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SUBJECTIVE LOUDNESS OF SONIC BOOM: N-WAVE AND MINIMIZED ('LOW-B--ETC(U)
NOV 77 A NIEDZWIECKI, H S RIBNER AFOSR-75-2808
UNCLASSIFIED UTIAS-TN-215 AFOSR-TR-78-0122 NL

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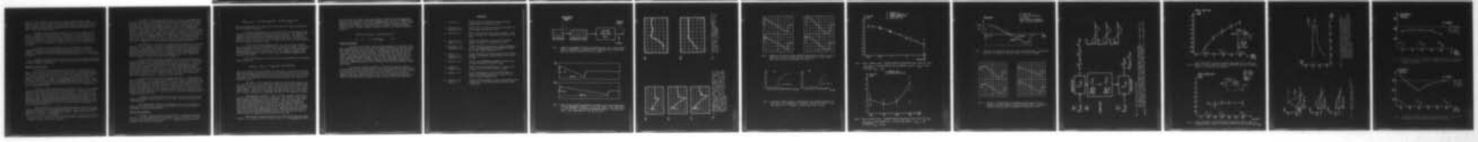

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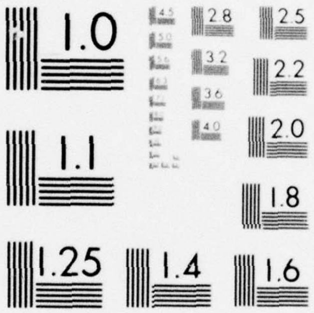

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SUBJECTIVE LOUDNESS OF SONIC-BOOM: N-WAVE AND MINIMIZED ('LOW-BOOM') SIGNATURES

by

A. Niedzwiecki and H. S. Ribner

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November, 1977

UTIAS Technical Note No. 215
CN ISSN 0082-5263

⑱ **REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER
AFOSR-TR- 78 - 0122 ✓

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
SUBJECTIVE LOUDNESS OF SONIC BOOM: N-WAVE AND MINIMIZED ('LOW-BOOM') SIGNATURES.

5. ~~TYPE OF REPORT & PERIOD COVERED~~
⑨ INTERIM Rept. 1 Jan - 31 Dec 77,
~~Jan. 1 - Dec. 31, 1977~~

6. PERFORMING ORG. ~~REPORT NUMBER~~
⑭ ~~UTIAS TN~~ [redacted]. 215 UTIAS-TN-215

7. AUTHOR(s)
⑩ A. NIEDZWIECKI
H. S. RIBNER

8. CONTRACT OR GRANT NUMBER(s)
⑮ ✓ AFOSR-75-2808 new

9. PERFORMING ORGANIZATION NAME AND ADDRESS
UNIVERSITY OF TORONTO,
INSTITUTE FOR AEROSPACE STUDIES, ✓
4925 DUFFERIN ST., DOWNSVIEW, ONTARIO, CANADA M3H 5T6

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
⑯ 2307A2 ⑰
61102F

11. CONTROLLING OFFICE NAME AND ADDRESS
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA
BLDG. 410,
BOLLING AIR FORCE BASE, D.C. 20332

12. ~~REPORT DATE~~
⑪ Nov [redacted]77

13. NUMBER OF PAGES
⑫ ~~33~~ 23 p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
ACOUSTICS
SONIC BOOM
AERO-ACOUSTICS
PSYCHOACOUSTICS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A loudspeaker-driven simulation booth with extended rise-time capability (down to 0.22 ms) has been used for subjective loudness tests of sonic booms. Test series I compared N-waves over a range of 0.22 to 10 ms rise time, 100 to 250 ms duration and 0.5 to 2.0 psf (24 to 96 N/m²) peak overpressure. In one sequence, tradeoff between rise time and overpressure was measured for equal loudness; in another, the tradeoff between duration and overpressure. For equal loudness 10 ms rise time required 8 dB higher overpressure than for 1 ms

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rise time. Duration had little effect in the range 100 to 200 ms but at 250 ms noticeably enhanced the loudness. These results confirm those measured by Shepherd and Sutherland, made at 1 ms rise time and above (except for the anomalous enhancement at 250 ms duration), and extend the measurements down to 0.22 ms. There is also good agreement with theoretical predictions (Johnson-Robinson, Zepler-Harel methods) except for the 10 ms rise time and 250 ms duration cases.

Test series II xompared certain 'flat-top' sonic boom signatures with a reference N-wave (0.5 psf, 1 ms rise time, 150 ms duration). According to current theory, such 'flat top' signatures would be generated by a special family of very long SST aircraft designed for minimized sonic boom: the front shock (Δp_{SH}) is followed by a linear rise to peak amplitude (Δp_{MAX}) followed by the usual linear decay. For equal subjective loudness, flat top vs N-wave (peak overpressure Δp_N) the peak amplitude of the 'flat top' signature was substantially higher than that of the N-wave; thus for equal amplitude the 'flat-top' signature was quieter. The results for equal loudness were well fitted by an empirical law $\Delta p_{SH} + 0.11\Delta p_{MAX} = \Delta p_N$; the equivalence shows how the front shock amplitude Δp_{SH} dominates the loudness. All this was found compatible with predictions by the method of Johnson and Robinson.

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Submitted October, 1977

November, 1977

UTIAS Technical Note No. 215
CN ISSN 0082-5263

Acknowledgement

This research was supported by funds from Transport Canada Research and Development Centre (TDC), the National Research Council of Canada, and the United States Air Force Office of Scientific Research under Grant AF-AFOSR 75-2808B.

Summary

A loudspeaker-driven simulation booth with extended rise-time capability (down to 0.22 ms) has been used for subjective loudness tests of sonic booms. Test series I compared N-waves over a range of 0.22 to 10 ms rise time, 100 to 250 ms duration and 0.5 to 2.0 psf (24 to 96 N/m^2) peak overpressure. In one sequence, tradeoff between rise time and overpressure was measured for equal loudness; in another, the tradeoff between duration and overpressure. For equal loudness 10 ms rise time required 8 dB higher overpressure than for 1 ms rise time. Duration had little effect in the range 100 to 200 ms but at 250 ms noticeably enhanced the loudness. These results confirm those measured by Shepherd and Sutherland, made at 1 ms rise time and above (except for the anomalous enhancement at 250 ms duration), and extend the measurements down to 0.22 ms. There is also good agreement with theoretical predictions (Johnson-Robinson, Zepler-Harel methods) except for the 10 ms rise time and 250 ms duration cases.

Test series II compared certain 'flat-top' sonic boom signatures with a reference N-wave (0.5 psf, 1 ms rise time, 150 ms duration). According to current theory, such 'flat top' signatures would be generated by a special family of very long SST aircraft designed for minimized sonic boom; the front shock (Δp_{SH}) is followed by a linear rise to peak amplitude (Δp_{MAX}) followed by the usual linear decay. For equal subjective loudness, flat top vs. N-wave (peak overpressure Δp_N, the peak amplitude of the 'flat top' signature was substantially higher than that of the N-wave; thus for equal amplitude the 'flat-top' signature was quieter. The results for equal loudness were well fitted by an empirical law $\Delta p_{SH} + 0.11\ \Delta p_{MAX} = \Delta p_N$; the equivalence shows how the front shock amplitude Δp_{SH} dominates the loudness. All this was found compatible with predictions by the method of Johnson and Robinson.

CONTENTS

PART I

SUBJECTIVE LOUDNESS OF N-WAVE SIGNATURES VS. RISE TIME AND DURATION

INTRODUCTION

There is continuing interest in human response to sonic-boom type pressure waveforms. In particular, the role of the rise time and duration of the N-wave signatures in controlling the subjective loudness have been under study. One of the central problems is the prediction of the loudness given the shape or spectrum of the sonic-boom signature.

To date several investigators have suggested alternative procedures for determining the apparent loudness of such impulsive sounds. Von Port (Ref. 1) in a spectral approach, utilized an "effective" continuous sound concept: he assumed that the ear integrated the signal power over a time duration of 70 milliseconds. In 1969, Johnson and Robinson (Ref. 2) carried out further sonic-boom subjective loudness studies, examining the separate effects of duration and rise time. The technique adopted in this later work follows the earlier work of Von Port in defining an equivalent continuous sound pressure level. The subjective loudness is then calculated using the 1/3 octave band procedures developed by Stevens (Ref. 3) for steady sounds. The results obtained showed no dependence of the subjective loudness on the duration of the boom. However, large loudness changes (about 25 phons) were predicted for rise-time and delay-time variations in the range 0-16 milliseconds.

Experimental subjective studies with sonic-boom signatures have been conducted by Zepler and Harel (Ref. 4) and also by Shepherd and Sutherland (Ref. 5). In the former case subjects compared signals presented by means of the high-quality earphones, with "practically flat" response between zero and 1500 Hz, to pure tones at 400 Hz. In the latter study special low frequency loudspeakers coupled to an airtight chamber (booth) were employed to develop the boom signatures; these were evaluated subjectively using a paired-comparison technique.

The present experiments are very similar in concept to those of Shepherd and Sutherland. However, the simulation booth has been designed for five-fold shorter rise time capability. Additionally, a computer-aided technique has been developed for more faithful wave form simulation.

EXPERIMENTAL TECHNIQUE

The UTIAS Sonic Boom Simulation Booth (Ref. 6) consists of an airtight 2.1 m^3 volume chamber driven by 12 loudspeakers mounted in apertures in the wall faced by the subject. The booth features a double-wall plywood construction with inside wall surfaces heavily lined with sound-absorbing fiberglass to minimize reflections and consequent resonances at the higher frequencies; the free-air volume is thus reduced to about 1.3 m^3.

Six 15 inch low-frequency loudspeakers and six 8 inch medium-frequency loudspeakers are used with a crossover network at 500 Hz. The electronic system consists of four dc -20,000 Hz 100 W amplifiers plus an equalizing network to compensate for speaker and booth coloration of the frequency response. The main element of the equalizing network is an Altec Lansing Model 729A "Acousta-Voicette" containing twenty-four one-third octave filters centered at frequencies from 12,000 Hz down to 63 Hz; each filter is adjustable over a range ± 12 dB. Additional filters utilizing summation circuitry are used to control the response of the system in the frequency range 0.1 Hz to 60 Hz. Careful adjustment of these filters compensates for the major part of the non-uniform frequency response of the basic system, elmininating much of the waveform distortion. The basic scheme of this sonic-boom simulation system is shown in Fig. 1.

In addition, a special noise-squelch circuit decreases the background noise: the system is triggered (using signals recorded on the second channel of the tape recorder) permitting the loudspeakers to be switched off during the intervals between the test sounds. The total simulation system has nearly flat response over the frequency range from 0.1 to 5000 Hz and permits a relatively accurate reproduction of N-wave and other pressure signatures.

The test signals used in the experiment were generated in digital form (Fig. 2) by the HP 2100A computer and converted to analogue form with conventional fast D/A equipment. The computer output was recorded on a Bruel and Kjaer FM tape recorder featuring uniform frequency response from dc to 5000 Hz. Examples of N-wave sonic-booms reproduced in this facility for the tests of Part I herein are shown in Figs. 3 and 4. A later improved waveform is exhibited in the top left panel of Fig. 5.* Substantial further improvement in waveform fidelity (Fig. 5) is afforded by a computer-based "predistortion" scheme, described and utilized in Part II; this scheme was not yet introduced in the Part I investigation described below.

Two separate series of sonic boom comparisons featuring N-wave signatures were carried out with twenty subjects (UTIAS male graduate students). In the first series the boom duration was held constant at 200 milliseconds, the rise times were varied over the range 0.22 to 10 ms, and the peak overpressures over the range 0.5 to 2.5 psf (25 to 96 N/m^2). For each rise time the overpressure was adjusted until the subject judged the signal to sound just as loud as a reference N-wave with 1 ms rise time, 1 psf (48 N/m^2) overpressure, and 200 ms duration. In this fashion contours of equal loudness vs. rise time were developed.

In the second series of tests the sonic-boom rise time was held constant at 1 millisecond and a second equal-loudness contour (overpressure ratio vs. duration) was defined by additional comparison tests using the signatures of duration time from 100 to 250 msec and overpressures from 0.5 to 2 psf (24 to 96 N/m^2). The reference N-wave was the same as the previous one.

The sonic-boom characteristic parameters were measured from the oscilloscope photographs using a B & K one-inch microphone incorporating a random-incidence corrector mounted in the booth at approximately the subject's ear level. In both cases the overpressure steps during the comparison experiment were 2 dB.

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* Figure 3 represents a substantial deterioration in waveform simulation compared with Figs. 4-9 of Ref. 6. This appears to have been associated with faults developing in the compensating filters (Fig. 1). Repairs and adjustments led to the improved N-wave simulation shown in the upper left hand panel of Fig. 5.

Audiograms were obtained before and after each experimental session for all observers. In addition these observers were examined by a qualified otolaryngologist and found to have normal hearing.

During each 15-20 minute test session sonic-boom signals in pairs were presented to the subjects while seated singly in the booth. They were required to identify which sound in the pair was judged to be the louder and to communicate this verbally through the intercom to the experimenter. Three judgement scores were used: "louder", "may be louder", and "equal loudness". Thus a set of five numerical scores was obtained:

Test boom louder = -2

Test boom may be louder = -1

Both equally loud = 0

Reference boom may be louder = 1

Reference boom louder = 2

The signals were presented to the observers in random order.

The results for each value of rise time or duration (obtained through the series of comparisons) were plotted in the form of graphs - relative loudness (in scores) vs. overpressure ratio between the test and reference signals, for every subject. Two typical examples are shown in Fig. 6. From each graph the overpressure ratio for equal loudness (score = 0) was determined and the average of these values for all twenty subjects was used to construct the final curves.

RESULTS AND DISCUSSION

The two experimentally determined equal-loudness contours for the N-wave signatures are plotted in Figs. 7 and 8, i.e., (i) overpressure ratio vs. rise time, Fig. 7 (duration 200 msec), (ii) overpressure ratio vs. duration, Fig. 8 (rise time 1 msec). The overpressure ratio is defined by $\Delta p_{\text{level ratio}}$ where,

$$\Delta p_{\text{level ratio}} = -20 \log_{10} \frac{\Delta p_{\text{test}}}{\Delta p_{\text{ref}}} = -20 \log_{10} \frac{\Delta p_{\text{test}}}{1 \text{ psf}}$$

Each subject carried out approximately 180 judgements during the course of the two test series. The curves drawn in Figs. 7 and 8 are based on the averaged data calculated from the experimental results for each individual subject. The experimentally determined standard deviation for each plotted point is indicated by the vertical bars on the graphs. It was noted that the deviations among the individual-comparison results increased progressively as the differences between the features of the reference-boom signature and the test-boom signature increased. This reflects the increasing comparison difficulties. The standard deviation is typically 1 dB; for booms with rise times of 10 msec (duration 200 msec) it rises up to 3.5 dB, and for booms having a duration of 250 msec (rise time 1 msec) it is about 1.4 dB.

Along with the present results (labeled Niedzwiecki) Fig. 7 reproduces the experimental results of Zepler and Harel (Ref. 4) and Shepherd and Sutherland (Ref. 5), along with the predictions by Johnson and Robinson (Ref. 2) (only the first two go down below 1 ms rise time). There is generally good agreement over the common range, essentially within the error bars. The predicted decrease in loudness with increasing rise time is very marked above 0.5 ms. At 10 ms rise time the results are somewhat divergent, but with a large experimental uncertainty. The present results seem to agree best with the predictions of Johnson and Robinson.

Both Shepherd and Sutherland (experiment), and Johnson and Robinson (theory) find a negligible influence of the sonic-boom duration on the subjective loudness. The results of the present study, on the other hand, indicate an abrupt rise in the equal-loudness curve of the overpressure vs. duration (Fig. 8) for duration of 250 msec (rise time 1 msec).

CONCLUDING REMARKS

Tentative conclusions based on the above indicate reasonably consistent trends with the earlier theoretical and experimental subjective boom data, except for the effects of the longer boom durations (in excess of 250 msec) shown in Fig. 8. The substantial rise in the equal-loudness contour in this case remains unexplained. The present experimental data adds additional confidence to the existing theoretical methods of predicting the subjective loudness of sonic boom N-wave signatures (especially the Johnson and Robinson procedure) in an expanded parameter range given by

Rise time	0.22 to 10 msec
Duration	100 to 250 msec
Peak overpressure, Δp	$\left\{\begin{array}{l}25 \text{ to } 50\ \mathrm{N/m^2} \\ 1 \text{ to } 2\ \mathrm{psf}\end{array}\right.$

PART II

SUBJECTIVE LOUDNESS OF 'LOW-BOOM' SIGNATURES VS. WAVE FORM PARAMETERS

INTRODUCTION

One of the major problems that has limited development of supersonic civil aviation is the human annoyance caused by the sonic-boom. Therefore a prominent avenue of research has been the exploration of sonic boom minimization techniques. A promising approach suggested by McLean (Ref. 7) (which requires very long aircraft) has been developed by Seebass and George (Ref. 8) for flight in an isothermal atmosphere. The mathematical theory has been extended to the real atmosphere by Darden (Refs. 9, 10). This theory permits minimization of either the initial shock of the signature or the maximum overpressure by means of a specially tailored distribution of the aircraft cross-section and lift.

By means of such tailoring Darden computed a family of minimized signatures associated with certain proposed "second generation" SST configurations

(Fig. 9). The expectation was that for a given aircraft volume, weight, flight altitude and Mach number, these signatures should sound less loud than normal N-waves. This inspired the present investigation aimed at simulating these signatures in the UTIAS loudspeaker-driven booth and conducting jury tests of the subjective loudness.

Darden's signatures donot exhibit full fore-and-aft symmetry (cf Fig. 9). However, the Johnson-Robinson method (Ref. 2) for predicting loudness is predicated on fore-aft symmetry. For this and other reasons of a practical nature it was decided to replace Darden's signatures by symmetric ones in the tests, the relationship being as in Fig. 9. The differences are not great, and it is thought their effect on the subjective loudness should be minimal.

In the present investigation it has been attempted to establish experimentally the relationship between the subjective loudness of these 'low-boom' signatures and their characteristic parameters, i.e., the flat top duration D_1, and the ratio shock overpressure/peak overpressure ($x = \Delta p_{SH}/\Delta p_{MAX}$; cf Fig. 9).

In the last section of the report the Johnson and Robinson theoretical loudness prediction procedure (Ref. 2) has been verified and extended to the new 'low-boom' family of signatures.

TECHNIQUE AND PROCEDURE

The paired-comparison observations with the 'low-boom' signatures were carried out in the same UTIAS facility as for Part I (N-wave signatures). However, it was found that the simulation technique had to be further refined to reproduce properly these "flat top" waves; the inadequacy of the basic scheme of reproduction is shown in the top right-hand trace of Fig. 5. A substantial effort led to a scheme for predistorting the electrical input signal to counter the loudspeaker-booth distortion. The bottom curves in Figs. 5 and 10 show the very satisfactory N-wave and flat-top signatures resulting from such a predistorted input.

The scheme of this predistortion is outlined in Fig. 11. The complex frequency response of the simulator is designated $\Gamma(\omega)$; if this were a real constant (flat response) there would be no distortion.* The essence of the idea is to alter the electrical input signal spectrum by the inverse of $\Gamma(\omega)$. Then $\Gamma(\omega)$ cancels out; the predistortion $\Gamma(\omega)$ precisely counteracts the real distortion $\Gamma(\omega)$. Note that this cancellation is effected by working in the frequency domain; the appealing but naive notion that one can cancel a distortion "bump" by a predistortion "valley" in the time-domain input signal is a crude oversimplification.

N-wave simulation is likewise greatly improved by use of the predistortion technique for the electrical input signal. This is shown on the left-hand panels of Fig. 5. It is unfortunate that the scheme had not yet been perfected for the Part I experiments.

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* More generally, a form $\Gamma_o e^{-i\omega t_o}$ for $\Gamma(\omega)$ would imply no distortion, but the signature would be delayed by a time t_o.

The steps of the predistortion procedure of Fig. 11 are implemented as follows: $F_1(t)$ is a test input signal (e.g., N-wave) and $F_2(t)$ the corresponding output signal from a microphone in the booth. $F_3(t)$ is the signal to be simulated: the desired microphone signal. The HP 2100A computer applies the standard Fast Fourier Transform procedure to derive the corresponding spectra: $\tilde{F}_1(\omega)$, $\tilde{F}_2(\omega)$, $\tilde{F}_3(\omega)$. Then the two spectral ratios in the centre box of Fig. 11 are evaluated to yield $\tilde{F}_4(\omega)$; this is a 'predistorted' input spectrum which will yield the desired output spectrum $\tilde{F}_3(\omega)$ according to (c) of Fig. 11. As predistorted input <u>signal</u> $F_4(t)$ in the time domain, the computer evaluates the inverse Fourier <u>transform</u> of $\tilde{F}_4(\omega)$. $F_4(t)$ is the correct predistorted electrical input signal that will yield the desired microphone signal $F_3(t)$ in the booth. Examples of $F_4(t)$ are shown in the upper panels of Fig. 10.

The whole process is done by a single Fortran program in the HP 2100A computer with 24K memory, Fast Fourier Transform hardware, and A/D and D/A converters. The computer-generated "predistorted" signatures are recorded on the Bruel and Kjaer FM tape recorder and played back into the amplifiers of the UTIAS Sonic-Boom Simulator. It is worth mention that the predistortion method can be applied to improve the reproduction of any type of impulsive sound, subject to bandwidth and amplitude limitations.

As for the previous N-wave experiments, the paired-comparison technique was employed. Two separate test-sessions were carried out. In the first set the flat top duration of the signatures was held constant ($D_1 = 30$ msec) and the ratio $x = \Delta p_{SH}/\Delta p_{MAX}$ (front shock overpressure/maximum overpressure ratio) varied within the range of 0.2 to 1.0. The equal-loudness contour (overpressure ratios vs. x) was defined through the comparison of these signatures with an N-wave reference signature having the same rise time (1 msec) and duration (150 msec), and overpressure $\Delta p_N = 0.5$ psf. Ten observers, all UTIAS male graduate students, took part in this experiment.

In the second test-series the overpressure ratio $x = \Delta p_{SH}/\Delta p_{MAX}$ was held constant at $x = 0.5$ and the equal-loudness contour (overpressure ratio vs. flat top duration) was determined for the 'low-boom' signatures having the flat top duration within the range of 10 msec to 60 msec at the duration 150 msec (i.e., from 0.0667 to 0.4 of the duration). The reference N-wave had the same duration (150 msec) and rise time (1 msec) as the previous one but the overpressure Δp_N was fixed at 1 psf. Eight observers, UTIAS male graduate students, took part in this experiment. In both cases the overpressure steps during the comparison tests were 2 dB.

Audiograms were obtained before and after each session for all test observers and each of them was found to have normal hearing by the qualified otolaryngologist.

The experimental procedure, the judgement scores and the manner of obtaining the equal-loudness curves were the same as in the previous N-wave experiment (see Part I for details).

RESULTS AND DISCUSSION

Two equal-loudness contours derived from the experimental results for the 'low-boom' signatures are illustrated in Figs. 12 and 13. The first one shows the overpressure level ratio vs. $x = \Delta p_{SH}/\Delta p_{MAX}$, where the overpressure level ratio is defined by,

$$\Delta p_{\text{level ratio}} = -20 \log_{10} \Delta p_{MAX}/\Delta p_N = -20 \log_{10} \Delta p_{MAX}/1 \text{ psf}$$

The second graph shows the overpressure level ratio vs. flat top duration D_1 of the 'low-boom' signature.

The plotted equal-loudness curves are based on the averaged values calculated from the experimental results for each subject. The vertical bars indicate the experimentally determined standard deviation. The standard deviation of the equal-loudness contour based on the ratio x is within the range 0.8 dB to 1.3 dB and in case of the curve based on the flat top duration D_1 it is between 0.6 dB and 1.1 dB.

It was found in the experiment (Fig. 12) that for equal loudness the overpressure level ratio increases by 11.7 dB for an increase of the value of the parameter 'x' from 0.2 to 1.0. The actual properly scaled waveforms judged as equally loud are shown in Fig. 14. The comparison suggests that the subjective loudness of the 'low-boom' type of signature depends mainly upon the front shock.

More specifically, the results are well approximated by the empirical formula (Fig. 15),

$$\Delta p_{N\text{-wave}} = \Delta p_{SH} + 0.11\ \Delta p_{MAX} \text{ (low boom signature)}$$

for equal loudness (at equal duration and rise time). This tells us that the peak pressure Δp_{MAX} contributes only one ninth as much to the loudness as the front shock (and similarly for the rear half of the wave); that is, the front (and rear) shock amplitudes (for fixed rise time) dominate the loudness, as indicated earlier.

The effect on the subjective loudness of the flat top duration D_1 was shown in Fig. 13. The overpressure level ratio for equal loudness varies less than 1 dB with the increase of the duration D_1 from 0.667 to 0.4 of the total duration. This change is within the range of the error of the experimental method. Therefore, we can infer that the duration of the flat top of the 'low-boom' signature has negligible influence on the subjective loudness.

The experimental results of the 'low-boom' comparison tests were supported by theoretical loudness calculations. The loudness of each signature, judged as equally loud as the reference N-wave, was calculated from the energy spectrum obtained by FFT procedure. The Johnson and Robinson (Ref. 2) procedure for N-waves, based on the Stevens Mark VI method for continuous sounds (Ref. 3), was followed in the calculations. The loudness was calculated for the positive parts of the signatures only with a doubling to allow for the mirror-image negative part. Johnson and Robinson justify this on the ground that the separation between the front and rear shock is sufficiently long compared to the auditory critical time.

The results of these calculations are compared with the calculated loudness of the reference N-wave in Figs. 16 and 17. The <u>calculated</u> loudness (in phons) for all studied 'low-boom signatures' differs from the calculated loudness of the reference N-wave which sounds equally loud by less than 1 phon. This very good agreement of the empirical and theoretical results supports the viability of the Johnson and Robinson (Ref. 2) loudness comparisons between N-waves and the 'low-boom' family of signatures within the range of parameters given by

$$0.0667 \leq (D_1 \text{ duration} = D_2 \text{ duration}) \leq 0.4$$

$$0.2 \leq (x = \Delta p_{SH}/\Delta p_{MAX}) \leq 1.0$$

CONCLUDING REMARKS

A series of jury tests of the perceived loudness of 'low-boom' sonic boom signatures have been carried out and compared with theoretical predictions. The results indicate that the loudness is dominated by the amplitude ΔP_{SH} and rise time of the front and rear shocks. The peak amplitude can thus be much larger than that of an N-wave that sound equally loud. Put another way, an N-wave of the same peak amplitude will sound much louder than some of the low boom signatures. Based on Darden's (Refs. 9, 10) calculations of possible 'low boom' signatures for realizable aircraft, the attainable loudness reductions are roughly equivalent to those resulting from halving the present N-wave amplitudes.

The relative loudness predictions of the Johnson-Robinson theory conformed very well to the measurements. Thus their potential for applicability to a much broader range of transient sounds is indicated. In view of the uncertainty of the role of impulsive sound on hearing loss, further research to establish the applicability should be made. It is already clear that the rise time of impulsive sounds is a major parameter along with the peak amplitude.

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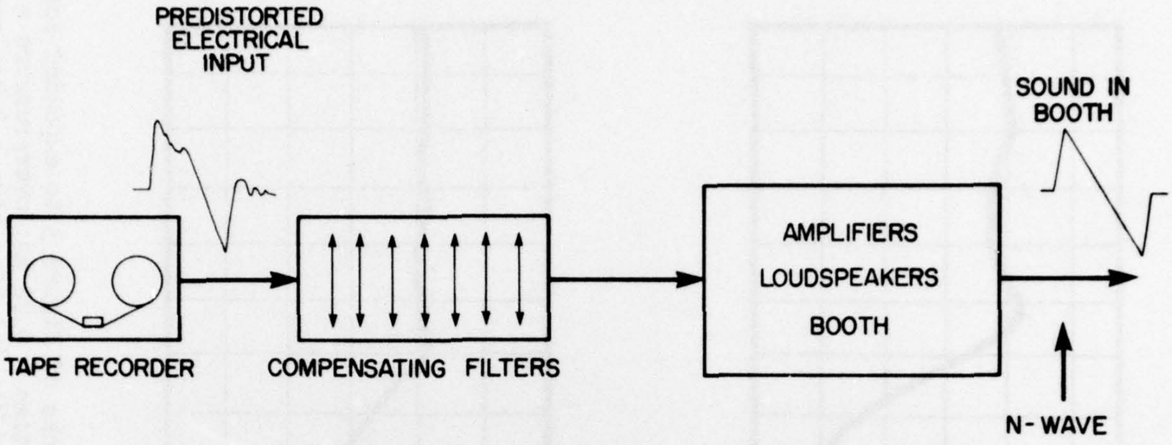

Fig. 1 Schematic arrangement of UTIAS loudspeaker-driven sonic boom simulation booth. Compensatory "predistortion" of electrical input signal (see text) was used for Part II, but not for part I.

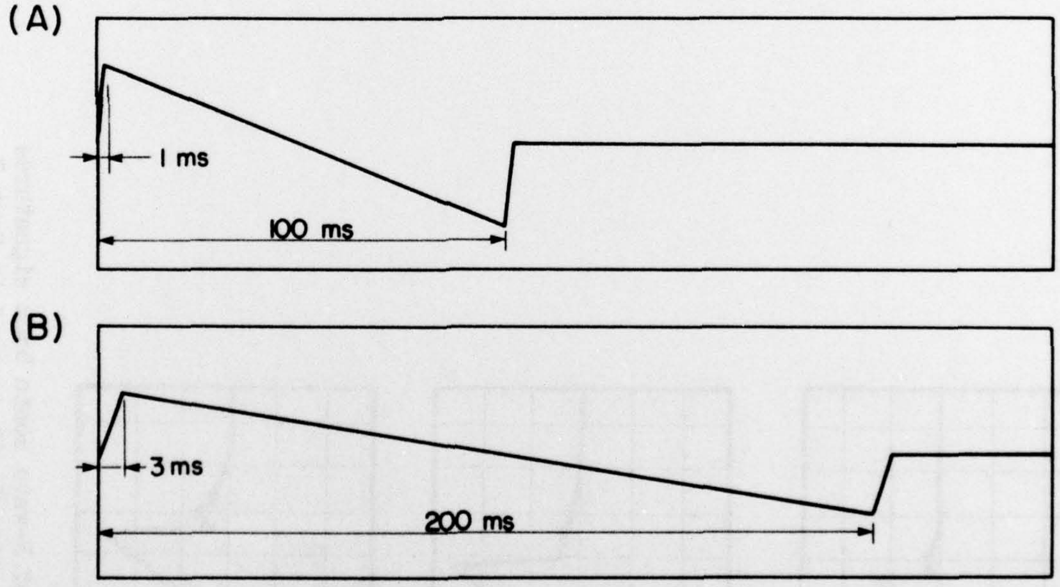

Fig. 2 Ideal N-wave signature generated by computer (rise time exaggerated). (a) Test signature: duration = 100 ms; rise time = 1 ms; overpressure = 2 psf (96 N/m^2); (b) Reference signature: duration = 200 ms; rise time = 3 ms; overpressure = 1.26 psf (60 N/m^2)

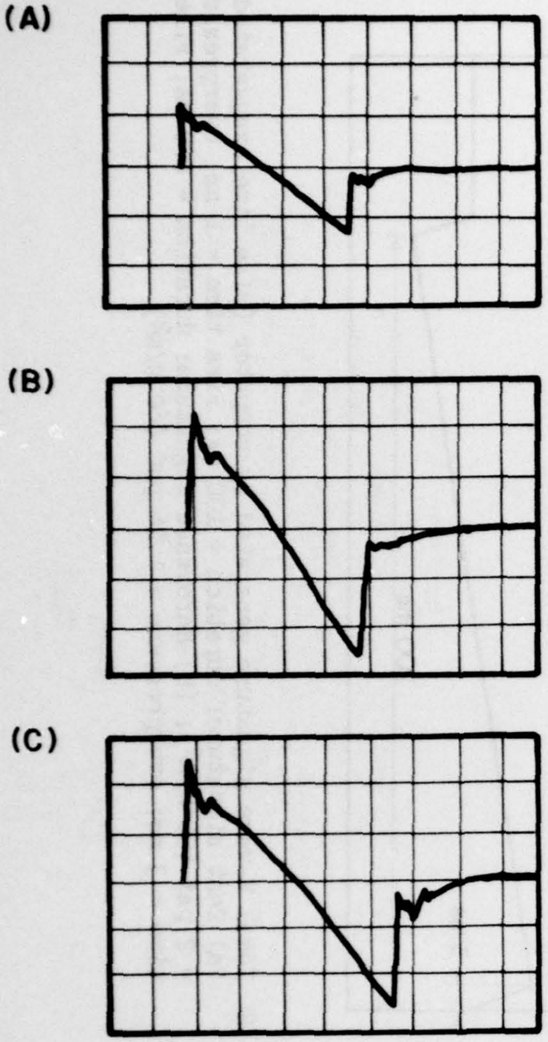

Fig. 3 Reproduction of N-wave sonic boom signatures by UTIAS simulation booth as used in Part I (no predistortion). (a) Rise time = 0.22 ms; duration = 200 ms; overpressure = 1 psf (48 N/m^2); (b) Rise time = 10 ms; duration = 200 ms; overpressure = 2 psf (96 N/m^2); (c) Rise time = 1 ms; duration = 250 ms; overpressure = 2 psf (96 N/m^2)

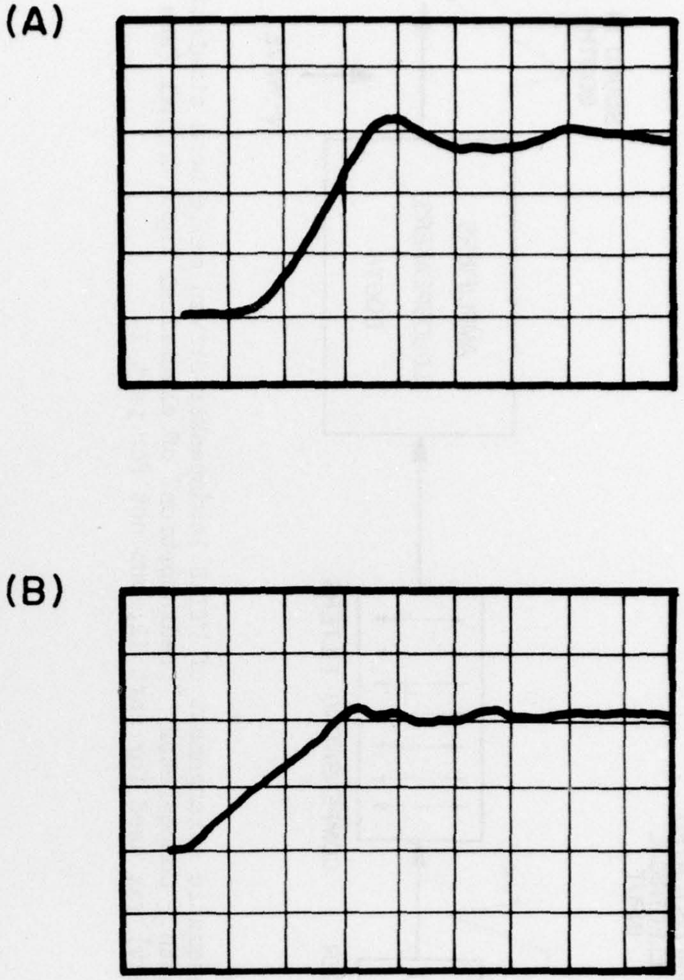

Fig. 4 Front shocks of Figure 3 to expanded scale. (a) Rise time = 0.22 ms; overpressure = 1 psf (48 N/m^2); (b) Rise time = 3 ms; overpressure = 1 psf (48 N/m^2).

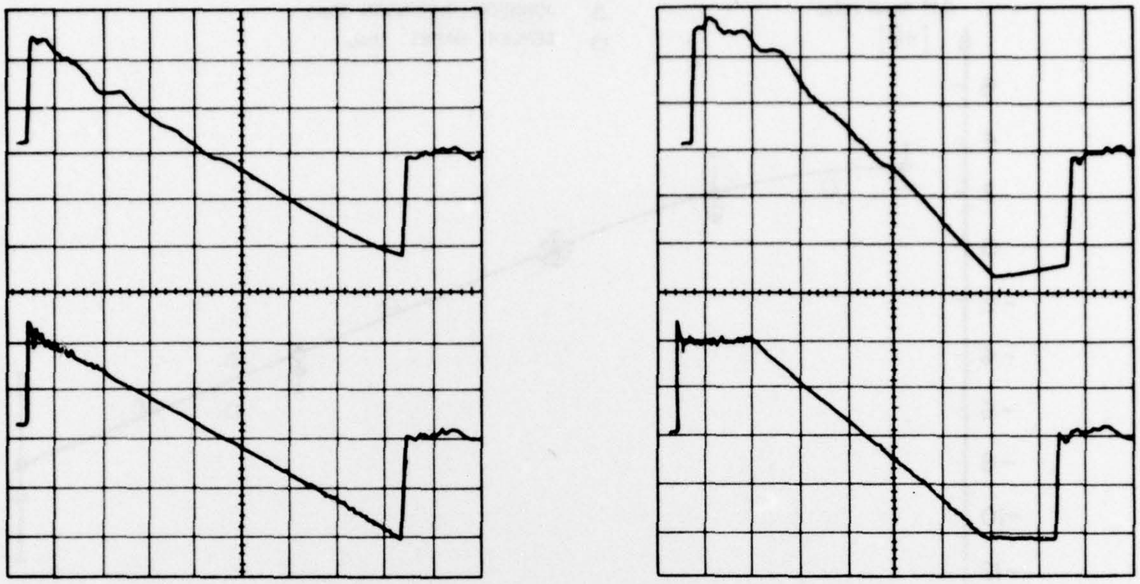

Fig. 5 Examples of pressure signals recorded by microphone in UTIAS simulation booth without (top) and with (bottom) predistortion of input signal. (See text concerning improvement over Figure 3.)

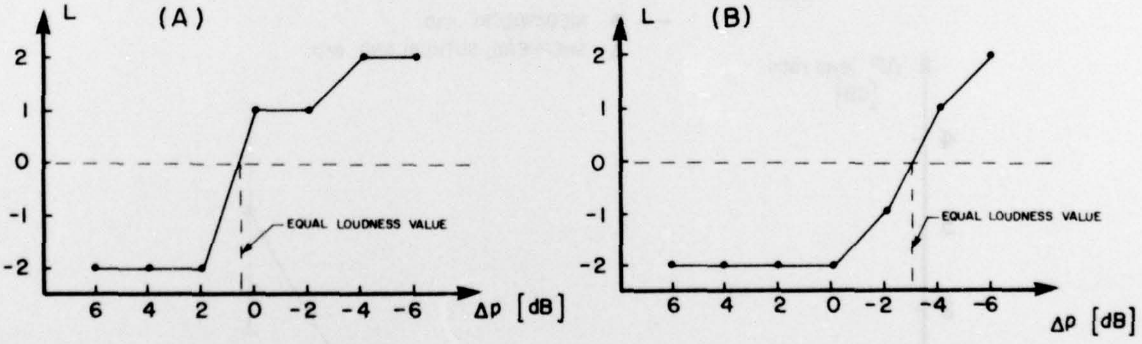

Fig. 6 Relative loudness scores vs overpressure ratio between reference and test boom. (a) Subject No. 4 - duration = 200 ms; rise time = 1 ms; (b) Subject No. 4 - duration = 200 ms; rise time = 0.5 ms.

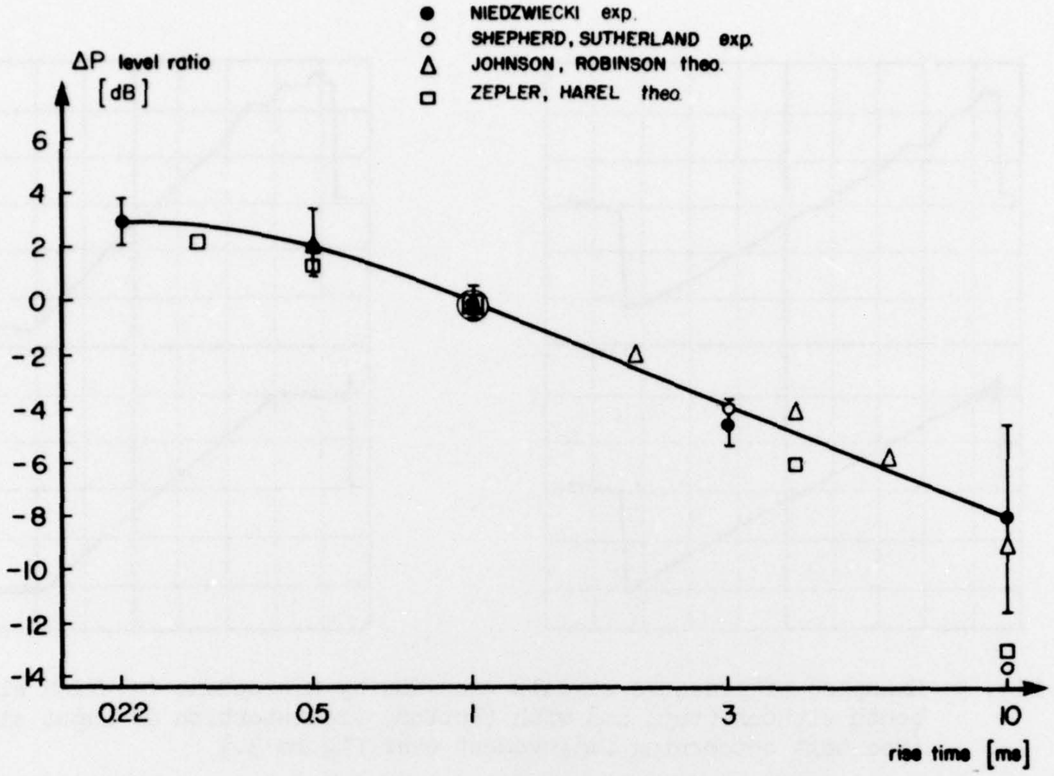

Fig. 7 Equal loudness curve. Tradeoff between overpressure level ratio (20 $\log_{10}$ $\Delta p_{ref}/\Delta p_{test}$) and rise time for 200 ms duration N-waves. Δp_{ref} = 1 psf (48 N/m^2), τ_{ref} = 1 ms.

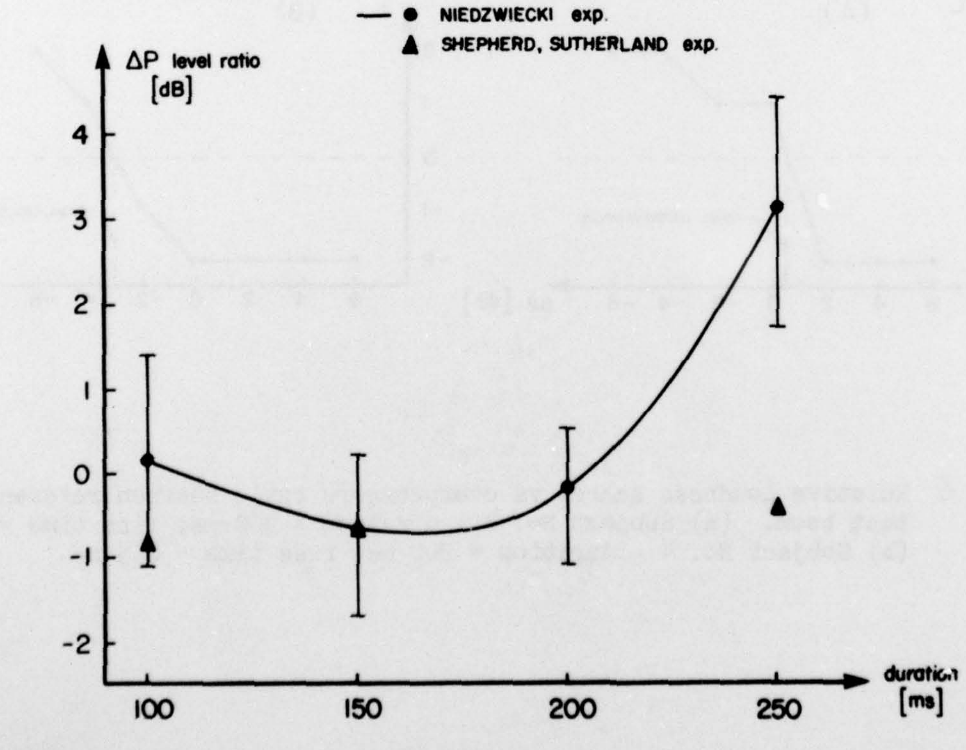

Fig. 8 Equal loudness curve. Tradeoff between overpressure level ratio (20 $\log_{10}$ $\Delta p_{ref}/\Delta p_{test}$) and duration for 1 ms rise time N-waves. Δp_{ref} = 1 psf (48 N/m^2); D_{ref} = 200 ms.

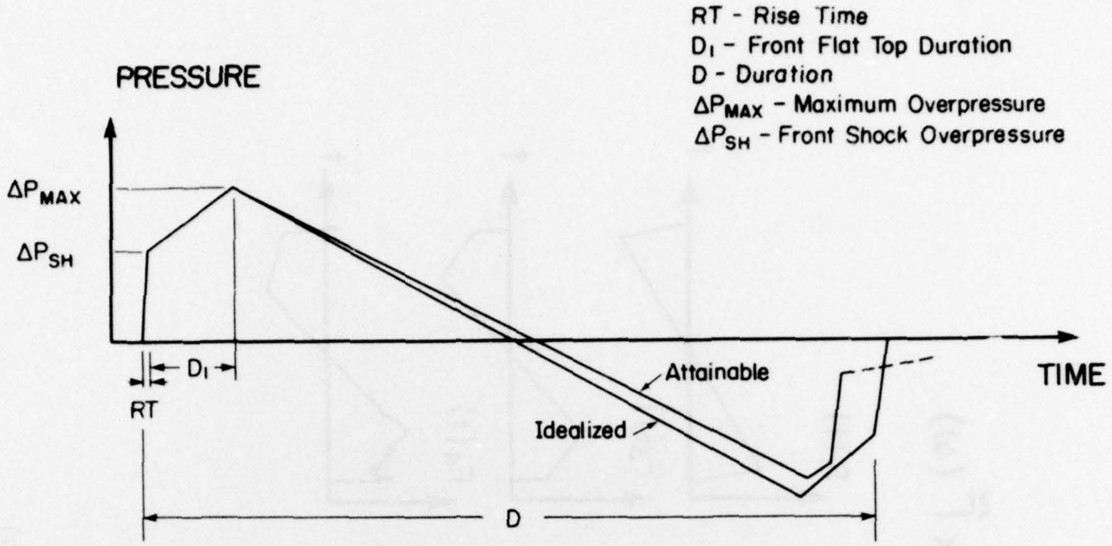

Fig. 9 Idealized vs attainable "low boom" sonic boom signatures. "Attainable" signifies realizable via aircraft design and flight procedure.

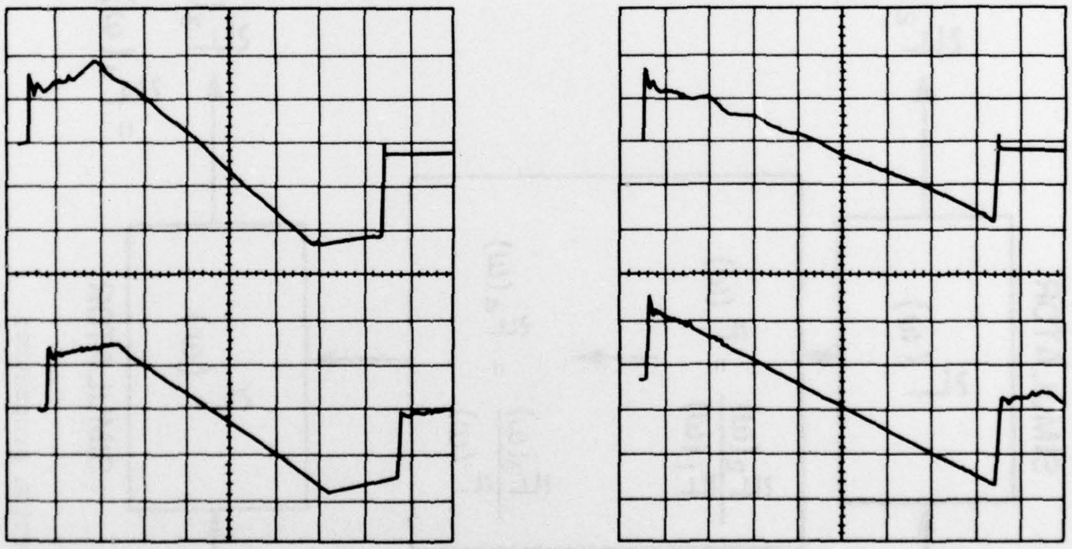

Fig. 10 Effect of "predistortion" of electrical input signals (top) to amplifiers driving UTIAS sonic boom simulation booth in achieving desired waveforms (bottom) recorded by microphone in booth.

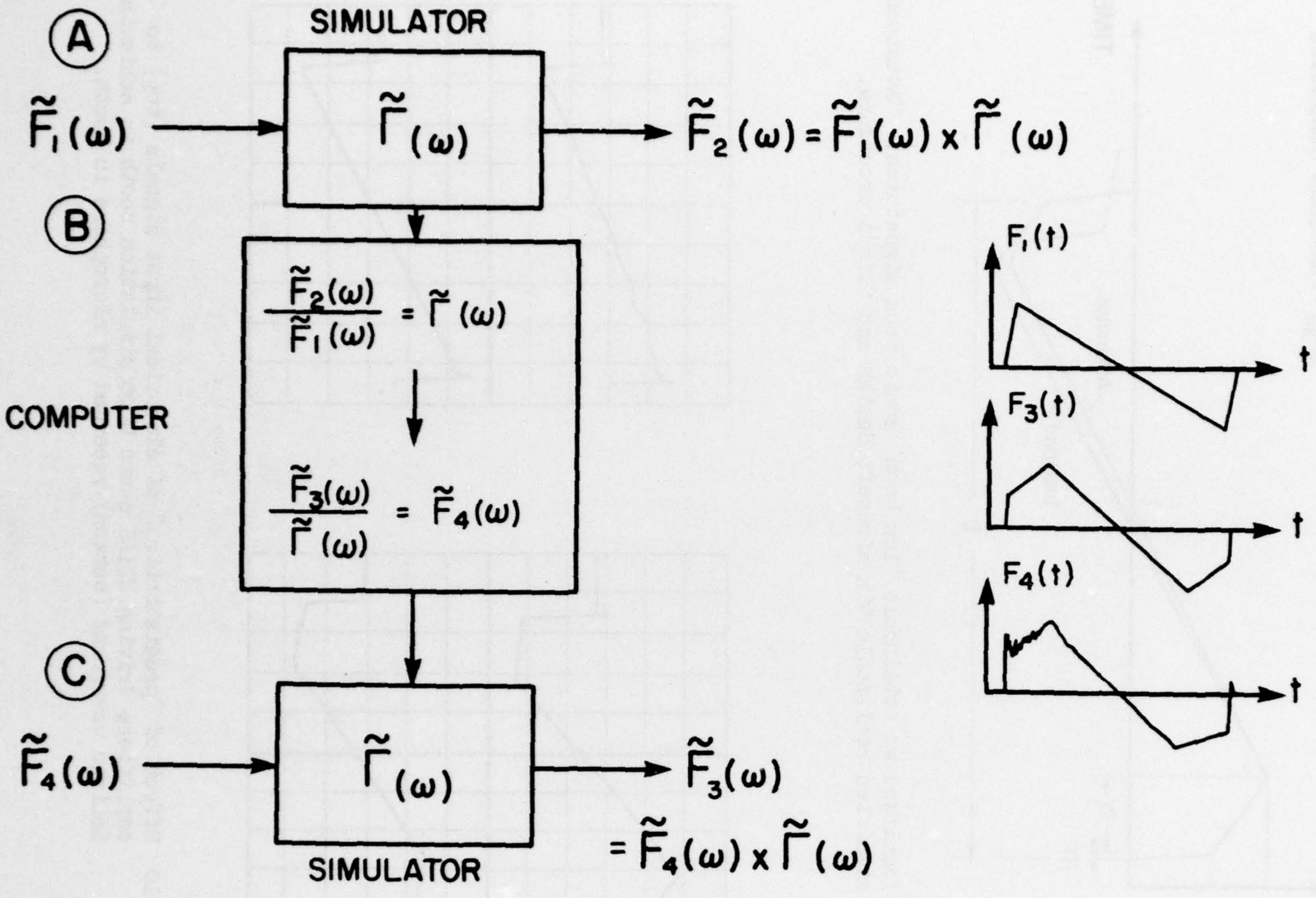

Fig. 11 The predistortion procedure:

(a) Transfer function measurement using signal $F_1(t)$ (see RH inset)
(b) Computation of transfer function of system $\tilde{\Gamma}(\omega)$ and "predistortion" of test signal $F_3(t)$
(c) Reproduction of "predistorted" signal $F_4(t)$ through the system

Computer performs implied direct and inverse FFT operations $F_1(t) \rightarrow \tilde{F}_1(\omega)$, etc., at appropriate points.

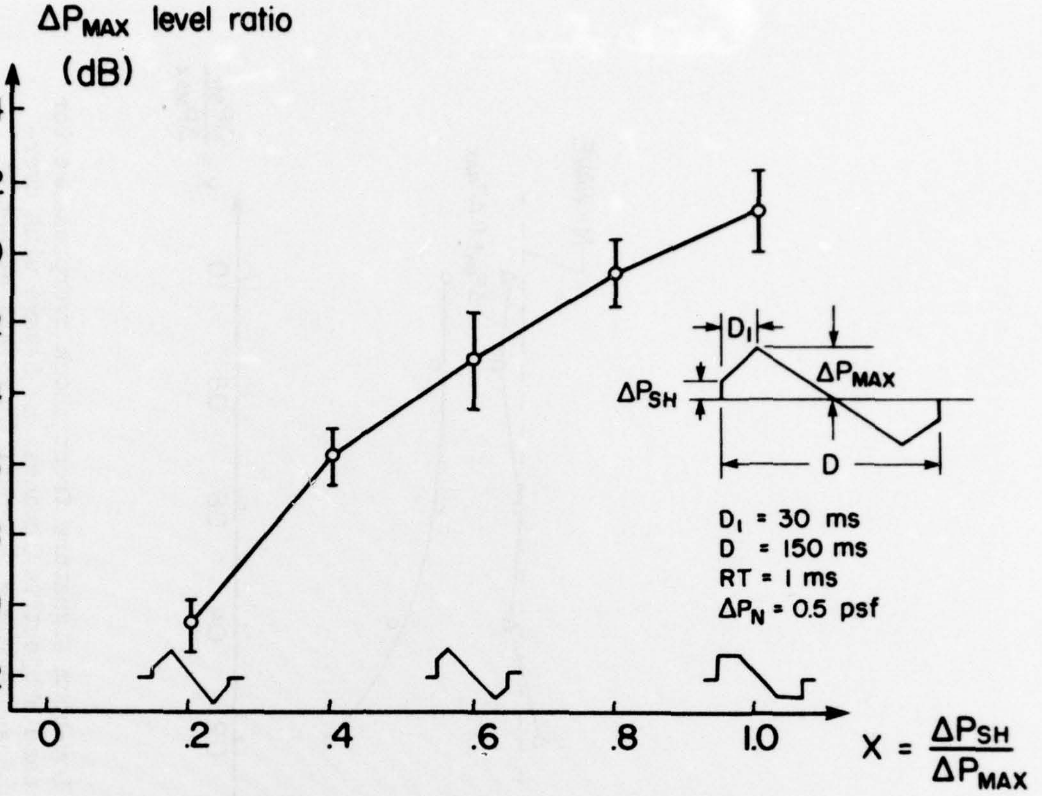

Fig. 12 N-wave amplitude vs low-boom signature amplitude (dB) for same subjective loudness: effect of ratio of front shock pressure to maximum pressure for fixed flat top duration.

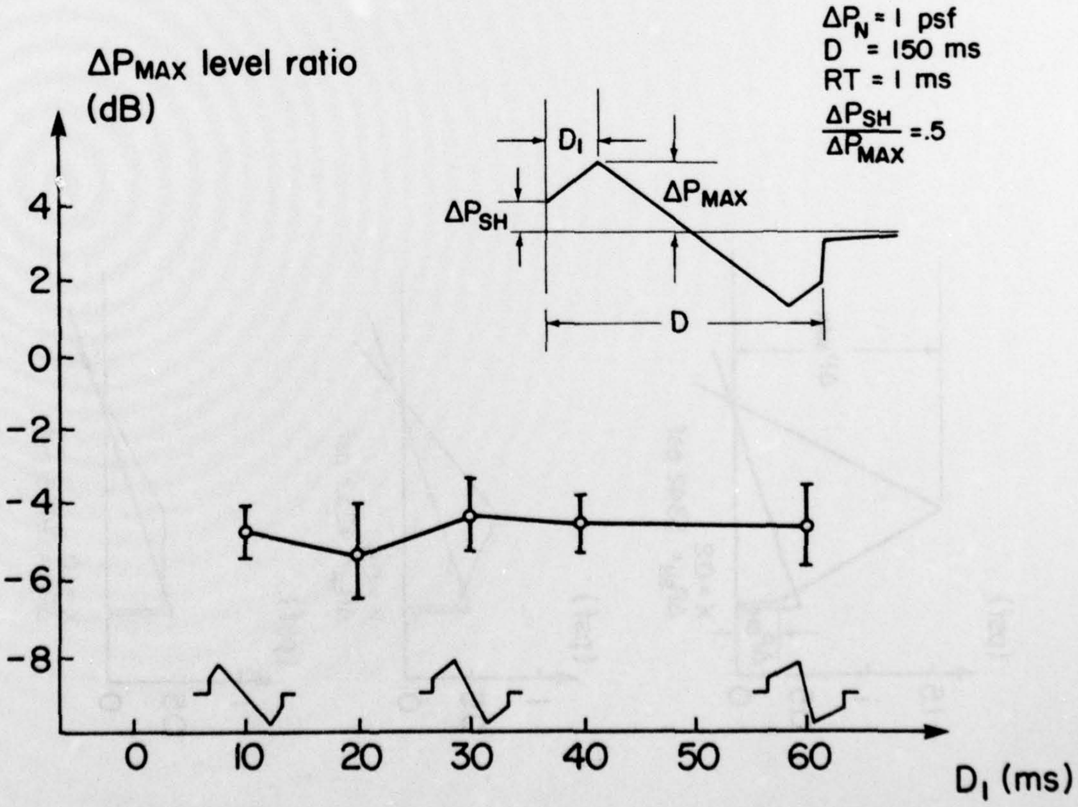

Fig. 13 N-wave amplitude vs low-boom signature amplitude (dB) for same subjective loudness: effect of flat top duration for fixed ratio $\Delta p_{SH}/\Delta p_{MAX}$.

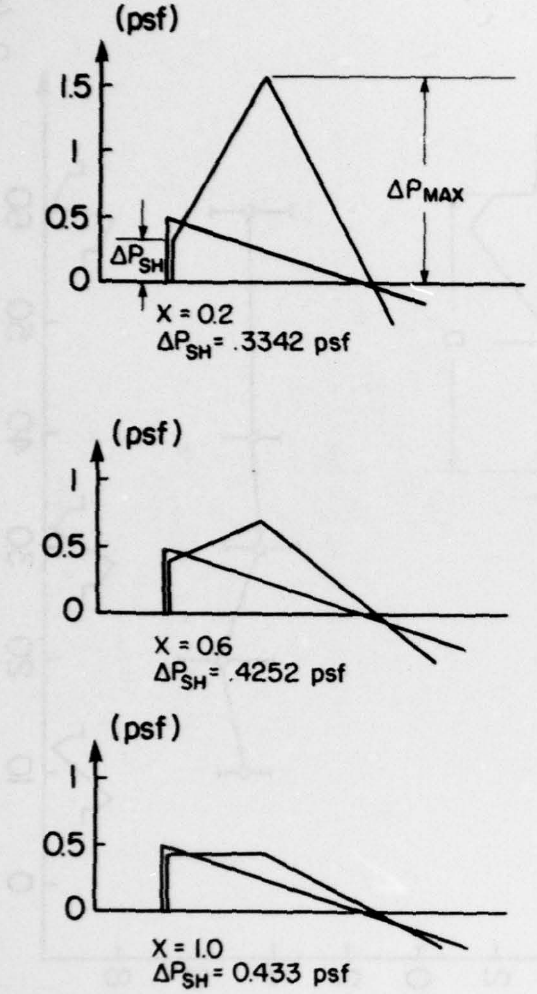

Fig. 14 Shapes of some pairs (low-boom and N-wave) judged equally loud.

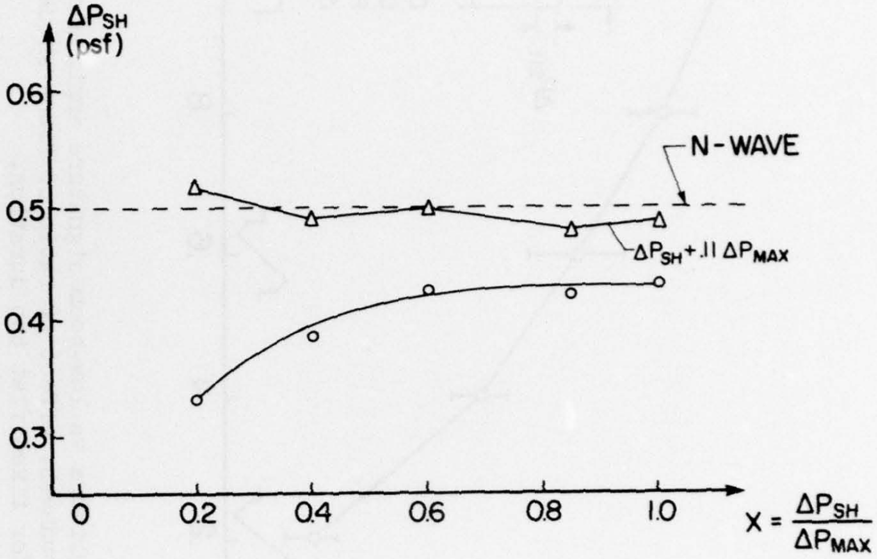

Fig. 15 Low-boom signature front shock overpressure for same subjective loudness as N-wave with overpressure $\Delta p_N = 0.5$ psf: (circles) effect of ratio front shock overpressure/maximum overpressure for fixed flat top duration; (triangles) calculated values of "effective overpressure" of equivalent N-wave.

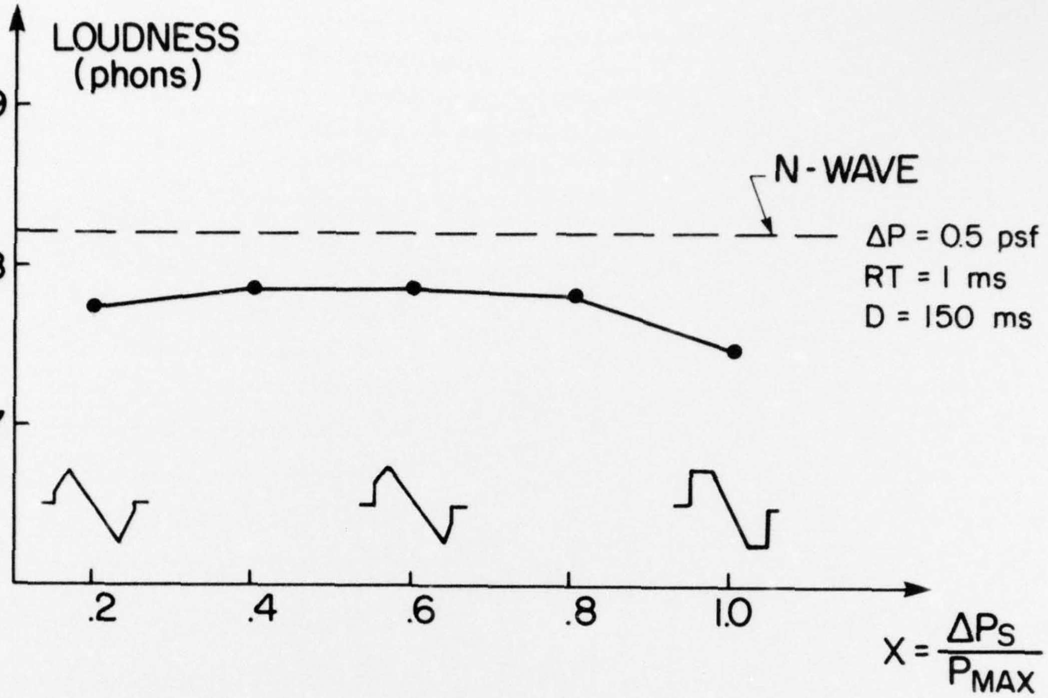

Fig. 16 Calculated loudness of signatures judged equally loud. Solid line: loudness of low-boom signatures vs ratio front shock overpressure/ maximum overpressure.

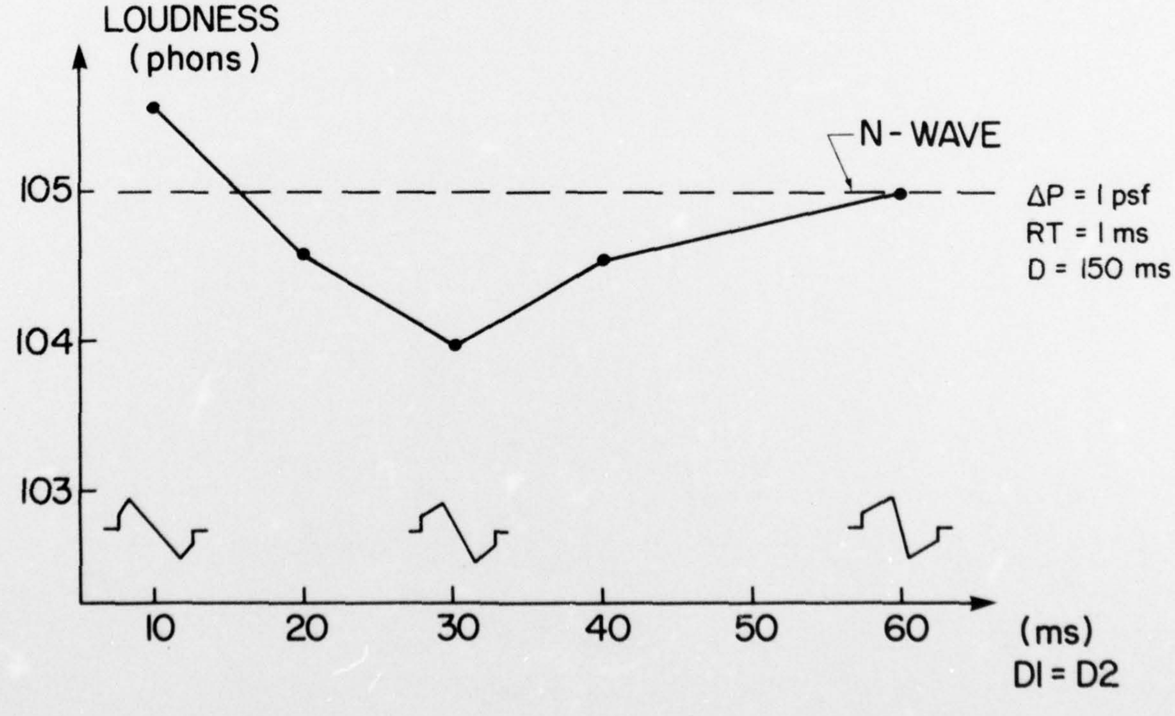

Fig. 17 Calculated loudness signatures judged equally loud. Solid line: loudness of low-boom signatures vs flat top duration.

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