

## Subjective evaluation of loudness of sonic booms indoors and outdoors

Yusuke Naka\*

Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka, 181-0015 Japan

(Received 5 October 2012, Accepted for publication 23 November 2012)

**Keywords:** Sonic boom, Loudness, Subjective evaluation

**PACS number:** 43.28.Mw, 43.50.Qp, 43.66.Lj [doi:10.1250/ast.34.225]

### 1. Introduction

Supersonic flights of civil aircraft over land are currently prohibited in many countries because of intense sonic booms. This restriction was made in the age of Concorde, the first-generation civil supersonic transport. With the development of sonic boom mitigation technologies, it is believed that levels of sonic booms can be significantly reduced compared to those of Concorde.

With this background, the Supersonic Task Group of International Civil Aviation Organization (ICAO) has been recently discussing possible revisions of the standards with the aim of achieving civil supersonic flights over land. For revising the standards, understandings of human responses to sonic booms, especially ones created by aircraft to which the “low-boom” technologies are applied, is critical, since the acoustic characteristics of sonic booms differ from other types of noises. For this purpose, subjective evaluation tests for loudness of sonic booms under indoor and outdoor circumstances were conducted and relationships between several metrics and subjective responses are investigated in this study.

### 2. Sonic boom simulator

In order to reproduce pressure time histories of sonic booms with high fidelity, a sonic boom simulator shown in Fig. 1 similar to the existing ones [1,2] has been developed at Japan Aerospace Exploration Agency (JAXA). The air pressure inside a small, nearly airtight booth is precisely controlled by using loudspeakers.

The interior surfaces of the booth is acoustically treated to reduce reverberation. The interior dimensions of the booth are 1.2 m wide  $\times$  0.9 m deep  $\times$  1.7 m high. Eight low-frequency loudspeakers are mounted on two of the walls, four on each of the walls. Four mid- to high-frequency loudspeakers are also mounted, although they were not used in this study, since the frequency response characteristics of the low-frequency loudspeakers were sufficient up to the range necessary to reproduce the intended stimulus sonic boom signatures.

As shown in Fig. 1(c), a window sash can be installed inside the booth to simulate an indoor listening environment. Different types and sizes of windows can be installed, although only one type of window sash was used in the indoor boom evaluation test in this study. The window sash was removed as shown in Fig. 1(b) when conducting the test for evaluating outdoor booms.

The playback system of the simulator is schematically depicted in Fig. 2. Due to the acoustic characteristics of the system (e.g. amplifier, loudspeaker, and acoustic modes inside the booth), the waveform of the sound inside the booth is quite different from that of the output signal from the PC. In order to reproduce the intended signature, the output signal from the PC was “pre-distorted” so as to compensate the distortion effects. An example of the target and synthesized waveforms are shown in Fig. 3. The synthesized signature agrees well with the target.

For the outdoor boom evaluation test, the stimulus sounds were synthesized such that the intended outdoor sonic booms were generated in the whole space inside the booth, indicated by the yellow region in Fig. 4(a). While for the indoor boom evaluation test, the intended outdoor boom signatures were reproduced in the small space between the window sash and one of the booth walls with a speaker array, indicated by the yellow region in Fig. 4(b). Only four loudspeakers near the window sash were used. In the space on the opposite side of the window where participants reside (the pink area in Fig. 4(b)), the simulated indoor sonic booms transmitted through the window and the wall were heard.

### 3. Evaluation tests

#### 3.1. Method

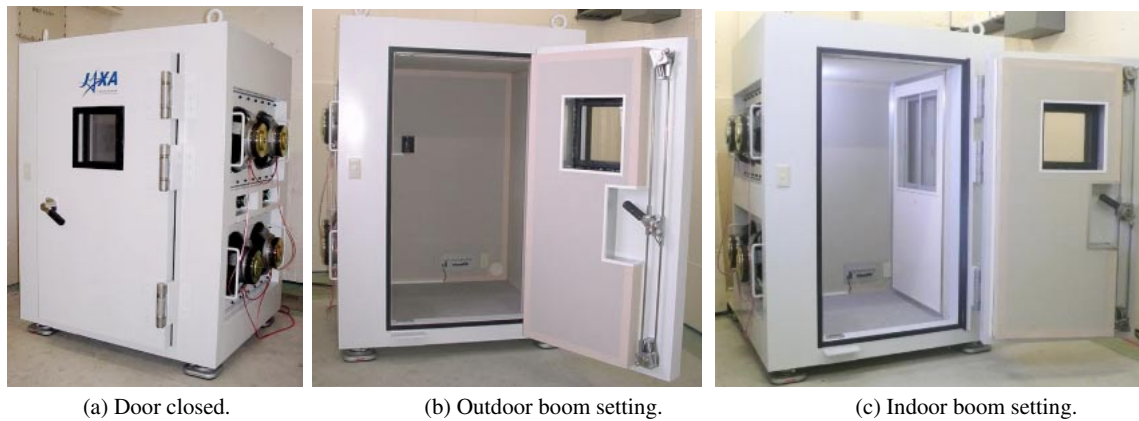
Two sets of subjective evaluation tests, one for outdoor booms and the other for indoor booms, were conducted. In both tests, the test participants were asked to judge the loudness of the stimulus boom sounds. The evaluation method and the test procedure were determined by following Ref. [3]. The magnitude estimation method with a reference boom stimulus, to which the loudness rating of 100 is assigned, was used. The reference boom was played every three stimulus booms.

Note that all the written and oral instructions and communications were given and taken in the Japanese language, as the native language of all of the participants were Japanese. Therefore, a Japanese word “*ookisa* (大きさ)” was used as the word corresponding to “loudness” in English.

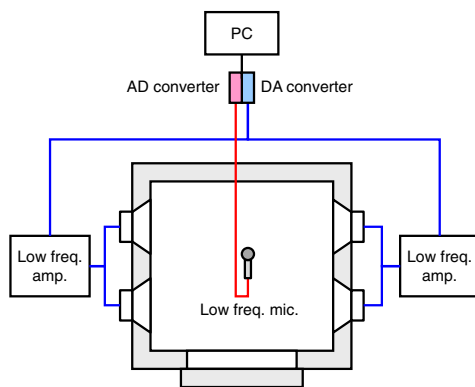
#### 3.2. Stimuli

Fifteen different outdoor sonic boom waveforms were used as the stimuli. The same set of signatures were used in both indoor and outdoor boom evaluation tests. Twelve were N-waves having different maximum overpressures and rise times. The combination of four values of overpressure and three values of rise time were used. The duration of the N-

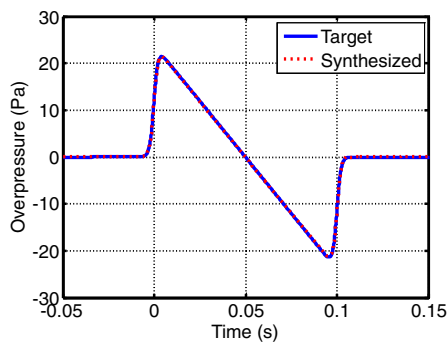
\*e-mail: naka.yusuke@jaxa.jp



**Fig. 1** JAXA sonic boom simulator.

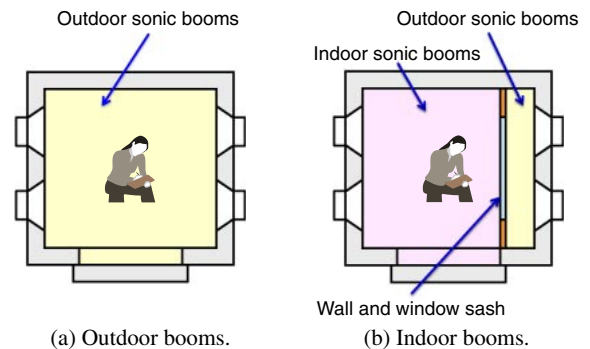


**Fig. 2** Playback system of sonic boom simulator.



**Fig. 3** Target and synthesized waveforms.

wave was fixed to 100 ms for all booms. One of these twelve N-waves was identical to the reference stimulus. The shock structure in the N-waves were thickened by using the hyperbolic tangent function [4]. The rise time was controlled by changing the thickness parameter in the hyperbolic tangent function. The remaining three stimuli were high-pass filtered N-waves with different cut-off frequencies (5, 10, and 20 Hz). Each of the fifteen kinds of stimuli were played twice. The stimulus booms were played with ten seconds of interval in a random order.

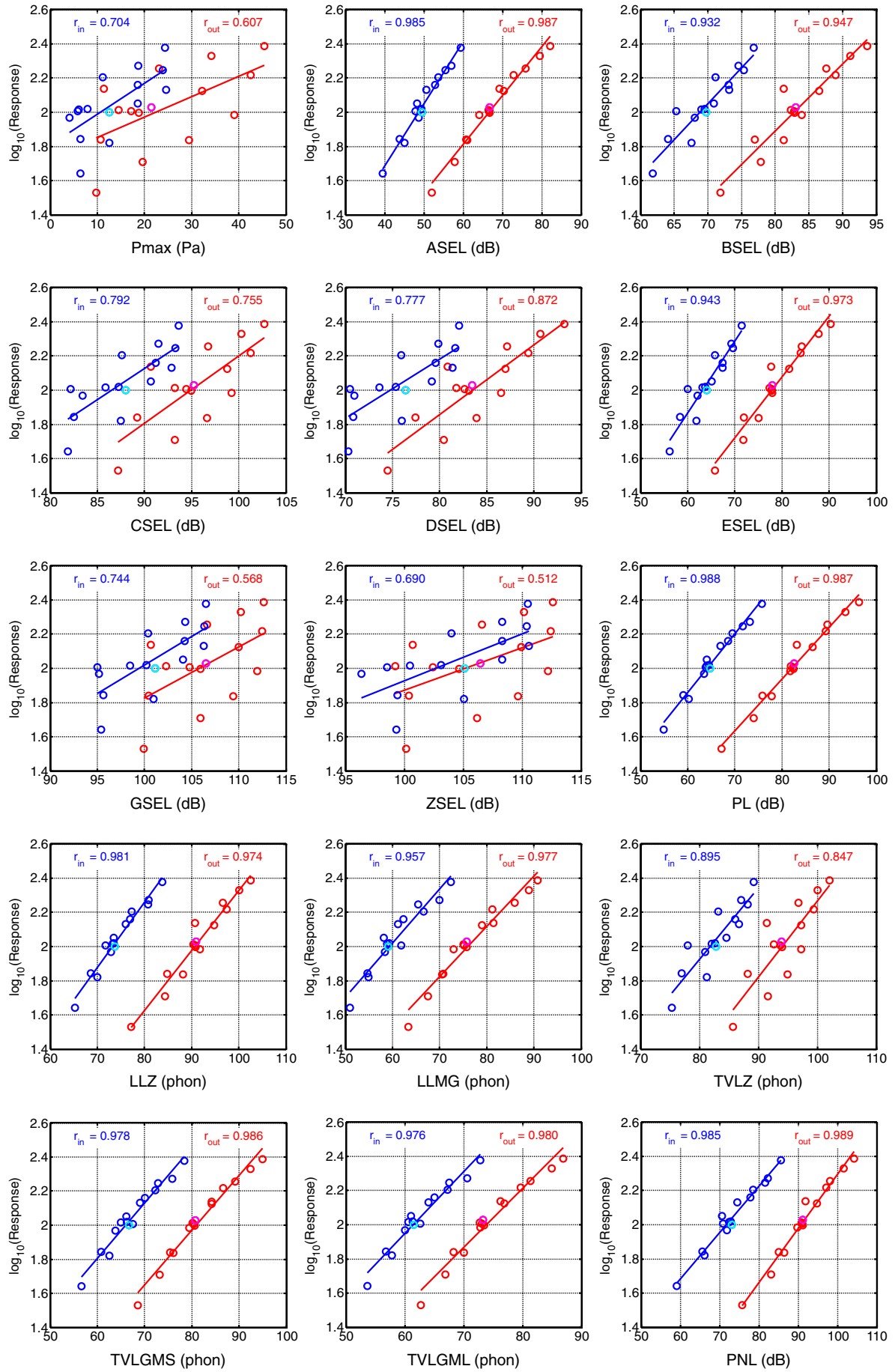


**Fig. 4** Schema of sonic boom reproduction.

#### 4. Results

The relations between 15 metrics and the logarithm of the participants' responses were investigated. The metrics considered are maximum overpressure ( $P_{\max}$ ), A-, B-, C-, D-, E-, G-, and un-weighted sound exposure levels (ASEL, BSEL, CSEL, DSEL, ESEL, GSEL, and ZSEL, respectively) [5], Stevens perceived level Mark VII (PL) [6], stationary loudness levels using Zwicker's (LLZ) and Moore and Glasberg's (LLMG) methods, maximum of time-varying loudness levels using Zwicker's (TVLZ) and Glasberg and Moore's methods (TVLGMS and TVLGML for short- and long-terms, respectively), and perceived noise level (PNL). For calculating PL, LLZ, and PNL, the 1/3-octave band level was adjusted by using a 70-ms critical time and 3-dB subtraction as described in Ref. [7]. LLZ, LLMG, TVLZ, TVLGMS, and TVLGML were calculated by using the Loudness Toolbox provided by GENESIS [8].

The results are shown in Table 1 and Fig. 5. The symbols with light colors (cyan and magenta) in Fig. 5 indicate the boom identical to the reference. The correlation coefficients for all of the loudness level metrics except TVLZ (for both indoor and outdoor booms) and LLMG (for indoor booms) are higher than 0.97. Among the sound exposure levels, high correlation is found for A- and E-weightings, and slightly lower for B-weighting. PNL is also highly correlated with the responses. Comparing the indoor and outdoor booms, the correlation coefficients are similar in most of the metrics.



**Fig. 5** Relation between metrics and participants' responses.

**Table 1** Pearson correlation coefficients between metrics and logarithm of participants' responses.

Metric	Unit	Outdoor	Indoor
$P_{\max}$	Pa	0.607	0.704
ASEL	dB	0.987	0.985
BSEL	dB	0.947	0.932
CSEL	dB	0.755	0.792
DSEL	dB	0.872	0.777
ESEL	dB	0.973	0.943
GSEL	dB	0.568	0.744
ZSEL	dB	0.512	0.690
PL	dB	0.987	0.988
LLZ	phon	0.974	0.981
LLMG	phon	0.977	0.957
TVLZ	phon	0.847	0.895
TVLGMS	phon	0.986	0.978
TVLGML	phon	0.980	0.976
PNL	dB	0.989	0.985

## 5. Summary

Loudness of outdoor and indoor sonic booms were subjectively evaluated. Most of the loudness level metrics,

sound exposure levels with A- and E-weightings, and PNL have high correlation with the subjectively evaluated loudness both indoors and outdoors.

## References

- [1] J. D. Leatherwood, K. P. Shepherd, and B. M. Sullivan, "A new simulator for assessing subjective effects of sonic booms," NASA-TM-104150 (1991).
- [2] A. Yamamoto and K. Sakai, "Sonic boom simulation system at KHI," *J. Jpn. Soc. Aeronaut. Space Sci.*, **43**, 739–740 (1995) (in Japanese).
- [3] B. M. Sullivan, "Human response to simulated low-intensity sonic booms," *Proc. Noise-Con 2004*, pp. 541–550 (2004).
- [4] A. D. Pierce, *Acoustics: An Introduction to Its Physical Principles and Applications* (Acoustical Society of America, New York, 1989), pp. 589–591.
- [5] ANSI S1.42-2001 (R2006), "Design response of weighting networks for acoustical measurements" (2006).
- [6] S. S. Stevens, "Perceived level of noise by Mark VII and Decibels (E)," *J. Acoust. Soc. Am.*, **51**, 575–601 (1972).
- [7] K. P. Shepherd and B. M. Sullivan, "A loudness calculation procedure applied to shaped sonic booms," NASA-TP-3134 (1991).
- [8] [http://www.genesis-acoustics.com/en/loudness\\_online-32.html](http://www.genesis-acoustics.com/en/loudness_online-32.html) (Accessed October 5, 2012).