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Evaluation of the Annoyance Due to Helicopter Rotor Noise

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SUMMARY

A program was conducted in which test participants, using specially designed equipment, adjusted the levels of various helicopter rotor spectra until the combination of the harmonic noise and a broadband background noise was judged equally annoying as a higher level of the same broadband noise spectrum. The subjective measure of added harmonic noise could then be equated to the difference in the two levels of broadband noise. The test participants also made subjective evaluations of the rotor noise signatures which they created.

The test stimuli consisted of three degrees of rotor impulsiveness, each presented at four blade passage rates. Each of these twelve harmonic sounds was combined with three broadband spectra and was adjusted to match the annoyance of three different sound pressure levels of broadband noise. The entire program thus consisted of one hundred and eight test conditions. Fifteen males and ten females participated in the test which provided twenty-seven hundred test points.

An analysis of variance was done on the amount of adjustment required to the harmonic rotor noise in order to obtain a difference in annoyance equivalent to that produced by the difference in broadband noise levels. The important variables were found to be level and impulsiveness.

The change in spectrum resulting from impulsiveness could be measured by considering both C-weighted sound pressure level and a higher frequency weighted measurement (dBA or PNdB). Since there is much precedent for measuring aircraft noise in terms of A-weighed sound pressure level or Perceived Noise Level, regression analyses were carried out correlating these measures of rotor noise with equivalent broadband levels and C-weighted level of the rotor noise:

$$dBA_R = 32.6 + 1.06\ dBA_{\overline{B}} - 0.401\ dBC_R \quad (r = .894) \qquad (1)$$

$$PNdB_R = 25.5 + 0.730\ PNL_{\overline{B}} \quad (r = .911) \qquad (2)$$

where:

Subscript $\underline{R}$ indicates rotor noise,
Subscript $\overline{B}$ indicates equivalent broadband noise.

Due to a growing interest in crest factor as a measure of impulsiveness, a follow-on study was conducted in which regression

analyses similar to those above were carried out using level and crest factor as the measures of rotor noise.

$$dBA_R = 48.0 + 0.783\ (cf) + 0.137\ (dBA_{\overline{B}}) \quad (r = .960) \quad (3)$$

$$PNL_{\overline{R}} = 37.8 + 0.524\ (PNL_{\overline{B}}) + 0.253\ (cf) \quad (r = .931) \quad (4)$$

Either of the above two sets of equations can be used to compare different rotor designs on an equal annoyance basis, during the helicopter design stage. However, since the prediction of crest factor, which is phase dependent, is considerably more complex and less proven, it is probable that Equations (1) or (2) will prove more useful.

It is noted, however, that the correlation coefficients resulting from the use of crest factor, as a measure of impulsiveness, are slightly higher than those obtained by the dBC measure. Therefore, if one is trying to predict the relative acceptability of two measured signals the use of Equations (3) or (4) might be indicated.

INTRODUCTION

When considered as a noise source, the helicopter presents an unusually complex picture, which is illustrated in Figure 1. Of the many elements of this acoustical signature, main rotor harmonic noise which is unique to the helicopter, is usually the characteristic by which the public identifies the aircraft as a helicopter. Rotor harmonic noise is comprised of a particular harmonic structure which is repeated at its fundamental frequency (the blade passage rate). This repetition rate usually lies in the range between 10 Hz and 20 Hz. The frequency structure and temporal variation of the sound can vary extensively, producing noises ranging from ones which are dominated by the first few harmonics and are generally described as beating or rumbling, to noises which are dominated by the higher harmonics. This latter sound can become very impulsive and is often described by such words as slapping or banging. Figure 2 shows data encompassing the range of helicopter noise. It is the more impulsive types of rotor noise which are responsible for most of the noise complaints against helicopters.

Several psychoacoustic studies have been conducted to evaluate subjective response to helicopter noise, and all have indicated some degree of correlation with conventional noise measurements such as Perceived Noise Level or A-weighted Sound Pressure Level. In the work of Reference 1, it was shown that due to the rather lengthy exposure times which were often involved, time duration effects, such as incorporated in Effective Perceived Noise Level or Single Event Noise Level, were important, but could not necessarily be extrapolated at a constant 3dB per doubling of time. An evaluation of the results of the Reference 1 program also indicated that measuring units such as EPNdB and dBA did not appear to be adequately sensitive to certain aspects of rotor noise, such as impulsiveness and repetition rate. Although these characteristics are not applicable to airplane noise a more detailed investigation of their role in evaluating helicopter subjective response to noise appeared to be warranted.

LIST OF SYMBOLS

cf	Crest Factor
dBA	A-Weighted Sound Pressure Level
dBC	C-Weighted Sound Pressure Level
MOA	Method of Adjustment
NCS	Numerical Category Scaling
PNL	Perceived Noise Level - PNdB
r	Correlation Coefficient
SPL	Sound Pressure Level - dB
Subscripts	
$\overline{B}$	Equivalent Broadband Noise
R	Rotor Noise

DESCRIPTION OF TEST PROGRAM

The objective of this program was to isolate main rotor noise from the other helicopter noise sources and to study the effects of specific changes in the detailed rotor signature on annoyance. In this manner, it might be possible to supplement existing aircraft noise evaluators so that they might better reflect the effects of rotor noise. A corollary goal was to provide information to the helicopter designer so that he can predict the impact of a new design on the community, or can evaluate the effectiveness of trading off various elements of rotor design (number of blades, tip speed, radius, etc.) in improving the acceptability of the rotor noise signature.

An underlying assumption was the acceptance of existing measurements, such as Perceived Noise Level and A-weighted Sound Pressure Level, as predictors of annoyance of broadband sounds. On this premise, it should be possible to equate the increase in annoyance caused by superimposing a harmonic noise on a broadband noise to the annoyance which would result from increasing the broadband noise itself. This concept is illustrated in Figure 3.

Preparation of Test Signatures

In order to conduct the test program it was necessary to have the required harmonic and broadband sounds on magnetic tape for presentation to test subjects. Such a process started with selection of the desired characteristics. For the harmonic noises, it was desired to evaluate three levels of impulsiveness at four different repetition rates (10, 15, 20 and 30 Hz). The three rotor noise samples illustrated in Figure 2, which are from actual data, were selected as models because they represent a wide variety of impulsiveness and waveform.

The procedure for turning the raw input data, which was on magnetic tape, into a usable test tape is illustrated in Figure 4. Data from the input tape was read into the memory of a data averager and stored in the circulating digital memory. A Boeing Vertol modification to the averager permitted control of the memory readout rate by means of an external variable clock. The data was thus read out, at the specified rate, through a set of twenty-four parallel, adjustable, one-third octave band filters. The outputs of the filters were recombined and fed both to a wide band FM tape recorder and also to an artificial ear on which was mounted one earphone of the type which was worn by the test subjects. The output of the earphone was monitored so that a frequency analysis of the signature which was being constructed could be observed. By monitoring the earphone in real time, while adjusting the one-third octave band filters, the output signal was compensated for frequency response of the headset or any other part of the system, so that the desired final spectrum was obtained. Figure 5 shows the waveforms and narrow band spectra for each rotor noise sample as measured through the headset, while Figure 6 presents corresponding one-third octave band data.

A headset was chosen instead of a loudspeaker because the headset is far superior with respect to preserving time domain (waveform) relationships which are primary to defining impulsiveness. A comparison of a high quality speaker system and the high fidelity headset used in this program is shown in Figure 7.

Broadband noise samples were recorded and shaped in a similar manner except that a noise generator was used as a source and then shaped. The spectra of the three broadband noises used are illustrated in Figure 8. They are typical of the spectrum of the broadband noise of a rotor alone, a rotor with a gas turbine as measured very close to a helicopter, and a rotor with a more moderate gas turbine noise such as might be measured several hundred feet away.

Test Procedure

The program was essentially a Paired Comparison Test in which the subject actively participated in the creation of one of the pair of sounds. The procedure, illustrated in Figures 9 and 10, was one in which a broadband sound of preselected level (65, 70 or 80 dBA) and spectrum was presented as a reference sound; the same broadband spectrum at a lower level (60 dBA) was also presented as part of a test sound along with a particular harmonic rotor noise whose level could be controlled by the test participant. The task was to adjust the level of the harmonic noise until the total test sound (harmonic and broadband) was judged to be equally annoying as the reference broadband sound. This type of testing is generally called method of adjustment (MOA). The subject was permitted to switch between the reference and test sounds and to make adjustments to the test sound harmonic level as many times as required. When a judged equality in annoyance was reached, the subject pressed a button which caused a one-third octave spectrum of the test sound (through a headset which was mounted on an artificial ear and was in parallel with his own headset) to be recorded.

A schematic diagram of the circuitry employed is shown in Figure 11.

The subject also filled out a form evaluating the sound which had just been created. A copy of the instructions given to each subject, along with the evaluation form is contained in Appendix A. The first question provided the primary subjective response to be used for comparison with the measured data. A bipolar scale was used to avoid biasing the results by implying that all rotor noise must be unpleasant. This is called the numerical category scaling (NCS) procedure. The word list of Question II was not considered as fundamental to this program. However, it was felt that collecting this information might help to better quantify some terms which have been used to describe rotor noise, such as "banging" or "slapping". The third question is in essence redundant to the first, but was added to provide a second, slightly less personalized, form of response.

Data Analysis

As discussed in the preceding section, each time a test subject completed the task of creating a harmonic sound which, in his opinion, was equally annoying as a reference sound, a one-third octave band analysis of the noise in a parallel headset was recorded producing a record similar to that presented in Figure 12. In addition to the spectrum, this data also provided A-weighted and C-weighted Sound Pressure Levels. A total of 2700 records of this type were made during the program. In order to obtain Perceived Noise Level, a calibration curve relating dBA and PNdB was prepared for each test sound. Each curve, a sample of which is shown in Figure 13, consisted of several points, including the highest dBA measurement and the lowest dBA measurement obtained for the particular test sound, along with enough intermediate points to define the curve. The Perceived Noise Level for each individual response could then be determined from the A-weighted Sound Pressure Level. Appendix B contains a tabulation of the measured acoustical data along with the subjective evaluations which were made of each sound and the crest factor for each sound.

Crest factor is classically defined as the ratio of peak value to rms value of a signal (or peak SPL minus rms SPL). In his study of rotor noise (Reference 2) Lawton defined an idealized crest factor as "peak SPL of impulses minus rms SPL of continuous noise." This definition of crest factor is the one used in this study. The reason for this distinction is illustrated in Figure 14. As the peak rotor levels increase with respect to the lower noise between peaks the rms value of the complete signal is determined by the rms of the peaks. Since for any specified waveform, the ratio of peak to rms is a calculatable constant, the crest factor also tends to reach a constant value although the absolute level of the peak may continue to increase. The idealized crest factor, however, will continue to increase with increasing peak level and therefore is a more suitable unit for correlation in psychoacoustic studies.

Idealized crest factor must be used with caution. The measurement of crest factor, while relatively simple for simple waveforms can become quite subjective when faced with actual complex signals of the types shown in Figure 5. In these cases, the maximum and minimum values of the pressure time history may not be very obvious. Another problem with using crest factor is that the measurement is phase sensitive and therefore, introduces requirements for phase as well as frequency calibration of acquisition and reproduction systems.

Since the decision to include crest factor in the study was not made until the testing had been completed, the crest factors then were obtained in the following manner:

The test setup was reassembled and the knob which the test subjects used to adjust the level of the harmonic noise was set at 8 different positions to cover the range of data. At each of these 8 levels, for the 12 different rotor noises, readings were made of the peak linear SPL, peak A-weighted SPL and rms A-weighted SPL.

Plots (such as Figure 15) were then made of the rms A-weighted SPL vs the peak SPL for each of the 12 rotor noises. The mean value of the rms A-weighted SPL obtained from all the test subjects for each test sample is then entered on the appropriate graph to obtain the peak SPL corresponding to both linear and A-weighted SPL.

The A-weighted SPL of the continuous noise present in each of the rotor noise samples was then subtracted from the A-weighted peak values obtained as above to give the crest factor referred from hereafter as cf (dBA). Similarly, the linear SPL of the continuous noise was subtracted from the peak linear to give a second crest factor referred to in this study as cf (linear).

For example, test sample 1A1 shown in Figure 15 had a mean rms A-weighted SPL of 75.3 dB so a peak A-weighted SPL of 82 dBA and a peak linear SPL of 109 dB were obtained from Figure 15. The rms A-weighted SPL of the continuous noise for broadband shape A was 59.5 and the rms linear SPL was 73.5, so the cf (dBA) is then (82 dB - 59.5 dB) = 22.5 dB and the cf (linear) is (109 dB - 73.5 dB)= 35.5 dB.

Test Participants

The participants in this program were fifteen males and ten females between the ages of twenty-one and thirty-six. All were members (or wives of members) of the Swarthmore-Wallingford Chapter of the Pennsylvania Jaycees. Since payment was to the organization, for use in community activities, the subjects were in a sense volunteers.

Audiometric screening was performed using a portable audiometer. In order to minimize scatter due to variation in hearing acuity, potential candidates were rejected if their threshold, at any frequency, was more than 10 dB below the group mean. Using this criterion, twenty-seven candidates were screened to obtain twenty-five participants.

EVALUATION OF RESULTS

The fundamental results of the test program are presented in Figure 16 which shows the increase in harmonic rotor noise which was judged to be equally as annoying as a specified increase in broadband noise. The similar slopes indicates that regardless of which unit (PNdB, dBA or dBC) are used as a measurement, the sensitivity to change in harmonic level with respect to broadband level is just about the same. What is significantly different about the three measurements is their ability to separate impulsive and non-impulsive signatures. As might be expected dBC gives most weight to the non-impulsive signatures. As might be expected dBC gives most weight to the non-impulsive signals whose levels are set by the lowest frequency content, while dBA places more emphasis on the higher frequency content of the impulsive signals. It is particularly interesting that PNdB despite its high frequency emphasis does not display a similar trait to dBA. This is probably due to the non-linearity of the Noy unit with level which can result in the maximum Noy value occupying due to high level low frequency noise for certain rotor signatures.

Figure 17 presents the subjective evaluations from the numerical category scaling (NCS procedure). It shows that some very interesting paradoxes occurred in comparing the absolute sound pressure levels obtained during the MOA tests and the subjective ratings from the NCS procedure. Although two test sounds were adjusted to be equally annoying to the same reference sound in the MOA tests, they were not rated the same. In addition, the test sounds were not rated the same as the reference broadband sound to which they were voth supposed to be subjectively equal. These two findings were quite consistent across the set of test sounds. For example, in Figure 17, the reference broadband sound A1 had a mean subjective rating of 3.6 NCS units. A non-impulsive sound with a repetition rate of 10 which had been adjusted to be equally annoying to the reference sound A1 had a mean rating of 1.35. Similarly, a multiple impulsive sound and single impulsive sound both with a repetition rate of 10 which were adjusted to be equally annoying as A1 had mean subjective ratings of 2.36 and 3.16, respectively. Although it might appear that the ratings of the harmonic noises should have been equal not only to each other, but also to the reference sound, (i.e., all three subjective ratings should be equal to 3.6) obviously this was not the case.

In addition, the figure also shows that for the same reference broadband sound, the non-impulsive sound was consistently rated significantly lower than the multiple impulsive sound which was in turn rated signficantly lower than the single impulsive sound. It was also noted that the relative rating of the broadband sound with respect to the harmonic rotor sounds was a function of absolute level, since at low levels the broadband noise was rated on the low side of the rotor noise while at high levels the opposite was true.

Since it is generally concluded that the MOA is more accurate and less biased than the NCS procedure, the conclusions of this study will be based on the MOA results. This is substantiated in Appendix B where the standard deviations of the MOA results range from about three to six dB; whereas the NCS results range from six to twelve dB (which corresponds to one to two NCS units). An analysis and discussion of results from the NCS procedure can be found in Appendix C.

The test program, as constructed, encompassed five independent variables: the level of the sound, the impulsiveness of the sound, the repetition rate, the spectrum shape of the reference broadband noise, and the sex of the test participant. As a first step in evaluating the results, it was necessary to determine which of these variables, or combinations of variables, had a significant effect in determining the evaluation of helicopter rotor noise.

In order to establish statistical validity, an Analysis of Variance (ANOVA) was performed on the data obtained from the MOA using the methods described in References 3 and 4. Since the number of levels for each factor was not equal (e.q., 4 rates, 3 levels and waveforms, 2 sexes) a k-way analysis of variance was used. Statistical significance is indicated when the calculated F value of a variable, or combination of variables, exceeds the tabulated F value. The calculated F value is the ratio of the mean square of the variable to the error mean square. The tabulated F value, which is a function of the number of degrees of freedom of the variable, the error degrees of freedom, and the selected level of significance (in this case chosen as 95%) can be found in standard tables. The results of this analysis on the A-weighted SPL data are presented in Table I and similarly, the results on the Perceived Noise Level and C-weighted SPL data are given in Tables II and III, respectively.

These analyses indicate that A-weighted SPL and Perceived Noise Level are very level sensitive measurements whereas C-weighted SPL is very sensitive to harmonic structure. These results do not imply that the other factors do not affect peoples' evaluation of the rotor noises, but that the measurements in themselves are not necessarily sensitive to these factors. For example, the test subjects may have had a tendency to adjust the level of the harmonic noise to a different knob position depending on the rate, but the various sound pressure level measurements may not necessarily be all that rate sensitive.

In order to quantify the role of each important variable in determining the evaluation of the test results, a linear regression analysis of the mean response values was done using the variables indicated as significant (or nearly significant) by the ANOVA. The general form of the solution is

$$\text{ROTOR NOISE LEVEL} = F_0 + F_1 \text{ (Equivalent Broadband Level)} + F_2 \text{ (Impulse)}$$

In order to conduct the dBA analysis, it is necessary to have a quantity to express impulse. Since the ANOVA showed that the C-weighting is very sensitive to impulse, it was decided to use this as a measure of impulsiveness. The results of the regression analyses are:

$$dBA_R = 32.6 + 1.06\ dBA_{\overline{B}} - 0.401\ dBC \quad (r = .894) \qquad (1)$$

$$PNdB_R = 25.5 + .723\ PNdB_{\overline{B}} \quad (r = .908) \qquad (2)$$

The relatively high correlation coefficients indicate that the above equations are adequate.

TABLE I. ANOVA A-WEIGHTED SPL

Source	Sum of Squares	d.f.	Mean Square	Calculated F - Value
R	32.0690	3	10.6897	0.0207
H	2228.7501	2	1114.3751	2.1557
X	46.9467	1	46.9467	0.0908
L	4934.1382	2	2467.0691	4.7725*
S	6.7618	2	3.4715	0.0066
RH	129.2747	6	21.5458	0.0417
RX	11.8846	3	3.9615	0.0077
RL	11.3456	6	1.8909	0.0037
RS	4.3142	6	0.7190	0.0014
HX	17.9284	2	8.9642	0.0173
HL	107.1174	4	26.7794	0.0518
HS	22.1913	4	5.5478	0.0107
XL	24.8248	2	12.4124	0.0240
XS	2.0751	2	1.0376	0.0020
LS	1.6582	4	0.4146	0.0008
RHX	18.0942	6	3.0157	0.0058
RHL	41.3344	12	3.4445	0.0067
RHS	19.2483	12	1.6040	0.0031
RXL	3.6700	6	0.6117	0.0012
RXS	3.5919	6	0.5987	0.0012
RLS	19.4558	12	1.6213	0.0031
HXL	7.5530	4	1.8883	0.0037
HXS	5.0569	4	1.2642	0.0024
HLS	7.9729	8	0.9966	0.0019
XLS	9.7238	4	2.4310	0.0047
RHXL	19.1033	12	1.5919	0.0031
RHXS	3.6406	12	0.3034	0.0006
RHLS	30.7542	24	1.2814	0.0025
RXLS	9.2347	12	0.7696	0.0015
HXLS	6.6551	8	0.8319	0.0016
RHXLS	27.8119	24	1.1588	0.0022
SUBCLASS	7814.1811	215		
WITHIN	1272699.604	2462	516.9373	
TOTAL	14902150.0	2677		

*Statistically Significant

KEY

R - Rate
H - Impulse
X - Sex
BL - BB Level
BS - BB Shape

F - Distribution $\alpha = 0.05$ (95%)

γ_1, γ_2	F-Value	γ_1, γ_2	F-Value
1, ∞	3.8415	6, ∞	2.0986
2, ∞	2.9957	8, ∞	1.9384
3, ∞	2.6049	12, ∞	1.7522
4, ∞	2.3719	24, ∞	1.5173

TABLE II. ANOVA PERCEIVED NOISE LEVEL

Source	Sum of Squares	d.f.	Mean Square	Calculated F - Value
R	150.8952	3	50.2984	0.0695
H	153.8603	2	76.9302	0.1063
X	38.8452	1	38.8452	0.0537
L	4433.0586	2	2216.5293	3.0638*
S	2.5544	2	1.2772	0.0018
RH	388.8179	6	64.8030	0.0896
RX	8.2211	3	2.7404	0.0038
RL	15.8407	6	2.6401	0.0036
RS	15.0882	6	2.5147	0.0035
HX	10.3462	2	5.1731	0.0072
HL	25.7486	4	6.4372	0.0089
HS	13.1744	4	3.2936	0.0046
XL	14.7057	2	7.3529	0.0102
XS	4.1670	2	2.0835	0.0029
LS	10.7978	4	2.6995	0.0037
RHX	11.9097	6	1.9850	0.0027
RHL	38.1888	12	3.1824	0.0044
RHS	46.7596	12	3.8966	0.0054
RXL	3.6981	6	0.6164	0.0009
RXS	2.4978	6	0.4163	0.0006
RLS	30.6419	12	2.5535	0.0035
HXL	5.3121	4	1.3280	0.0018
HXS	3.8541	4	0.9635	0.0013
HLS	15.0717	8	1.8840	0.0026
XLS	6.2146	4	1.5537	0.0021
RHXL	16.5919	12	1.3827	0.0019
RHXS	6.6556	12	0.5546	0.0008
RHLS	72.0554	24	3.0023	0.0041
RXLS	6.8939	12	0.5745	0.0008
HXLS	7.2926	8	0.9116	0.0013
RHXLS	15.7144	24	0.6548	0.0009
SUBCLASS	5575.4733	215		
WITHIN	1778283.168	2458	723.4675	
TOTAL	20687477.5	2673		

*Statistically Significant

KEY

R - Rate

H - Impulse

X - Sex

BL - BB Level

BS - BB Shape

F - Distribution $\alpha = 0.05$ (95%)

γ_1, γ_2	F-Value	γ_1, γ_2	F-Value
1, ∞	3.8415	6, ∞	2.0986
2, ∞	2.9957	8, ∞	1.9384
3, ∞	2.6049	12, ∞	1.7522
4, ∞	2.3719	24, ∞	1.5173

TABLE III. ANOVA C-WEIGHTED SPL

Source	Sum of Sources	d.f.	Mean Source	Calculated F - Value
R	574.3817	3	191.4606	0.2444
H	5529.0700	2	2764.535	3.5291 *
X	26.8817	1	26.8817	0.0343
L	4625.5553	2	2312.7777	2.9524
S	14.2008	2	7.1004	0.0091
RH	125.7589	6	20.9598	0.0268
RX	3.8254	3	1.2751	0.0016
RL	22.9125	6	3.8188	0.0049
RS	8.1725	6	1.3621	0.0017
HX	15.8044	2	7.9022	0.0101
HL	99.0006	4	24.7502	0.0316
HS	27.2217	4	6.8054	0.0087
XL	9.6753	2	4.8377	0.0062
XS	0.1169	2	0.0585	0.0001
LS	11.2239	4	2.8060	0.0036
RHX	29.7852	6	4.9642	0.0063
RHL	23.0428	12	1.9202	0.0025
RHS	32.7061	12	2.7255	0.0035
RXL	12.3844	6	2.0641	0.0026
RXS	6.8505	6	1.1418	0.0015
RLS	32.6083	12	2.7174	0.0035
HXL	1.0794	4	0.2699	0.0003
HXS	4.2228	4	1.0557	0.0013
HLS	16.4186	8	2.0523	0.0026
XLS	10.5794	4	2.6449	0.0034
RHXL	11.7476	12	0.9790	0.0012
RHXS	7.3732	12	0.6144	0.0008
RHLS	35.2947	24	1.4706	0.0019
RXLS	8.9432	12	0.7453	0.0010
HXLS	2.0175	8	0.2522	0.0003
RHXLS	22.9632	24	0.9568	0.0012
SUBCLASS	11351.8183	215		
WITHIN	1809537.855	2310	783.3497	
TOTAL	18964618.0	2525		

*Statistically Significant

KEY
R - Rate
H - Impulse
X - Sex
BL - BB Level
BS - BB Shape

F - Distribution $\alpha = 0.05$ (95%)

γ_1, γ_2	F Value	γ_1, γ_2	F Value
1, ∞	3.8415	6, ∞	2.0986
2, ∞	2.9957	8, ∞	1.9384
3, ∞	2.6049	12, ∞	1.7522
4, ∞	2.3719	24, ∞	1.5173

Using Equation (1), Figure 18 was developed. It offers an adjustment to the measured rotor A-weighted SPL by the measured rotor C-weighted SPL to obtain a subjectively equivalent A-weighted broadband level. For instance, the combination of a 90 dBA and 109 dBC measured rotor noise is equivalent to a 95 dBA broadband level, but the combination of a 90 dBA and 94.5 dBC measured rotor noise is equivalent to a 90 dBA broadband level.

Figure 19 presents the equivalent broadband PNL as a function of the measured rotor PNL. Examination of this figure shows that at a level of 95 PNdB the measured rotor PNL and equivalent broadband PNL are equal. For lower values of rotor PNL the equivalent broadband level will be less than the measured level while for values of measured PNL greater than 95 PNL the equivalent broadband level is greater than the measured.

As was mentioned previously, growing interest in measuring impulsiveness by the measure of crest factor (Reference 2) was developing during the time of this study. Because of this interest, two additional sets of equations were developed. These equations were based on the idealized crest factor, which was defined in the section on Data Analysis. Both linear and A-weighted data was used to determine the corresponding crest factors.

A regression analysis was then performed correlating the measures of the rotor noise with the reference broadband level and crest factor.

The equations, using the crest factor are:

$$dBA_R = 48.0 + 0.783\ (cf\ (dBA)) + 0.137\ (dBA_{\bar{B}}) \qquad (r = .960) \qquad (3)$$

$$PNL_R = 37.8 + 0.524\ (PNL_{\bar{B}}) + 0.253\ (cf\ (dBA)) \qquad (r = .931) \qquad (4)$$

$$dBA_R = 7.23 + 1.04\ (dBA_{\bar{B}}) - 0.367\ (cf\ (Linear) \qquad (r = .915) \qquad (5)$$

$$PNL_R = 25.2 + 0.737\ (PNL_{\bar{B}}) - 0.018\ (cf\ (Linear)) \qquad (r = .909) \qquad (6)$$

It can be seen by comparing Equation (3) with (5) and Equation (4) with (6) that better correlation is obtained when using cf (dBA) rather than the cf (linear). Therefore, the impulsiveness will be represented by the cf (dBA).

Crest factor, as a measure of impulsiveness, must be interpreted carefully. Generally speaking, an increasing crest factor implies that the signal is becoming more impulsive, but this is not necessarily true. Figure 20, which illustrates this point, shows a somewhat typical non-banging rotor noise waveform (a). The idealized crest factor is small, i.e., the broadband noise present in the signal is very close to the peak noise. Now, if the broadband noise is reduced and the peak level held constant as shown in part (b), then the crest factor has gone up. A similar crest factor increase, however, could also have resulted from an increase in both the peak and broadband levels as illustrated in (c). If crest factor alone is considered as a measure of impulsiveness, then it could be said that either rotor (b) or (c) is a banging rotor. What does happen is that while a banging rotor tends to have a high crest factor, it also has a high peak level. The peak SPL becomes much higher in a banging rotor than a non-banging one. The broadband noise may or may not increase, but if it does, it certainly does not do so at the rate the peak level does so hence both level and crest factor are very high on a banging rotor.

Using Equations (5) and (6), Figures 21 and 22 were developed to offer an adjustment to the SPL of the rotor noise by the crest factor.

CONCLUSIONS

Evaluation of helicopter rotor noise by the method of adjustment was found to be a function of level and impulsiveness. In order to quantify the relationship, a unit of impulsiveness was required. Two different measures of impulsiveness were used in this study. These were C-weighted SPL and crest factor. The following two sets of equations were found to best relate the measure of rotor noise with level and impulse.

<u>Impulse Measure = dBC</u>

$$dBA_R = 32.6 + 1.06\ dBA_{\bar{B}} - 0.401\ dBC_R \quad (r = .894) \qquad (1)$$

$$PNdB_R = 25.5 + 0.730\ PNdB_{\bar{B}} \quad (r = .911 \qquad (2)$$

<u>Impulse Measure = Crest Factor</u>

$$dBA_R = 48.0 + 0.783\ (cf) + 0.137\ (dBA_{\bar{B}}) \quad (r = .960) \qquad (3)$$

$$PNdB_R = 37.8 + 0.524\ (PNL_{\bar{B}}) + 0.253\ (cf) \quad (r = .931) \qquad (4)$$

Using the above equations, or using Figures 18, 19, 21 and 22, it is possible to compare different rotor designs, or to trade off rotor design parameters during development of a helicopter.

For application to preliminary design studies, where predicted rotor noise signatures must be used, Equations (1) and (2) are recommended because they depend only on prediction of the sound pressure level spectrum. Crest factor, however, also requires prediction of a reconstituted waveform and hence requires the phasing between harmonic components, which is considerably more complex and less certain.

Another application of the results of this study is in making comparative evaluations between signatures of different existing rotors by converting them to their equivalent broadband levels. In this case crest factor may be used, if desired, provided that the data can be presented as a time history and a good estimate of the level between rotor pulses can be made in order to calculate an idealized crest factor. Note that the rms value of the signal including rotor pulses should not be used.

An unresolved question remains with regard to the apparent inconsistency that when different rotor sounds were adjusted to be equally annoying as a broadband reference sound, subsequent subjective ratings of the rotor sounds were not equal to each other, or to the broadband reference sound. The major tangible effect appears to be that repetition rate was not a significant variable by evaluation of MOA results, but was significant according to subjective ratings. It is the opinion of the authors that the explanation of this discrepancy would provide signficant insight into subjective response of people to rotor noise, and should be pursued.

In view of the results of some testing conducted by Boeing Vertol prior to this program, the authors have some reservation about the apparent relative insensitivity to the rotor blade passage period. It is possible that the use of a headset, which, although it preserved waveform better than a speaker provides only a partial stimulus since it presented the signal only directly at the ear. There is some reason to conjecture that the annoyance due to these high pressure near infra-sonic harmonics may be associated with feelings of pressure on other body surfaces. This effect should be investigated further because it is particularly applicable to persons located indoors where window and room acoustics have been observed to amplify rotor harmonic noise.

APPENDIX A

This appendix contains the instructions to test subjects and the questionnaire used by the test subjects in evaluating the created test sound.

APPENDIX A

INSTRUCTIONS TO TEST SUBJECTS

(Test subjects read these instructions while the test administrator reads them aloud)

You will be involved in a study regarding the subjective acceptability of helicopter noise. You will hear two sounds and your task is to make one sound equal in annoyance to the other sound.

You will be wearing a headset and seated in front of a panel. The panel has a switch marked with positions REF and TEST and an adjustable knob.

At the start of each test, put the switch in the REF position. You will hear a sound through your headset; put the switch in the TEST position and you will now hear another sound. Turning the knob makes the sound level at TEST get louder or softer. (Turning the knob while the switch is in the REF position does not change the sound level of the REF.)

Your task is to listen to the REF sound, change to TEST and listen to that sound and adjust the knob until the TEST sound is equally annoying to you as that at REF. You may flip back and forth between the REF and TEST sounds until you are satisfied with your judgment.

Once you have finished adjusting the knob, press the RECORD button, so that your knob setting may be recorded. Do <u>not</u> adjust the knob anymore for this test point.

After pressing the record button, please fill out the provided questionnaire. Leave the switch in the TEST position while filling out the questionnaire since it is the TEST sound which is the created sound discussed in the questionnaire. Put the finished questionnaire aside and begin the next test.

Your task is to make one sound equally annoying as another. There are no right or wrong answers in a test like this. When you have made a judgment that the TEST sound is equally unwanted as the REF sound, push the RECORD button.

APPENDIX A

Test Participant ________________ Test No.__________

HELICOPTER NOISE ANNOYANCE TEST

I. Please indicate your reaction to the test sound you have just created(switch in TEST position) by placing a check mark in the box below the appropriate point on the scale.

extremely pleasant ← neutral → extremely unpleasant

5	4	3	2	1	0	1	2	3	4	5

II. Please check as many of the following words which help you to describe the created test sound.

piercing	☐	burring	☐	clicking	☐	thundering	☐
booming	☐	roaring	☐	popping	☐	beating	☐
subdued	☐	muted	☐	deafening	☐	banging	☐
slapping	☐	loud	☐	buzzing	☐	faint	☐
muffled	☐	impulsive	☐	soft	☐	high-pitched	☐
blaring	☐	droning	☐	shrilling	☐	metallic	☐
resonant	☐	purring	☐	humming	☐	low-pitched	☐
screaming	☐	sharp	☐	swishing	☐	hissing	☐
thumping	☐	bumping	☐	explosive	☐	pulsing	☐
cracking	☐	thudding	☐	hammering	☐	jarring	☐

Other____

III. What do you think the reaction of people, in general would be to the sound if they were exposed to it in their daily lives?

not annoyed — somewhat annoyed — extremely annoyed

APPENDIX B

This Appendix Contains the Data Obtained for the Various Test Sounds.

A List of Symbols is as Follows:

NI	-	Non-Impulsive
MI	-	Multiple Impulse
SI	-	Single Impulse
A	-	Broadband Shape A (Ref. Fig. 8)
B	-	Broadband Shape B (Ref. Fig. 8)
C	-	Broadband Shape C (Ref. Fig. 8)
1	-	Broadband Level (80 dBA)
2	-	Broadband Level (70 dBA)
3	-	Broadband Level (65 dBA)
$\bar{x}$	-	Mean of Sample Population
s	-	Standard Deviation of Sample Population
n	-	Number of Test Subjects
dBA	-	A Weighted Sound Pressure Level
dBC	-	C Weighted Sound Pressure Level
PNL	-	Perceived Noise Level
SRI	-	Subjective Rating Index
SRA	-	Subjective Rating Annoyance Question
cf (dBA)	-	Crest Factor dBA
cf (Linear)	-	Crest Factor Linear

APPENDIX B

TEST SOUND					DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
TYPE	BBS	BBL	RATE								
NI	A	1	10	$\bar{x}$	73.1	97.9	88.1	1.35	1.75	21.5	37
				s	4.3	4.0	4.1	2.67	1.59		
				n	25	9	25	24	24		
	A	2		$\bar{x}$	66.5	94.0	84.5	0.24	1.40	14	29.5
				s	2.5	4.8	3.5	1.59	1.02		
				n	24	24	24	25	25		
	A	3		$\bar{x}$	64.8	91.7	80.4	0.32	1.32	12.5	27
				s	3.5	5.1	3.6	2.06	1.13		
				n	25	24	25	25	25		
	B	1		$\bar{x}$	72.7	96.0	88.2	1.24	1.90	18	37
				s	4.0	4.9	4.6	2.52	1.47		
				n	25	8	25	25	25		
	B	2		$\bar{x}$	68.9	95.2	84.6	0.2	1.32	14	33
				s	2.8	3.8	2.1	1.6	1.03		
				n	25	22	25	25	25		
	B	3		$\bar{x}$	65.3	88.0	79.9	-0.16	1.30	10	28.5
				s	3.7	5.2	4.8	1.72	0.84		
				n	25	23	25	25	25		
	C	1		$\bar{x}$	72.2	99.7	90.2	0.79	1.71	20.8	36.5
				s	3.7	3.5	2.9	2.26	1.35		
				n	25	16	25	24	28		
	C	2		$\bar{x}$	67.6	95.3	85.3	0.28	1.22	15.8	31
				s	3.4	3.6	3.1	1.95	1.03		
				n	24	21	24	25	25		
	C	3	10	$\bar{x}$	63.9	89.1	79.7	-0.60	1.03	11.8	26.5
				s	3.9	5.8	2.7	2.04	0.94		
				n	25	24	25	25	25		
	A	1	15	$\bar{x}$	75.8	98.7	95.5	2.04	2.4	23.5	36.5
				s	8.0	4.8	8.7	1.90	1.1		
				n	24	17	24	25	25		
	A	2		$\bar{x}$	68.6	94.4	87.3	0.48	1.19	14.5	29
				s	3.1	4.2	3.9	1.16	1.37		
				n	25	24	25	25	25		
	A	3		$\bar{x}$	66.6	91.2	84.9	0.32	1.33	12	26
				s	3.9	6.1	5.7	1.57	1.05		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	78.2	97.2	87.0	2.29	2.44	24.5	39
				s	9.9	4.6	8.4	1.76	1.10		
				n	23	11	23	24	24		
	B	2		$\bar{x}$	69.8	93.7	88.0	1.12	1.82	12.5	31
				s	4.0	4.8	4.7	1.56	0.86		
				n	24	20	24	25	25		
	B	3		$\bar{x}$	66.4	91.1	82.5	-0.04	1.3	9.5	26.5
				s	3.2	5.3	3.8	1.72	1.1		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	77.0	100.9	96.7	2.46	2.39	26.3	38
				s	6.4	5.1	5.6	1.25	1.22		
				n	22	15	22	24	25		

APPENDIX B

TEST SOUND										cf	cf
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	(dBA)	(Linear)
NI	C	2	15	$\bar{x}$	69.5	95.4	87.3	0.88	1.68	15.8	31
				s	3.9	4.5	4.7	1.42	0.94		
				n	25	22	25	24	24		
	C	3	15	$\bar{x}$	66.1	90.7	83.4	-0.16	1.17	12.3	26
				s	3.9	5.9	4.7	1.62	0.97		
				n	25	25	25	25	24		
	A	1	20	$\bar{x}$	75.3	98.0	91.5	2.28	2.42	22.5	35.5
				s	3.6	3.1	2.6	1.67	1.25		
				n	24	19	24	24	24		
	A	2		$\bar{x}$	67.8	89.9	84.8	0.92	1.50	15.0	28.0
				s	3.0	4.4	2.4	1.74	1.09		
				n	25	25	25	24	25		
	A	3		$\bar{x}$	66.9	88.2	81.3	0.88	1.55	14.0	26.5
				s	3.3	4.2	3.1	1.90	1.13		
				n	25	25	25	24	25		
	B	1		$\bar{x}$	76.3	99.2	92.8	1.48	2.05	21	37.5
				s	3.6	3.6	3.1	2.00	1.23		
				n	25	16	25	25	25		
	B	2		$\bar{x}$	69.4	92.6	85.6	0.60	1.61	14	30.5
				s	3.8	4.3	5.3	1.96	1.09		
				n	25	22	25	25	25		
	B	3		$\bar{x}$	67.7	90.5	83.7	0.04	1.24	12	28
				s	3.4	4.4	4.1	1.65	0.84		
				n	25	23	25	25	25		
	C	1		$\bar{x}$	75.6	98.4	92.3	1.25	1.94	22.8	36.5
				s	3.1	3.5	3.6	2.15	1.26		
				n	24	17	24	24	24		
	C	2		$\bar{x}$	69.5	93.0	86.7	0.44	1.39	17.3	30
				s	4.4	5.1	5.2	1.98	1.09		
				n	25	23	25	25	25		
	C	3	20	$\bar{x}$	66.9	88.6	83.3	0.52	1.33	14.8	27
				s	3.8	4.6	3.2	2.06	1.07		
				n	25	25	25	25	25		
	A	1	30	$\bar{x}$	77.0	95.9	93.8	2.04	2.18	23	31.5
				s	4.1	4.5	4.5	2.26	1.30		
				n	25	13	25	25	25		
	A	2		$\bar{x}$	69.9	91.0	86.5	0.64	1.50	15.5	24
				s	3.8	4.6	4.1	1.58	1.01		
				n	25	24	25	25	25		
	A	3		$\bar{x}$	67.1	87.5	84.4	0.28	1.22	12.5	20
				s	4.4	5.5	3.8	1.81	0.93		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	76.6	98.9	96.1	1.20	2.01	19.5	31.5
				s	3.8	5.1	3.1	1.80	1.00		
				n	25	18	25	25	25		
	B	2		$\bar{x}$	70.4	92.7	87.8	0.72	1.50	13.5	25.5
				s	3.5	4.1	3.0	1.86	1.09		
				n	25	25	25	25	25		

APPENDIX B

TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
NI	B	3	30	$\bar{x}$	68.2	87.6	83.8	0.08	1.25	10.5	22
				s	4.1	6.7	4.8	1.89	1.09		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	77.1	98.9	95.4	1.31	1.90	22.8	31.5
				s	2.8	3.7	2.7	1.80	1.23		
				n	25	19	25	24	23		
	C	2		$\bar{x}$	70.5	93.1	87.4	0.92	1.51	16.3	25
				s	4.3	4.7	4.2	1.93	1.07		
				n	25	25	25	25	25		
NI	C	3	30	$\bar{x}$	66.4	87.8	83.1	0.00	1.10	12.3	20
				s	3.5	5.3	3.5	1.94	1.18		
				n	25	25	25	25	25		
MI	A	1	10	$\bar{x}$	80.8	89.9	92.9	2.36	2.56	30.5	24
				s	3.3	3.8	3.7	1.22	0.90		
				n	25	25	25	25	25		
	A	2		$\bar{x}$	73.7	82.7	86.2	1.72	2.26	23	17
				s	3.7	3.8	3.7	1.28	0.72		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	68.9	77.7	82.1	1.16	1.74	18	12.5
				s	5.3	5.7	5.0	1.40	0.87		
				n	24	24	24	24	24		
	B	1		$\bar{x}$	82.3	90.0	93.8	2.96	3.10	29	26
				s	6.5	5.1	6.1	1.31	0.87		
				n	25	25	25	25	25		
	B	2		$\bar{x}$	73.9	82.5	86.9	1.44	2.22	21	18
				s	6.5	7.2	6.5	1.04	0.78		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	69.3	77.4	82.3	0.72	1.50	15.5	13
				s	6.4	7.5	5.8	1.95	0.96		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	81.5	90.9	93.4	2.88	2.99	31.8	25
				s	5.0	5.0	4.5	1.17	0.71		
				n	25	25	25	25	25		
	C	2		$\bar{x}$	74.0	83.0	86.3	1.36	2.06	24.3	17.5
				s	4.8	5.1	4.6	1.41	0.90		
				n	25	25	25	25	25		
	C	3	10	$\bar{x}$	68.7	77.7	82.1	0.12	1.46	18.3	12.5
				s	4.7	4.9	4.0	1.76	1.08		
				n	25	25	25	25	25		
	A	1	15	$\bar{x}$	81.4	93.3	95.5	2.68	2.99	30.5	25.5
				s	4.4	4.7	4.5	1.41	0.76		
				n	25	25	25	25	25		
	A	2		$\bar{x}$	74.8	86.3	88.0	1.48	1.92	23	19
				s	4.6	5.0	4.9	1.64	1.08		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	68.3	79.6	82.5	0.88	1.50	17	13.5
				s	4.3	4.9	3.7	1.54	0.94		
				n	25	25	25	25	25		

APPENDIX B

TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAO	cf (dBA)	cf (Linear)
MI	B	1	15	$\bar{x}$	81.7	92.2	95.1	2.76	2.97	28	26.5
				s	5.6	5.2	5.5	1.13	0.76		
				n	25	23	25	25	25		
	B	2		$\bar{x}$	72.9	83.7	87.0	1.32	1.97	18.5	18
				s	5.8	6.9	5.6	0.95	0.74		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	68.8	79.4	83.0	0.73	1.78	14.5	14
				s	5.4	6.5	5.5	1.75	1.06		
				n	25	25	25	24	24		
	C	1		$\bar{x}$	80.9	93.1	94.9	3.00	3.23	29.8	25.5
				s	5.2	5.3	5.3	1.15	0.80		
				n	25	25	25	25	25		
	C	2		$\bar{x}$	70.6	82.0	84.6	0.96	1.70	19.3	15.5
				s	5.6	6.1	5.8	1.46	1.0		
				n	25	25	25	24	24		
	C	3	15	$\bar{x}$	68.3	79.4	82.7	1.27	2.00	17.3	14
				s	5.7	7.1	5.3	1.50	0.98		
				n	25	25	25	25	25		
	A	1	20	$\bar{x}$	81.6	90.0	93.6	2.92	3.18	30	20.5
				s	3.9	4.5	3.3	1.68	0.94		
				n	25	25	25	25	25		
	A	2		$\bar{x}$	72.9	80.9	84.5	1.48	2.30	20.5	13
				s	4.3	4.4	3.9	1.58	0.76		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	70.9	79.3	82.4	0.48	1.71	19	11.5
				s	5.0	5.3	4.8	1.71	1.10		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	81.0	89.3	93.0	3.17	3.24	26	20.5
				s	5.9	5.7	5.8	1.24	0.80		
				n	25	25	25	24	25		
	B	2		$\bar{x}$	71.8	80.1	85.4	1.40	2.14	16.5	12.5
				s	5.3	5.3	5.0	1.41	0.88		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	69.3	77.1	83.3	0.76	1.58	14	11
				s	5.4	6.1	5.2	1.45	0.92		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	81.5	89.8	93.9	2.20	2.86	30.3	21
				s	4.6	4.6	4.7	2.16	1.03		
				n	24	24	24	25	25		
	C	2		$\bar{x}$	73.0	81.9	85.9	1.92	2.24	20.8	13.5
				s	5.6	4.6	4.9	1.35	0.93		
				n	24	24	24	25	25		
	C	3	20	$\bar{x}$	67.0	74.9	80.0	0.2	1.24	15.3	9.5
				s	5.3	5.2	5.5	1.8	1.18		
				n	25	25	25	25	25		
	A	1	30	$\bar{x}$	80.9	88.6	94.1	3.46	3.32	29	21.5
				s	4.0	3.9	3.6	1.38	0.91		
				n	24	24	24	24	25		

APPENDIX B

TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
MI	A	2	30	$\bar{x}$	72.7	80.9	85.9	1.88	2.16	21.5	15
				s	4.3	4.4	3.9	1.20	1.07		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	68.5	75.9	81.8	0.68	1.88	17.5	12
				s	3.9	3.8	4.1	1.31	0.97		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	79.2	86.4	92.1	3.60	3.31	24	20.5
				s	6.3	6.5	5.7	1.15	0.71		
				n	25	25	25	25	25		
	B	2		$\bar{x}$	72.3	79.3	85.7	1.80	2.53	17.5	15
				s	5.2	5.5	5.3	1.94	1.04		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	67.9	74.5	81.3	1.92	2.32	13.5	12
				s	5.3	5.9	5.0	1.04	0.67		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	79.4	87.6	91.9	2.24	2.73	27.8	21
				s	5.4	5.3	4.8	1.36	1.00		
				n	25	25	25	25	24		
	C	2		$\bar{x}$	72.1	80.5	85.4	1.92	2.31	20.8	15
				s	6.0	6.5	6.3	1.06	0.83		
				n	25	25	25	24	25		
MI	C	3	30	$\bar{x}$	68.8	76.6	82.0	1.52	2.15	17.8	12.5
				s	5.8	5.7	5.8	1.29	1.03		
				n	25	25	25	25	25		
SI	A	1	10	$\bar{x}$	85.7	92.5	96.6	3.16	3.20	34	27
				s	4.9	4.4	4.6	1.28	0.89		
				n	24	22	24	25	25		
	A	2		$\bar{x}$	78.2	85.3	89.5	1.80	2.00	26.5	19
				s	4.9	4.9	4.5	1.32	1.09		
				n	24	24	24	25	25		
	A	3		$\bar{x}$	73.2	80.7	85.2	1.42	1.81	21	14
				s	6.3	6.1	5.8	1.06	0.83		
				n	25	25	25	24	24		
	B	1		$\bar{x}$	85.1	91.3	96.9	2.28	2.74	30	26.5
				s	6.1	4.8	5.4	1.37	0.85		
				n	25	23	25	25	25		
	B	2		$\bar{x}$	76.2	83.4	88.9	1.67	2.34	21.5	17.5
				s	7.5	7.9	6.6	1.09	0.78		
				n	25	25	25	24	25		
	B	3		$\bar{x}$	71.2	78.3	84.3	0.56	1.61	16	12.5
				s	6.7	6.6	4.4	2.12	1.11		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	86.0	92.3	97.4	3.40	3.41	33.8	27.5
				s	5.6	4.2	5.3	1.68	0.79		
				n	25	23	25	25	25		
	C	2		$\bar{x}$	77.9	85.4	91.2	1.64	2.16	26.8	19.5
				s	6.9	6.8	5.8	1.41	1.06		
				n	25	25	25	25	25		

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TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
SI	C	3	10	$\bar{x}$	71.0	78.5	83.9	1.44	1.88	19.3	7.5
				s	6.3	6.7	5.1	1.83	1.04		
				n	25	25	25	25	25		
	A	1	15	$\bar{x}$	84.9	90.7	95.7	3.74	3.41	32	20
				s	4.9	4.3	4.7	1.10	0.67		
				n	25	24	25	25	25		
	A	2		$\bar{x}$	78.9	84.8	90.2	1.68	2.44	25	14
				s	7.0	6.9	5.9	0.80	0.76		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	74.1	79.7	86.0	1.12	2.10	20	10
				s	6.8	6.3	6.0	1.33	0.82		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	85.3	90.9	97.3	3.52	3.37	29.5	20.5
				s	5.3	5.3	5.6	1.73	1.09		
				n	24	24	24	25	25		
	B	2		$\bar{x}$	77.5	83.7	89.8	1.72	2.20	20	13.5
				s	7.8	8.3	6.6	1.02	0.76		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	72.9	78.4	85.9	1.12	1.88	16.5	9.5
				s	7.1	7.3	6.4	1.09	0.85		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	85.7	91.1	96.7	3.48	3.32	32.8	21
				s	5.2	5.2	5.3	1.05	0.76		
				n	25	25	25	25	25		
	C	2		$\bar{x}$	78.0	83.3	89.6	2.12	2.52	20	10
				s	6.6	6.2	5.5	0.88	0.65		
				n	25	25	25	25	25		
	C	3	15	$\bar{x}$	74.8	80.4	87.0	0.76	1.90	20.8	11
				s	7.0	6.7	5.7	1.67	0.88		
				n	25	25	25	25	25		
	A	1	20	$\bar{x}$	85.4	88.1	94.9	3.84	3.72	33	22
				s	5.3	5.1	4.1	1.03	0.54		
				n	25	25	25	25	25		
	A	2		$\bar{x}$	77.6	80.6	86.9	2.44	2.71	24.5	14.5
				s	6.5	5.4	6.0	1.23	0.91		
				n	25	25	25	25	25		
	A	3		$\bar{x}$	74.0	77.0	83.8	1.64	2.29	21	11
				s	6.7	5.2	5.5	1.29	0.91		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	85.2	87.7	94.3	3.52	3.53	29.5	22
				s	6.0	5.8	4.9	1.12	0.75		
				n	25	25	25	25	25		
	B	2		$\bar{x}$	76.4	79.6	87.1	2.84	2.76	20.5	14
				s	7.8	6.8	6.0	1.43	0.94		
				n	25	25	25	25	25		
	B	3		$\bar{x}$	72.4	75.7	83.9	1.80	2.37	16.5	10
				s	7.7	6.3	6.3	1.76	1.23		
				n	25	25	25	25	25		

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TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
SI	C	1	20	$\bar{x}$	84.5	87.1	93.3	3.76	3.56	31.8	21.5
				s	7.7	7.3	6.6	1.16	0.63		
				n	25	25	25	25	25		
	C	2		$\bar{x}$	77.1	80.1	87.5	2.72	2.83	24.8	14.5
				s	7.4	6.8	6.0	1.10	0.89		
				n	25	25	25	25	25		
	C	3	20	$\bar{x}$	73.2	76.6	84.0	1.28	1.96	20.3	10.5
				s	6.3	5.3	4.2	1.34	0.96		
				n	25	25	25	25	25		
	A	1	30	$\bar{x}$	85.1	86.1	92.5	3.17	3.28	32	20
				s	5.1	5.3	4.0	1.20	0.79		
				n	25	25	25	25	25		
	A	2		$\bar{x}$	78.1	79.9	86.3	3.28	3.30	24.5	12.5
				s	7.4	5.8	6.1	1.40	0.83		
				n	24	24	24	24	24		
	A	3		$\bar{x}$	69.4	72.6	78.9	1.44	2.03	15.5	4
				s	3.0	4.7	5.5	1.78	1.20		
				n	25	25	25	25	25		
	B	1		$\bar{x}$	83.6	85.2	90.8	3.48	3.42	27.5	19
				s	6.3	6.1	4.8	1.16	0.80		
				n	25	25	25	25	25		
	B	2		$\bar{x}$	74.9	77.3	84.3	2.72	2.92	21.3	10
				s	7.3	5.5	6.1	1.72	0.86		
				n	24	24	24	24	24		
	B	3		$\bar{x}$	70.7	74.1	81.1	1.92	2.48	13.5	6
				s	7.6	5.6	4.7	1.55	0.92		
				n	25	25	25	25	25		
	C	1		$\bar{x}$	83.7	84.8	91.0	2.3	2.6	30.8	19
				s	6.0	5.5	5.3	1.4	1.1		
				n	24	24	24	24	24		
	C	2		$\bar{x}$	74.8	77.1	84.7	2.40	2.78	21.3	10
				s	5.7	4.5	4.7	1.35	0.75		
				n	25	25	25	25	25		
SI	C	3	30	$\bar{x}$	68.6	72.9	79.7	1.08	1.90	14.3	3.5
				s	5.9	4.5	4.2	1.61	1.11		
				n	25	25	25	25	25		
	A	1		$\bar{x}$	80	84	93.1	3.6	3.2		
				s				1.0	0.7		
				n				22	22		
	A	2		$\bar{x}$	70	73.5	83.8	0.8	1.7		
				s				1.7	0.9		
				n				22	22		
	A	3		$\bar{x}$	65	70	78.3	0.1	1.3		
				s				2.2	1.0		
				n				21	22		
	B	1		$\bar{x}$	80	79	93.9	3.5	3.3		
				s				1.2	0.7		
				n				22	21		

APPENDIX B

TEST SOUND											
TYPE	BBS	BBL	RATE		DBA	DBC	PNL	SRI	SRAQ	cf (dBA)	cf (Linear)
	B	2		$\bar{x}$	70	71	83.7	1.2	1.9		
				s				1.8	1.1		
				n				22	22		
	B	3		$\bar{x}$	65	66	79.2	0	1.5		
				s				2.2	1.0		
				n				21	22		
	C	1		$\bar{x}$	80	81	93.7	2.9	3.0		
				s				1.3	1.0		
				n				22	22		
	C	2		$\bar{x}$	70	71	83.4	1.2	1.8		
				s				1.8	1.0		
				n				22	22		
	C	3		$\bar{x}$	65	63	78.8	0.2	1.4		
				s				2.0	1.0		
				n				22	22		

APPENDIX C

This appendix contains an analysis and discussion on the results obtained from the numerical category scaling procedure.

APPENDIX C

As discussed in the body of the report on Page 8, an inconsistency was found between subjective ratings of various noise samples which were supposed to be equally annoying. A decision was made to present the results obtained from the method of adjustment as the primary finding. This appendix contains an analysis and discussion of the results obtained from the numerical category scaling procedure.

The test program, as constructed, encompassed five independent variables: the level of the sound, the impulsiveness of the sound, the repetition rate, the spectrum shape of the reference broadband noise, and the sex of the test participant. As a first step in evaluating the results, it is necessary to determine which of these variables, or combinations of variables, had a significant effect in determining the subjective evaluation of helicopter rotor noise.

An analysis of variance was performed on the subjective responses obtained from the numerical category scaling (NCS) procedure using the methods described in References (3) and (4). The results of this analysis are found in Table A-I.

Statistical significance is indicated when the calculated F value of a variable or combination of variables exceeds the tabulated F value. A review of Table A-I shows that the following variables were found to be significant with respect to subjective evaluation of the noise samples.

Variable	Calculated F Value	Tabulated F Value
Level	148.934	2.996
Impulse	92.796	2.996
Sex	48.127	3.841
Rate	4.660	2.605
Sex & Level	5.523	2.996
Rate & Impulse	2.187	2.099

The sex of the participant proved to be significant, not because the women adjusted the sound to a different level than did the men when judging subjective equality, but because, when evaluating sounds of the same level, the men rated them more unpleasant. No explanation for the difference is evident.

One test variable which did not appear to be significant was the spectrum shape of the broadband noise. Three variations were included in the test design, not because it was thought to be important, but rather in the hope that it would

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TABLE C- I. ANOVA SUBJECTIVE RATINGS

Source	Sum of Squares	d.f.	Mean Square	Calculated F - Value
R	6.286	3	2.0953	4.6580*
H	83.453	2	41.7265	92.7586*
X	21.461	1	21.641	47.7081*
L	133.984	2	66.9920	148.9241*
S	1.622	2	0.8110	1.8029
RH	5.901	6	0.9835	2.1863*
RX	0.317	3	0.1057	0.2349
RL	4.514	6	0.7523	1.6724
RS	2.413	6	0.4022	0.8940
HX	0.414	2	0.2070	0.4602
HL	2.763	4	0.6908	1.5355
HS	0.854	4	0.2135	0.4746
XL	4.967	2	2.4835	5.5209*
XS	0.142	2	0.0710	0.1578
LS	0.576	4	0.1440	0.3201
RHX	0.528	6	0.0880	0.1956
RHL	4.723	12	0.3936	0.8749
RHS	4.852	12	0.4043	0.8988
RXL	1.335	6	0.2225	0.4946
RXS	1.009	6	0.1682	0.3738
RLS	4.002	12	0.3335	0.7414
HXL	0.439	4	0.1098	0.2440
HXS	0.392	4	0.0980	0.2179
HLS	0.566	8	0.0708	0.1573
XLS	0.635	4	0.1588	0.3529
RHXL	1.852	12	0.1543	0.3431
RHXS	2.307	12	0.1923	0.4274
RHLS	6.435	24	0.2681	0.5960
RXLS	1.691	12	0.1409	0.3133
HXLS	1.075	8	0.1344	0.2987
RHXLS	3.253	24	0.1355	0.3013
SUBCLASS	304.941	215		
WITHIN	1108.855	2465	0.4498	
TOTAL	16441.75	2680		

*Statistically Significant

KEY
R - Rate
H - Impulse
X - Sex
L - BB Level
S - BB Shape

F - Distribution $\alpha = 0.05$ (95%)

γ_1, γ_2	F-Value	γ_1, γ_2	F-Value
1, ∞	3.8415	6, ∞	2.0986
2, ∞	2.9957	8, ∞	1.9384
3, ∞	2.6049	12, ∞	1.7522
4, ∞	2.3719	24, ∞	1.5173

not. Verification by the subjective ANOVA permits combining the data obtained with different broadband spectra in the evaluation procedure.

In order to quantify the role of each of the significant variables in determining the subjective response, a linear regression analysis was done using the variables indicated as significant by the ANOVA. The variable of sex was dropped since the desired result should be applicable to both men and women. The resulting form for the solution is:

$$SRI = F_0 + F_1 \text{ (Level)} + F_2 \text{ (Impulse)} + F_3 \text{ (Rate)}$$

where SRI = Subjective Rating Index (Question I on Rating Form)

- 5 = Extremely Pleasant
0 = Neutral
+ 5 = Extremely Unpleasant

In order to conduct the analysis, it was necessary to have a quantity to express impulse (level and rate are already in measurable units). As illustrated in Figures C-1 and C-2, the value of dBC will greatly exceed that of dBA for low frequency dominated, non-impulsive rotor noise; but the two values will approach each other as the higher harmonic content increases to produce the impulsive sound. Application of these measurements to the rotor noise signatures produced by the subjects during this program reveals:

Waveform	dBC-dBA
Non-Impulsive	20-25 dB
Multiple Impulse	5-12 dB
Single Impulse	2- 8 dB

Using this measure for impulsiveness, it was now possible to perform the regression analysis. A separate analysis was done with level measured in units of PNdB, dBA and dBC with the following results:

$$SRI = -10.98 + .149(\text{PNdB}) - .065(\text{dBC-dBA}) + .016 \text{ (Rate)} \quad r = .938$$
$$SRI = -9.56 + .149(\text{dBA}) - .020(\text{dBC-dBA}) + .018 \text{ (Rate)} \quad r = .957$$
$$SRI = -9.56 + .149(\text{dBA}) - .169(\text{dBC-dBA}) + .018 \text{ (Rate)} \quad r = .957$$

The correlation coefficients of .938 (PNdB), .957 (dBA), and .957 (dBC), were all quite high and indicate that the above regression equations are quite adequate.

Given a set of input data, each of the three equations will predict the Subjective Response Index (SRI) with good accuracy and selection of units is immaterial. There would, however, be little argument for using Perceived Noise Level since it is more complex to measure and had a slightly lower correlation. Figure C-3 shows the correlation between the calculated mean SRI and the mean SRI which the group indicated for all test conditions. A graphical solution for SRI in terms of dBA and dBC is presented in Figure C-1.

In addition to indicating their individual SRI for each sound in response to Question I of the rating form, the subjects were also asked, "What do you think the reaction of people, in general, would be if they were exposed to it in their daily lives?" (Question III). The correlation of the SRI and the annoyance evaluation are presented in Figure C-5a. This figure indicates that the non-impulsive sounds were never regarded as extremely annoying or unpleasant. The figure also illustrates that even when people felt neutral about the quality of the sound they would still be slightly annoyed by it if they were exposed to it in their daily lives. This implies that people may not accept the intrusion of a sound merely because they do not find it unpleasant.

The subjects were also asked to evaluate the nine broadband reference sounds (3 spectra at 3 levels) using the same scales as they did for the harmonic noise. Figure C-5b presents these ratings as a function of the Perceived Noise Level of each broadband sample. Perceived Noise Level was chosen because of the large background of experience available in interpreting subjective response to broadband airplane noise in terms of these units. As can be seen, the 95 PNdB range, generally considered borderline for airplanes, corresponded to an SRI in the 3-4 range. This should not be rigorously applied to establishing a limit for SRI, but it is not a totally unreasonable guideline.

Application of the SRI calculation to an actual case can be evaluated by using the data of Figure C-6. This data was taken of flybys of the Boeing-Vertol CH-47A and CH-47C helicopters. The difference in acoustical data is attributable to a change in longitudinal cyclic trim between the two helicopters which increases the vertical clearance between the rotors on the CH-47C model and hence avoids blade-vortex intersections which produce highly impulsive noise. This data is very typical in that reduction of the impulse affects all rotor harmonics, but has the greatest effect in the 250 Hz to 500 Hz range. The reduction in SRI from 4.28 to 2.04 indicates that a substantial reduction in annoyance should have been achieved. Although no rigorous psychoacoustic testing has been conducted using this data, the manufaxturers' experience bears out such a conclusion which supported the decision to incorporate the cyclic trim change on the production aircraft.

Another set of instructive cases can be examined by considering a progression of hypothetical data as shown in the following table:

CONDITION	dBC	dBA	dBC-dBA	RATE	SRI
I - Impulsive Rotor	100	95	5	20	4.86
II - Non-Impulsive Rotor	100	80	20	20	2.32
III - Impulsive Rotor SRI - 2.32	83	78	5	20	2.32
IV - Reduce Blade Passage Rate	83	78	5	10	2.14

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Starting with an impulsive rotor and an SRI of 4.86, a reduction in impulsiveness with no decrease in dBC still produces a substantial reduction in SRI to 2.32. If it were desired to hold this rating without reducing impulsiveness, a 17 dB reduction in dBC and dBA would be required (Case III). Case IV shows the further improvement which might be obtained by reducing the fundamental blade passage period.

A tabulation of the most often used descriptive words for each sound is contained in Appendix D. Although it cannot be used as hard data, it does provide additional clues as to what is meant by some of the terms which are used by the public to describe helicopter rotor noise. One of the more interesting, if not unexpected, indications is the change in descriptors of impulse noise as blade passage frequency increased. At the lower frequencies, terms like "hammering" and "pulsing" were widely used, while at a passage frequency of 30 Hz these terms disappeared and were replaced by "buzzing", "droning", "blaring", etc. Essentially, the descriptions changed from ones which describe a series of separable acoustical events to ones which describe tones.

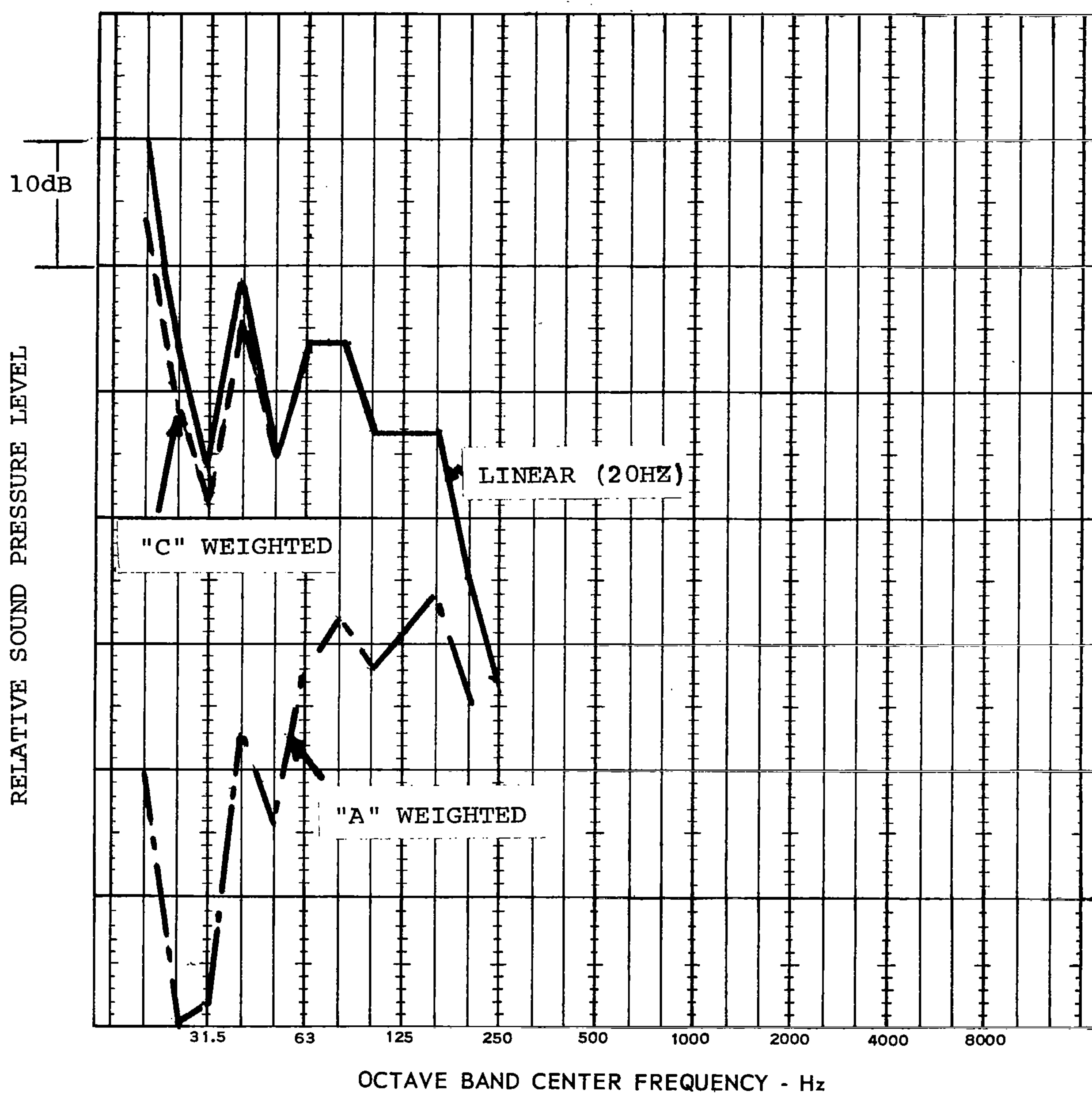

Figure C-1. Effect of Spectrum Weighting
Non-Impulsive Rotor

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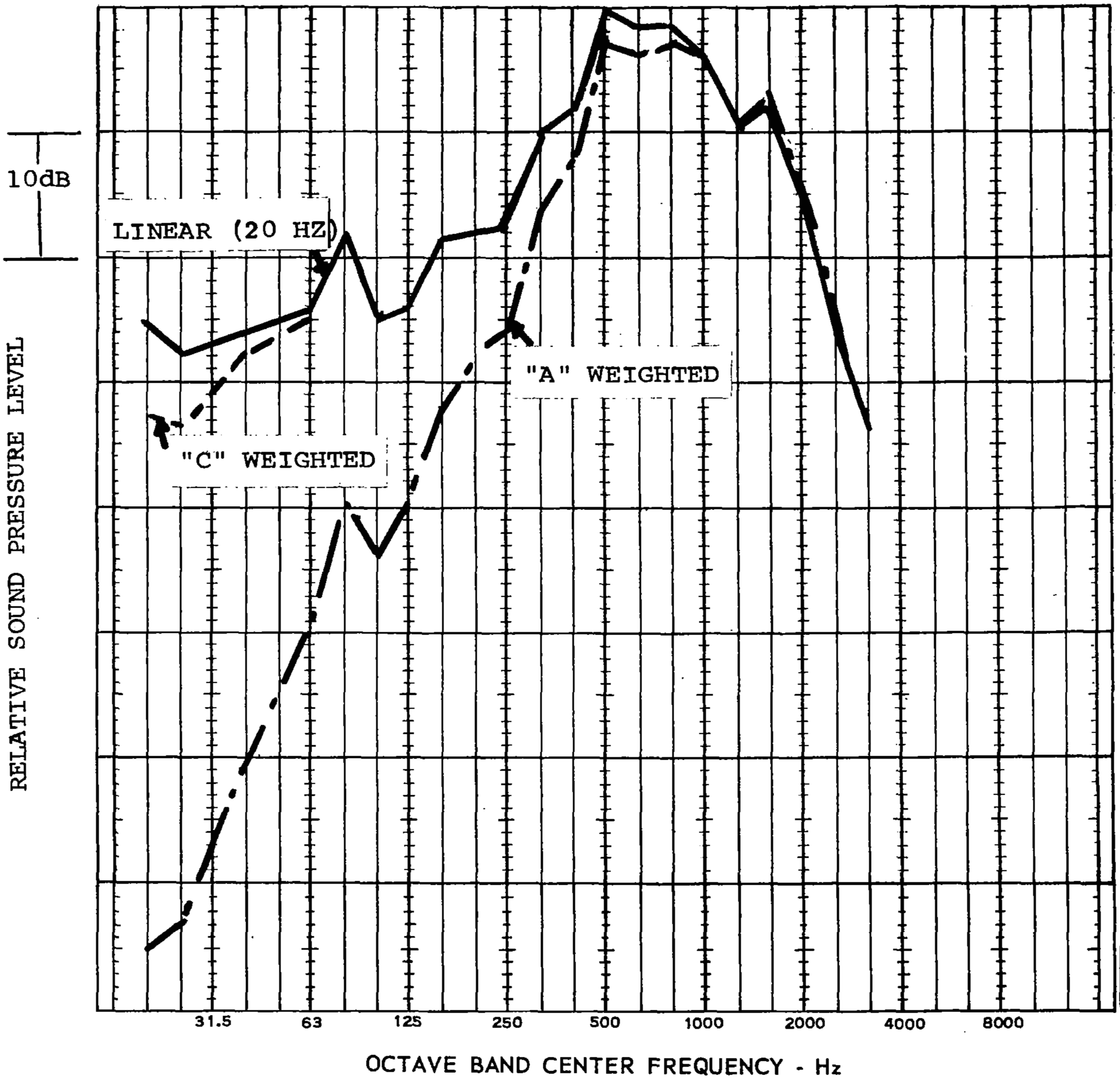

Figure C-2. Effect of Spectrum Weighting
Impulsive Rotor

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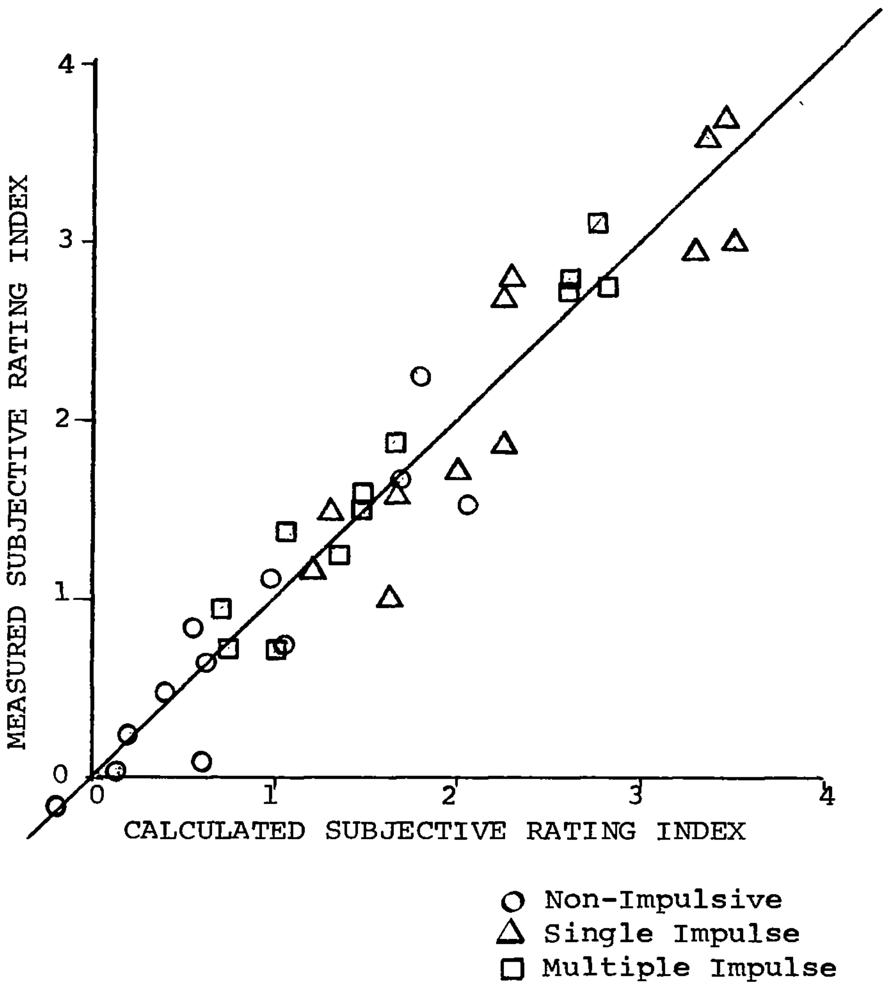

Figure C-3. Correlation of Calculated & Measured SRI

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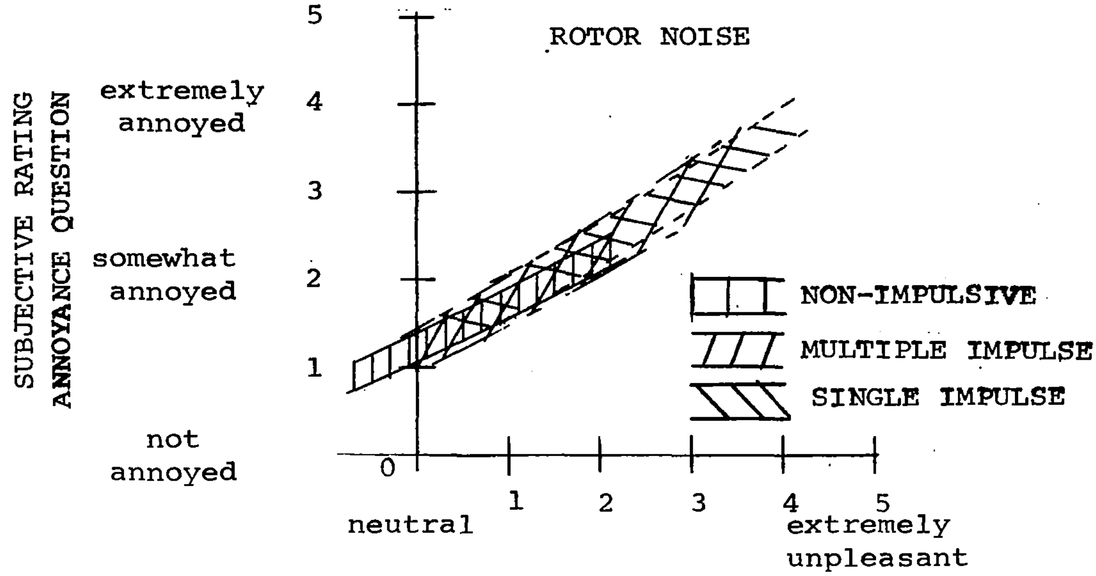
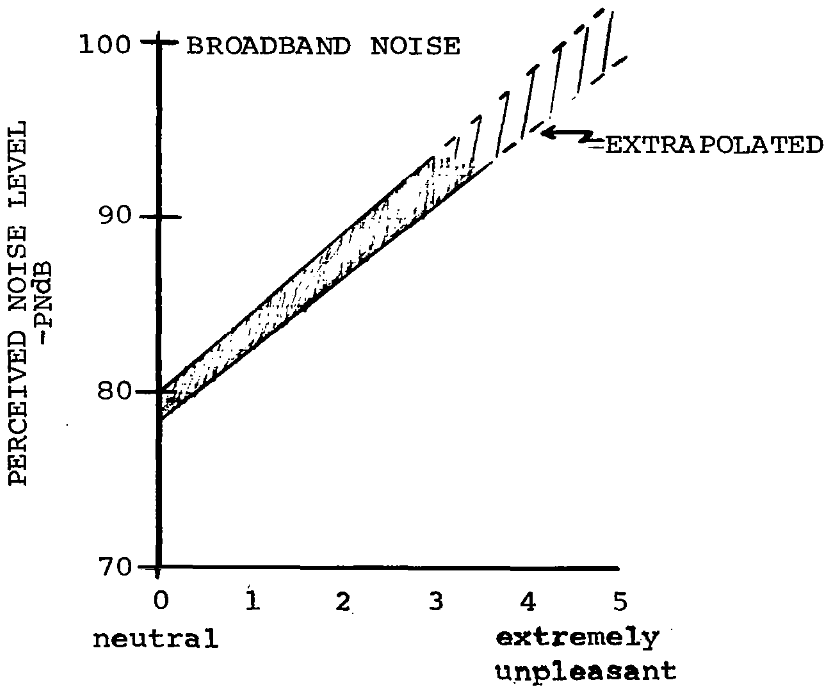


(a)



(b)

Figure C-4. Evaluation of Subjective Rating Index

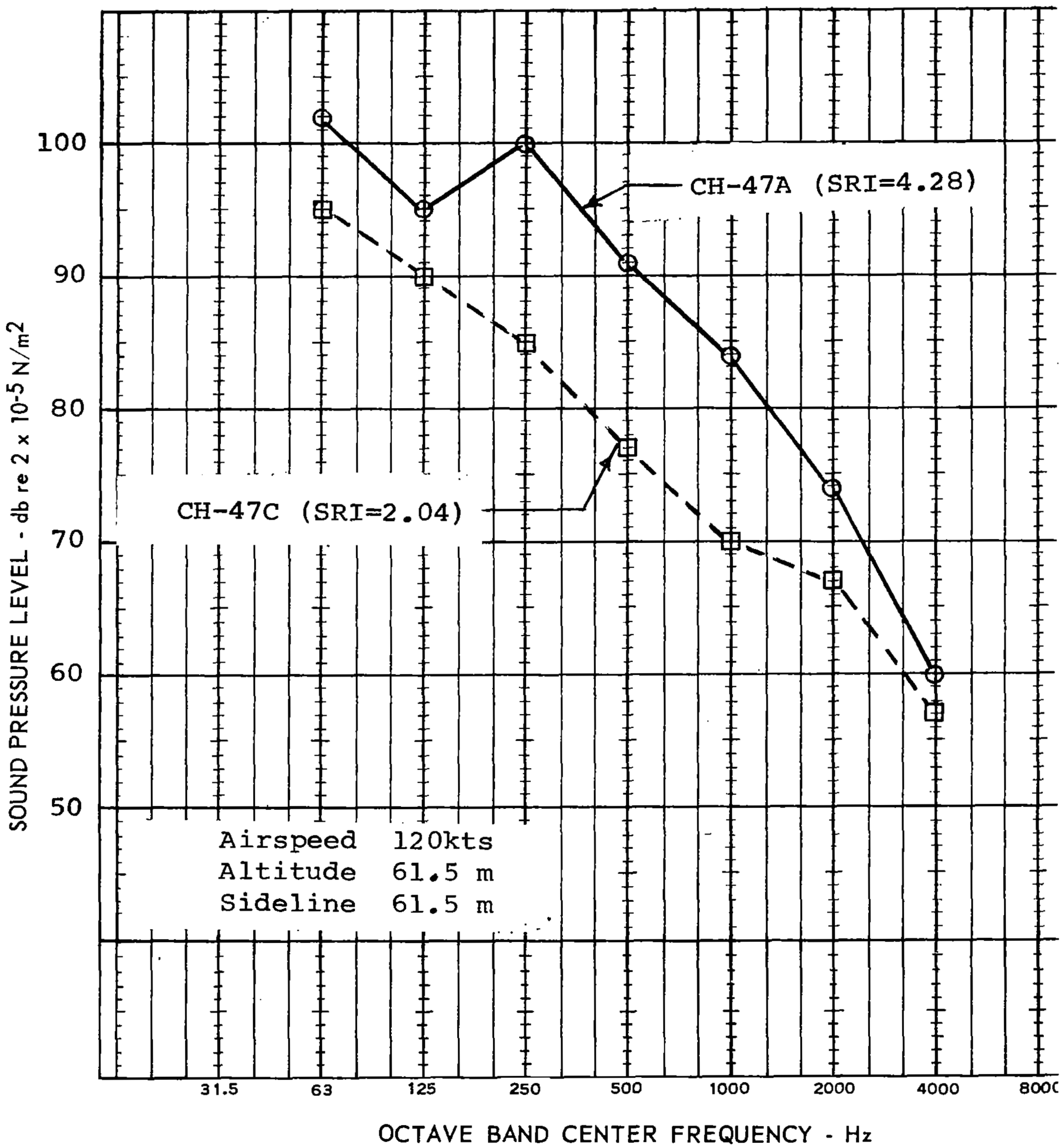


Figure C-5. External Flyby Noise, CH-47 Helicopters

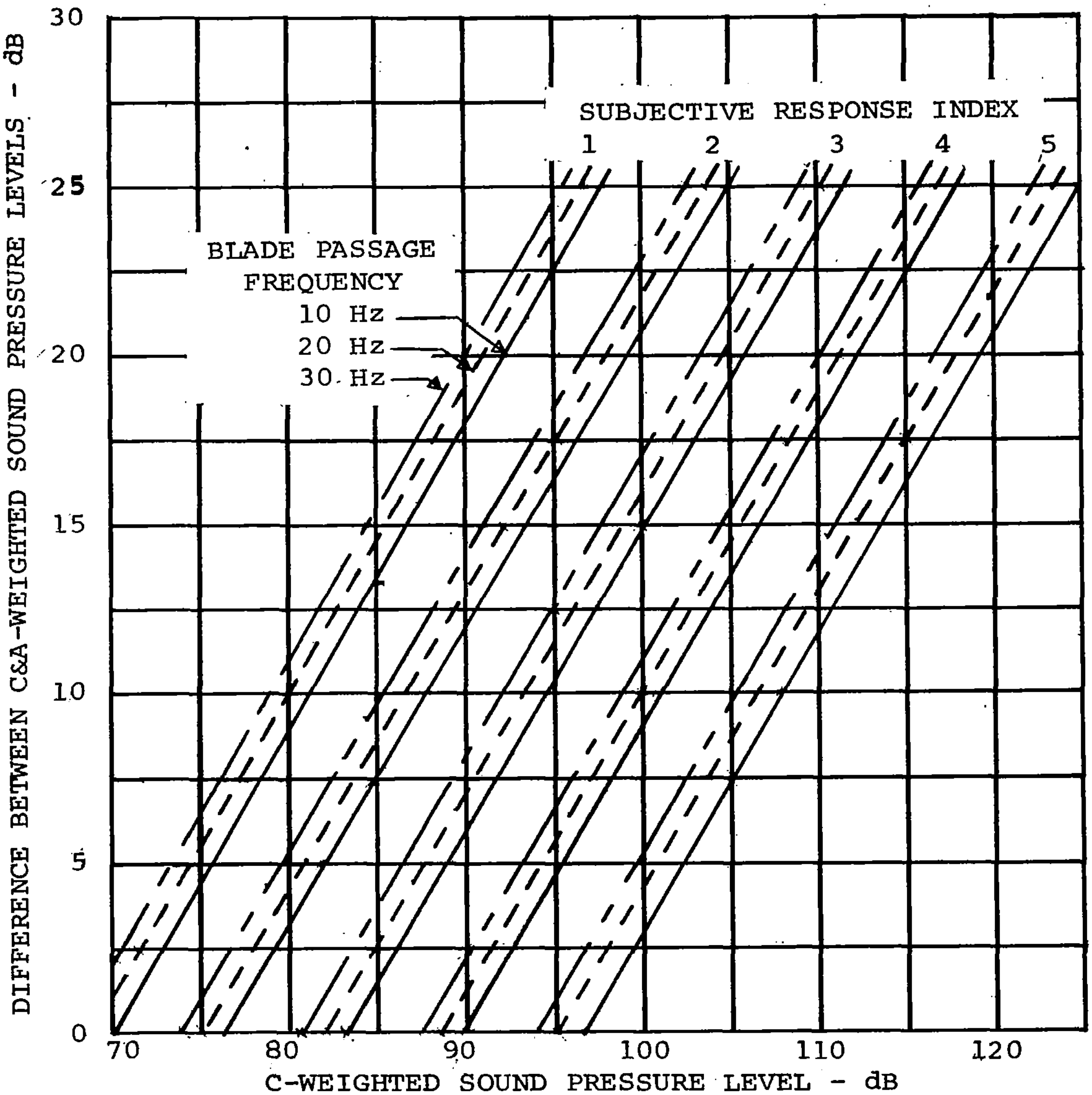


Figure C-6. Subjective Response Index Prediction Chart

APPENDIX D

This appendix tabulates by repetition rate the most frequently used words obtained from the test subjects to describe the test sounds.

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RATE 10

LEVEL (dBA)	NON-IMPULSIVE	MULTIPLE IMPULSE	SINGLE IMPULSE
60-69	Muffled (67) Muted (51) Subdued (45) Swishing (31) Hissing (30)	Muffled (21) Hammering (20) Hissing (18) Burring (16) Pulsing (15) Thumping (15) Beating (15)	
70-79	Muted (28) Thumping (23) Swishing (23) Muffled (22) Low-Pitched (20) Hissing (20)	Hammering (28) Thumping (23) Beating (23) Swishing (18) Hissing (18)	Droning (49) Hammering (40) Beating (35) Burring (35) Burring (22)
80-89		Beating (39) Hammering (36) Thumping (24) Loud (23) Pulsing (21)	Hammering (32) Loud (31) Beating (26) Burring (23) Pulsing (20) Thumping (20)

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RATE 15

LEVEL (dBA)	NON-IMPULSIVE	MULTIPLE IMPULSE	SINGLE IMPULSE
60-69	Muffled (74) Hissing (53) Subdued (49) Swishing (48) Muted (31)	Hammering (24) Muffled (23) Purring (19) Burring (18) Muted (15) Droning (15) Hissing (15)	
70-79	Muffled (31) Pulsing (27) Thumping (23) Low-Pitched (21) Beating (20)	Muffled (27) Burring (25) Beating (19) Hammering (17) Hissing (17)	Hammering (66) Beating (45) Burring (34) Hissing (25) Muffled (17) Droning (17) Swishing (17)
80-89		Loud (32) Hammering (32) Beating (26) Burring (19) Hissing (18)	Humming (39) Loud (35) Thumping (22) Pulsing (18) Burring (16) Thudding (16)

APPENDIX D

RATE 20

LEVEL (dBA)	NON-IMPULSIVE	MULTIPLE IMPULSE	SINGLE IMPULSE
60-69	Muffled (67) Hissing (57) Swishing (47) Subdued (46) Muted (43)	Hissing (28) Muffled (27) Purring (23) Muted (20) Subdued (18)	
70-79	Muffled (32) Hissing (30) Swishing (23) Droning (21) Humming (19)	Burring (24) Droning (24) Hammering (24) Beating (20) Purring (14)	Buzzing (55) Burring (41) Hissing (39) High-Pitched (32) Droning (31)
80-89		Loud (32) Hammering (30) Burring (24) Droning (20) Beating (18)	Loud (39) Hammering (30) Burring (21) Blaring (20) Jarring (20) High-Pitched (17) Buzzing (17)

APPENDIX D

RATE 30

LEVEL (dBA)	NON-IMPULSIVE	MULTIPLE IMPULSE	SINGLE IMPULSE
60-69	Muffled (31) Subdued (28) Humming (24) Hissing (22) Muted (21)	Buzzing (32) Burring (26) Droning (19) Hissing (18) Muted (13) Hammering (13)	Buzzing (42) Hissing (20) Sharp (16) Muffled (15) Burring (15) Droning (14)
70-79	Muffled (59) Hissing (49) Humming (48) Swishing (24) Droning (23)	Buzzing (63) Burring (38) Loud (31) Droning (22) Hissing (21)	Buzzing (36) High-Pitched (23) Burring (20) Droning (20) Loud (19) Blaring (18)
80-89			Buzzing (31) Blaring (26) Burring (25) High-Pitched (30) Piercing (14)

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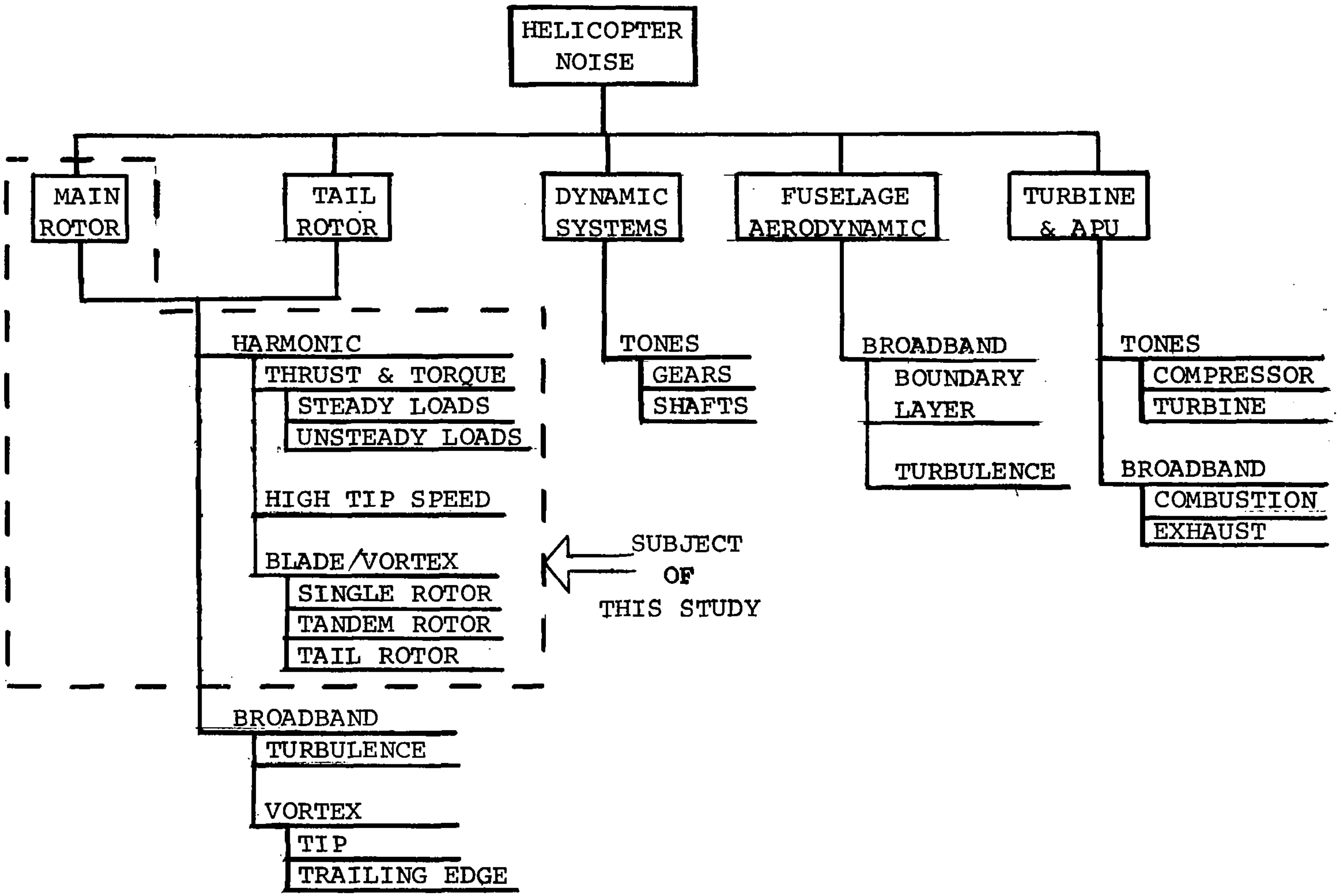


FIGURE 1. Sources of Helicopter External Noise

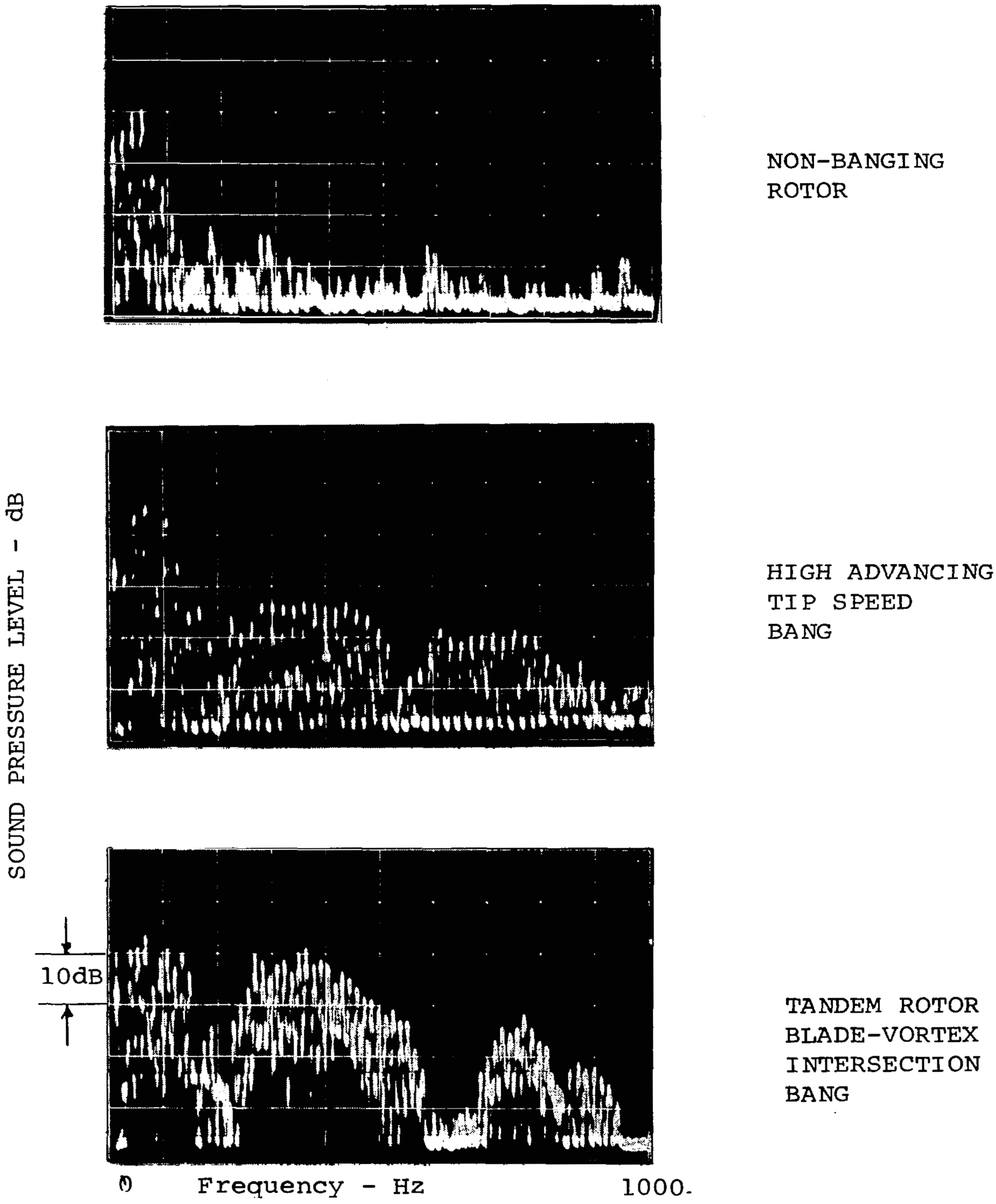
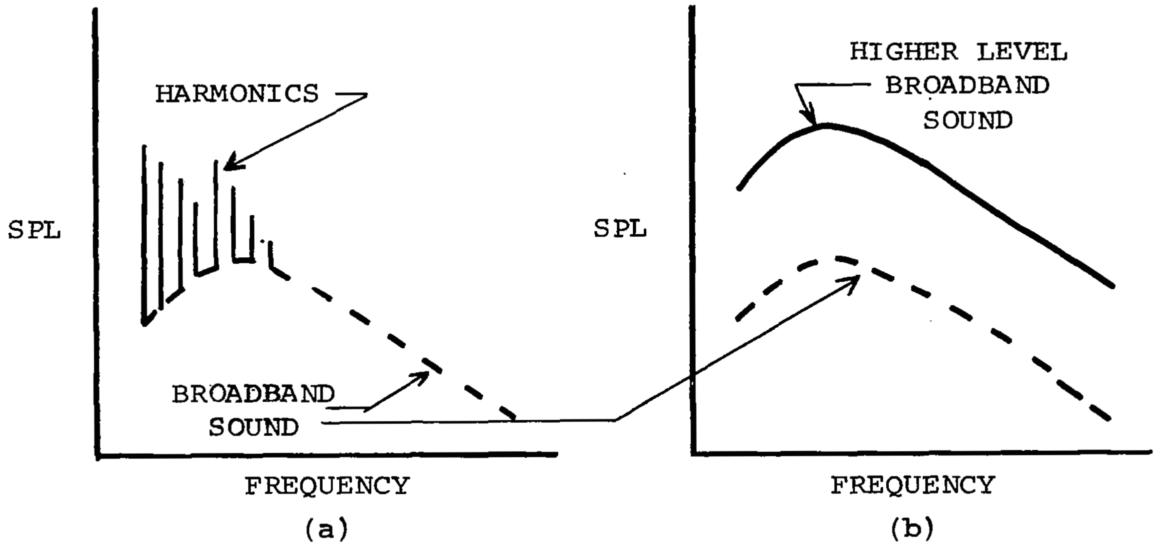


Figure 2. Narrow Band Spectra - Rotor Noise



WHEN THE SOUND OF FIGURE 3(a) IS JUDGED EQUALLY ANNOYING AS THE HIGHER LEVEL BROADBAND SOUND OF FIGURE 3(b), THE INCREASE IN ANNOYANCE DUE TO ROTOR HARMONICS CAN BE EQUATED TO THE INCREASE IN ANNOYANCE DUE TO INCREASING THE BROADBAND NOISE.

Figure 3. Program Concept

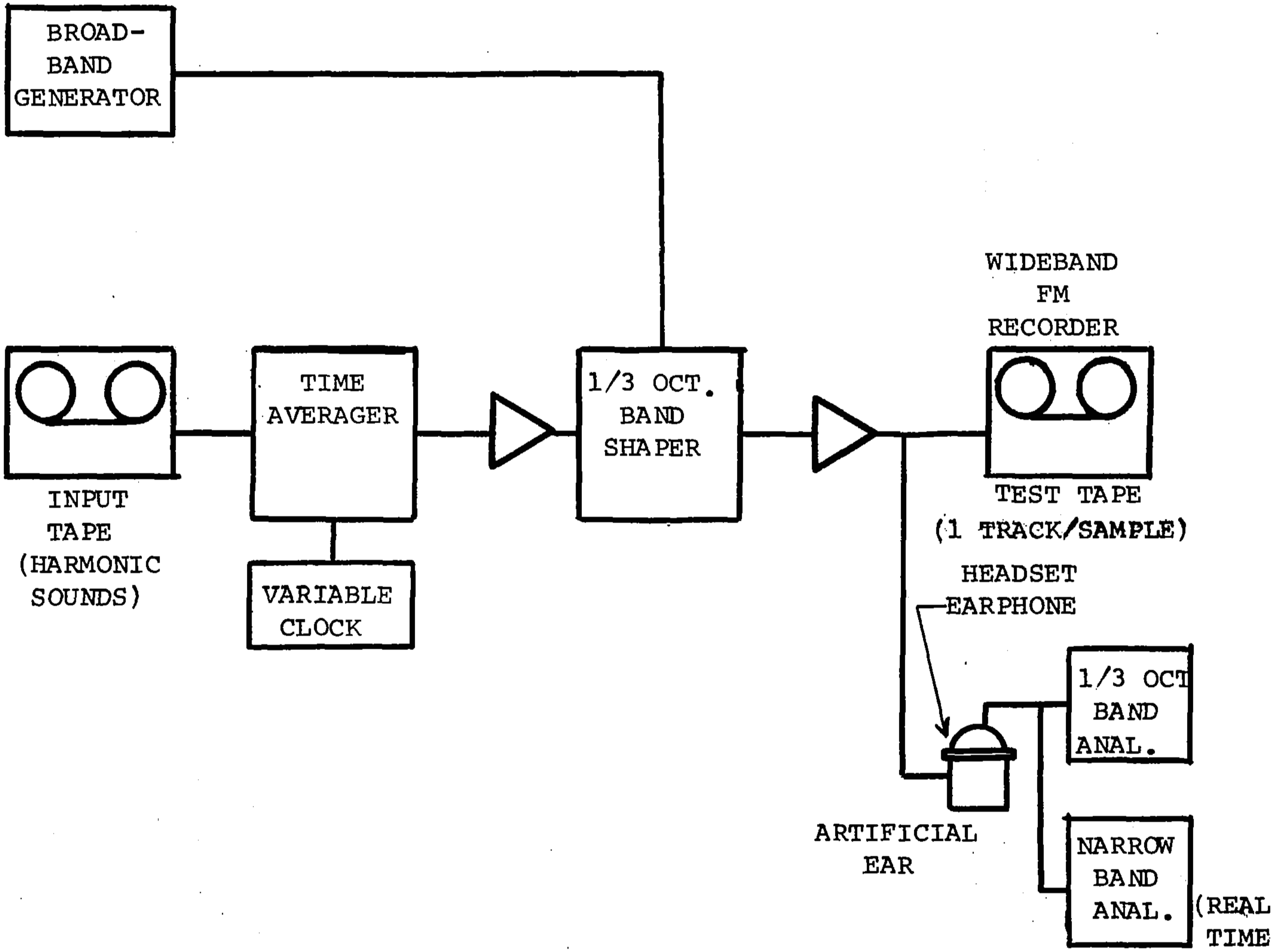


Figure 4. Noise Synthesis System

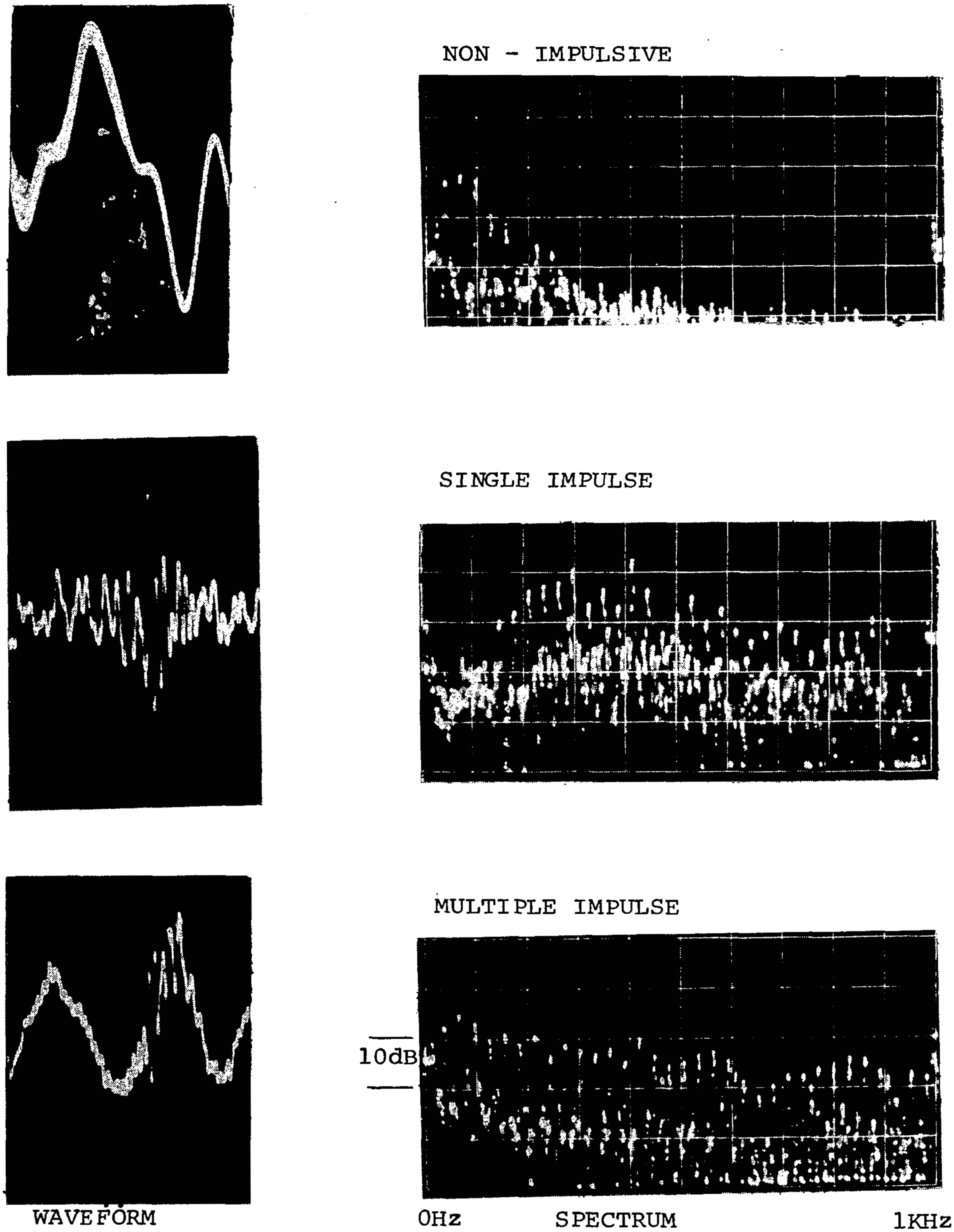


Figure 5. Test Signals Measured Through Headset

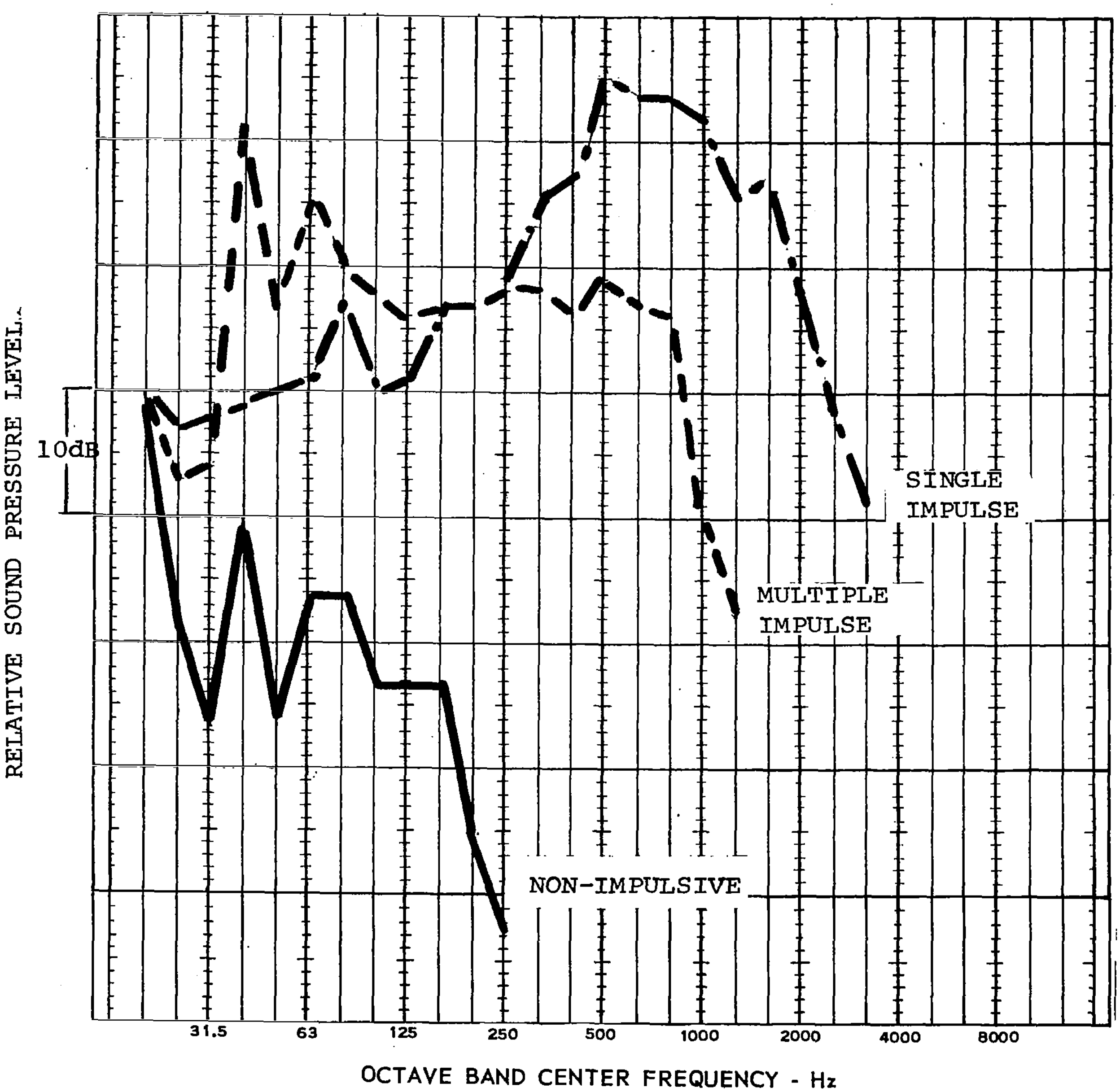


Figure 6. One-Third Octave Band Spectra Rotor Noise Samples

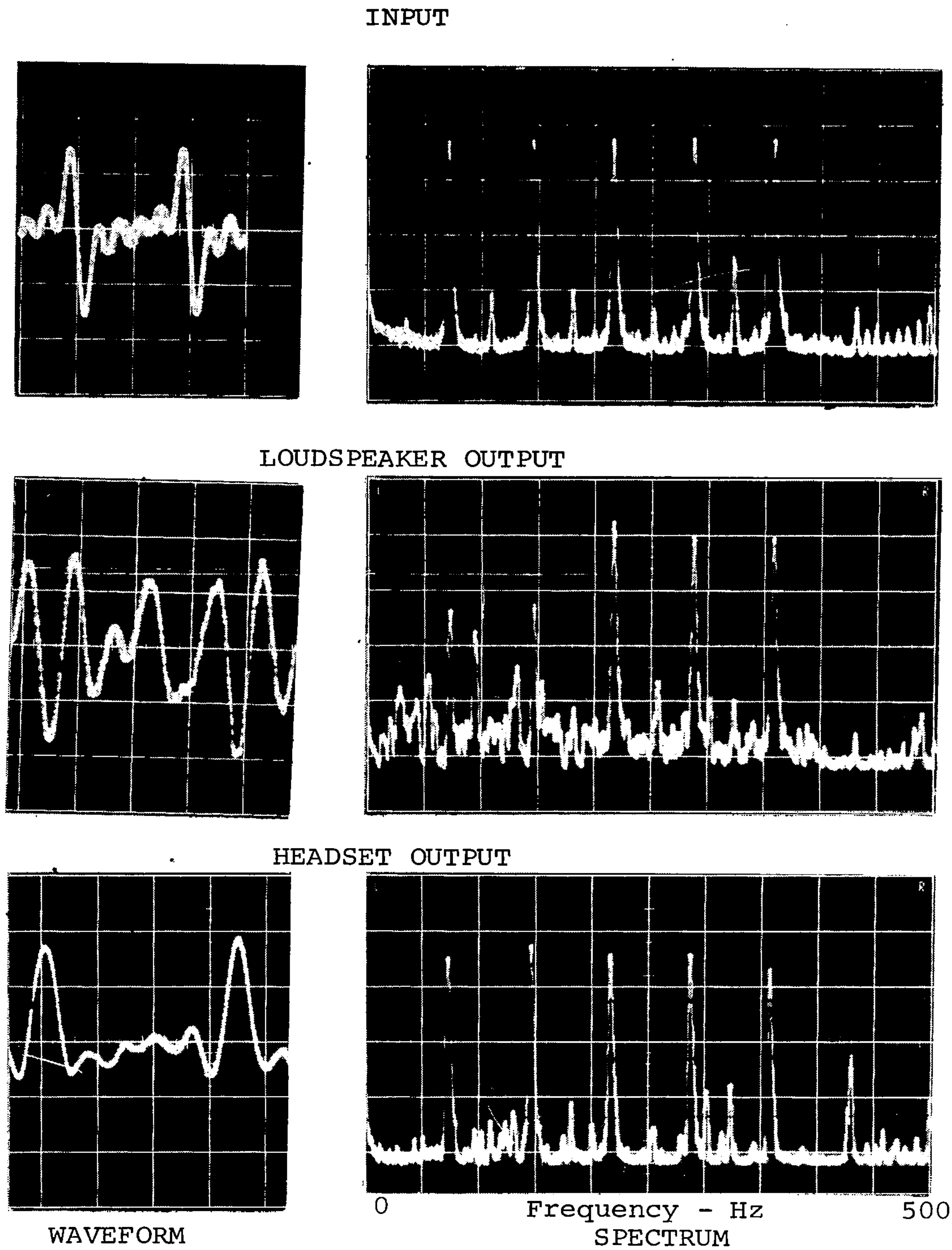
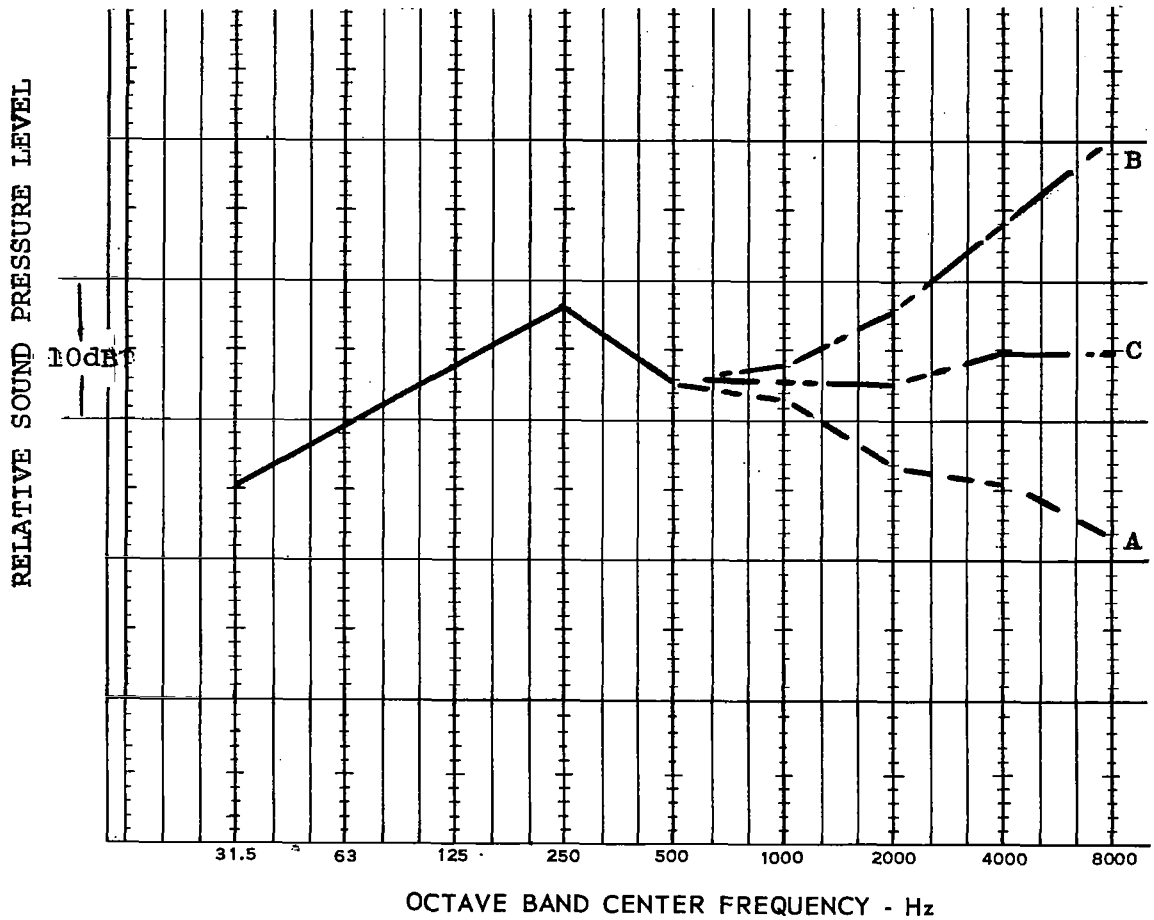


Figure 7. Rotor Noise Reproduction - Loudspeaker & Headset



A– SHAPE OF BROADBAND ROTOR NOISE– NASA LRC ANOPS ROTOR NOISE PREDICTION.

B– CURVE A WITH MAXIMUM ENGINE NOISE MEASURED DURING NASA CIVIL HELICOPTER NOISE ASSESSMENT PROGRAM.

C– HALF WAY BETWEEN CURVES A AND B.

Figure 8. Broadband Noise Samples

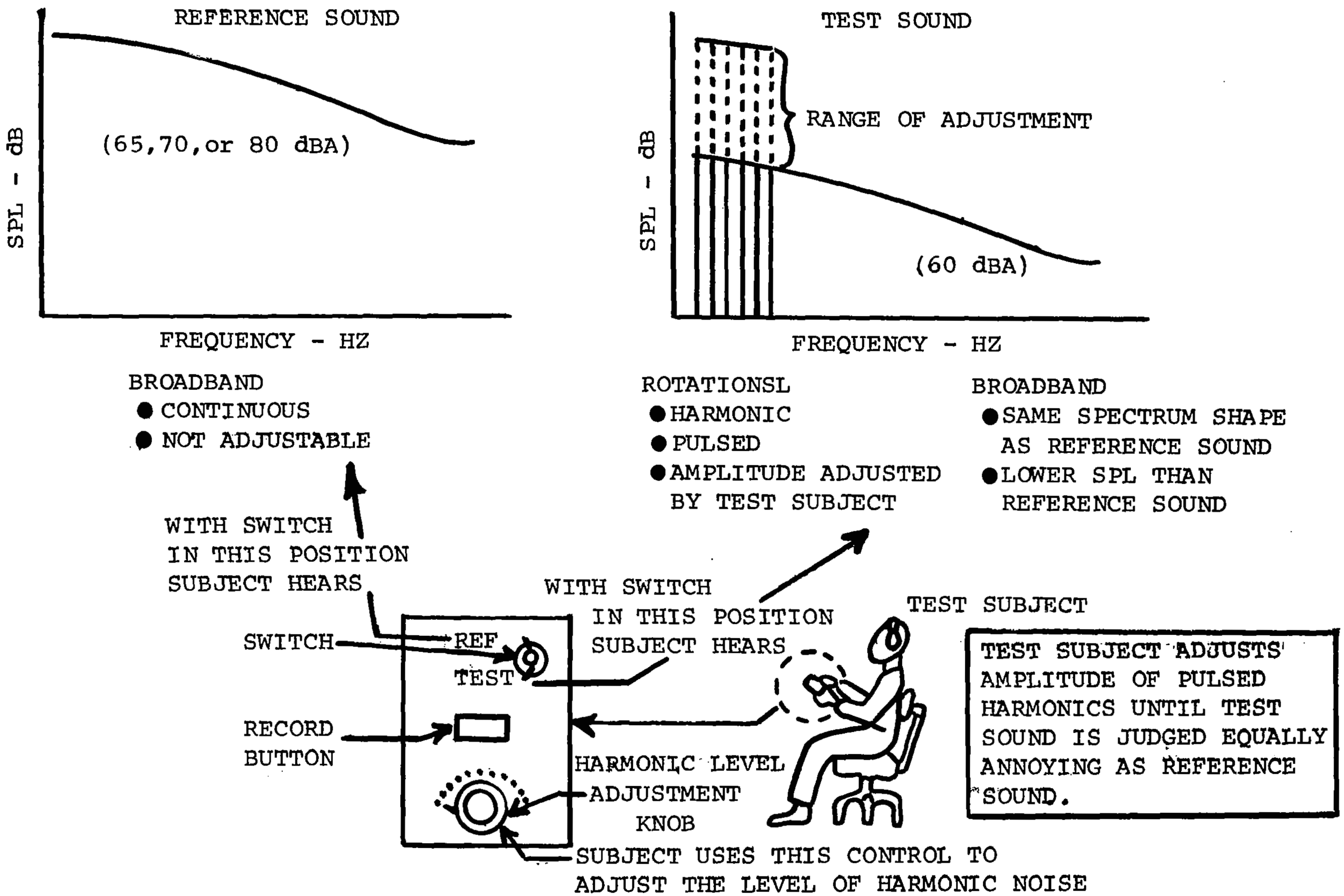


Figure 9. Test Procedure

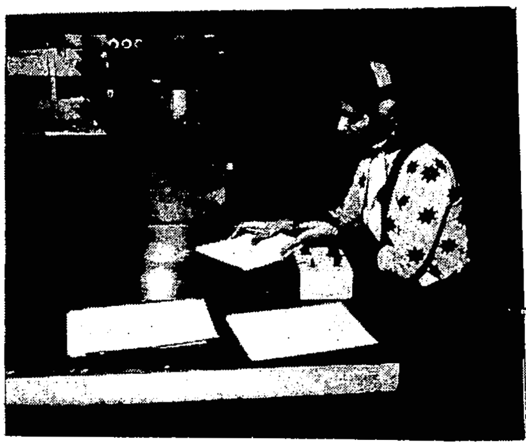


Figure 10. Photorgaphs of Test Arrangement

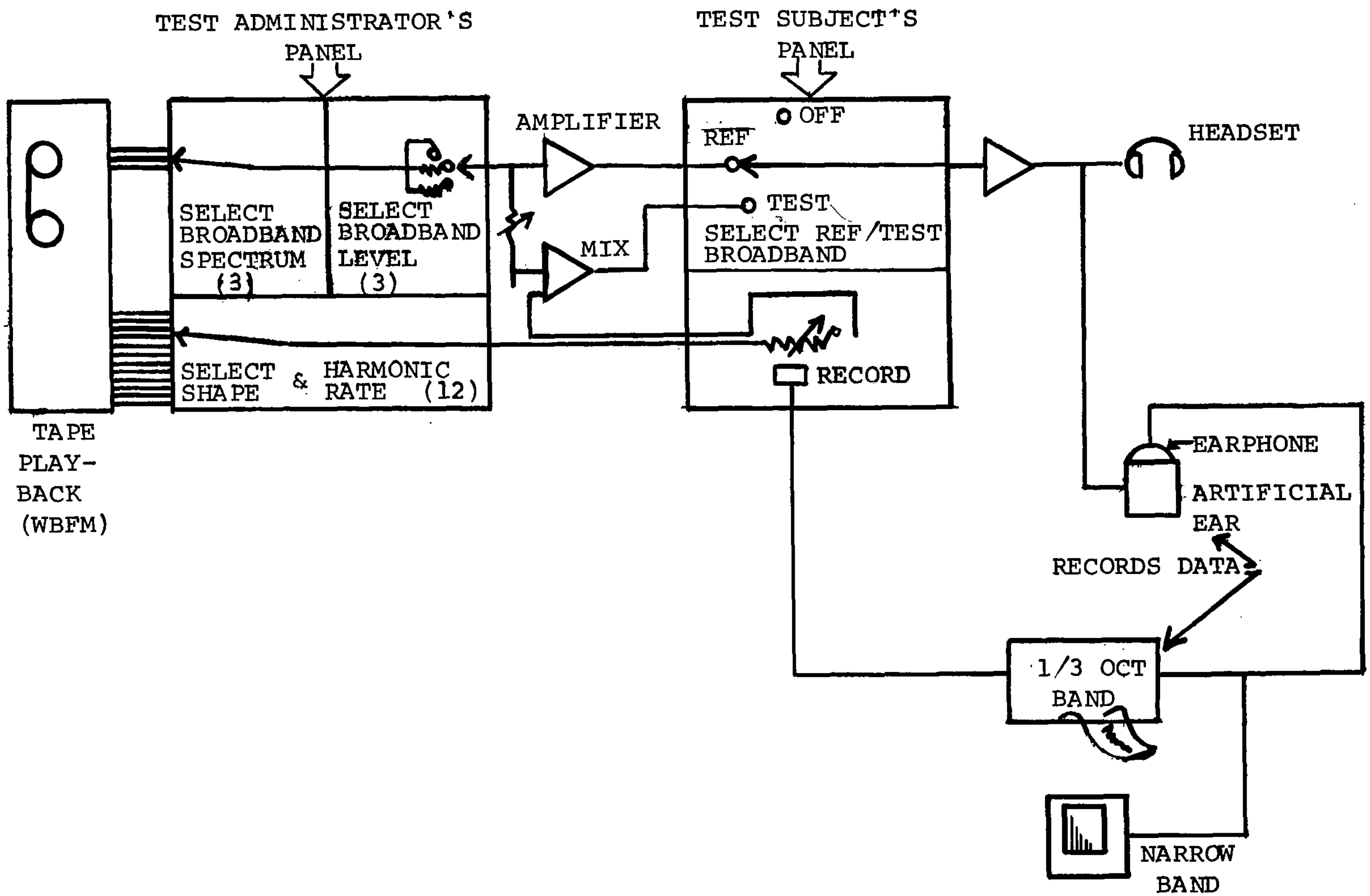


Figure 11. Test Instrumentation Diagram

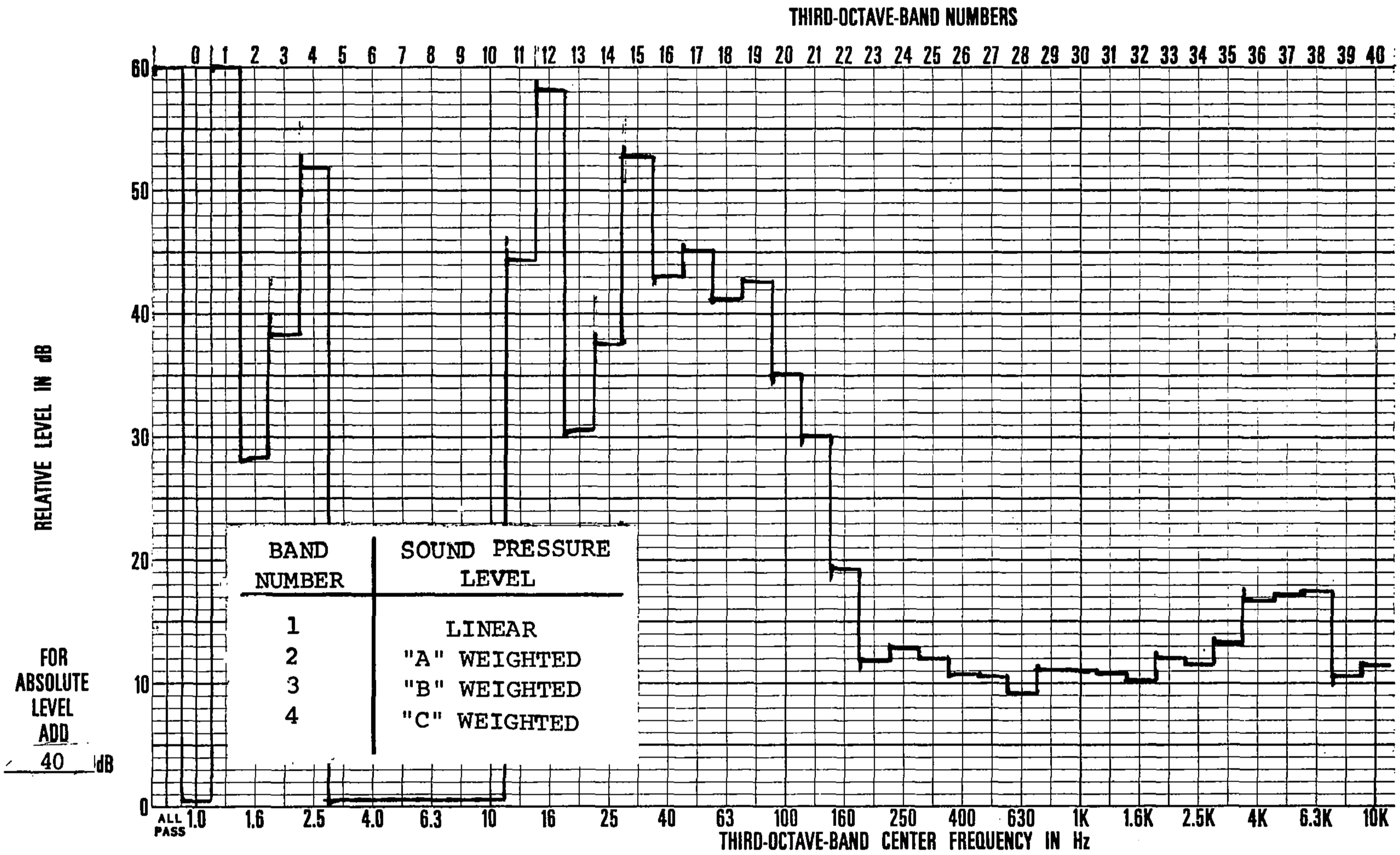


Figure 12. Typical One-Third Octave Band Chart

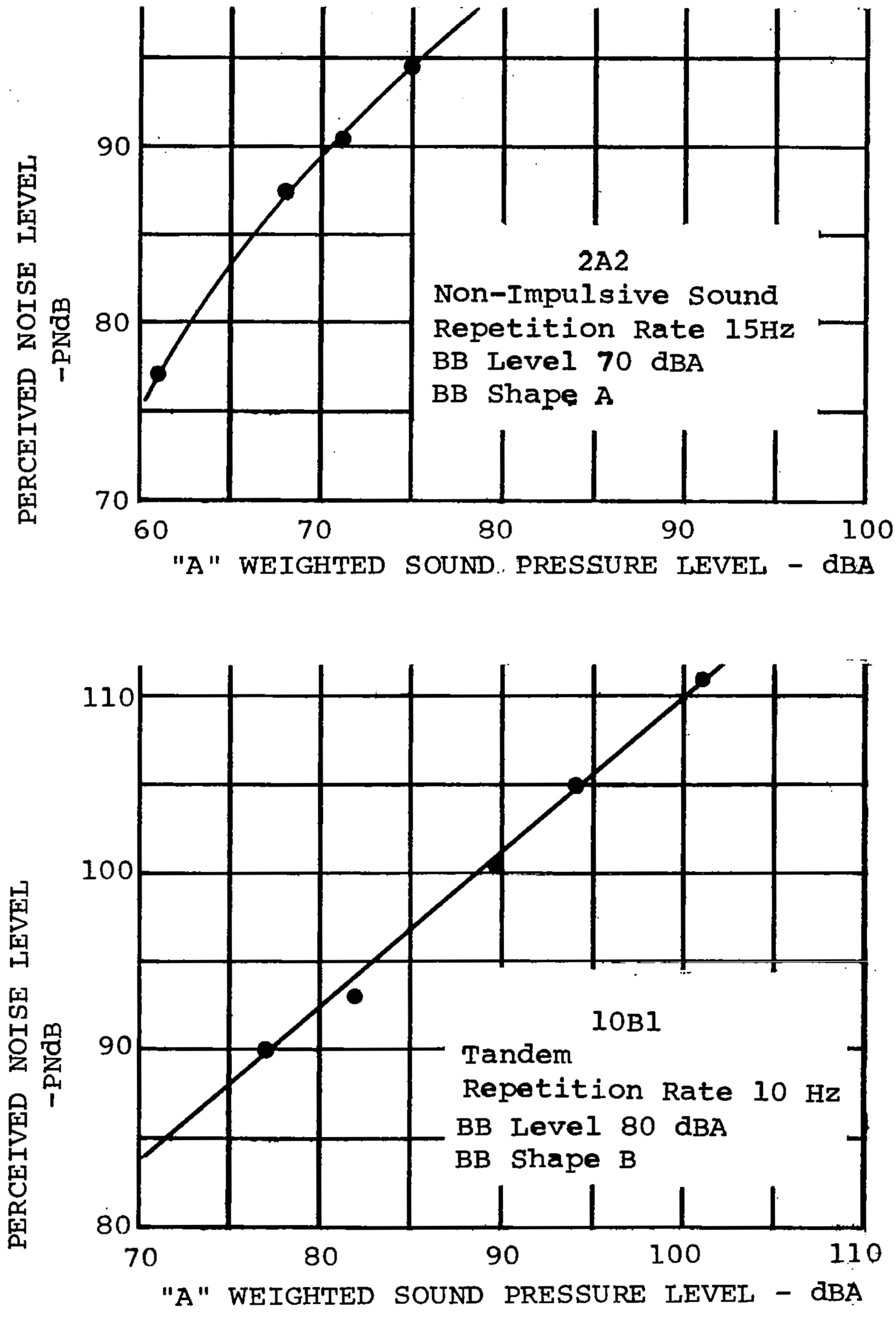
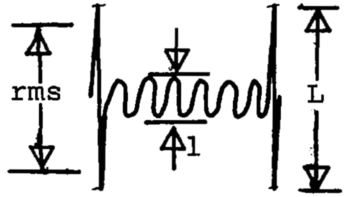


Figure 13. Examples of "A" Weighted Sound Pressure Level and Perceived Noise Level Calibration Curves.



	Linear	Log
Crest Factor (cf)	$\frac{L}{rms}$	$L_{dB} - rms_{dB}$
Idealized Crest Factor (cf_i)	$\frac{L}{l}$	$L_{dB} - l_{dB}$

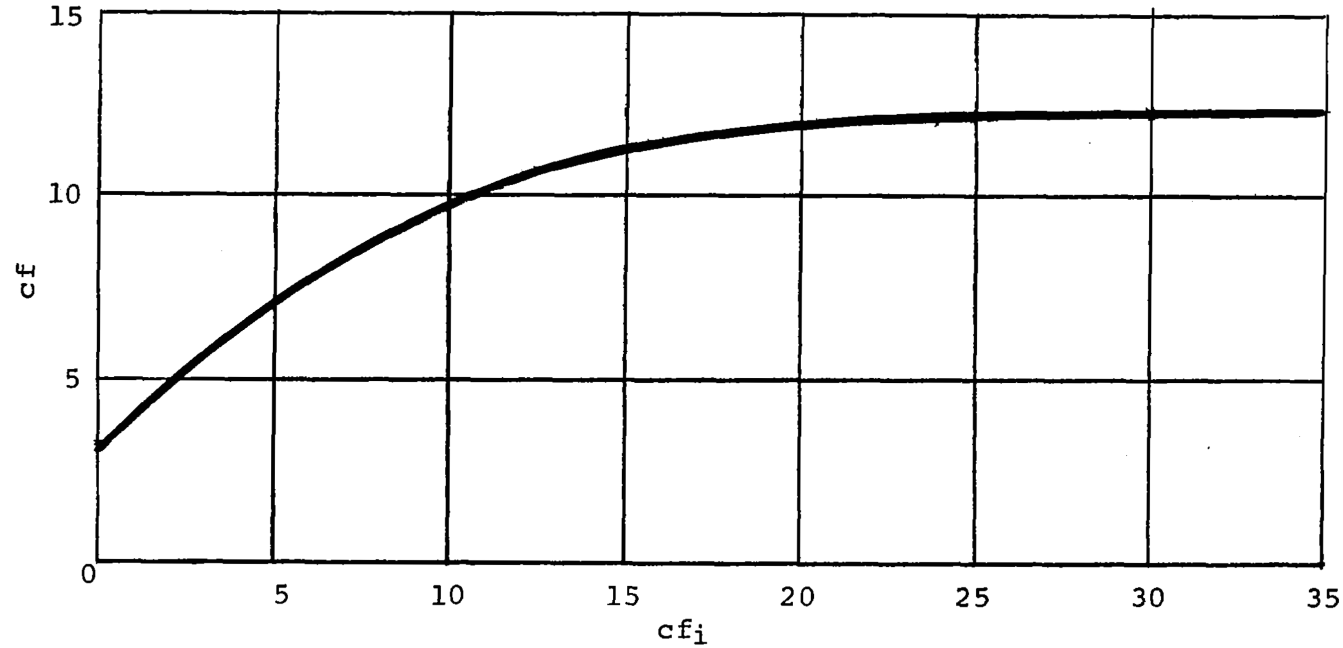


Figure 14. Relationship Between Crest Factor and Idealized Crest Factor

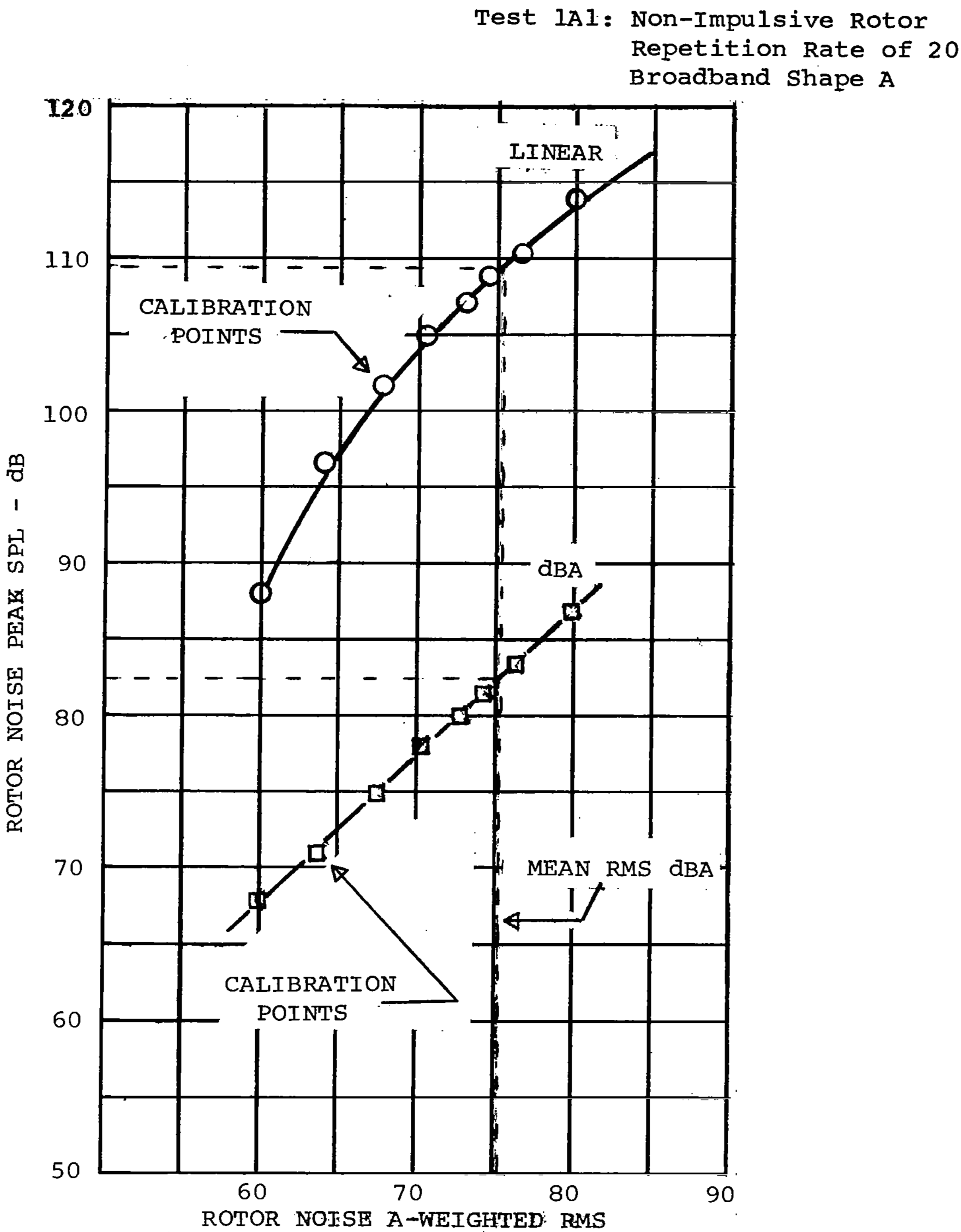


Figure 15. Example of Method for Obtaining Peak SPLs for Rotor Noise Samples

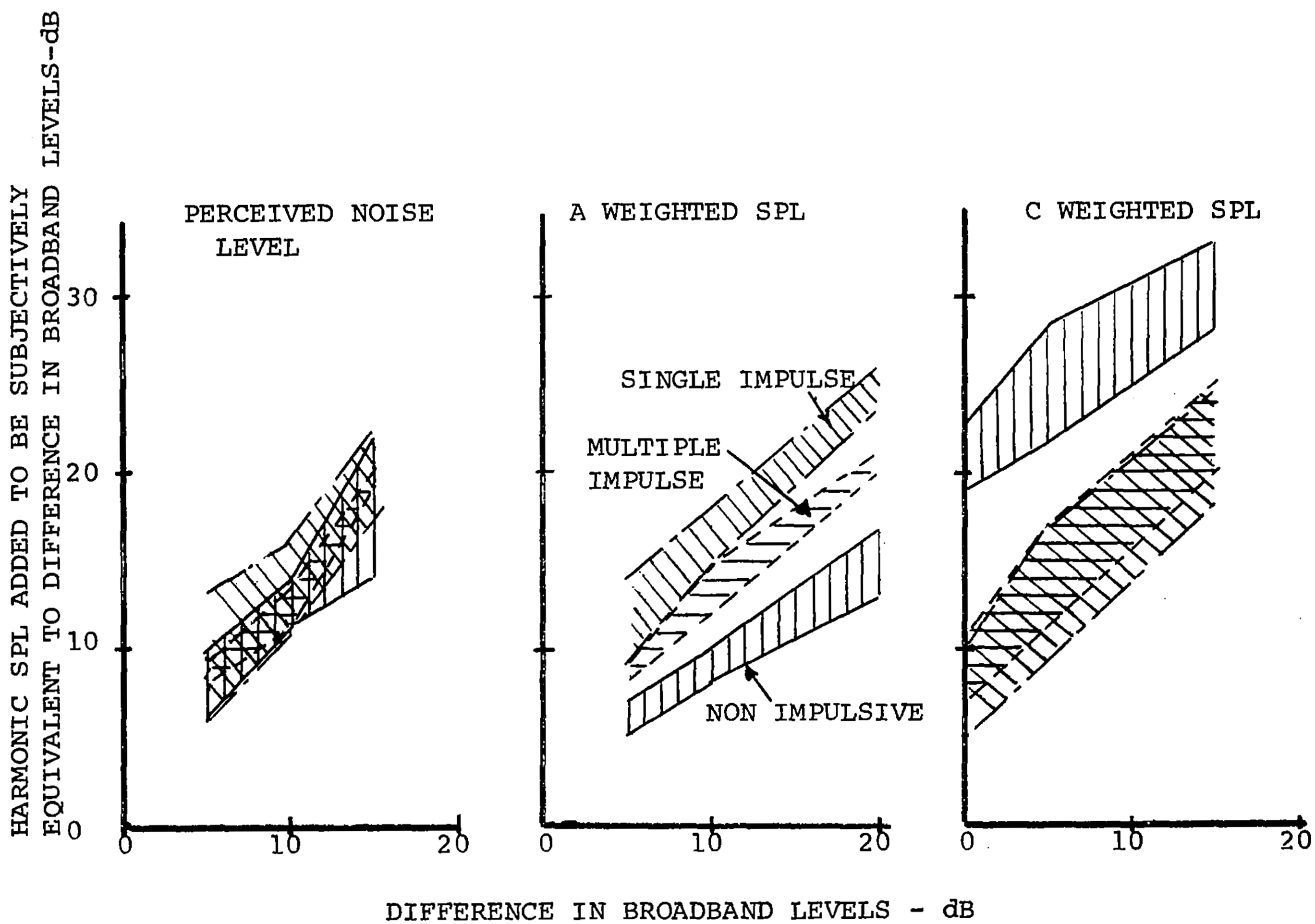


Figure 16. Method of Adjustment Test Results.

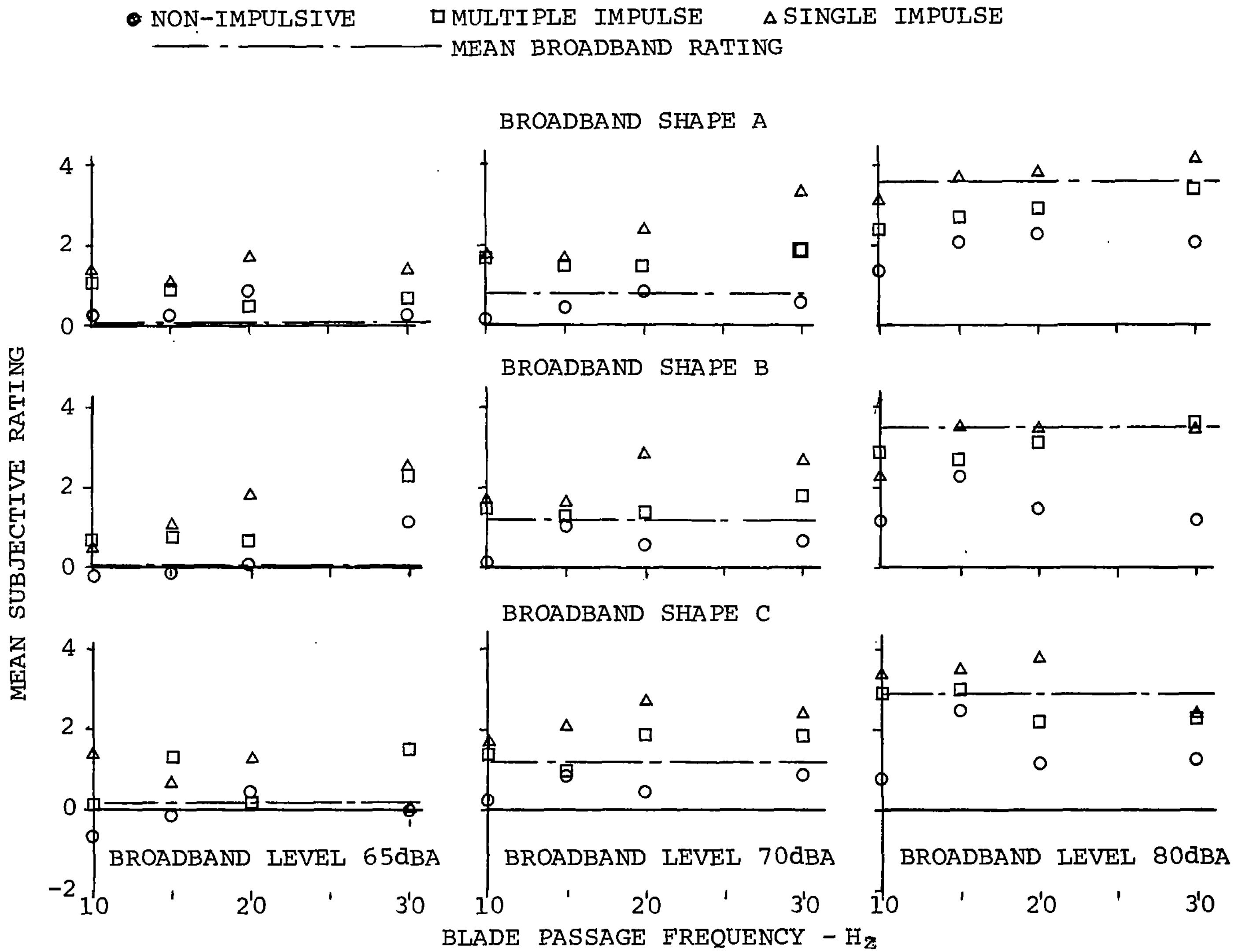


Figure 17. Numerical Category Scaling Procedure Results

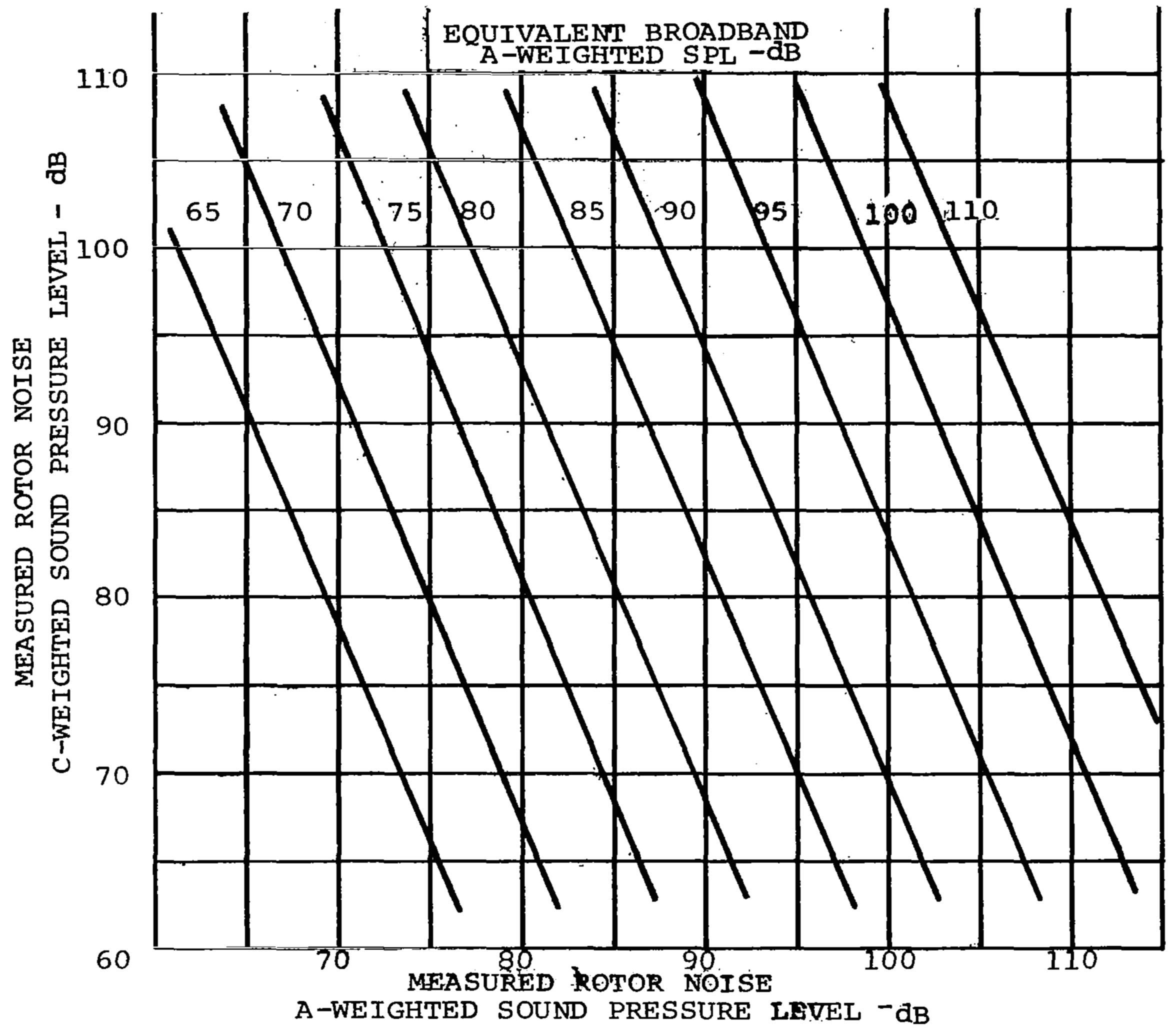


Figure 18. Determination of Equivalent Broadband A-Weighted SPL Using C-Weighted SPL.

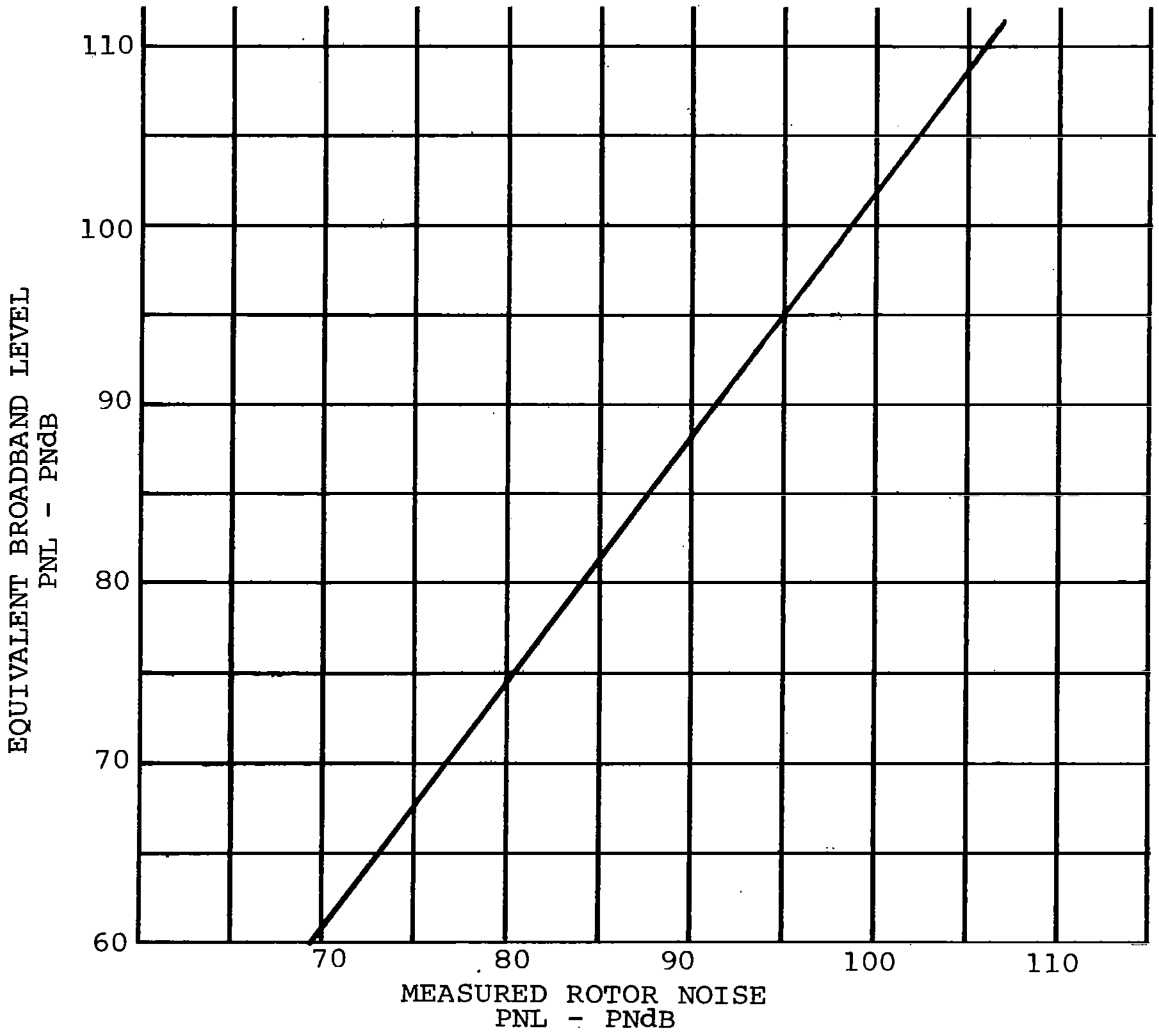


Figure 19. Correlation Between PNL of Rotor Noise and PNL of Equivalent Broadband Noise.

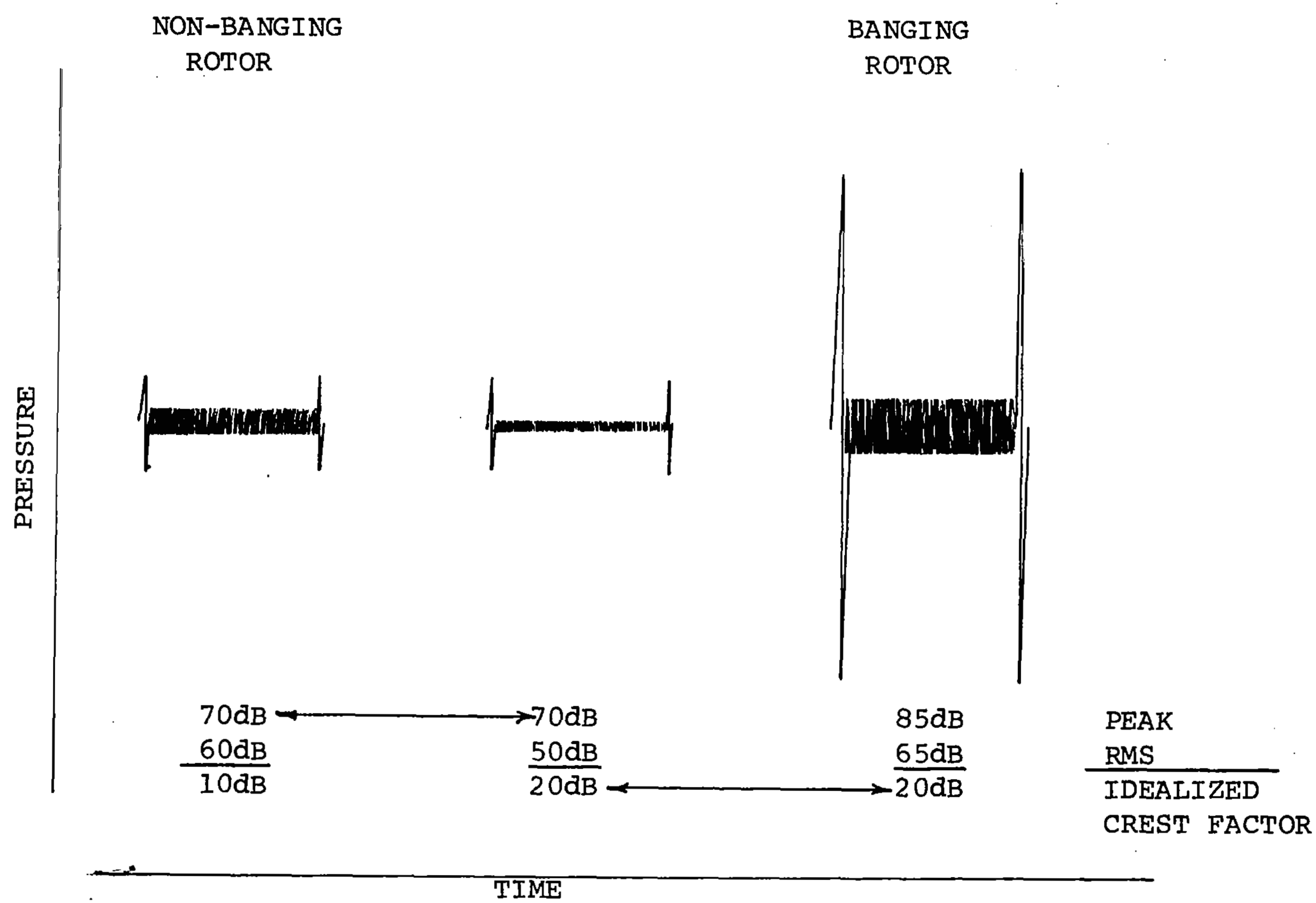


Figure 20. Elements of a Banging Rotor

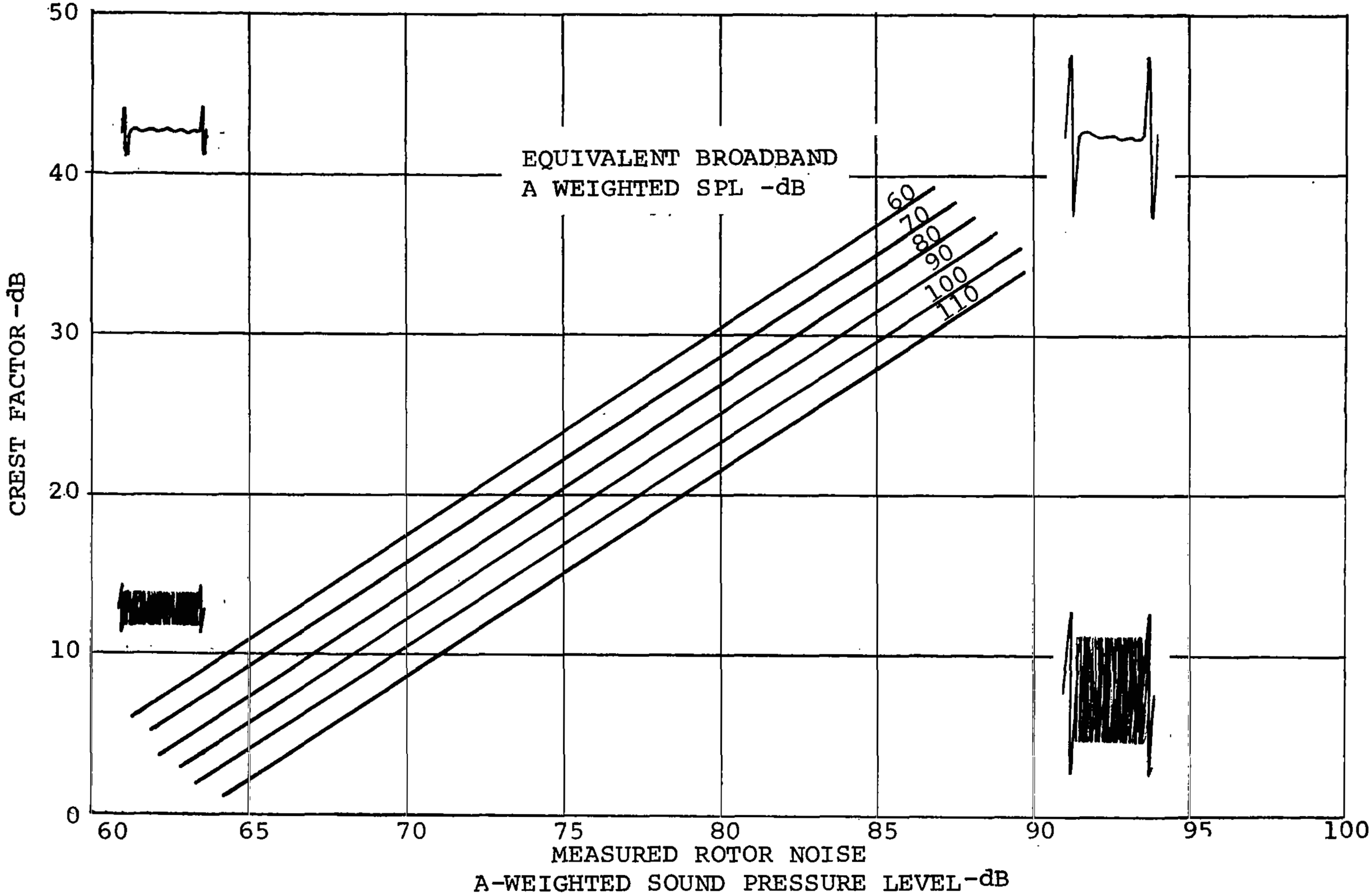


Figure 21. Determination of Equivalent Broadband A-Weighted SPL Using Crest Factor

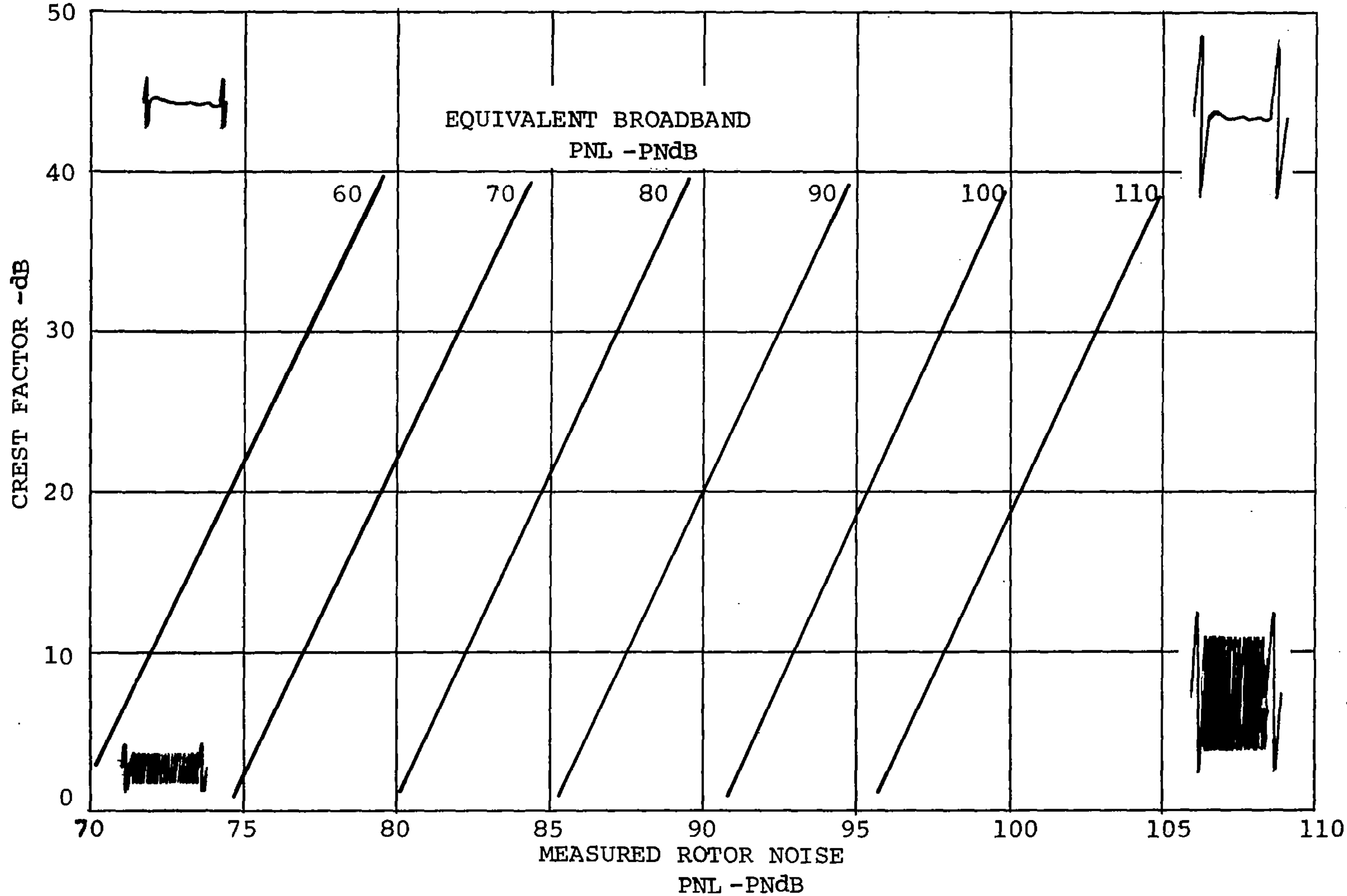


Figure 22. Determination of Equivalent Broadband PNL Using Crest Factor

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16. Abstract

A program was conducted in which 25 test subjects adjusted the levels of various helicopter rotor spectra until the combination of the harmonic noise and a broadband background noise was judged equally annoying as a higher level of the same broadband noise spectrum. The subjective measure of added harmonic noise was equated to the difference in the two levels of broadband noise. The test participants also made subjective evaluations of the rotor noise signatures which they created. The test stimuli consisted of three degrees of rotor impulsiveness, each presented at four blade passage rates. Each of these 12 harmonic sounds was combined with three broadband spectra and was adjusted to match the annoyance of three different sound pressure levels of broadband noise.

Analysis of variance indicated that the important variables were level and impulsiveness. Regression analyses indicated that inclusion of crest factor improved correlation between the subjective measures and various objective or physical measures.

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