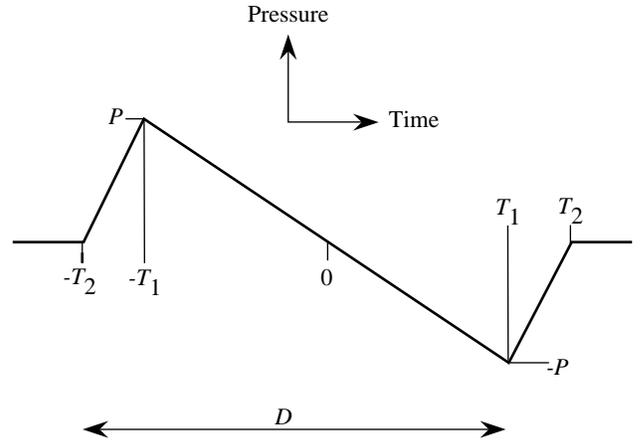


Figure 1. N-wave sonic boom signature.

Defining $\tau = T_2 - T_1$ and $D = T_1 + T_2$ yields the following expression which is equivalent to those derived in references 1 and 6:

$$F(\omega) = \frac{i4P \left(\tau \sin \frac{\omega D}{2} \cos \frac{\omega \tau}{2} - D \sin \frac{\omega \tau}{2} \cos \frac{\omega D}{2} \right)}{\omega^2 \tau (D - \tau)} \quad (2)$$

For the case of instantaneous rise time ($T_2 - T_1 = 0$), equation (1) reduces to

$$F(\omega) = \frac{i2P(\sin \omega T_1 - \omega T_1 \cos \omega T_1)}{\omega^2 T_1}$$

which is equivalent to Howes' formulation (ref. 5)

$$F(\omega) = iPD \left[\frac{\sin \frac{\omega D}{2}}{\left(\frac{\omega D}{2}\right)^2} - \frac{\cos \frac{\omega D}{2}}{\frac{\omega D}{2}} \right]$$

since, in this case, $D = 2T_1$.

The function $|F(\omega)|^2$ determines the energy spectral density that is presented in figure 2 for an N-wave having a peak overpressure of 50 N/m^2 , a total duration ($2T_2$) of 0.35 sec, and a rise time (τ) of 0.008 sec. The energy spectrum level in the figure is given per Hertz, the reference pressure is $2 \times 10^{-5} \text{ N/m}^2$, and the reference time is 1 sec. The function cycles rapidly between successive zeros which, after the first few cycles, are equispaced at intervals of $1/D$ in frequency. Above about 40 Hz (indicated by the dashed line in fig. 2 at $1/\pi\tau$ Hz), the maxima are seen to be modulated at a much slower rate. This rate is determined by the rise time of the N-wave.

Figure 2. Energy spectrum of N-wave sonic boom with peak overpressure of 50 N/m^2 , rise time of 0.008 sec, and total duration of 0.35 sec.

As long as the rise time is much shorter than the total duration, the envelope of the spectrum can be represented by the following three straight-line segments:

1. At the lowest frequencies, the spectrum level rises at 6 dB/octave and peaks at a frequency of approximately $\sqrt{3}/\pi D$ Hz. The amplitude at this frequency is controlled by the peak overpressure and total duration ($|F(\omega)|^2 = P^2 D^2/3$).
2. The spectrum level then decays at 6 dB/octave to a frequency equal to $1/\pi\tau$. At this frequency, the amplitude is controlled by the peak overpressure and rise time ($|F(\omega)|^2 = P^2 \tau^2$).
3. Above this frequency, the spectrum level decays at 12 dB/octave.

Examining the effects of changes in the parameters defining an N-wave is instructive. For the

case of zero rise time, the third straight-line segment (12 dB/octave) does not occur; the spectrum level merely continues to decay at 6 dB/octave. A doubling of overpressure just raises the entire spectrum by 6 dB. A doubling of the total duration increases the maximum spectrum level by 6 dB and halves the frequency at which the maximum occurs. The net result is an increase of 3 dB in the energy content of the signal. The maximum in the spectrum moves along the line having a negative slope of 6 dB/octave so that only the lowest frequencies are affected by a change in total duration. A doubling of rise time halves the frequency at which the transition occurs to the 12-dB/octave segment. Thus, the rise time for constant overpressure controls the high frequency content of the spectrum.

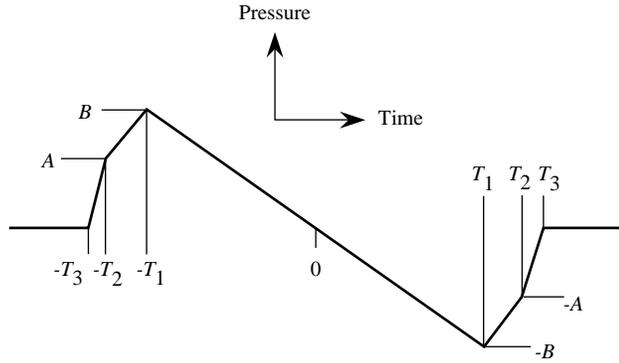
Shaped booms. For a long airplane (e.g., 100 m long), it has been suggested (refs. 8 and 9) that the midfield sonic boom pressure signature may not have fully evolved into an N-wave at ground level. Thus, an airplane can possibly be designed and operated to yield a sonic boom that differs from an N-wave in such a way that the impact on people is reduced. Darden's approach (ref. 9) permits minimization of either the initial shock or the maximum overpressure of the signature by means of careful tailoring of the airplane volume and lift distributions. These two possibilities are illustrated in figure 3. A front-shock minimized signature (fig. 3(a)) is characterized by an initial shock of short rise time followed by a more gentle rise to the peak overpressure. The case of a flat-top signature ($A = B$ in fig. 3(b)) is frequently referred to as having minimized overpressure.

From using the nomenclature of figure 3(a), the Fourier transform of the shaped signature was found to be

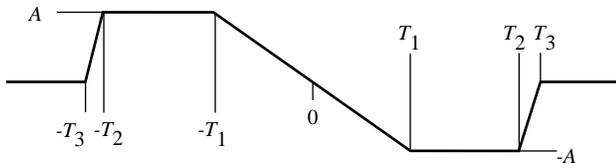
$$F(\omega) = \frac{i2A(T_3 \sin \omega T_2 - T_2 \sin \omega T_3)}{\omega^2 T_2 (T_3 - T_2)} + \frac{i2 \left(B - A \frac{T_1}{T_2} \right) (T_2 \sin \omega T_1 - T_1 \sin \omega T_2)}{\omega^2 T_1 (T_2 - T_1)}$$

Examination of this equation reveals that the first expression is equal to the Fourier transform of an N-wave having a peak overpressure of A and a rise time of $T_3 - T_2$. The second expression corresponds to an N-wave having a rise time of $T_2 - T_1$ and a peak overpressure of $B - (AT_1/T_2)$. Thus, the shaped sonic boom of figure 3(a) may be considered to be a combination of two N-waves. The first N-wave is defined by the initial shock amplitude (A) and its associated (short) rise time, and the second by a

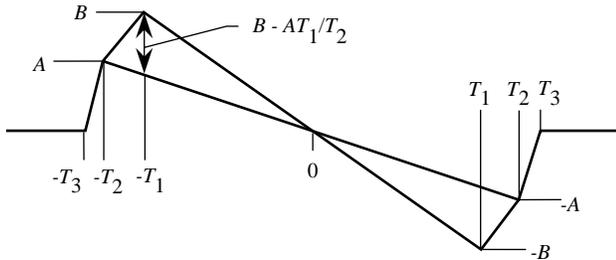
relatively long rise time having the amplitude defined previously. This is illustrated in figure 3(c).



(a) Front-shock minimized signature.



(b) Flat-top signature ($A = B$).



(c) Front-shock minimized signature showing combination of two N-waves.

Figure 3. Shaped sonic boom signatures.

For the case of a flat-top signature ($A = B$ in fig. 3(b)), the previous equation reduces to

$$F(\omega) = \frac{i2A[(T_3 - T_2) \sin \omega T_1 - T_1(\sin \omega T_3 - \sin \omega T_2)]}{\omega^2 T_1 (T_3 - T_2)}$$

A spectrum of a flat-top signature is presented in figure 4 in which the total duration is 0.35 sec, the peak overpressure is 50 N/m², the initial rise time ($T_3 - T_2$) is 0.008 sec, and the secondary rise time ($T_2 - T_1$) is 0.04 sec. This spectrum is virtually indistinguishable from the spectrum of the N-wave (fig. 2), which has the same duration and peak overpressure and a rise time equal to the initial rise time of the flat-top signature.

Figure 4. Energy spectrum of flat-top sonic boom.

An example spectrum for a shaped sonic boom is presented in figure 5. Once again, the initial rise time was chosen to be 0.008 sec with a duration of 0.35 sec and an initial shock amplitude A of 50 N/m². The secondary rise time is 0.04 sec and the peak overpressure is 100 N/m². At the lowest frequencies, the spectrum level is 6 dB higher than the N-wave spectrum of figure 2 because of the doubling of overpressure. Above about 10 Hz, the envelopes of the N-wave and shaped-boom spectra are remarkably similar, with the latter distinguished by more erratic modulations because of the effect of the secondary rise time. It is apparent that at the lowest frequencies, the spectrum of the shaped boom is controlled by the peak overpressure and duration. This illustrates that a shaped boom, with a far higher overpressure than an N-wave, can contain similar acoustic energy except at the very lowest frequencies where the human ear is extremely insensitive. Assuming that the secondary

Figure 5. Energy spectrum of front-shock minimized sonic boom.

rise time is substantially longer than the initial rise time, the spectrum levels of a shaped boom will generally be controlled by the initial shock amplitude and rise time at all but the lowest frequencies.

One-Third Octave Band Sound Pressure Level Spectrum

The energy within any arbitrary waveform $p(t)$ is proportional to

$$\int_{-\infty}^{\infty} [p(t)]^2 dt$$

which is equal to

$$\frac{1}{2\pi} \int_{-\infty}^{\infty} |F(\omega)|^2 d\omega = \frac{1}{\pi} \int_0^{\infty} |F(\omega)|^2 d\omega$$

by Parseval's theorem and the fact that $|F(\omega)|$ is an even function of ω .

The energy E within any frequency band ω_1 to ω_2 is thus

$$E = \frac{1}{\pi} \int_{\omega_1}^{\omega_2} |F(\omega)|^2 d\omega \quad (3)$$

The calculation of one-third octave band energy levels can thus be performed by using a suitable numerical integration method. This calculation can be checked by summing the energy over all bands and confirming that the result is equal to the integral of $[p(t)]^2$. This integral, which is independent of the rise time, is given as

$$\int_{-\infty}^{\infty} [p(t)]^2 dt = \frac{2}{3} P^2 T_2$$

for the N-wave in figure 1 and is given as

$$\int_{-\infty}^{\infty} [p(t)]^2 dt = \frac{2}{3} [(A+B)(BT_2 - AT_1) + A^2T_3]$$

for the shaped boom in figure 3.

In order to apply a loudness calculation procedure, it is necessary to convert the one-third octave band energy levels into equivalent one-third octave band sound pressure levels. Loudness calculation procedures are designed for use with sounds that are continuous in time, and one-third octave band sound pressure levels are typically required as input. In order to use the one-third octave band energy levels described previously (having dimensions of (Pressure)² × Time) in a loudness calculation procedure, they must be converted into equivalent one-third octave band sound pressure levels (having

dimensions of (Pressure)²). The procedure recommended by Johnson and Robinson (ref. 1) has been adopted. This procedure is based on the assumption that although the duration of a sonic boom from a commercial transport is 200–400 msec, the sound energy in the audio frequency range is contained in the two pulses that occur at the front and rear of the waveform. Furthermore, it is assumed that these pulses have durations that are shorter than the critical time of the auditory system. This critical time is the time necessary to evoke a full auditory response, with the result that the loudness of acoustical stimuli of shorter duration is governed by sound energy. A sound having a duration longer than the critical time will evoke no greater sensation of loudness no matter how long it persists, and therefore loudness is controlled by sound intensity in this instance. According to Johnson and Robinson (ref. 1), the value of this critical time is approximately 0.07 sec. Thus, the calculated band energy levels are divided by 0.07 and converted to sound pressure level by using the standard reference pressure of 2×10^{-5} N/m².

As noted previously, the sound energy in the audio frequency range is contained mostly within the two pulses that occur at the front and rear of the waveform. For any supersonic transport the time between these pulses will be much greater than the auditory critical time, and the two pulses will be heard as distinct events. However, the energy spectral density functions presented previously included the entire waveform; thus, the sound pressure levels should be reduced by 3 dB before calculating loudness. This correction assumes that the waveform is symmetrical, both front and rear, so that the two pulses will be equally loud.

Calculation of Loudness Level

The loudness method selected for this investigation is Stevens' Mark VII (ref. 10). This method is in contrast to that used by Johnson and Robinson (ref. 1). The equal loudness contours in the Mark VII method extend to a very low frequency (1 Hz), and thus they are appropriate for sonic booms that contain significant low frequency energy. The calculation procedure for loudness level assumes that the noise signal has been measured in one-third octave bands. The sound pressure levels in each band are converted into a perceived value (in sones) and then totaled according to a summation rule. The total is then converted into a calculated Perceived Level by means of the power function relating perceived magnitude to sound pressure. A doubling of loudness in sones is accomplished by raising the signal level by 9 dB.

The spectrum of a one-third octave band sound pressure level is required as input to the loudness calculation procedure. This spectrum can be obtained from the spectral density formulations and procedure presented previously, or, for other sonic boom shapes, it can be calculated by using widely available Fast Fourier Transform computer routines.

Loudness of Sonic Booms

Loudness of N-Waves

Calculated loudness results are presented for a range of those parameters that can be used to describe an N-wave. In particular, the range of values of overpressure and rise time were selected to encompass values likely to be encountered in practice.

The duration of sonic boom signatures associated with any supersonic transport airplane (200–400 msec) will be much longer than the auditory critical time. Under these conditions, calculated loudness is independent of the total duration of the signature. The relationship of loudness level with both peak overpressure and rise time is illustrated in figure 6 for

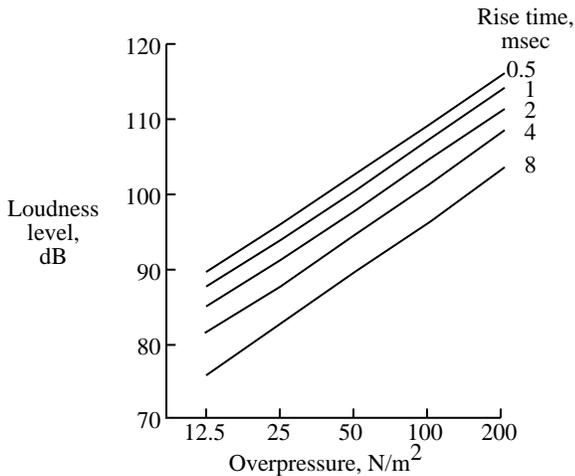


Figure 6. Loudness level of N-waves for outdoor listening conditions.

a range of N-wave sonic booms, each with a total duration of 350 msec. Loudness level increases approximately 7 dB per doubling of overpressure and decreases with increasing rise time. This latter observation reflects the relationship between the rise time and the high-frequency content of the sonic boom illustrated in figure 2. A change in loudness level of 9 dB represents a halving, or doubling, of loudness. These observations regarding the loudness of N-wave sonic booms have generally been confirmed by several experimental investigations (e.g., refs. 11–14).

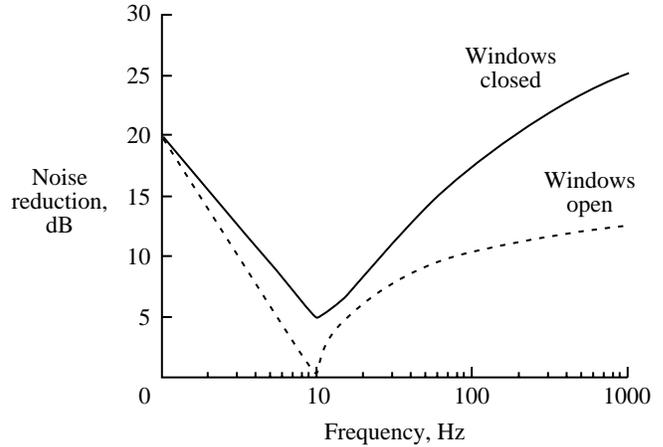


Figure 7. Noise reduction for typical residential structures.

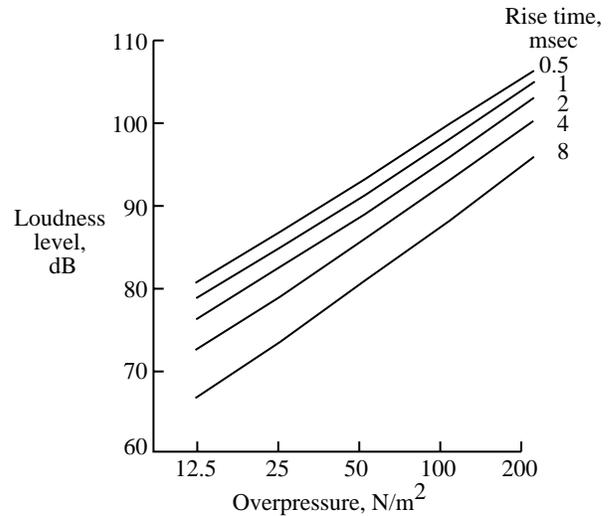


Figure 8. Loudness level of N-waves for indoor listening conditions and with windows open.

Estimates were made of the loudness of sonic booms as they would be heard indoors, based on measured noise reduction provided by typical dwellings. The curves of noise reduction presented in figure 7 were derived from measured data (refs. 15 and 16) for a range of houses, both with windows open and closed. These noise reduction values were applied to the sonic boom spectra before the loudness calculation was performed. Figures 8 and 9 illustrate the relationship of indoor loudness level with both overpressure and rise time of N-wave sonic booms. In these figures the overpressure and rise time are characteristics of the N-wave incident on the structure. The trends are very similar to those obtained outdoors, with the loudness levels approximately 10 dB lower with windows open and 20 dB lower with windows closed. This assessment of indoor levels obviously makes no attempt to include the effects of

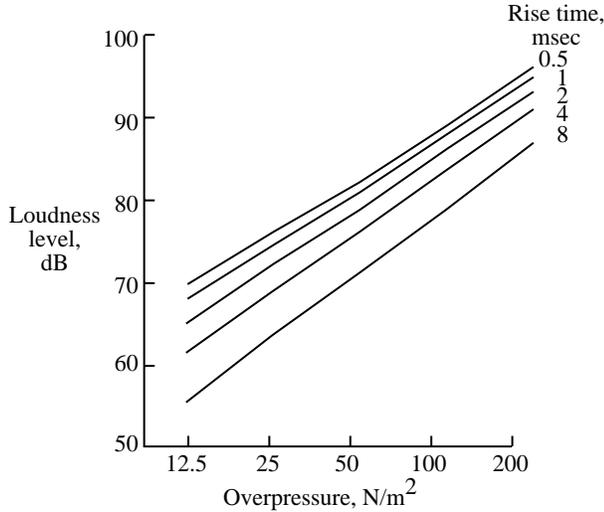


Figure 9. Loudness level of N-waves for indoors and windows closed.

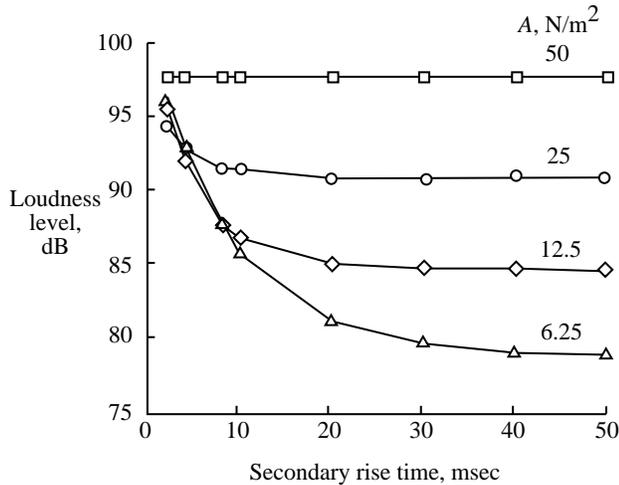


Figure 10. Loudness level of shaped booms for outdoor listening conditions with peak overpressure of 50 N/m^2 and initial rise time of 2 msec.

structural vibrations or secondary acoustic radiation due to vibration-induced rattling of objects.

Loudness of Shaped Booms

As was previously noted for N-waves, the duration of a shaped boom has no effect on the loudness level for the range of interest (200–400 msec). For illustrative purposes the range of shaped sonic booms is constrained such that the peak overpressure (B in fig. 3(a)) is fixed at 50 N/m^2 , the initial rise time ($T_3 - T_2$ in fig. 3(a)) is fixed at 2 msec, and the total duration is fixed at 350 msec. Figure 10 presents outdoor loudness levels for a range of values of the initial shock amplitude and secondary rise time (A and $T_2 - T_1$, in fig. 3(a)). For the case of $A = B$ (a flat-top

signature shown in fig. 3(b)), the loudness level is independent of the secondary rise time and equal to the loudness of an N-wave having the same overpressure and rise time as the initial shock of the flat-top signature. Reduced levels of the initial shock amplitude lead to substantially reduced loudness, particularly for large values of the secondary rise time. This observation was confirmed in an experimental investigation conducted by Niedzwiecki and Ribner (ref. 17), which is the only study to incorporate shaped sonic booms.

The noise reduction values in figure 7 were used to calculate indoor loudness levels for the same range of shaped booms as described previously. Figures 11 and 12 show the results for the conditions of windows open and windows closed, respectively. The loudness level of the flat-top signatures is independent of the secondary rise time, as was noted for outdoor loudness. The effect of a reduced initial shock amplitude is also very similar to that observed for the outdoor case.

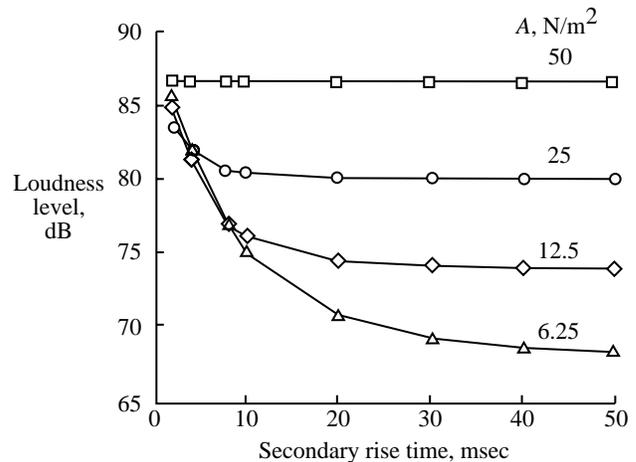


Figure 11. Loudness level of shaped booms for indoor listening conditions and with windows open.

The example loudness calculations described previously were for a constant value of initial rise time (2 msec). The range of practical interest for this parameter is approximately 1–8 msec. Figure 13 shows outdoor loudness levels for a range of shaped booms for which the initial rise time is 8 msec. All other parameters remain the same. The same trends that were evident in the previous cases can be observed here. The flat-top signature is equivalent to an N-wave having the same characteristics as the initial shock. The curves for lower initial shock amplitudes also exhibit a reduced loudness level for increasing values of secondary rise time. However, compared

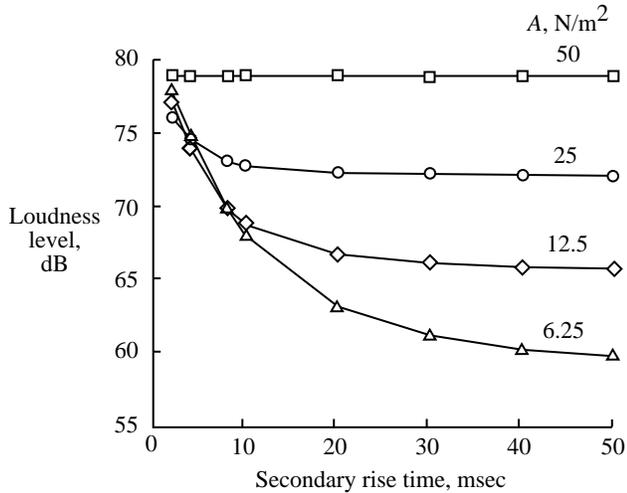


Figure 12. Loudness level of shaped booms for indoor listening conditions and with windows closed.

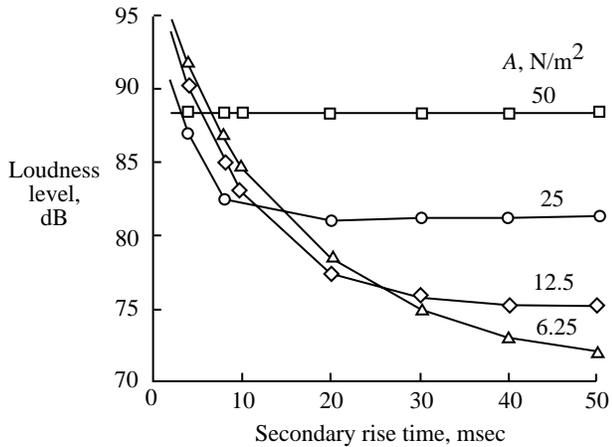


Figure 13. Loudness level of shaped booms for outdoor listening conditions with peak overpressure of 50 N/m^2 and initial rise time of 8 msec.

with the previous case, the rate at which loudness level decays with increasing secondary rise time is reduced. For small values of the initial shock amplitude and for values of the secondary rise time smaller than those of the initial rise time, figure 13 indicates that the loudness of the shaped boom exceeds the loudness of the flat-top signature. This difference is due to the loudness contribution of the second segment exceeding the loudness contribution of the initial shock.

Concluding Remarks

A procedure for the calculation of the loudness of sonic booms has been described. This procedure was applied to a range of sonic booms, both classical N-waves and shaped booms, that might be of practical interest for a supersonic transport airplane. It was concluded that the loudness of N-wave sonic booms is controlled by rise time and overpressure. The loudness of shaped booms is highly dependent on the characteristics of the initial shock. A comparison of the results of calculations for N-waves and shaped booms indicates that shaped booms may have significantly reduced loudness relative to N-waves having the same peak overpressure. This was found for both indoor and outdoor listening conditions. This result implies that a supersonic transport designed to yield minimized sonic booms may be substantially more acceptable than an unconstrained design. Clearly, other studies involving many other aspects of sonic boom impact are required before the issue of overland supersonic flight can be resolved.

NASA Langley Research Center
 Hampton, VA 23665-5225
 October 24, 1991

Appendix

Calculation of Other Sonic Boom Impact Metrics

It has been proposed (ref. 2) that the assessment of high-energy impulsive sounds, such as a sonic boom, artillery firing, and quarry blasts, should be based on the use of a C-weighted sound exposure level to describe single impulsive sounds and on the use of a day-night average C-weighted level to describe the cumulative effect of such sounds. The sound exposure level is the level (in decibels) of the time integral of squared, weighted sound pressure over a given time period or event, with reference to the square of the standard reference pressure (2×10^{-5} N/m²) and a reference duration of 1 sec. The calculation of the C-weighted sound exposure level can be obtained by using the energy spectral density formulations presented previously corrected for the C-weighting function. A useful expression for the C-weighting W_C as a function of frequency f (given in Hertz) is

$$W_C(f) = \frac{1.00715 \left(\frac{f}{f_1}\right)^2}{\left[1 + \left(\frac{f}{f_1}\right)^2\right] \left[1 + \left(\frac{f}{f_2}\right)^2\right]}$$

where $f_1 = 20.598997$ Hz and $f_2 = 12194.22$ Hz.

The weighting in decibels to be added to the energy spectral density values is given by $20 \log W_C$. The frequency-weighted energy spectral density should then be integrated over all frequencies by using equation (3). It should be noted that this calculation does not include corrections for the auditory critical time and the double boom because the sound exposure level has a reference duration of 1 sec.

The most common method for the assessment of environmental noises is by means of the day-night average A-weighted sound pressure level. The appropriate measure for a single event is A-weighted sound exposure level. The calculation of this quantity parallels the C-weighted sound exposure level, except that the A-weighting is used which can be conveniently computed (ref. 18) by using

$$W_A(\omega) = \frac{C s^4}{\prod_{i=1}^6 (s + 2\pi p_i)}$$

where $C = 7.397234 \times 10^9$, $p_{1,2} = 20.6$, $p_3 = 107.7$, $p_4 = 737.9$, $p_{5,6} = 12200$, and s is the complex frequency $i\omega$. The weighting in decibels to be added to the energy spectral density values is $20 \log W_A$.

References

1. Johnson, D. R.; and Robinson, D. W.: Procedure for Calculating the Loudness of Sonic Bangs. *Acustica*, vol. 21, no. 6, 1969, pp. 307–318.
2. *American National Standard Method for Assessment of High-Energy Impulsive Sounds With Respect to Residential Communities*. ANSI S12.4–1986 (ASA 63-1986), American Inst. of Physics, c.1986.
3. Brown, Jessica G.; and Haglund, George T.: Sonic Boom Loudness Study and Airplane Configuration Development. AIAA-88-4467, Sept. 1988.
4. Young, J. R.: Energy Spectral Density of the Sonic Boom. *J. Acoust. Soc. America*, vol. 40, no. 2, Aug. 1966, pp. 496–498.
5. Howes, Walton L.: Farfield Spectrum of the Sonic Boom. *J. Acoust. Soc. America*, vol. 41, no. 3, Mar. 1967, pp. 716–718.
6. Oncley, P. B.; and Dunn, D. G.: Frequency Spectrum of N Waves With Finite Rise Times. *J. Acoust. Soc. America*, vol. 43, no. 4, Apr. 1968, pp. 889–890.
7. Pease, C. B.: A Note on the Spectrum Analysis of Transients and the Loudness of Sonic Bangs. *J. Sound & Vibration*, vol. 6, no. 3, Nov. 1967, pp. 310–314.
8. Seebass, R.; and George, A. R.: Sonic-Boom Minimization. *J. Acoust. Soc. America*, vol. 51, no. 2, pt. 3, Feb. 1972, pp. 686–694.
9. Darden, Christine M.: *Minimization of Sonic-Boom Parameters in Real and Isothermal Atmospheres*, NASA TN D-7842, 1975.
10. Stevens, S. S.: Perceived Level of Noise by Mark VII and Decibels (E). *J. Acoust. Soc. America*, vol. 51, no. 2, pt. 2, Feb. 1972, pp. 575–601.
11. Broadbent, D. E.; and Robinson, D. W.: Subjective Measurements of the Relative Annoyance of Simulated Sonic Bangs and Aircraft Noise. *J. Sound & Vibration*, vol. 1, no. 2, Apr. 1964, pp. 162–174.
12. Zepler, E. E.; and Harel, J. R. P.: The Loudness of Sonic Booms and Other Impulsive Sounds. *J. Sound & Vibration*, vol. 2, no. 3, July 1965, pp. 249–256.
13. Pearsons, K. S.; and Kryter, K. D.: *Laboratory Tests of Subjective Reactions to Sonic Booms*. NASA CR-187, [1965].
14. Johnson, D. R.; and Robinson, D. W.: The Subjective Evaluation of Sonic Bangs. *Acustica*, vol. 18, no. 5, 1967, pp. 241–258.
15. *House Noise-Reduction Measurements for Use in Studies of Aircraft Flyover Noise*. AIR 1081, Soc. of Automotive Engineers, Inc., Oct. 1971.
16. *Measurement and Evaluation of Environmental Noise From Wind Energy Conversion Systems in Alameda and Riverside Counties*. WR 88-19 (Contract C-87-112/File 3162), Wyle Research, Oct. 1988.
17. Niedzwiecki, A.; and Ribner, H. S.: Subjective Loudness of “Minimized” Sonic Boom Waveforms. *J. Acoustic Soc. America*, vol. 64, no. 6, Dec. 1978, pp. 1622–1626.
18. Aarts, R. M.: Algebraic Expression for A-Weighting Response. *J. Sound & Vibration*, vol. 115, no. 2, May 1987, p. 372.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, D.C. 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 1991	3. REPORT TYPE AND DATES COVERED Technical Paper		
4. TITLE AND SUBTITLE A Loudness Calculation Procedure Applied to Shaped Sonic Booms			5. FUNDING NUMBERS WU 537-03-21-03	
6. AUTHOR(S) Kevin P. Shepherd and Brenda M. Sullivan				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23665-5225			8. PERFORMING ORGANIZATION REPORT NUMBER L-16913	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TP-3134	
11. SUPPLEMENTARY NOTES Shepherd: Langley Research Center, Hampton, VA; Sullivan: Lockheed Engineering & Sciences Co., Hampton, VA.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 71			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The economic viability of a supersonic commercial transport airplane would be much enhanced if it could fly supersonically over land. Efforts to design an airplane to produce a minimized sonic boom at the ground require knowledge of the impact of sonic booms on people. Loudness, being a fundamental and well-understood characteristic of human hearing, was chosen as a means of quantifying the magnitude of sonic boom impact on people. This paper describes in detail a procedure that can be used to calculate the loudness of sonic booms. The procedure is applied to a wide range of sonic booms, both classical N-waves and a variety of other shapes of booms. The loudness of N-waves is controlled by overpressure and the associated rise time. The loudness of shaped booms is highly dependent on the characteristics of the initial shock. A comparison of the calculated loudness values indicates that shaped booms may have significantly reduced loudness relative to N-waves having the same peak overpressure. This result implies that a supersonic transport designed to yield minimized sonic booms may be substantially more acceptable than an unconstrained design.				
14. SUBJECT TERMS Sonic boom; Noise; Loudness; Aircraft noise			15. NUMBER OF PAGES 11	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	