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Human Response to Simulated Low-Intensity Sonic Booms

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1. INTRODUCTION

NASA's High Speed Research (HSR) program in the 1990s was intended to develop a technology base for a future High-Speed Civil Transport (HSCT). As part of this program, the NASA Langley Research Center sonic boom simulator (SBS) was built[1] and used for a series of tests on subjective response to sonic booms. At the end of the HSR program, an HSCT was deemed impractical, but since then interest in supersonic flight has reawakened, this time focusing on a smaller aircraft suitable for a business jet. To respond to this interest, the Langley sonic boom simulator has been refurbished. The upgraded computer-controlled playback system is based on an SGI O2 computer, in place of the previous DEC MicroVAX. As the frequency response of the booth is not flat, an equalization filter is required. Because of the changes made during the renovation (new loudspeakers), the previous equalization filter no longer performed as well as before, so a new equalization filter has been designed. Booms to be presented in the booth are preprocessed using the filter. When the preprocessed signals are presented into the booth and measured with a microphone, the results are very similar to the intended shapes. Signals with short rise times and sharp "corners" are observed to have a small amount of "ringing" in the response.

During the HSR program a considerable number of subjective tests were completed in the SBS. A summary of that research is given in Leatherwood et al.[2] (Individual reports are available at http://techreports.larc.nasa.gov/ltrs/ltrs.html.) Topics of study included shaped sonic booms, asymmetrical booms, realistic (recorded) boom waveforms, indoor and outdoor booms shapes, among other factors. One conclusion of that research was that a loudness metric, like the Stevens' Perceived Level (PL)[3, 4], predicted human reaction much more accurately than overpressure or unweighted sound pressure level. Structural vibration and rattle were not included in these studies.

2. LOW-INTENSITY BOOM TEST

The emphasis of the testing performed under HSR was on relatively long (300 ms) booms with a fairly high level of overpressure. The emphasis in the present program is on lower level booms (less than 1 psf) with shorter duration (~100 ms). In order to study this range of booms, a test was designed that included various predicted waveforms for candidate low-boom aircraft designs submitted by a number of aircraft manufacturers and others. The test also included shapes based on the classic N-waves; further details are given below (see Section "Test Stimuli").

A. Experimental Method

(i) Simulator

The experimental apparatus used in this study was the Langley Research Center's sonic boom simulator as originally described in Leatherwood et al.[1] The simulator, shown in fig. 1, is a person-rated, airtight, loudspeaker-driven booth capable of accurately reproducing user-specified sonic boom signatures at peak sound pressure levels up to about 135 dB. Input waveforms are computer generated and preprocessed to compensate for irregularities in the frequency and phase response characteristics of the booth. Preprocessing is accomplished by means of a broadband digital equalization filter. Construction details and operating procedures for the sonic boom simulator are given in Leatherwood et al.[1]

(ii) Subjects

Forty subjects completed the test, of whom 25 were females and 15 were males, with an age range of 24 to 71, and an average age of 46.4. Subjects were selected from a subject pool of local residents, and were paid to participate, They were audiometrically screened to insure hearing within 40 dB of ISO Standard ISO 389-1:1998[5].

(iii) Test Design

(a) Test Stimuli

Twenty-four predicted waveforms resulting from designs of candidate low-boom aircraft ("candidate booms") were supplied by a number of aircraft designers. All were presented in the simulator at the levels expected for the aircraft operating under cruise conditions. This resulted in a range of PL from 71 to 89 dB (A-weighted sound exposure level ranged from 54 to 76 dB).

These were all asymmetrical booms, i.e. the front and rear parts of the pressure time waveforms differed. In previous studies[2,6], it was shown that asymmetrical waveforms were judged to be less annoying/loud than symmetric ones with the same overall value of PL. To further investigate the asymmetry effect, it was decided to create symmetrical booms out of twenty candidate booms. This was done by repeating the front part (from the start to the zero-crossing point), inverted in time and pressure, to form a back part, thus making a symmetrical boom based on the front part of each candidate boom (see fig. 2). Another set of symmetrical booms was created by repeating the back part (from the zero-crossing point to the end) in an inverted form to make a front part, thus forming a symmetrical boom based on the back part of each candidate boom.

All "symmetricized" signals except one were presented in the booth at the predicted levels for the original front or back part. One symmetricized boom was presented at a level higher than predicted to bring it within the range of 70-90 PLdB. Two candidate booms and two symmetricized booms were presented at up to two additional levels to increase the range of loudness levels for booms of large asymmetries. The test used a total of 27 presentations of candidate booms and 43 symmetricized booms.

As well as the candidate booms and the symmetricized booms, the test included some "standard" shapes based on the classic N-wave. The classic N-wave has a zero rise time for the front and rear shocks which in the real world are "thickened" during propagation through the atmosphere to a finite rise time. Different prediction methods for thickening sonic booms have been proposed.. The simplest method is a straight-line thickening, but a curvilinear method (based on a tanh shape) corresponds more to the boom shapes seen in practice and to the shapes predicted from theoretical propagation through a real atmosphere (see fig. 3). Booms using both these shapes were included in this test. All of these were symmetrical and were not associated with any particular aircraft design. These simulated shapes were grouped into "tanh" for the shapes using tanh thickening and "ramp" for those using straight line thickening. Because they were created in the laboratory and so were not constrained to the relationship expected between rise time and overpressure in real sonic booms, the lengths, rise times and overpressures could be varied parametrically. Fifteen tanh shapes were chosen, which were presented at different amplifications in order to create a range of loudness levels, for a total of 33 test stimuli. Fifteen ramp shapes were chosen, which were presented at different amplifications in order to create a range of loudness levels, for a total of 32 test stimuli. Boom duration was varied from 50 to 200 ms and rise time from 3 to 36 ms. (The range of shapes are given in Table 1). All stimuli were presented at levels that gave PL values within the range 70-90 dB. Presentation levels were chosen to obtain a fairly uniform distribution of levels throughout the range. Figure 4 shows a sample of the pressure-time histories of the waveforms used in this study.

(b) Scaling Method

As the stimuli in this study were of relatively low loudness level, it was felt that the judgment of "annoyance" might cause some difficulties, in that some stimuli might be considered too quiet to be annoying. Therefore it was decided to use the criterion word "loudness." Subjects were asked to judge how loud each of the test sounds was compared to a reference sound. The reference was designated 100; the other test sounds were each to be assigned a number representing its loudness by comparison to the reference at 100. Though the magnitude estimation method initially seems difficult, after training and practice subjects were found to perform the task with ease. The reference sound was a ramp shape of 150 ms duration and 3 ms rise time, and was presented at 82 PLdB.

(c) Test Structure

Based on the findings of a previous study[7], the test structure consisted of one reference sound followed by three test sounds. The reference sound was then repeated, followed by three more test sounds. The repetition of the reference sound served to ground the subjects' responses. Each subject heard four sessions, three of 36 test sounds and one of 33. Ten random orders of the sounds were created, each of which was divided into four sessions. By reversing the order within sessions and balancing the presentation order of the sessions, a different presentation order of the test signals was used for each subject.

(v) Data Analysis

The booms were recorded in the SBS using a Bruel and Kjaer type-4193 low-frequency microphone. The resulting pressure/time histories were computer-processed to calculate four loudness metrics as well as Sound Exposure Level in terms of three frequency weightings. The Sound Exposure Level metrics[8] were: unweighted Sound Exposure Level (USEL), C-weighted Sound Exposure Level (CSEL), and A-weighted Sound Exposure Level (ASEL). The loudness metrics were Stevens Mark VII Perceived Level (PL)[3,4], Perceived Noise Level (PNL)[8,9], Loudness Level using the Zwicker method (LLZ)[10,11], and Loudness Level using the method of Moore, Glasberg, and Baer (LLMG)[12]. All loudness metrics were based on the entire boom signal, as is described for PL in Shepherd and Sullivan[3].

The central tendency parameter used to characterize the subjective rating scores for each stimulus was the geometric mean of the magnitude estimates. It is most appropriate (see Stevens[13], for example) to use geometric averaging with magnitude estimation since the distribution of the logarithms of the magnitude estimates is approximately normal. Furthermore, subjective loudness is a power function of the physical intensity of a sound. Such a power function is linear when expressed in terms of the logarithms of the subjective loudness and sound pressure level in dB.

B. Results

(i) Metrics

Values of the Pearsons correlation (R) between the mean logarithmic loudness response and the various metrics for this study are given in Table 2. Clearly, unweighted and C-weighted SELs perform significantly less well than the other metrics. Table 3 shows R values for the present low-intensity boom test and for three of the previous tests performed under HSR, one that used simulated outdoor boom shapes[14], one that included symmetrical and asymmetrical boom shapes[6] and one that included waveforms based on recordings of sonic booms made by two USAF aircraft[15], showing similar trends across metrics. Figure 5 shows scatter plots of the mean of the logarithm of the subjective ratings for each of the complete set of 135 test sounds plotted against the values of various metrics, and demonstrates the better, more linear fits (thus higher correlation coefficients) of PL, SELA, etc. (The different groups of booms are indicated by symbol and color.) The candidate booms, with more complex waveforms than the N-waves, give results that do not differ significantly from those for the symmetric and N-wave booms.

(ii) Effect of Boom Asymmetry

The effect of asymmetry described in Leatherwood et al.[2,6] was investigated using the results of this low-intensity boom study. In the previous studies, it was found that asymmetric waveforms with a front shock having a lower calculated loudness than the rear shock were rated less loud by subjects than was predicted by PL. The difference in dB between the calculated PL of the front and rear parts of the boom was called the asymmetry factor. If the front part has a higher PL than the rear, this factor is given a positive sign. The results obtained in the present study were used to compare the ratings of 21 presentations of candidate booms with their front- and rear-symmetricized counterparts. Figure 6 shows the residual loudness rating (the actual value of the mean logarithmic response minus the value predicted by the straight line linear regression on PL) plotted against the asymmetry factor. It can be seen that the scatter in the data for the symmetrical booms is of the same order as that for the asymmetric booms. Thus no asymmetry effect is shown for booms with asymmetry values in PL between –5 and +6 dB. This is in agreement with the previous work, in which a significant asymmetry effect was only found for booms having front end loudnesses that were lower than the rear end by 10 PLdB or more.

(iii) Effect of Thickening Algorithms

An indicator variable analysis[16,17] was performed to investigate the different boom categories. Using the PL metric, it was found that the interaction terms were not significant, and therefore the slope of response against PL did not differ significantly between the categories. However, it was found that the intercepts varied significantly. Figure 7 shows scatterplots of the mean log response against PL for all booms, divided by category. Figure 7(a) shows the regression lines for each separate category, showing the similarity of slope across categories, while fig. 7(b) shows the regression lines calculated when a constant slope is assumed. The intercept for the candidate boom category does not differ significantly from that for the symmetricized booms. However, the intercept for the ramp-thickened boom category was found to differ from that for the tanh-thickened booms ($p=0.0012$); the two regression lines were found to be separated by 1.2 PLdB so a ramp boom is judged louder than a tanh boom of the same PL value by an amount equivalent to 1.2 dB. It is clear that the different thickening algorithms produce booms with different PL values, because of the added high-frequency energy in the ramp thickened booms. However, this PL difference underestimates the difference in loudness response. Thus when studying the loudness of sonic booms, it would be inadvisable to mix booms thickened with the tanh formulation with those thickened using the ramp method, because this effect is not accounted for by PL. SELA showed the same difference between tanh and tamp thickening, with a spacing between the regression lines of 2.5 dB; MGLL and LLZ showed a significant interaction between response and level across categories so the condition of equal slopes could not be assumed.

(ii) Zwicker Loudness and Boom Category Considerations

One interesting feature in Table 2 is the relatively modest performance of LLZ in the present study. When the different categories of boom used here (candidate, symmetricized, ramp, tanh) are separated (as shown in Table 2), it can be seen that LLZ performs noticeably less well with the tanh-thickened shapes than the other loudness metrics, while performing as well or better for the other categories. Further examination shows that there is a noticeable difference in the regression lines on LLZ for different rise-time values. Figure 8(a) shows the regression lines for responses to the tanh booms on PL and fig. 8(b) those on LLZ). Indicator analyses on the results of the tanh-thickened booms for PL and LLZ were performed. For PL, the slopes do not vary significantly across rise time, and the intercepts are statistically the same except for the 3 ms rise-time, which is separated from the others by 2.7 dB. For LLZ, again the slopes do not vary significantly across rise time, but the intercepts show differences for all rise times, except that those for 27 ms and 36 ms are statistically the same. Figures 8(c) and 8(d) show the regression lines from the indicator variable analysis for the ramp booms on PL and LLZ. The successive separations for LLZ are about 2 – 3 phons, and the order is consistent from 3 ms rise time, through 9 and 18 ms, to 27 and 36 ms, which are very close to each other. Thus, as the rise time gets shorter, there is an increase in loudness for booms of the same calculated LLZ. The same analysis was run on the data from the ramp-thickened booms, with the results shown in fig. 9. For PL, there is no significant differences in slope or intercept of the regression lines. For LLZ, the slopes are statistically equivalent, but there is some difference in the intercepts. However, instead of the progression of intercept with rise time, it was found that the 3 ms and the 36 ms rise-times from one group, and the 9, 18 and 27 ms rise times form another group, with about 2.5 phons separation.

3. CONCLUSIONS

In order to study sonic booms of low level (less than 1 psf) and short duration (~100 ms), a test was conducted at NASA Langley Research Center that included various predicted waveforms from designs of candidate low-boom aircraft. The test also included shapes based on the classic N-waves. The results of the low-intensity boom study fit well with the results of the previous NASA sonic boom simulator studies. The Stevens Perceived Loudness metric (PL) was found to be the best predictor of loudness (and, in the previous studies, annoyance). A-weighted Sound Exposure Level, Perceived Noise Level and Loudness Level using the method of Moore, Glasberg, and Baer were also good predictors of loudness. Asymmetry effects due to differences between the front and rear shocks of the boom were found to be not significant.

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Table 1 – Summary of parameters of N-wave booms

Rise time, ms	Duration, ms	# Levels for ramp shapes	# Levels for tanh shapes
3	50	3	3
	100	4	4
	150	2	3
	200	2	2
9	50	1	1
	100	2	2
	150	2	2
	200	2	2
18	100	2	2
	150	2	2
	200	2	2
27	150	2	2
	200	2	2
36	150	2	2
	200	2	2

Table 2 – Pearson Correlation Coefficients between subjective rating and calculated metric for Low-Intensity Boom Study. Also shown are results for various categories of boom used in this study.

Metric	all	Boom Categories				
	booms	tanh	ramp	candidate	symm.	all except tanh
PL	0.931	0.941	0.979	0.938	0.950	0.950
ASEL	0.930	0.955	0.968	0.934	0.939	0.946
PNL	0.919	0.938	0.966	0.926	0.929	0.936
MGLL	0.916	0.915	0.976	0.935	0.906	0.925
LLZ	0.838	0.659	0.928	0.955	0.951	0.924
CSEL	0.498	0.274	0.596	0.798	0.665	0.619
USEL	0.295	0.040	0.130	0.761	0.356	0.404

Table 3 – Pearson Correlation Coefficients between subjective rating and calculated metric for the present study and three previous sonic boom studies[14,15,16]

Metric	Low Booms	Outdoor	Sym/Asym	Realistic booms
PL	0.931	0.957	0.971	0.954
ASEL	0.930	0.944	0.968	0.917
LLZ	0.838	0.915	0.956	0.966
CSEL	0.498	0.812	0.913	0.850
USEL	0.295	0.650	0.864	0.770

Fig 1 – Sonic boom simulator at NASA Langley Research Center.

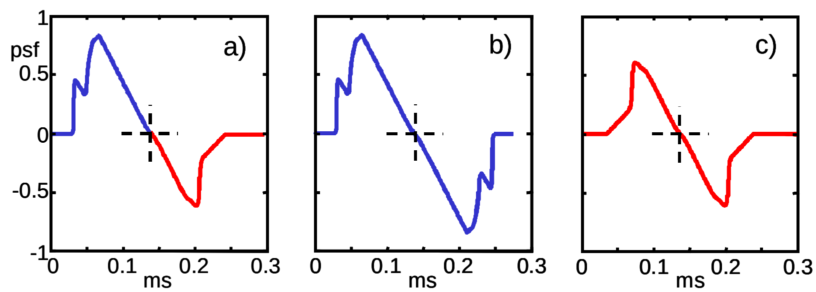

Fig 2 - Example of creating symmetrical booms from asymmetrical waveforms:
a) Original boom shape, b) Symmetricized using front part,
c) Symmetricized using back part

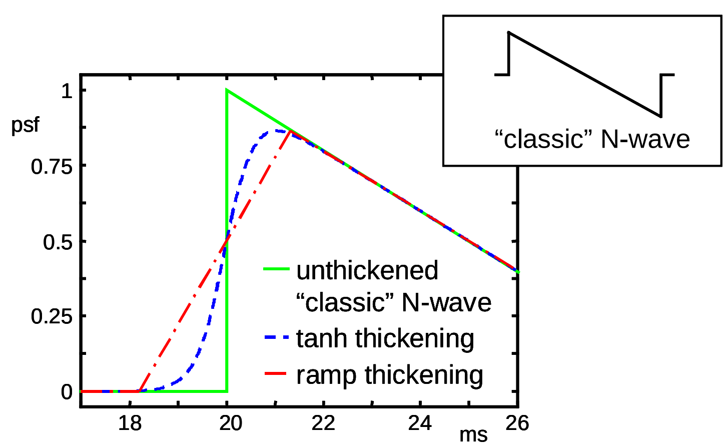

Fig 3 - Front shock of sample unthickened "classic" N-wave, with two thickened shapes, based on tanh and ramp.

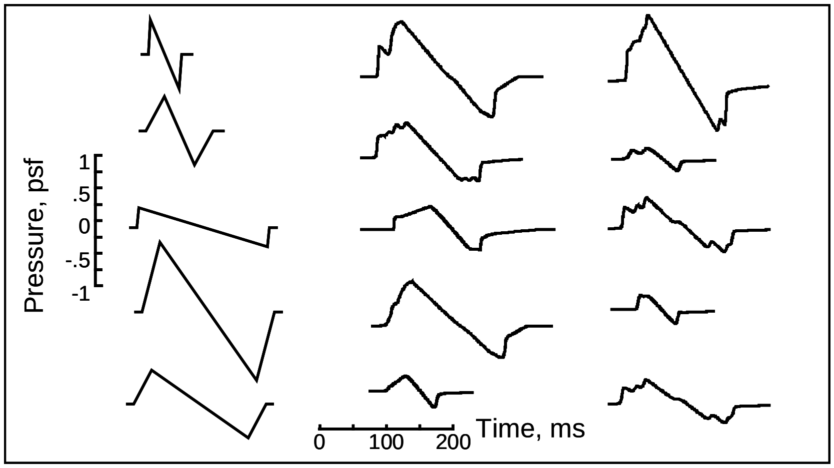

Fig 4 - Sample boom waveforms from Low-Intensity Boom study

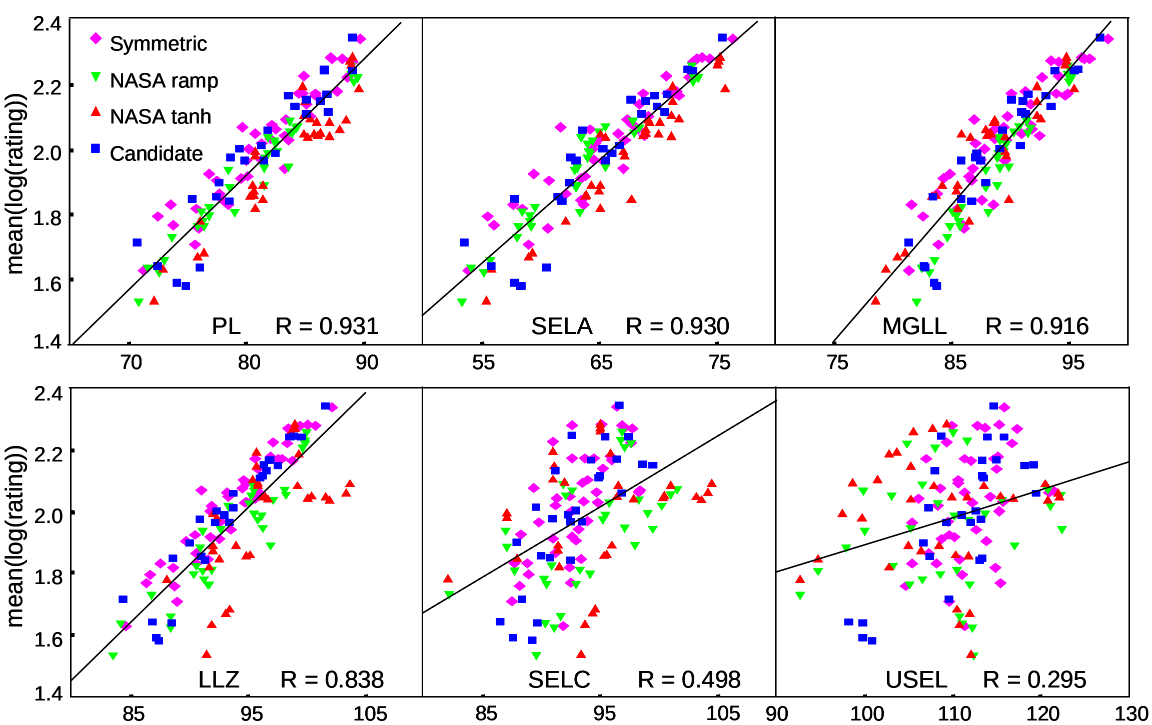

Fig 5 - Distributions of the mean logarithm subjective rating against the values of various metrics. Also shown are the correlation coefficients (R).

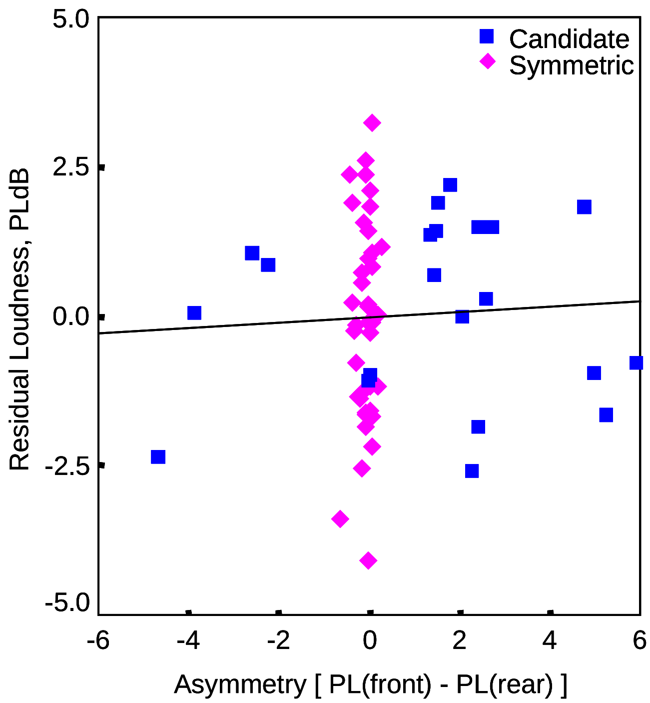

Fig 6 – Residual PL data as a function of front/back asymmetry in PL for 21 asymmetric booms, and their symmetricized equivalents.

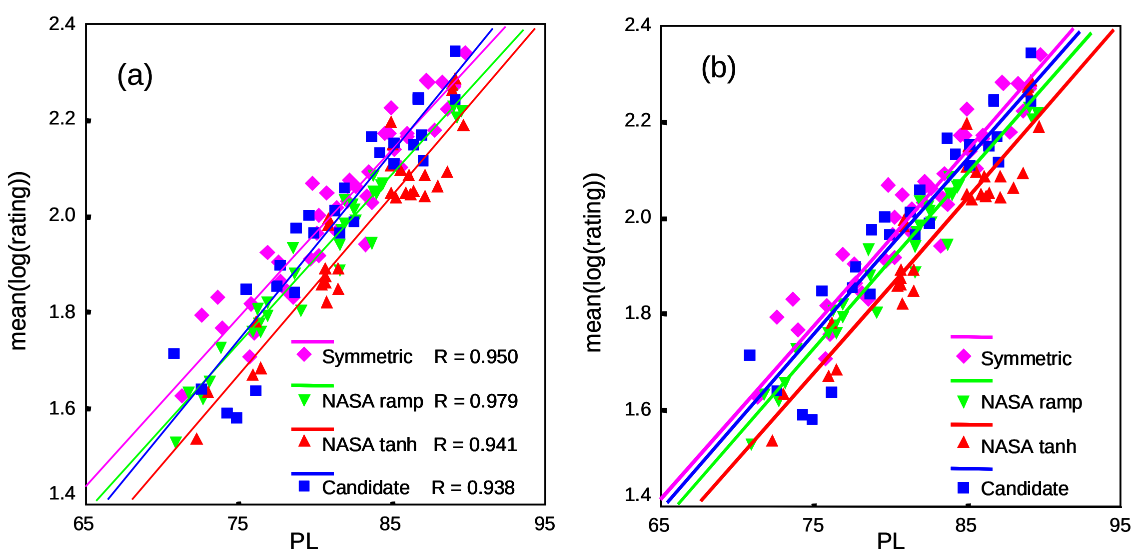

Fig 7 - Distributions of the mean logarithm subjective rating against the values of PL for the different boom categories

(a) showing linear regression lines and the correlation coefficients (R) for each category

(b) showing regression lines from the indicator variable analysis, assuming same slope for all categories.

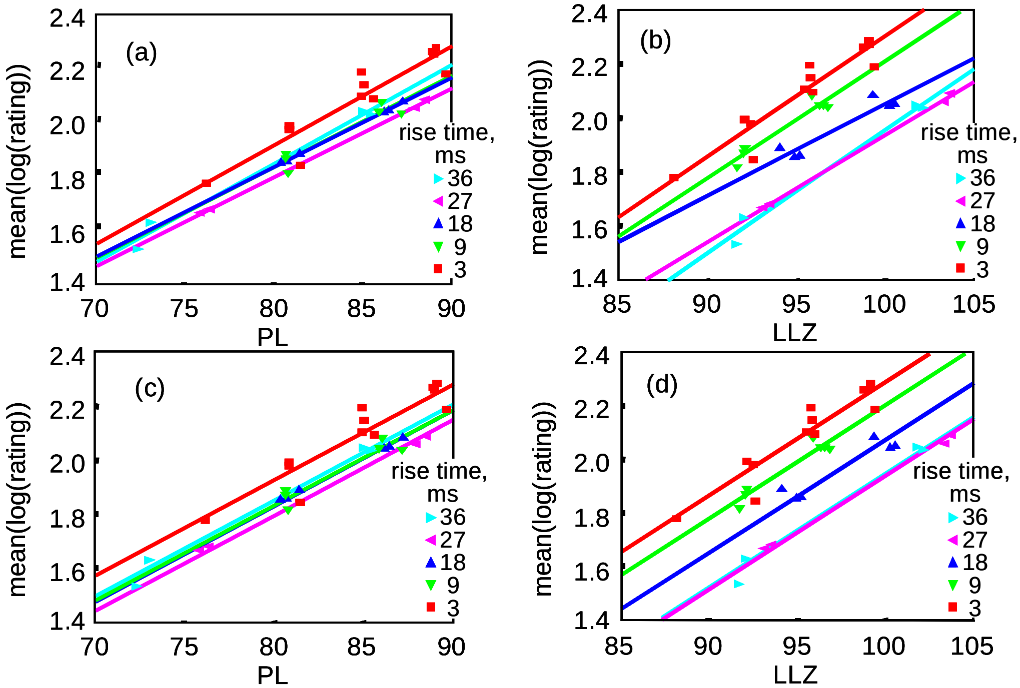

Fig 8 - Distributions of the mean logarithm subjective rating against metric values for the tanh-thickened booms for different values of rise time
(a) and (b) showing linear regression lines for individual rise times for PL and LLZ
(c) and (d) showing regression lines from the indicator variable analysis for PL and LLZ, assuming same slope for all rise times within each metric

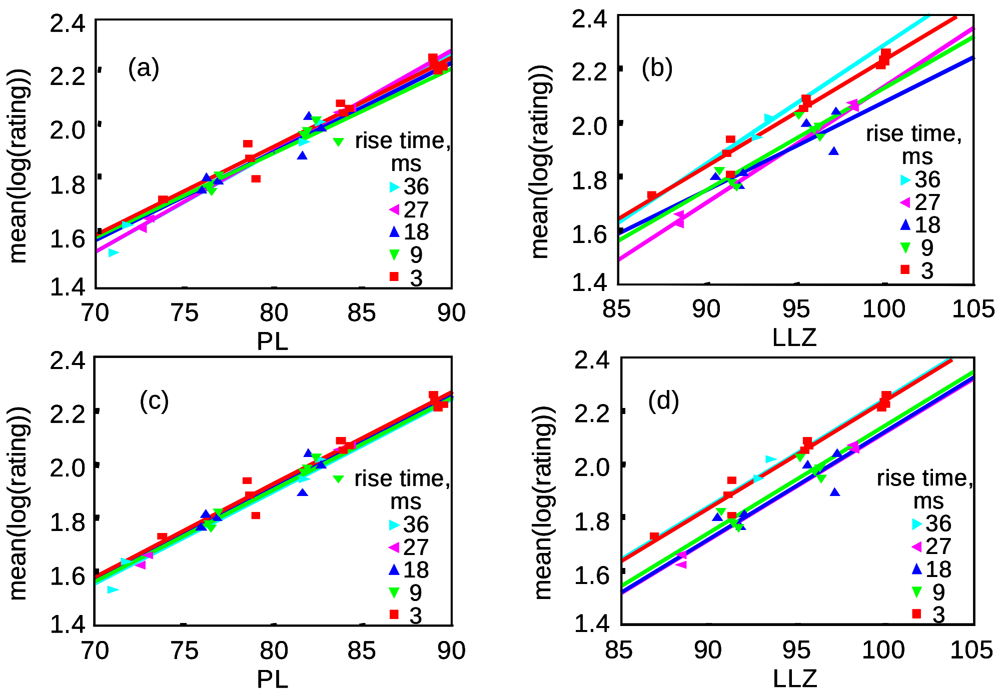

Fig 9 - Distributions of the mean logarithm subjective rating against metric values for the ramp-thickened booms for different values of rise time
(a) and (b) showing linear regression lines for individual rise times for PL and LLZ
(c) and (d) showing regression lines from the indicator variable analysis for PL and LLZ, assuming same slope for all rise times within each metric