ANNOYANCE DUE TO SIMULATED BLADE-SLAP NOISE

Clemans A. Powell
NASA Langley Research Center

SUMMARY

A study conducted at the NASA Langley Research Center was previously reported in which the effects of several characteristics of blade-slap noise on annoyance response were studied concurrently. These characteristics or parameters were the sound pressure level of the continuous noise used to simulate helicopter broadband noise, the ratio of impulse peak to broadband noise or crest factor, the number of pressure excursions comprising an impulse event, the rise and fall time of the individual impulses, and the repetition frequency of the impulses. Forty subjects made repeated judgments on a set of 36 noise stimuli which included 32 simulated helicopter blade-slap noises characterized by the above five parameters and four nonimpulsive broadband noises. Each parameter was found to have a significant effect on the annoyance judgments.

In the present study, additional analyses were conducted to determine the correlation between subjective response and various physical measures for the range of parameters studied. A small but significant improvement in the predictive ability of PNL was provided by an A-weighted crest factor correction. No significant improvement in predictive ability was provided by a rate correction.

INTRODUCTION

Human reaction to helicopter noise, in general, cannot be quantified or predicted as well as the noise from conventional take-off and landing aircraft. It is generally agreed that the discrepancy in prediction, usually an underestimation of annoyance response, is caused by factors associated with the pulsative nature of helicopter noise. Depending on the particular helicopter and flight conditions, the impulsiveness of helicopter noise can range from marginally perceptible modulation to severe repetitive bands or slapping sounds.

Because of the underestimation of annoyance of helicopter noise by various aircraft noise-rating scales, some researchers have suggested modifying the noise-rating scales or adding an impulse noise correction. Although considerable research has been conducted to determine the appropriate modifications or corrections, these efforts have been generally unsuccessful or inconclusive. Field annoyance studies suffer from a lack of control over

the physical parameters affecting the intensity of blade slap. It is generally not possible to separate the subjective effects of changes in blade slap from subjective effects of changes in other acoustical parameters which result from using different helicopter types or the same type under different operating conditions. Laboratory annoyance studies using recordings of actual helicopter noises, while suffering from a similar confounding of effects, also suffer from inadequacy of reproduction of the complex and phase sensitive time histories of helicopter flyover noise. To solve many of the problems associated with subjective tests using actual helicopter noises or recordings, some researchers have resorted to using simulations of helicopter noises. Most of these studies, however, have been confined to testing only one out of many characteristics of blade-slap noise which could be responsible for the reported discrepancies in prediction of annoyance response to such noises.

The study described in this paper was conducted to examine the subjective effects of several characteristics of repetitive impulse noise. Five variables were chosen to characterize helicopter blade slap and these characteristics or parameters were varied concurrently to investigate possible interactive effects. Human subjects listened to and rated the annoyance of short bursts of the simulated blade-slap noises. Some results of this study have been previously reported in reference 1, which indicated that each of the parameters had a significant effect on annoyance response. Additional analyses have been conducted which indicated that various objective measures such as PNL and L_A were also sensitive to changes in the parameters. The results of these analyses and the correlation between subjective and objective measures are reported herein. Comparisons are made between the results of this experiment and a study conducted by Boeing Vertol (ref. 2).

DESIGN AND PRELIMINARY RESULTS

A detailed description of the experimental design, procedures, and equipment used in the experiments is given in reference 1. The following paragraphs will summarize the design and present the preliminary results as presented in that reference.

Experimental Design

The following five parameters were chosen to characterize helicopter blade-slap noise consisting of a series of repeated impulses upon a continuous noise:

1. The sound pressure of the continuous noise used to simulate helicopter broadband noise.

2. The ratio of impulse peak to broadband noise sound pressure levels (idealized crest factor).

3. The number of pressure excursions making one complete impulse, ideally the number of sine waves in a single impulse.

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4. The frequency of sine waves used to synthesize the individual impulses.

5. The repetition rate of the impulses.

A set of 32 simulated blade-slap noises was created which included each of these parameters in a high or low condition in the manner of a 2^5 factorial design. The high and low conditions for each parameter are given in table I. In addition to the impulsive noises, four samples of the nonimpulsive, broad-band noise were included in the set for judgments by the subjects. The 36 noise stimuli were randomly ordered into four groups of nine stimuli each. The order of presentation of the stimuli groups was counterbalanced between groups of test subjects.

Special precautions were taken to reduce the influence of room reflec-tions and to insure that the subjects experienced the desired waveforms. Sound-absorbing panels which can be seen in figure 1 were used to reduce room reflections. The impulsive and continuous portions of the stimuli were synthesized and recorded on separate channels of a stereo tape recorder. A specially modified low-frequency loudspeaker was used to reproduce the impulsive waveforms. During stimuli preparation, the impulsive signals were monitored at the test subject's head location and the recorded signals modified to reproduce the waveforms called for in the experimental design. The stimuli heard by the subjects were constant level 10-sec bursts of noise with 0.5 sec on ramp and off ramp.

Twenty male and twenty female subjects made judgments on each of the complete sets of noise stimuli and a complete replication of the stimuli. Each judgment was made on a continuous numerical scale from 0 to 9, from "no annoyance" to "maximum annoyance."

Data Analysis and Results

The 2560 annoyance judgments made on the impulsive noises were analyzed using an analysis of variance procedure, an abbreviated version of which is presented in table II. Each of the five parameters was found to have a significant effect at the 0.01 level on the annoyance response of the impulsive blade-slap noises. Figure 2 illustrates the magnitude and direction of the effect of each of the five parameters on the mean annoyance response. For example, the mean annoyance rating for the impulsive noises with one sine wave per impulse was less than the mean annoyance rating for the impulsive noises with three sine waves per impulse. From this figure, it can be seen that the level of continuous noise and the idealized crest factor had large, positive effects on mean annoyance. The number of sine waves, the frequency of sine waves, and the repetition frequency had much smaller, positive effects although each was statistically significant.

These findings, although of academic interest, do not resolve the question of whether or not the present noise-rating scales underestimate the annoyance potential of impulsive noises as compared with nonimpulsive noises.

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To provide some information on this question, the author of reference 1 performed correlation analyses between the subjective ratings of both the impulsive and nonimpulsive noises and various noise-rating scales. These analyses indicated that the perceived noise level scale underestimated by about 2 dB the annoyance potential of the impulsive noises.

The next section of this report will present the results of additional analyses which were performed on the data from reference 1 to determine whether or not this underestimation of the annoyance potential of the impulsive noises was related in any systematic way with the five parameters varied in the experiment.

ADDITIONAL ANALYSES AND RESULTS

Analyses

The first step of additional analyses was to determine which of the noise-rating scales examined in the experiment provided the best overall correlation with the mean response data for each noise condition. Linear least square regression analyses were performed with the mean response data as the dependent variable and with the physically measured data for each rating scale as independent variables. The correlations in terms of the Pearson product moment correlation coefficients for the mean response and each rating scale are presented in table III. In addition, the correlations between the various rating scales are also presented. The mean data were obviously highly correlated with the measured values of each rating scale, as were the measured values between rating scales. Because of the high correlation between rating scales, the differences in correlation for the different rating scales with the mean response are not significant. However, since PNL was more highly correlated than the other rating scales and since it forms the basic measure for the accepted standard measure (EPNL) for conventional aircraft noise, the further analyses were conducted using PNL as the primary physical measure.

The results of the regression analysis of the mean response on the PNL values for the stimuli are presented in figure 3. The nonimpulsive noise stimuli are represented by the solid circular symbols and the impulsive noise stimuli by the open circular symbols. The least squares linear regression for these points is indicated by the solid line. As is typical for this type judgment scale, there appears to be some slight curvature in trend of the data points at the ends of the range. In order to reduce this nonlinear behavior, the following procedure was used to convert the mean subjective data into subjectively equivalent noise levels for further comparison between the various noise conditions. A polynomial regression was performed in the form

$$X_i = a + by_i + cy_i^2 + dy_i^3$$

where X_i is the PNL value for the ith stimulus and y_i is the corresponding mean subjective response. The resulting best fit regression was found to be

$$X = 64.76 + 6.874y - 0.670y^2 + 0.044y^3$$

The predicted or subjectively equivalent noise level for each stimulus was calculated by substituting the respective mean response value into the regression relationship. For further discussion, the subjectively equivalent noise levels will be designated simply as equivalent levels. The equivalent level (Eq.L.) of each stimulus is plotted in figure 4 against the respective measured PNL values. A close comparison of the data in figures 3 and 4 indicates the improvement in linearity between the subjective response and noise level in PNL.

The difference in annoyance between the impulsive noise stimuli and the continuous noise which served as simulated helicopter broadband noise was determined by subtracting the equivalent levels of the nonimpulsive noise stimuli from those of the respective impulsive noise stimuli. The values thus obtained (ΔEq.L.) represent the increase in annoyance due to the addition of the impulsive noise on the continuous background noise. Similarly, the difference in the PNL values of the impulsive noise stimuli and the respective nonimpulsive noise stimuli (ΔPNL) represents the increase in PNL attributed to the addition of the impulsive noise. A comparison of these two sets of values is presented in figure 5. The open symbols represent those data with a continuous noise level of 65 dB (OASPL) and the solid symbols represent those with a continuous level of 80 dB (OASPL). From this figure, it can be seen that, in general, the addition of the impulsive noise produced a greater increase in annoyance than was accounted for by the increase in PNL. The excess annoyance did not appear to be strongly related to the level of continuous noise.

The same data are reproduced in figures 6 to 9 with the other factors of the experimental design as separable parameters. The data in figure 6 are separated by the different symbols into the conditions of high and low idealized crest factor. Although the data are clearly grouped by this parameter, the change in PNL mirrors the change in effective noise level equally as well for the high idealized crest factor as for the low idealized crest factor conditions. In figure 7, the data are separated by the repetition rate of the impulses. No clear separation of the data is provided by the repetition rate factor. In figure 8, the data are separated by the number of sine waves in the impulse events. Based on the greater number of data points below the line of equality for the 3-sine wave condition as compared with the 1-sine wave condition, there appears to be some relationship between the annoyance of the impulsive noises and the number of sine waves that is not accounted for by PNL. Figure 9 presents the data separated by the frequency of sine waves in the impulse events. There appears to be no consistent effect of the frequency of sine waves on the increase in annoyance due to impulsiveness which is not accounted for by a change in PNL.

In order to more accurately quantify the effects of the various factors of the experiment, a correlation analysis was performed between the factors, subjective measures, and objective measures previously described. Two additional correlates were considered in the analysis and are defined as follows. The underestimation of PNL to account for the subjective differences between the impulsive and nonimpulsive noise annoyance was defined as

$$\Delta S = \Delta Eq.L. - \Delta PNL$$

where $\Delta Eq.L.$ was the difference between the equivalent level for the impulsive and nonimpulsive noises and ΔPNL was the difference between the perceived noise levels of the impulsive and nonimpulsive noises. An A-weighted impulsive correction was defined as

$$\Delta CF_A = L_A(peak) - L_A(rms) - 12$$

The correlation matrix for the subjective measures, objective measures, and experimental factors is presented in table IV.

The high correlation of the effective level with PNL is indicative that, in general, PNL predicted the subjective response very well, the unexplained error being only 4 percent of the total variation in subjective response over a wide range (28 PNdB) of noise levels. The standard error of estimate using PNL as a predictor of effective noise level was 1.72 dB. The only experimental factor which was found to be significantly correlated with the equivalent level was the idealized crest factor. The idealized crest factor, however, was also found to be significantly correlated with PNL to approximately the same degree.

Similarly, the change in equivalent level between the impulsive and nonimpulsive noises was found to be significantly correlated with the change in PNL and the idealized crest factor. Again, however, the idealized crest factor was found to be significantly correlated with a change in PNL.

The difference (ΔS) between the change in equivalent level and the change in PNL was found to be significantly correlated with the crest factor correction but not with the idealized crest factor. There was, however, a significant negative correlation of ΔS and the number of sine waves comprising the impulse events. Qualitative indications of this trend were presented in figure 8 and in previous discussions. The number of sine waves was also sufficiently and negatively correlated with ΔCF_A so that it is doubtful that any improvement in prediction beyond that afforded by ΔCF_A would be realized.

Least square regression analyses (fig. 10) were performed with the underestimation of PNL for impulsive noises ΔS as the dependent variable and the impulsive correction ΔCF_A as the independent variable. The regression

equation thus obtained was

$$\Delta S = -0.04 + .400 \times \Delta CF_A$$

The standard error of estimate (SEE) for the regression was 1.52 dB. It should be pointed out, however, that this value is only 0.2 dB improvement in the predictive ability of PNL with no impulsive correction.

There has been recent evidence (ref. 3) that the rate of the impulse events correlates equally as well with the underestimate of PNL or EPNL as does various impulsive corrections. This trend has not been confirmed with the results of the present experiment.

Comparison With Other Research

In a recent experiment conducted by Boeing Vertol and reported in reference 2, subjects adjusted the impulsiveness of simulated blade-slap noises until they were as equally annoying as continuous noises with spectra simulative of helicopter broadband noise. The impulsive noises were presented simultaneously with broadband noise with the same spectra as the reference noises but at a lower fixed level. The subjects' task was to vary the level of the impulsive portion of the test stimuli to match the annoyance of the reference stimuli. The experiment was factorial in design and consisted of 108 pairs of stimuli comprised of three different broadband spectra, three levels of reference broadband noise, three impulsiveness conditions, and four impulse repetition rates. At the completion of each adjustment for equality of annoyance, the level of the impulsive noises in terms of various physical measures was recorded. The average of these levels over subjects provided measures of the level for equal annoyance for the impulsive stimuli. The difference in level between the reference broadband stimuli and the test impulsive stimuli at the point of equality thereby represented the underestimation of the physical measure. Regression analyses were performed with the underestimation (in terms of PNL) as the dependent variable and with ΔCF_A and rate as independent variables. Significant correlation was found only for the crest factor correction. The relationship was found to be

$$\Delta S = -3.37 + 0.113 \Delta CF_A$$

with a correlation coefficient of 0.265, which for 106 degrees of freedom is significant at the 0.99 level. The standard error of estimate was 2.65 dB.

Although a significant dependence was found on the A-weighted crest factor correction, the slope for the dependence was considerably less than was found in the NASA experiment.

One possible reason for the differences in results could be the differences in the manner of presentation of the noise stimuli. The stimuli for the NASA experiment were presented via loudspeaker whereas those for the Boeing Vertol experiment were presented over headphones. The differences in results, thereby, could have been the result of the difference in whole-body response and auditory response.

CONCLUDING REMARKS

Additional analyses have been conducted on data obtained from a previously reported experiment which was conducted to systematically investigate the effects of various parameters of helicopter blade-slap noise. Five parameters were chosen to synthesize blade-slap noise. These were the sound pressure level of the continuous broadband noise, the idealized crest factor of the impulses above the continuous noise, the number of sine waves in a single impulse, the frequency of the sine waves, and the impulse repetition frequency. Forty subjects judged the annoyance of each of the noises.

Although each of the parameters was found to have a positive and significant effect on judged annoyance, each parameter was found in the analysis reported herein to produce a similar change in measured noise level in terms of PNL.

A slight but significant improvement in the predictive ability of PNL was provided by the addition of an A-weighted crest factor correction. No significant improvement was provided by the addition of a correction proportional to the rate of impulses.

Further analysis of a recent experiment conducted by Boeing Vertol under NASA contract indicated a similar lack of need for a rate correction. Results from this experiment, however, indicated a significant but smaller crest factor correction than was indicated in the NASA experiment.

REFERENCES

1. Lawton, Ben William: Subjective Assessment of Simulated Helicopter Blade-Slap Noise. NASA TN D-8359, 1977.

2. Sternfeld, Harry, Jr.; and Doyle, Linda Bukowski: Evaluation of the Annoyance Due to Helicopter Rotor Noise. NASA CR-3001, 1978.

3. Galloway, William J.: Subjective Evaluation of Helicopter Blade-Slap Noise. Helicopter Acoustics, NASA CP-2052, Pt. II, 1978. (Paper no. 20 of this compilation.)

TABLE I.- VALUES ASSIGNED TO FIVE PARAMETERS CHOSEN TO

SIMULATE HELICOPTER BLADE SLAP

Parameter	Value of Parameter	
	Low	High
Number of sine waves in impulse	1	3
Sine wave frequency, Hz	200	400
Repetition frequency of impulses, Hz.	8	20
Level of continuous noise, dB[a].	65	80
Idealized crest factor[b] of impulsive noise, dB. . .	15	25

[a]SPL dB referenced to 20 μPa.

[b]Crest factor is defined as ratio of peak to root-mean-square pressure for an acoustic signal.

$$\text{Crest factor} = \frac{\text{Peak pressure}}{\text{rms pressure}}$$

When converted to dB scale, crest factor is peak SPL minus rms SPL. For purposes of defining noises used in this study, an idealized crest factor was specified, peak SPL of impulses minus rms SPL of continuous noise.

TABLE II.- RESULTS OF ABBREVIATED ANALYSIS OF VARIANCE

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio[a]
Number of sine waves	1	77.006	77.006	22.510
Frequency of sine waves	1	104.248	104.248	30.473
Impulse repetition frequency	1	55.460	55.460	16.212
Level of continuous noise	1	9307.838	9307.838	2720.795
Idealized crest factor	1	1460.170	1460.170	426.825
Error	2554	8737.289	3.421	--------
Total	2559	19742.011		

[a]These F-ratio values are significant at 0.01 level. For one and infinite degrees of freedom at this level, the critical F-value equals 6.63.

TABLE III.- CORRELATION MATRIX OF MEAN SUBJECTIVE RESPONSE

AND PHYSICAL DESCRIPTORS

	OASPL, rms	OASPL, peak	L_A, rms	L_A, peak	L_A, impulse	PNL
Mean response	0.965	0.972	0.976	0.954	0.966	0.978
OASPL, rms		.975	.976	.921	.964	.990
OASPL, peak			.974	.969	.974	.977
L_A, rms				.968	.993	.994
L_A, peak					.925	.947
L_A, impulse						.984

TABLE IV.- CORRELATION MATRIX OF SUBJECTIVE MEASURES,

OBJECTIVE MEASURES, AND EXPERIMENTAL FACTORS

	ΔEq.L.	PNL	ΔPNL	ΔS	$ΔCF_A$	Idealized crest factor	Rate	Number	Frequency
Eq.L.	[b]0.547	[b]0.980	[a]0.417	0.268	0.005	[a]0.370	0.076	0.079	0.107
ΔEq.L.		[b].499	[b].890	.202	.112	[b].842	.172	.180	.244
PNL			[b].457	.073	-.103	[a].372	.115	.166	.052
ΔPNL				-.267	-.129	[b].860	.266	[a].383	.119
ΔS					[b].513	-.065	-.206	[a]-.441	.259
$ΔCF_A$						.203	[b]-.454	[b]-.522	[b].559

[a]Correlation coefficient significant at 0.05 level.

[b]Correlation coefficient significant at 0.01 level.
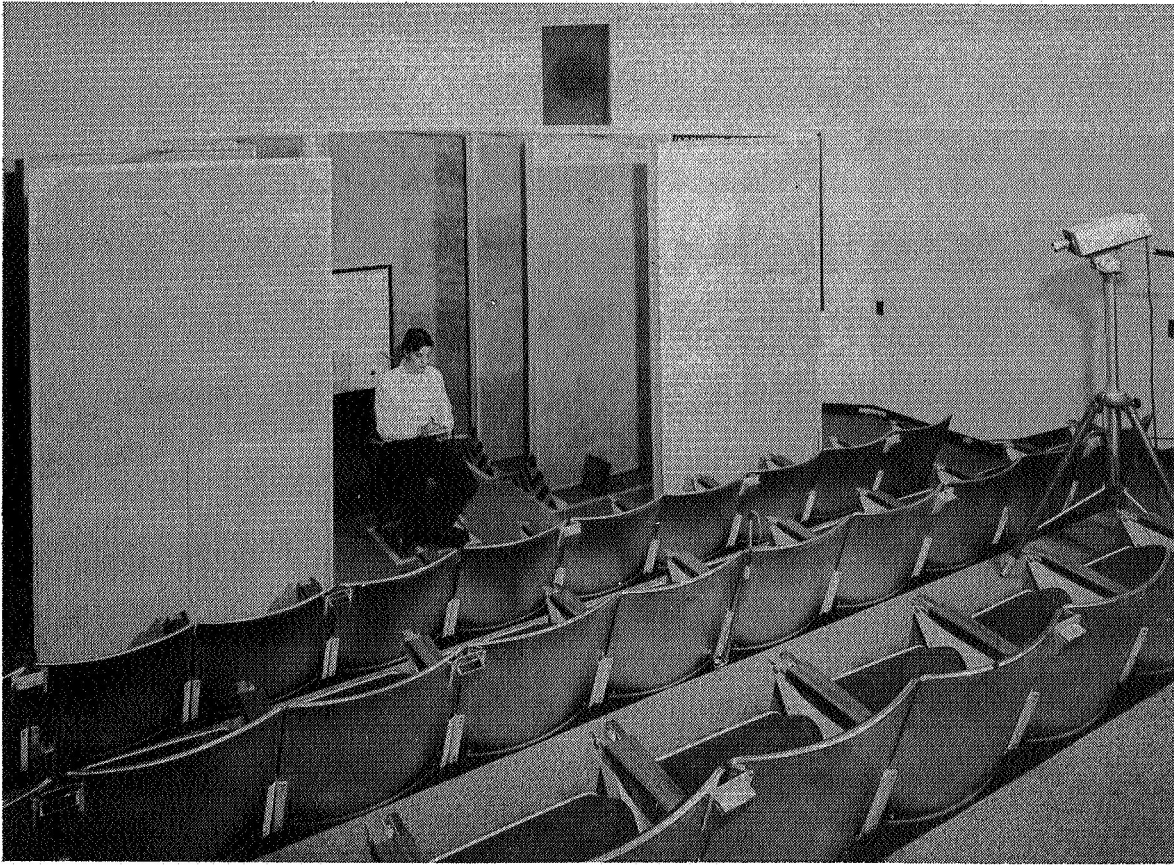
Figure 1.- Photograph of test chamber showing orientation of subject and loudspeakers.
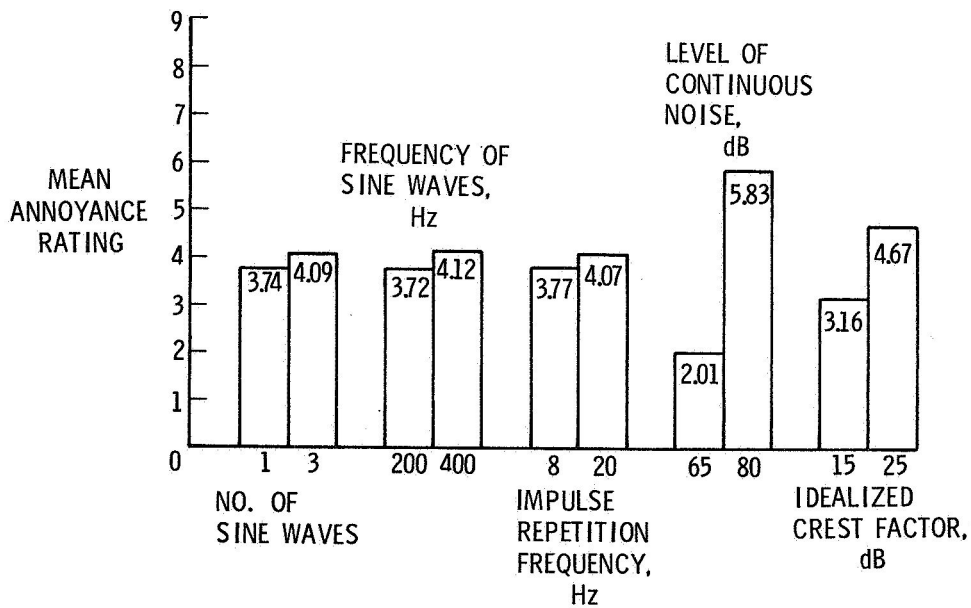
Figure 2.- Annoyance effects of five parameters used to synthesize impulsive test noises.
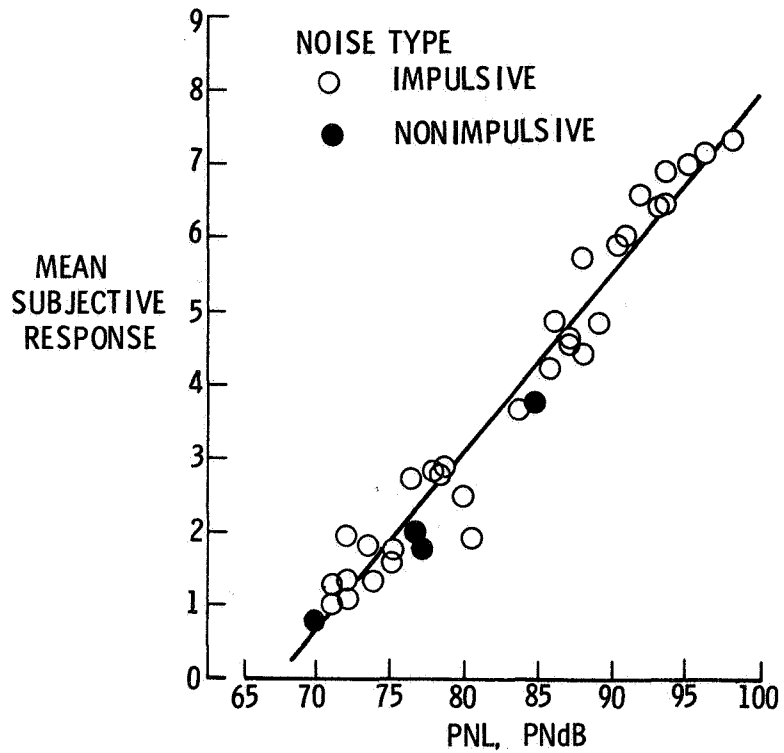
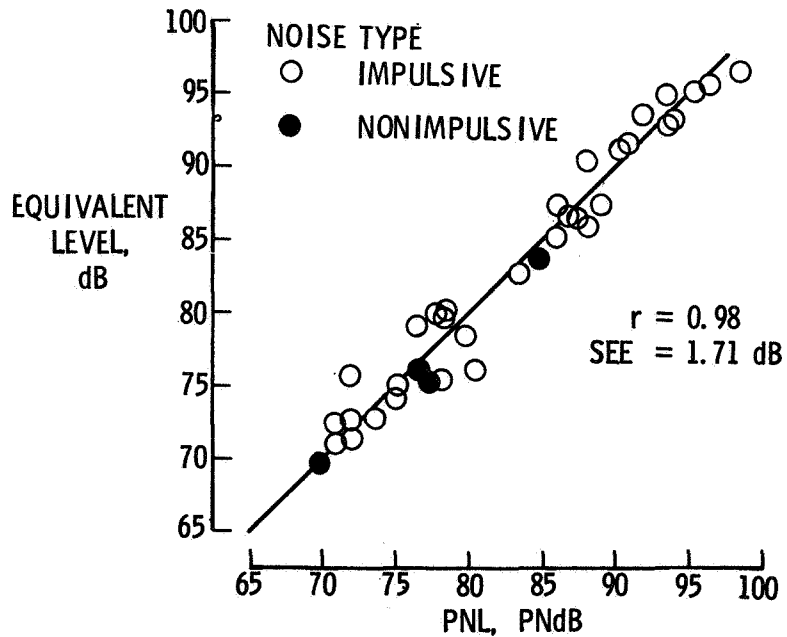Figure 3.- Mean subjective response to impulsive and nonimpulsive noises.

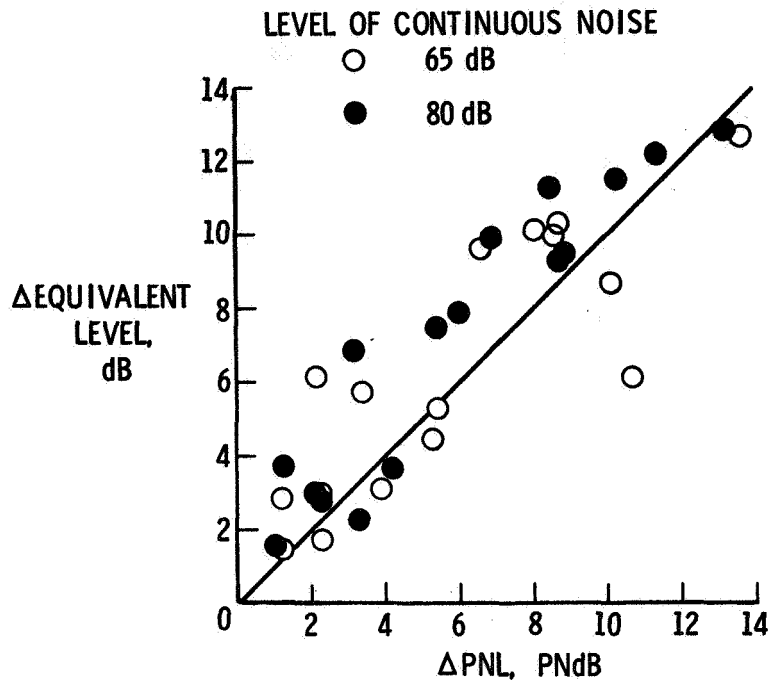Figure 4.- Correlation of equivalent noise level with PNL for impulsive and nonimpulsive noises.

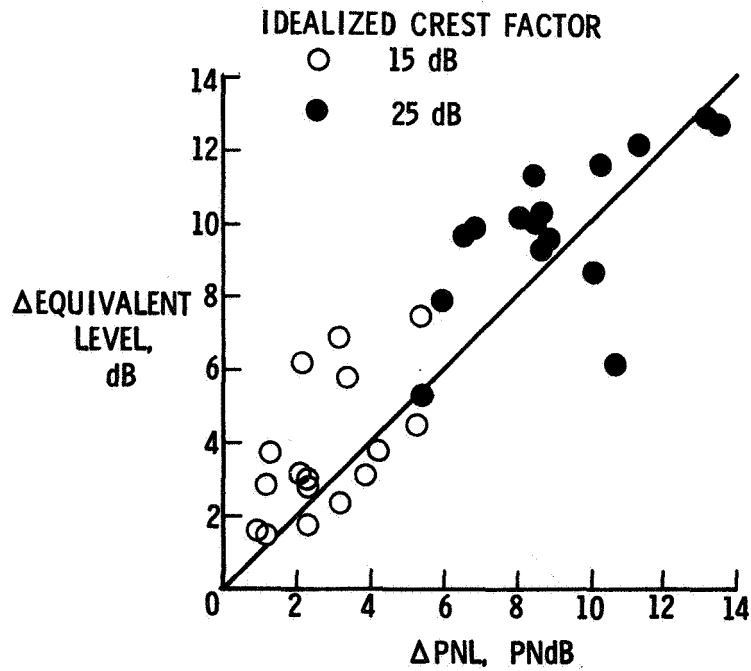Figure 5.- Effects of impulsiveness for two levels of continuous noise.
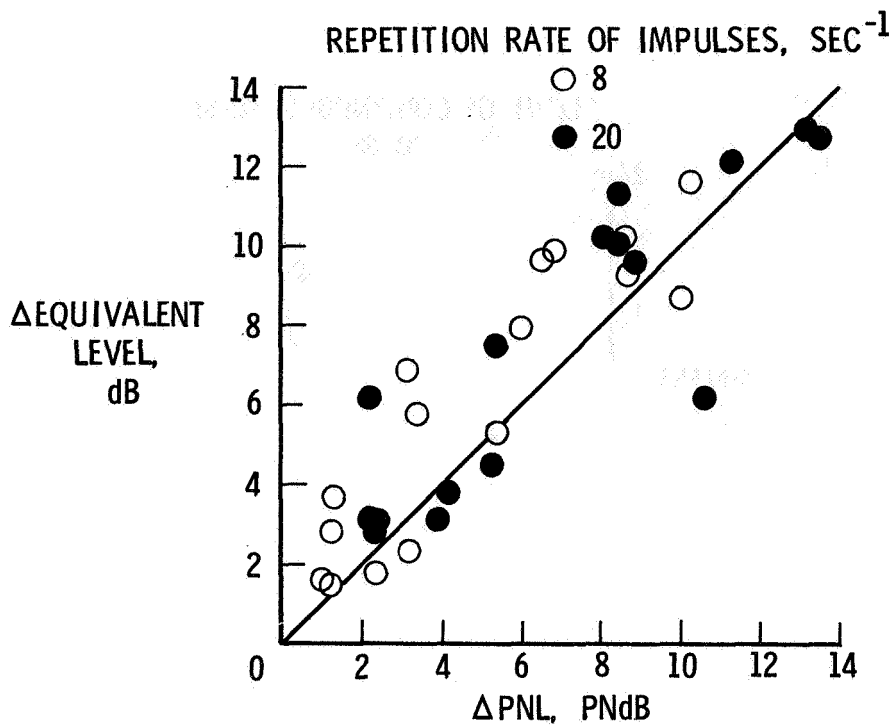

Figure 6.- Effects of impulsiveness for two levels of idealized crest factor.

Figure 7.- Effects of impulsiveness for two repetition rates
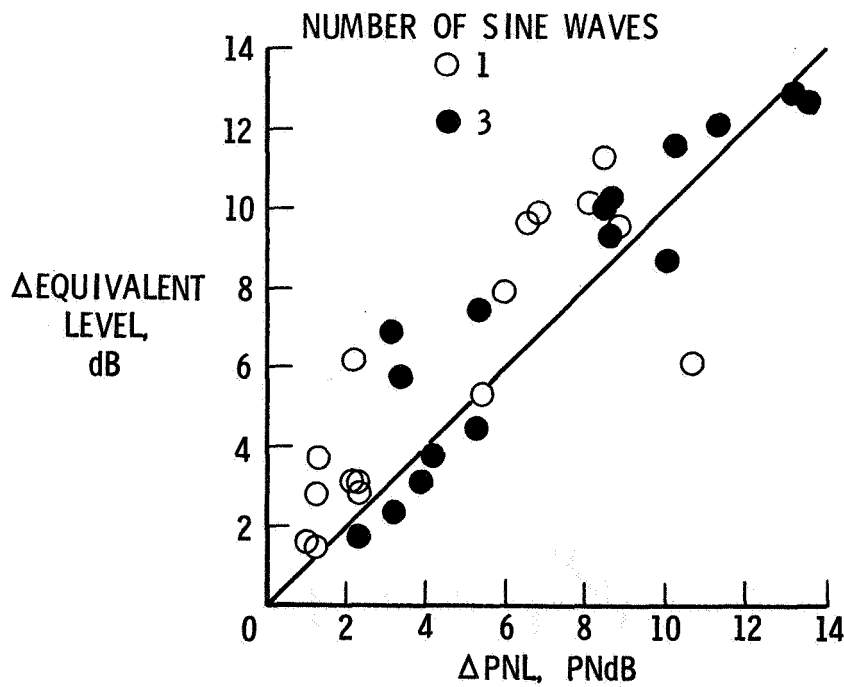of impulsive events.

Figure 8.- Effects of impulsiveness for two numbers of sine waves
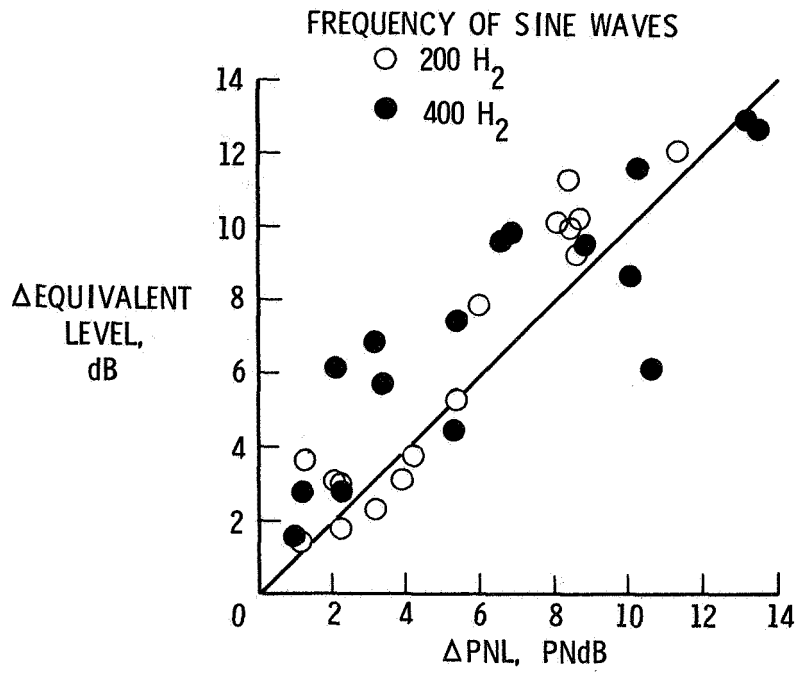comprising an impulse event.

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Figure 9.- Effects of impulsiveness for two frequencies of sine waves
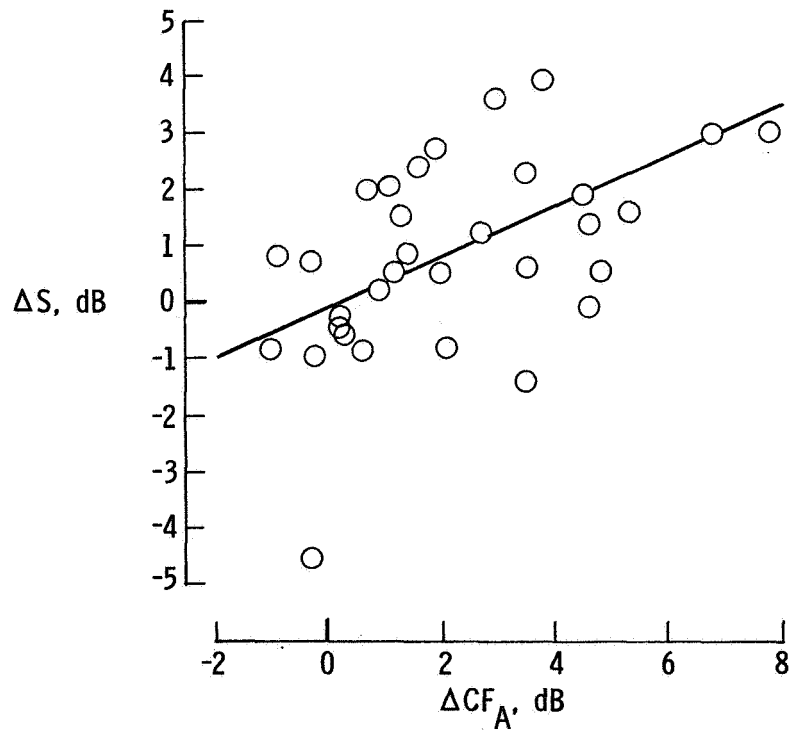comprising an impulse event.

Figure 10.- Underestimation of PNL for impulsive noises.