NASA
Technical
Paper
1969

February 1982

Effects of Repetition Rate and Impulsiveness of Simulated Helicopter Rotor Noise on Annoyance

Clemans A. Powell
and David A. McCurdy

NASA

NASA Technical Paper 1969

1982

Effects of Repetition Rate and Impulsiveness of Simulated Helicopter Rotor Noise on Annoyance

Clemans A. Powell
and David A. McCurdy
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical Information Branch

SUMMARY

Annoyance judgments of 82 different simulated helicopter rotor-noise stimuli were obtained in an anechoic chamber to examine effects of repetition rate and impulsiveness. The stimuli were generated by computer from predicted Fourier harmonic structure with amplitude and phase components corrected for effects of the audio reproduction system. Impulse repetition rates covered a range of 10 Hz to 115 Hz; crest factors covered a range of 3.2 dB to 19.3 dB. Each stimulus was judged at 3 sound pressure levels by 48 subjects. Judgments were converted from a continuous numerical annoyance scale to a decibel-like scale by comparing them to judgments of annoyance of a 115-Hz tone presented over a wide range of sound pressure levels. Increases in annoyance with increases in repetition rate were found which were not predicted by common loudness or annoyance metrics and which were independent of noise level. The ability to predict effects of impulsiveness varied for the noise metrics and was found to be dependent on noise level. The ability to predict the effects of impulsiveness was not generally improved by any of several proposed "impulsiveness corrections." Instead, the effects of impulsiveness were found to be systematically related to the frequency content of the stimuli. A modified frequency weighting was developed which offers improved annoyance prediction for the rotor noises used in the experiments.

INTRODUCTION

A concern has existed for many years over the quantification of helicopter noise, particularly for noise-certification and other annoyance-assessment purposes. During this time numerous subjective or psychoacoustic studies, such as those reported in references 1 to 10, have been conducted to determine the best objective measure, or metric, to reflect the annoyance potential ("noisiness") of the diverse character of helicopter noise. In addition, a number of other studies, such as references 11 and 12, have been conducted to determine the best metric for aircraft noise in general and have included helicopter noises in the test plans. The results of these studies have usually indicated that none of the current metrics predict helicopter-noise annoyances very well. Furthermore, a metric that performs well in one test may prove to be inferior in another test. For example, effective perceived noise level (EPNL) was found to be a better predictor than A-weighted sound pressure level L_A in references 11 and 12, whereas L_A was found to be equally as good a predictor of annoyance as EPNL in references 6 and 10. (A list of symbols and abbreviations used in this paper appears after the references.) Such variability in performance indicates that none of the current metrics is optimal and that the performance of a metric in a given test can be dependent on the particular set of noises investigated in the test or on some other biasing factor.

The character of helicopter noise is very diverse. Each of the primary noise sources - main rotor, tail rotor, and propulsion system - produces distinctive noises which can be quite variable, both between different helicopter models and for a given model under different operating conditions. As a consequence, a metric for helicopter-noise annoyance prediction must be capable of accounting for a wide range of spectral and temporal variables. Although the wide diversity in characteristics of helicopter noise exists, the impulsive nature of some helicopter noise has been most frequently singled out as the primary contributor to the lack of reliable annoyance prediction. Therefore, much helicopter-noise annoyance research has concentrated on the impulsiveness, or "blade-slap" phenomenon (refs. 5, 7, 8, 9, 10, and 13), and various corrections have been proposed to account for the phenomenon. The results of this research have also been highly variable. In many cases involving actual or recorded helicopter noises, higher impulsive sounds were found to be less annoying than lower impulsive sounds (refs. 8 to 10). In the studies reported in references 6, 8, and 10, some helicopters with pronounced tail-rotor noise were found to be more annoying, at equal noise levels, than other helicopters with pronounced main-rotor blade slap.

A major problem with many of the psychoacoustic studies in this area of research is the lack of experimental control. This arises from the fact that in actual or recorded helicopter noise many of the spectral and temporal variables are highly correlated. For example, duration is related to distance, which in turn has effects on noise level through spherical spreading and atmospheric sound attenuation. Since atmospheric attenuation is frequency dependent, the spectra of a given noise are also related to distance. As a consequence, it is very difficult to separate the annoyance effects due to spectral and temporal variables in tests which use actual or recorded noises.

It is also very difficult to separate the annoyance effects due to separate noise sources. For this reason, a number of studies (refs. 5, 13, and 14, for example) have used simulated noises to investigate effects of particular parameters on annoyance resulting from main-rotor and tail-rotor noise separately. These studies, however, introduce two additional problems associated with simulation studies. One problem is illustrated by reference 5, in which a large number of parameters related to main-rotor blade-slap noise were varied. However, each parameter was presented at only two levels. Although the effect of each parameter on annoyance was found to be significant, the tests provided little information useful for prediction purposes. On the other hand, in reference 13 a single variable, repetition rate, was varied over a fairly wide range. However, other parameters such as impulsiveness were either held constant or allowed to vary uncontrolled with repetition rate. In reference 14 the only variable was the ratio of tail-rotor noise to broadband noise. As a consequence, the results of these two studies provide very little information on possible interaction effects with other acoustic parameters.

The objective of the present study is to provide basic information on annoyance effects of repetition rate and impulsiveness of helicopter rotor noise. The type of rotor noise considered in the study is commonly called thickness noise (ref. 15). The results of the study are considered to be applicable for this type of noise from both main and tail rotors. Rotor characteristics of current helicopters which determine the production of this type of noise cover a nearly continuous range of blade-passage frequencies and have considerable overlap in tip speed and blade chord. Main-rotor blade-passage frequencies for eight U.S. helicopters are reported in reference 16 to be 11 Hz to 32 Hz; tail-rotor blade passage frequencies are 55 Hz to 104 Hz. Main- and tail-rotor tip speeds are reported to be 201 m/sec to 248 m/sec and 187 m/sec to 226 m/sec. Main- and tail-rotor chords are reported to be 0.17 m to 0.66 m and 0.12 m to 0.39 m.

In order to meet the objective, computer generated simulations of rotor noise were presented to human test subjects for annoyance judgments in two experiments. These simulations encompassed the above-stated blade-passage frequency range and the range of impulsiveness anticipated for the above-stated blade-tip speeds and blade sizes. Each parameter was systematically varied within the set of stimuli. By comparing the subjective judgments with objective acoustic measurements of each noise it was possible to assess the ability of various noise metrics to quantify annoyance response to this type of impulsive noise and to provide information for improvement in the noise metrics.

EXPERIMENTAL METHOD

Facility

The two experiments were conducted in the anechoic listening room in the Langley Aircraft Noise Reduction Laboratory (fig. 1). The facility is of double-wall construction with vibration isolation and provides an A-weighted ambient noise level of approximately 15 dB. The wall, ceiling, and floor surfaces are covered with foam wedges 40 cm deep with 20-cm by 20-cm bases. The working floor is constructed of cables woven into a 4-cm by 4-cm grid. The usable length, width, and height of the room are 3.7 m, 2.5 m, and 2.1 m.

The noise stimuli were presented to the subjects over separate high- and low-frequency loudspeaker systems, each with independent power amplifiers. The high-frequency system consisted of coaxial cone and horn drivers for the frequency range from 100 Hz to 10 000 Hz. The low-frequency system contained a single cone driver for a usable frequency range of 10 Hz to 100 Hz.

Noise Stimuli

The pressure pulse shapes for the stimuli used in the two experiments were based on predicted thickness noise (ref. 15) for helicopter rotor blades of typical airfoil shape and chord. Two examples of predicted thickness noises are presented in figure 2. The pulse trains indicated in the figure by the two sets of repeated pulses have approximately the same peak pressure relative to ambient atmospheric pressure but with different pulse widths. They also have the same repetition rate (10 Hz) and, therefore, the same period between pulses (0.1 sec). The spectra, or amplitudes, of the Fourier harmonic components which are summed to produce the pulse trains are also illustrated. The fundamental frequency in both cases is 10 Hz, which is the repetition rate. The lower, narrower set of the two pulse shapes has a greater number of high-frequency components than does the upper, wider set of the two pulse shapes. The frequency of the component with the greatest amplitude in each spectrum is also greater for the narrower pulse shape. The shape of the envelope of harmonic components is largely determined by the pulse width whereas the total number of components in a given envelope is determined by the repetition rate.

A common measure of impulsiveness is the crest factor, which can be defined as the ratio of the peak pressure to rms pressure. For repeated pulse trains used in the experiments described in this report, the crest factor monotonically increases with the ratio of the period to width of the pulses. For the wider pulse and narrower pulse cases indicated in figure 2, the crest factors expressed in decibels are 10.3 dB and 14.8 dB. The range of crest factors for all stimuli used is from 3.2 dB to 19.3 dB. Specific characteristics for the design stimuli will be discussed in subsequent sections.

The noise stimuli for both experiments were produced in real time with a digital computer system by summing the Fourier amplitude components with the appropriate phase relationships. The harmonically related Fourier amplitude and phase components required to produce the design stimuli were modified to account for amplifier, loudspeaker, and room characteristics. These characteristics were determined by measuring both phase and amplitude transfer relationships between an input electrical signal and the resultant pressure signal at the test subjects' head positions. The modified Fourier components were appropriately summed to produce digital time histories of single pulses, which were stored on computer disk. During the subjective tests the appropriate time histories were retrieved from the disk, placed on computer memory, and repetitively processed through a digital-to-analog converter to provide electrical pulse trains. These pulse trains contained the appropriate frequency and phase information such that the resultant pressure signals at the subjects' listening positions were accurate reproductions of helicopter rotor thickness noise. The duration of each stimulus was 6 sec; the interstimuli period was 5 sec.

First experiment.- The design goal of this experiment was to keep the pulse width, and thus the envelope of harmonic components, essentially constant as repetition rate was varied. Thickness-noise pulse shapes were predicted for a two-blade rotor of typical airfoil and chord rotating at 5 rps and with seven different diameters. These diameters corresponded to blade-tip Mach numbers of 0.91, 0.90, 0.88, 0.85, 0.81, 0.70, and 0.63. In addition, predictions were made for rotors with each of these blade diameters and with 3, 5, 8, 12, 17, and 23 blades. Therefore, repetition rates of 10, 15, 25, 40, 60, 85, and 115 Hz were generated. Actual pressure time histories, narrow-band spectral analyses, and 1/3-octave-band analyses of 9 of the 49 different conditions are illustrated in figures 3 to 11. For a given blade-tip speed or pulse shape, as the repetition rate is increased, the pulse width and overall frequency envelope remain essentially constant. Although the frequency of the fundamental component increases with the repetition rate, the higher frequency and subjectively more important components remain relatively independent of repetition rate when considered in the broadband sense. Each of the 49 different stimuli plus a replication of the 40-Hz repetition rate and Mach 0.85 impulsiveness condition were presented at three overall sound pressure levels (approximately 68 dB, 74 dB, and 80 dB). In addition, pure tones of 115 Hz and 1000 Hz were presented at six overall sound pressure levels from approximately 50 dB to 86 dB. These stimuli were to be used to convert annoyance judgments to a decibel-like scale, as will be described in a later section.

Second experiment.- The design goal of this experiment was to keep the total number and amplitudes of the harmonic components constant as repetition rate was varied. The same predictions were used for the seven basic pulse shapes at the 10-Hz repetition rate as were used in the first experiment. Repetition rate was varied by simply varying the frequency of the fundamental component while keeping the same harmonic structure. Again, repetition rates of 10, 15, 25, 40, 60, 85, and 115 Hz were used. Because the range of frequencies exceeded reasonable limits (5 kHz) for the higher harmonics of some of the stimuli with high repetition rates, nine combinations of repetition rate and impulsiveness were not used. Representative examples of the stimuli used in this experiment are illustrated in figures 3 to 5 and in figures 12 to 17. As can be seen in these figures, the relative pulse shape (ratio of pulse width to period between pulses) and crest factor based on overall sound pressure levels remain essentially constant as repetition rate is increased, although the pulse widths decrease. As was done in the first experiment, each of the different repetition-rate and impulsiveness conditions were presented at three overall sound pressure levels. In addition, pure tones of 115 Hz and 1000 Hz were presented at six overall sound pressure levels. To maintain the same total number of stimuli as in the first experiment (162), some conditions of mixed low and high repetition rates were included as a pilot experiment for effects of combined main- and tail-rotor noises. The results for these conditions are not considered further in this report.

Design

First experiment.- The basic design of the experiment was a within-subjects 7 by 7 by 3 factorial design for pulse width (impulsiveness), repetition rate, and sound pressure level. The 147 primary test stimuli plus the 15 additional stimuli (115-Hz tones, 1000-Hz tones, and replications) were randomly ordered and divided into six groupings of 27 sounds each. Each grouping constituted a session of noises. The order of presentation of the sessions to six groups of subjects was based on rows of a Latin-square design. An additional six groups of subjects were presented sessions with stimuli in reversed order within the session. As a consequence of these measures, some balance and control of order and learning effects were maintained.

Second experiment.- The design of this experiment was very similar to the first. The exception was the exchange of 27 mixed low- and high-repetition-rate stimuli for certain conditions of impulsiveness, repetition rate, and level. The total of 162 stimuli were similarly randomly ordered and divided into six sessions of 27 sounds each. The same type of Latin-square presentation order of sessions and reversed order of stimuli within sessions were used as in the first experiment.

Subjects

The subjects who were used in both experiments were supplied to NASA under contract. These subjects were drawn from the general population of the cities of Hampton and Newport News and from York County in Virginia. Approximately one-fourth of the subjects were affiliated with various civic organizations, with the result that payment for their services went to the organizations. The remainder were paid directly for their services. All subjects had normal hearing abilities (ANSI 1969). A total of 48 individuals were used in each experiment.

Procedure

Upon arrival at the laboratory, the subject groups were seated in a conference room and given a set of instruction sheets, a consent form, and a set of scoring sheets. Copies of these items are given in the appendix. After reading the instruction sheets, the subjects completed the consent form, which is required of all subjects who participate in subjective experiments in the laboratory. The subjects were given a brief verbal explanation of the scoring sheets and then asked by the test conductor if they had any questions about the test. Throughout the experiment, the same person served as the test conductor.

The subjects were then ushered by the test conductor into the test facility and seated. A demonstration of three practice stimuli was given while the test conductor remained in the test facility. In order for subjects to gain experience scoring the sounds, they were instructed to make and record judgments of the practice stimuli on the practice scoring sheet. Afterwards, the test conductor again asked if there were any questions concerning the test. The test conductor left the facility and the first of six test sessions began. At the conclusion of each session the test conductor reentered the facility, collected the scoring sheets, and issued new sheets for the next session. A 10-minute rest break was given to the subjects between the third and fourth sessions. Each session lasted about 5 minutes.

Subjective Measure

The annoyance response of the subjects to each noise stimulus was obtained on a continuous scale of 0 to 10, the end points of which were labeled "Not Annoying At All" and "Extremely Annoying." A copy of a scoring sheet is included in the appendix. The subjects indicated their level of annoyance by making a mark across the scale for each stimulus. The location of these marks were later converted to numerical scores using a digitizing tablet and were directly stored in computer data files. The accuracy of the digitizing process was better than 1 percent of full scale.

RESULTS AND DISCUSSION

Acoustical Analyses of Stimuli

Each noise stimulus was analyzed to provide 1/3-octave-band sound pressure levels for use in computing a number of commonly used noise metrics or rating scales. These measurements were made using a 1.27-cm-diameter condenser microphone located at a position midway between the head positions of the two subjects. Preliminary analyses indicated differences of less than 1 dB in 1/3-octave-band sound pressure levels from 50 Hz to 5 kHz between this location and either subject location, whether or not subjects were present. The 1/3-octave-band analyses were performed with a real-time analysis system with 0.5-sec exponential time averaging and digital filtering. Calculated values for six common noise metrics for each stimulus at the highest presented sound pressure level are given in tables I and II for the first and second experiments.

Several other analyses were performed for each stimulus and the results are presented in tables I and II. These included tone corrections ΔT according to the method of reference 17, three impulsiveness measures, and the 1/3-octave-band center frequency F_M containing the greatest D-weighted energy.

One of the measures of impulsiveness ΔC_1, has been proposed by the ISO as a correction to account for impulsiveness of helicopter noise for certification purposes. For this method, the acoustic signal voltage is A-weighted and sampled at 5 kHz. For every 0.5-sec period of the signal, an impulsiveness descriptor I is calculated from the sampled voltage V_i such that

$$I = \frac{n \sum_{i=1}^{n} V_i^4}{\left(\sum_{i=1}^{n} V_i^2 \right)^2} - 1$$

where $n = 2500$. This descriptor is then converted to decibel-like units with the following:

$$X = 10 \log I$$

The correction factor ΔC_1 is then given by

$$\Delta C_1 = 0.8(X - 3) \qquad (0\ \text{dB} \leq \Delta C_1 \leq 6.0\ \text{dB})$$

Another impulsiveness measure considered in the analyses is identical to the ISO-proposed measure but without the limitation of 6.0-dB maximum. Consequently,

$$\Delta C_2 = 0.8(X - 3) \qquad (\Delta C_2 \geq 0\ \text{dB})$$

The final impulsiveness measure considered in this report is an A-weighted crest-factor correction defined as

$$\Delta C_3 = (L_{A,peak} - L_{A,rms}) - 12 \qquad (\Delta C_3 \geq 0\ \text{dB})$$

where $L_{A,peak}$ is the peak A-weighted sound pressure level and $L_{A,rms}$ is the root-mean-square A-weighted sound pressure level of the acoustic signal. The factor of 12 dB is subtracted so that no corrections would be applied to a broadband random noise.

Analyses of Subjective Data

The means (across subjects) of the digitized annoyance scores were calculated for each stimulus. These annoyance scores were converted to subjective noise levels L_S having decibel-like properties through the following process. For each separate experiment, third-order polynomial regression analyses were performed using data obtained for the 115-Hz pure-tone stimuli. The dependent variable was the calculated PNL and the independent variable was the mean subjective score for each of the six levels presented in each experiment. Figure 18 presents the two sets of data in the resulting best-fit curves. The regression equations thusly determined were subsequently used to predict the equivalent level of a 115-Hz tone which would produce the same mean annoyance score as each noise stimulus in the separate experiments. These equivalent levels were then considered as the subjective noise level for each stimulus and are presented in tables III and IV.

As indicated in figure 18, very good agreement is found between the annoyance scores for the two experiments. The differences between the two regression equations are not statistically significant, although there is a trend for slightly greater annoyance scores at the lower noise levels in the first experiment. It can only be supposed that this is an indication that the set of specific noise stimuli in the experiment somewhat affected the reported annoyance judgments. Because of this trend the results of the separate regressions were used to calculate subjective noise levels.

It was originally planned to use the 1000-Hz pure-tone data to convert the subjective scores to subjective noise levels. It was found, however, that the subjective scores of the 1000-Hz tone did not cover the range of judgment scores for the rotor noise stimuli as did the 115-Hz tone. It was also felt that the character of the 1000-Hz tone was so different from that of the other stimuli that some bias might be introduced.

Effects of Repetition Rate and Impulsiveness

It was indicated in references 5, 7, and 13 that annoyance judgments of helicopter rotor noise are related to both repetiton and impulsiveness. The question of major importance is how well these effects are predicted by various noise metrics. In order to investigate this "prediction ability" in detail, the differences between the subjective noise level L_S and the measured or calculated noise levels for each of the six metrics investigated were determined for each stimulus in each experiment. These differences were thus considered to be the prediction errors for each stimulus and metric. The prediction errors for each metric were first tested for effects of repetition rate and impulsiveness using analysis-of-variance techniques. Those factors found to significantly affect the error were subsequently investigated in more detail.

First experiment.- Since the first experiment was a complete factorial design, straightforward factorial analyses of variance were used to test for effects of repetition rate, impulsiveness, noise level, and interactions for each noise metric. The error term for these analyses was taken to be the interaction of repetition rate, impulsiveness, and noise level. A summary of these analyses is presented in tables V and VI for L_A and PNL. For both metrics null hypotheses were rejected (at $p \leq 0.05$) for the factors of repetition rate, impulsiveness, and their interaction. Null hypotheses were not rejected for noise level or the interaction of repetition rate and noise level but were rejected for the interaction of impulsiveness and noise level. Very similar results were found for the other four metrics considered. However, since L_A and PNL are the most commonly used metrics, further discussions will primarily address the effects related specifically to these two. Those factors and interactions for which null hypotheses could be rejected were considered to significantly affect the error in annoyance prediction and therefore were investigated in more detail.

Figure 19 shows the effect of repetition rate on annoyance prediction error for L_A and PNL. The value plotted for each repetition rate is the mean of differences in L_S and L_A and L_S and PNL across the seven impulsiveness and three noise-level conditions. The subjective noise level L_S for each stimulus was based on the PNL values for the 115-Hz pure tone. The rather large difference between L_S and L_A is therefore in part due to the difference in frequency weighting between PNL and L_A at 115 Hz. As a consequence the absolute value of the prediction errors is less important than the change in predition error across the test conditions. As indicated in figure 19, a generally consistent increase in prediction error is found for increasing repetition rate, an increase of about 4 dB for L_A and 5 dB for PNL over the range of repetition rates. Similar effects of repetition rate are found in references 5 and 7 over smaller ranges of repetition rates. This topic is discussed further in later sections.

The overall effects of impulsiveness and the interaction of impulsiveness with noise level are indicated in figure 20. The mean prediction errors averaged across the repetition-rate conditions are plotted against a simple ordinal scale of numerical ranking of impulsiveness for each noise-level case. Although there are generally increasing trends of prediction error with impulsiveness, there are major differences between the L_A and PNL noise metrics and for the separate noise-level cases. The change in error prediction is considerably less for L_A than for PNL across the impulsiveness conditions. For the lowest noise-level conditions, the change in error prediction with impulsiveness for PNL is approximately 13 dB. For both metrics there is a consistent trend for less effect of impulsiveness on error prediction with increased noise level. In fact, at the highest noise level for L_A, prediction error decreases slightly for increased impulsiveness.

Second experiment.- Since the design of the second experiment was not a complete factorial and contained missing cells, a modified analysis-of-variance technique was used to examine the effects of repetition rate and impulsiveness on prediction error. Summaries of the results from the analyses are presented in tables VII and VIII for L_A and PNL. The first step in these analyses was to determine an error term for significance testing. This was done by considering the design as a two-factor factorial of noise-level and impulse treatments (combined effects of repetition rate and impulsiveness). The interaction of impulse treatments with noise level was considered as the error term. The impulse-treatments term was then separated into main-factor and interaction (repetition rate by impulsiveness) terms. The main-factor term was subsequently considered in two ways: first, as the sum of a repetition-rate factor and an impulsiveness factor adjusted for repetition rate, and second, as the sum of an impulsiveness factor and a repetition-rate factor adjusted for impulsiveness. Null hypotheses were rejected (at $p \leqslant 0.05$) for adjusted impulsiveness and adjusted repetition rate but not for the interaction between repetition rate and impulsiveness.

It is interesting to note that the null hypothesis was also rejected for noise level, a finding different from the first experiment. This finding may be explained in part by the particular relationship used to convert from mean subjective annoyance scores to subjective noise levels. It was mentioned in a previous section that some differences were found between the two experiments in the relationship of mean subjective annoyance scores and measured PNL for the 115-Hz pure tone (fig. 18). As a result of these differences, for equal mean subjective annoyance scores a higher PNL and consequently higher subjective noise level L_S was reported in the second experiment for the cases with low overall sound pressure levels. This trend was in the same direction as the one producing the noise-level effect in the analyses of variance of tables VII and VIII.

The effect of repetition rate on annoyance prediction error for L_A and PNL is indicated in figure 21. As in the first experiment, a consistent trend is found for increasing prediction error with increasing repetition rate. The increase is only slightly greater for L_A (about 7 dB) but is much greater (about 12 dB) for PNL as compared with the respective 4- and 5-dB increases in the first experiment. In contrast to the first experiment, the spectral contents of stimuli are directly related to the repetition rate. As a consequence, the different frequency weightings of different noise metrics would be expected to produce somewhat different effects.

The effect of the different impulsiveness conditions on prediction error for the second experiment is indicated in figure 22. For L_A, a general overall trend of a decrease in error with higher impulsiveness is shown. For PNL, an increase in error and then a decrease with higher impulsiveness is shown. It should be remembered that the design was incomplete and the higher repetition rates were not examined at the higher impulsiveness conditions. Because of the strong effect of repetition rate, particularly for PNL, the change in slope could be a direct result of the incomplete test design.

Relationship of prediction error and physical measures.- As indicated in the two previous sections, differences were found in the effects of repetition rate and impulsiveness for the noise metrics L_A and PNL. A comparison of prediction errors for the different noise metrics investigated in this study is given in table IX. The standard deviation in prediction error, the difference between the subjective noise level and the measured or calulated noise level, of the different metrics is given for each experiment separately and combined. Comparatively small differences are found between the experiments. The standard deviations for the combined experiments are also very similar to those of the individual experiments. Therefore, no particular bias or consistent error difference is found between the experiments. There are, however, greater differences found between the noise metrics. The smallest standard deviations are produced by L_A. Based on F-ratio tests of variances, the standard deviation for L_A is significantly different from those of the other metrics.

To provide additional information on the nature of the exhibited effects of repetition rate and impulsiveness on prediction error and perhaps to provide a means of correcting noise metrics for these effects, a number of correlation analyses were performed. Summaries of these analyses, in terms of Pearson product-moment correlation coefficients, are presented in tables X and XI. In table X the correlations between prediction error and various physical parameters are given for each noise metric and for each experiment separately and combined. The physical parameters considered were the tone corrections ΔT; the three impulsiveness corrections ΔC_1, ΔC_2, and ΔC_3; a linear and a logarithmic repetition-rate parameter F_R and $\log F_R$; and a linear and a logarithmic parameter of the center frequency of the 1/3-octave band containing the greatest D-weighted sound pressure level. For a rough indication of significance at the 0.01 level, a value of 0.2 could be used. From table X it is seen that the two experiments were generally consistent. As a consequence, more attention will be given to the combined results.

Significant correlations are found across the noise metrics between prediction error and tone correction, repetition rate, and the logarithm of repetition rate. Greater correlation is found in the second experiment for the repetition-rate parameters, which is a reflection of the greater effect of repetition rate found in the second experiment. The logarithm of repetition rate is also found to be slightly more correlated to the prediction error than is repetition rate. The ISO impulse correction factor ΔC_1 is significantly correlated for the L_D, L_E, PNL, and LL metrics but not for PL or L_A. The unlimited ISO correction factor ΔC_2 is generally less correlated than ΔC_1. The A-weighted crest factor ΔC_3 is either not significantly correlated or is negatively correlated. The frequency parameter F_M and its logarithmic form are found to be significantly correlated to prediction error for all metrics except L_A.

The correlations between the various physical parameters are presented in table XI. The tone correction ΔT is positively and significantly correlated with repetition rate F_R. Because of this and the fact that prediction errors were more highly correlated with F_R than ΔT, it is thought that the significant correlations of prediction errors with ΔT were actually a reflection of the repetition-rate effect.

Although the correlation of prediction error and the ISO impulse correction factor ΔC_1 is significant for L_D, L_E, PNL, and LL, it does not explain much of the variance in prediction error (less than 16 percent in any case). The three impulse parameters are each highly correlated with the others and, in general, highly correlated with the frequency parameter F_M and its logarithmic form.

A number of findings have indicated that what might at first glance appear to be effects of impulsiveness on annoyance may in fact be results of deficiencies in the frequency weightings used in some noise metrics. The following section will discuss this hypothesis in more detail and examine the data in hand for a potential improvement in the frequency weighting for noise metrics.

Alternative Frequency Weighting

In the previous sections it was shown that prediction error is more correlated with the frequency parameter F_M and its logarithmic form than with impulsiveness measures ΔC_1, ΔC_2, or ΔC_3, although the frequency parameter and impulsiveness measures are highly correlated with each other. (See tables X and XI.) It was also shown that the correlations of prediction error and impulsiveness measures are dependent on the noise metric. (See table X.) Those metrics which deemphasize low-frequency content the most, L_A and PL, indicate negative or insignificant correlation between prediction error and impulsiveness measure ΔC_1. In addition, it was shown in the analyses of variance for the first experiment (tables V and VI) that a significant interaction existed between the impulsiveness condition and the noise level; no test could be made for the second experiment. While these facts are not individually conclusive, when considered together they do indicate that the observed "impulsiveness" effects could be due to effects of frequency content of the different stimuli and deficiencies in frequency weightings of the noise metrics.

The following two sections examine in more detail the relationship of prediction error and the frequency content of the spectra and an experimentally determined frequency weighting which was found to reflect that relationship.

Comparison of prediction error and dominant frequency.- The frequency parameter F_M was defined to be the 1/3-octave-band center frequency with the greatest D-weighted energy and was, therefore, considered as a first approximation to be the subjectively dominant frequency for each stimulus. It was found in the correlation analysis (table X) that the logarithm of F_M was more highly correlated to prediction error than F_M for all metrics except L_A. As a consequence, the logarithm of F_M was used to examine the relationship of prediction error to the subjectively dominant frequency. In the following analysis only the data obtained for the highest overall noise level for each stimulus condition were considered.

The prediction error was considered as the dependent variable in a third-order least-squares polynomial regression analysis for each noise metric. The logarithm of the dominant frequency F_M was considered to be the independent variable in each case. Representative examples are presented in figures 23 and 24 for L_A and PNL. Although the scatter is comparatively large in each case, significant trends are observed. The data for other metrics were very similar to that for PNL. Standard errors of estimate of L_A and PNL were 2.8 dB and 3.1 dB as compared with simple standard deviations of prediction error of 3.3 dB and 3.7 dB.

Modified frequency weightings.- Based on these regressions and similar regressions for the other metrics, corrections (predicted values) for each metric at each 1/3-octave-band center frequency from 25 Hz to 1000 Hz (50 Hz to 1000 Hz for PNL) were determined. The data for each metric were then normalized to produce a 0-dB correction at 1000 Hz. The corrections for each metric were applied to the frequency weightings for the metric and the resultants were considered as data points for a subsequent regression analysis. These corrected frequency weightings were considered as the dependent variable in a third-order least-squares polynomial regression analysis with the logarithm of the 1/3-octave-band center frequencies as the independent variable. The best fit to these data is presented in figure 25 and is contrasted with standard A- and D-weightings. In general, this modified frequency weighting is between the A- and D-weighting curves.

The frequency weightings indicated in figure 25 were extended to higher frequencies by assuming the D-weighted values between 1 kHz and 10 kHz. Noise levels using the modified frequency weightings were calculated for each noise stimulus using two 1/3-octave-band summation procedures. The first noise level L_1' used the energy summation method commonly used for L_A, L_D, and L_E. The second noise level L_2' used the summation method used in the PNL calculation procedure, which considers the possibility of masking by the dominant band.

The standard deviation in error in annoyance prediction for these two modified noise metrics and for the other six noise metrics investigated are compared in table XII for the highest noise-level conditions of the stimuli. When the combined experiments are considered, the modified metrics produce less error than the other metrics. However, the modified metrics do not produce as much improvement over L_A as over the other metrics, and they produce no improvement over L_A in the separate experiments. It is realized that the dominant frequencies of the stimuli, upon which the modified weightings were based, were determined by the maximum D-weighted band levels. The rather large differences between the D-weighting and the improved or modified weighting could be the source of error. This potential error could be examined further by iteration using the modified weightings to produce new estimates of the dominant frequency bands. However, since the present investigation was not designed specifically to provide the optimum information on frequency weightings, such an iterative process would not be justified.

Although the L_2' procedure produced a slight improvement over L_1', additional research is necessary to determine if this improvement is significant. The present stimuli were, in general, dominated by a single band as indicated by the magnitude of tone corrections (tables I and II). As a result, the two modified metrics differed very little for most stimuli.

A final question concerning the modified noise metrics is in order: Are the effects of the repetition rate accounted for or reduced? Based on results of correlation analyses, a significant effect of repetition rate remained in prediction error L_1' and L_2'. The correlation coefficients for the logarithm of repetition rate and prediction error for the two modified metrics were 0.58 and 0.48. Comparable values for the other metrics ranged from 0.55 to 0.69 for the combined experiments (table X). As a consequence, although the modified weightings somewhat reduce the effects, they do not adequately account for the repetition-rate effects observed.

CONCLUSIONS

Two experiments were conducted to determine the effects of repetition rate and impulsiveness on annoyance due to simulated helicopter rotor noise. In one experiment the pulse shape (relationship of pulse width to height) was held constant across various repetition rates; in the other experiment the crest factor (relationship of pulse width to repetition period) was held constant. Repetition rates and impulsiveness covered the range of both helicopter main- and tail-rotor thickness noises. In the first experiment 49 different combinations of repetition rate and impulsiveness were examined; in the second experiment 40 combinations were examined. In each experiment these stimuli were judged for annoyance at 3 noise levels by 48 subjects. Based on these judgments and statistical comparisons of the judgments with numerous noise metrics, the following conclusions were noted:

1. Annoyance increased with repetition rate more than predicted by all noise metrics examined. The increased annoyance was as great as the equivalent of a 4-dB increase in noise level after correcting or accounting for other spectral effects.

2. Annoyance also increased with impulsiveness more than predicted by most noise metrics examined, including perceived noise level (PNL). Prediction errors associated with impulsiveness were as great as 13 dB.

3. Interaction effects between impulsiveness and noise level were such that greater increases in annoyance with impulsiveness were found for lower overall noise levels than for higher noise levels.

4. The annoyance prediction errors for most noise metrics were more highly correlated with the frequency of the subjectively dominant 1/3-octave band than with physical measures of impulsiveness. Based on this finding and the previously mentioned finding of an interaction of impulsiveness with noise level, the observed effects of impulsiveness appeared to result from inaccuracies in the frequency weightings used in the different noise metrics rather than inherent inabilities to account for impulsiveness.

5. The A-weighted noise metric L_A was found to predict the annoyance responses with less error than the other metrics examined.

6. By using the annoyance data from these two experiments, a modified frequency weighting was developed which provided improved annoyance prediction.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
January 5, 1982

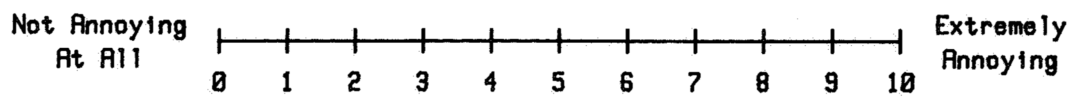
APPENDIX

INSTRUCTIONS, CONSENT FORM, AND RATING SHEET

INSTRUCTIONS

The experiment in which you are participating will help us understand some of the characteristics of aircraft sounds which can cause annoyance in airport communities. We would like you to judge how ANNOYING some sounds are. By ANNOYING we mean - UNWANTED, OBJECTIONABLE, DISTURBING, or UNPLEASANT.

The experiment consists of six 6-minute sessions. During each session 27 sounds will be presented for you to judge. Before each session you will be given a rating sheet with 27 scales like the one below.



After listening to each sound, please indicate how annoying you judge the sound to be by placing a mark across the scale. If you judge a sound to be only slightly annoying, then place your mark closer to the NOT ANNOYING AT ALL end of the scale. Similarly, if you judge a sound to be very annoying then place your mark closer to the EXTREMELY ANNOYING end of the scale. A moderately annoying judgment should be marked in the middle portion of the scale. A mark may be placed anywhere along the scale, not just at the numbered locations. You will have about 5 seconds after the sound to make and record your judgment. There are no right or wrong answers; we are only interested in your judgment of each sound.

Before the first session begins you will be given a practice rating sheet and three sounds will be presented to familiarize you with making and recording judgments. I will remain in the testing room with you during the practice time to answer any questions you may have.

Thank you for your help in conducting the experiment.

VOLUNTARY CONSENT FORM FOR SUBJECTS FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on ______________________________
Date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instructions of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
Signature of Subject

APPENDIX

RATING SHEET

Page 1

Subject No.________ Group________ Session________ Tape________

<u>Sound</u>

Sound													
1	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
2	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
3	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
4	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
5	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
6	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
7	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
8	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
9	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying
10	Not Annoying At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Annoying

REFERENCES

1. Crosse, G. W.; Davidson, I. M.; Hargest, T. J.; and Porter, M. J.: A Controlled Experiment on the Perception of Helicopter Rotor Noise. J. R. Aeronaut. Soc., vol. 64, no. 598, Oct. 1960, pp. 629-632.

2. Robinson, D. W.; and Bowsher, J. M.: A Subjective Experiment With Helicopter Noises. J. R. Aeronaut. Soc., vol. 65, no. 607, July 1961, pp. 635-637.

3. Sternfeld, Harry, Jr.; Hinterkeuser, Ernest G.; Hackman, Roy B.; and Davis, Jerry: Acceptability of VTOL Aircraft Noise Determined by Absolute Subjective Testing. NASA CR-2043, 1972.

4. MAN-Acoustics and Noise, Inc.: Noise Certification Considerations for Helicopters Based on Laboratory Investigations. FAA-RD-76-116, July 1976. (Available from DTIC as AD A032 028.)

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

6. Patterson, James H., Jr.; Moso, Ben T.; Schomer, Paul D.; and Camp, Robert T., Jr.: Subjective Ratings of Annoyance Produced by Rotary-Wing Aircraft Noise. USAARL Report No. 77-12, U.S. Army, May 1977. (Available from DTIC as AD A043 435.)

7. Galloway, William J.: Subjective Evaluation of Helicopter Blade Slap Noise. Helicopter Acoustics, NASA CP-2052, Pt. II, 1978, pp. 403-418.

8. Shepherd, Kevin P.: A Laboratory Study of the Subjective Response to Helicopter Blade-Slap Noise. NASA CR-158973, 1978.

9. Berry, B. F.; Fuller, H. C.; John, A. J.; and Robinson, D. W.: Th Rating of Helicopter Noise: Development of a Proposed Impulse Correction. NPL Acoustics Rep. Ac 93, British A.R.C., Dec. 1979.

10. Powell, Clemans A.: Subjective Field Study of Response to Impulsive Helicopter Noise. NASA TP-1833, 1981.

11. Kryter, K. D.; Johnson, P. J.; and Young, J. R.: Judgment Tests of Flyover Noise From Various Aircraft. NASA CR-1635, 1970.

12. Ollerhead, J. B.: An Evaluation of Methods for Scaling Aircraft Noise Perception. NASA CR-1883, 1971.

13. Stent, R. J.; and Southwood, B. J.: The Influence of Repetition Rate on the Subjective Assessment of Blade Slap. Appl. Acoustics Dep. Note 1221, Westland Helicopters, Ltd., Dec. 1978.

14. Southwood, B. J.; Helicopter Noise Certification Evaluation of Proposed Noise Rating Methods. Part 2 - The Subjective Assessment of Tail Rotor Noise. Res. Paper 576, Westland Helicopters, Ltd., July 1978.

15. Farassat, F.: Theory of Noise Generation From Moving Bodies With an Application to Helicopter Rotors. NASA TR R-451, 1975.

16. True, H. C.; Rickley, E. J.; and Letty, R. M.: Helicopter Noise Measurements Data Report. Volume I - Helicopter Models: Hughes 300-C, Hughes 500-C, Bell 47-G, Bell 206-L. FAA-RD-77-57, I, Apr. 1977. (Available from DTIC as AD A040 561.)

17. Noise Standards: Aircraft Type and Airworthiness Certification. Federal Aviation Regulations, vol. III, pt. 36, FAA, 1978.

18. Pearsons, Karl S.; and Bennett, Ricarda L.: Handbook of Noise Ratings. NASA CR-2376, 1974.

19. Bennett, Ricarda L.; and Pearsons, Karl S.: Handbook of Aircraft Noise Metrics. NASA CR-3406, 1981.

NOISE MEASURES, SYMBOLS, AND ABBREVIATIONS

Noise Measures

L_A A-weighted sound pressure level, dB

L_D D-weighted sound pressure level, dB

L_E E-weighted sound pressure level, dB

LL loudness level (Stevens Mark VI procedure), dB

PL perceived level (Stevens Mark VII procedure), dB

PNL perceived noise level, dB

A more detailed description of the noise measures used in this report can be found in references 18 and 19.

Symbols and Abbreviations

F_M center frequency of subjectively dominant 1/3-octave-noise band, Hz

F_R repetition rate of rotor-noise impulses, Hz

ISO International Organization for Standardization

L_S subjective noise level, dB

L'_1 predicted noise level using modified frequency weighting and energy summation, dB

L'_2 predicted noise level using modified frequency weighting and masked-band summation, dB

p probability

SPL sound pressure level

ΔC_1 impulsiveness correction using proposed ISO method, dB

ΔC_2 impulsiveness correction using proposed ISO method without limit of 6.0-dB maximum, dB

ΔC_3 impulsiveness correction using peak A-weighted sound-pressure-level method, dB

ΔT tone correction (from ref. 17), dB

TABLE I.- ACOUSTICAL ANALYSES OF HIGHEST SOUND-PRESSURE-LEVEL STIMULI

PRESENTED TO SUBJECTS IN FIRST EXPERIMENT

Impulsiveness condition	Repetition rate, Hz	L_A, dB	L_D, dB	L_E, dB	PNL, dB	PL, dB	LL, dB	ΔT, dB	ΔC_1, dB	ΔC_2, dB	ΔC_3, dB	F_M, Hz
1	10	50.6	64.0	60.9	68.6	58.8	69.4	0.4	0.5	0.5	0.3	32
2	10	52.6	66.4	63.6	70.3	60.0	70.8	.7	1.5	1.5	.9	63
3	10	61.5	72.9	70.8	76.4	67.9	77.5	.4	6.0	6.0	4.0	100
4	10	64.7	74.6	72.7	78.1	70.2	79.3	.3	6.0	9.3	6.2	160
5	10	66.9	75.9	74.1	79.8	72.0	80.5	2.5	6.0	10.1	7.2	200
6	10	68.8	76.5	75.1	81.2	73.1	81.2	2.9	6.0	10.3	7.2	250
7	10	70.2	77.2	76.2	82.3	74.3	82.3	2.8	6.0	10.6	7.4	250
1	15	50.0	63.9	61.0	67.8	57.7	68.6	.5	.7	.7	.1	32
2	15	52.9	67.1	64.0	70.7	60.3	71.4	.5	1.4	1.4	.7	63
3	15	61.9	73.4	71.3	76.4	67.9	74.7	.1	4.8	4.8	2.5	80
4	15	64.7	74.8	72.9	78.2	70.1	79.1	.3	6.0	7.3	5.0	125
5	15	67.4	76.1	74.4	80.1	71.8	80.1	.2	6.0	8.0	5.5	200
6	15	69.3	77.2	76.5	81.5	73.3	81.3	.3	6.0	8.7	5.5	200
7	15	71.2	78.6	77.3	83.1	74.9	82.7	.5	6.0	9.0	5.6	250
1	25	49.1	64.1	60.8	68.1	55.7	68.2	.2	0	0	0	25
2	25	54.1	68.2	65.6	71.5	60.8	71.8	.3	.7	.7	.3	80
3	25	61.8	73.3	71.3	76.5	67.5	77.5	.3	2.7	2.7	.6	80
4	25	64.7	74.8	72.9	78.1	69.6	78.5	.2	5.3	5.3	2.1	160
5	25	67.8	76.6	74.9	80.0	71.8	80.2	.2	6.0	6.7	3.6	160
6	25	69.2	77.1	75.7	81.4	72.8	80.8	.4	6.0	7.2	4.1	250
7	25	70.4	77.9	76.5	82.2	73.7	81.5	.6	6.0	7.3	4.3	250
1	40	50.2	62.9	61.3	69.8	57.6	68.5	1.8	.5	.5	0	40
2	40	54.3	67.0	65.4	72.9	60.8	71.7	2.1	.8	.8	.1	80
3	40	62.7	73.7	72.0	77.4	67.7	77.7	1.5	1.4	1.4	.5	80
4	40	65.7	75.5	73.7	78.9	69.8	78.9	1.3	3.8	3.8	.8	125
5	40	68.4	77.0	75.4	80.0	71.7	79.9	1.3	5.3	5.3	1.8	125
6	40	70.0	77.6	76.2	81.4	72.8	80.4	1.2	5.5	5.5	1.9	250
7	40	70.8	78.2	76.9	82.1	73.5	81.0	1.2	5.8	5.8	2.0	250
1	60	56.4	71.4	68.2	75.9	62.3	74.6	2.3	0	0	0	63
2	60	56.7	71.4	68.2	76.2	62.5	74.8	2.9	0	0	0	63
3	60	61.8	73.6	71.0	77.5	66.3	77.2	2.3	.8	.8	0	63
4	60	65.4	75.4	73.2	79.3	69.4	78.8	2.1	1.1	1.1	0	125
5	60	68.1	76.6	74.8	80.5	71.0	79.7	1.9	3.0	3.0	0	125
6	60	70.1	77.6	76.2	81.4	72.6	80.3	1.8	3.8	3.8	.2	316
7	60	71.4	78.6	77.3	83.5	73.7	81.2	1.8	3.9	3.9	.5	316
1	85	60.7	74.0	72.4	78.1	66.7	76.7	2.4	0	0	0	80
2	85	63.0	76.2	74.7	80.1	69.2	79.3	2.1	0	0	0	80
3	85	63.0	74.7	73.1	78.8	68.5	78.3	3.0	.3	.3	0	80
4	85	65.6	75.8	74.2	79.5	69.2	78.8	3.1	1.5	1.5	0	80
5	85	68.2	77.0	75.5	80.6	71.3	79.5	3.1	2.4	2.4	0	160
6	85	70.0	78.0	76.6	81.4	72.4	80.0	3.2	2.9	2.9	0	160
7	85	70.3	78.9	77.5	82.4	73.4	81.0	3.2	3.3	3.3	0	160
1	115	67.2	78.0	76.0	80.9	70.6	78.8	3.1	0	0	0	125
2	115	66.7	77.6	75.6	80.6	70.3	78.5	3.1	0	0	0	125
3	115	67.2	77.6	75.7	81.4	71.3	79.5	3.1	0	0	0	125
4	115	68.2	77.9	76.1	82.1	72.2	80.2	3.1	.4	.4	0	125
5	115	69.8	78.4	76.7	82.7	73.0	80.8	3.0	1.2	1.2	0	125
6	115	71.0	78.7	77.8	82.7	73.2	80.8	3.0	2.0	2.1	0	125
7	115	71.9	79.2	77.9	83.1	73.8	81.2	3.0	2.2	2.2	0	125

TABLE II.- ACOUSTICAL ANALYSES OF HIGHEST SOUND-PRESSURE-LEVEL STIMULI PRESENTED TO SUBJECTS IN SECOND EXPERIMENT

Impulsiveness condition	Repetition rate, Hz	L_A, dB	L_D, dB	L_E, dB	PNL, dB	PL, dB	LL, dB	ΔT, dB	ΔC_1, dB	ΔC_2, dB	ΔC_3, dB	F_M, Hz
1	10	48.7	62.1	59.0	66.7	56.9	67.4	0.4	0.5	0.5	0	32
2	10	51.4	65.2	62.4	69.1	58.8	69.6	.7	1.7	1.7	1.2	63
3	10	59.8	71.2	69.1	74.7	66.2	75.8	.4	4.3	4.3	3.9	100
4	10	63.0	72.9	71.0	76.4	68.5	77.6	.3	6.0	7.4	4.5	160
5	10	65.3	74.0	72.3	77.9	70.1	78.6	2.5	6.0	8.4	6.5	200
6	10	66.9	74.6	73.2	79.3	71.2	79.3	2.9	6.0	10.0	7.7	250
7	10	69.6	75.7	74.3	80.4	72.4	80.4	2.9	6.0	10.7	7.8	250
1	15	53.4	67.1	64.6	70.3	60.1	70.9	.3	1.5	1.5	.5	63
2	15	54.2	68.1	64.8	72.0	62.3	73.5	2.5	1.6	1.6	.5	50
3	15	63.8	73.5	71.6	76.8	69.0	77.8	.2	6.0	6.6	4.6	125
4	15	66.5	74.6	73.1	79.0	70.9	78.9	.4	6.0	8.9	6.3	200
5	15	68.5	75.4	74.2	80.9	73.1	81.0	.6	6.0	9.3	6.3	316
6	15	71.1	77.0	76.2	82.9	74.8	82.6	1.6	6.0	9.8	6.8	316
7	15	71.2	76.5	75.9	82.5	74.6	82.4	1.7	6.0	10.6	7.8	316
1	25	58.9	71.0	68.9	74.3	64.9	75.3	.2	1.6	1.6	1.7	80
2	25	62.0	72.6	70.7	75.8	67.2	76.7	.2	3.9	3.9	2.7	80
3	25	68.4	75.6	74.4	80.3	72.0	79.7	.4	6.0	7.8	5.0	250
4	25	71.1	76.9	76.1	82.4	74.4	82.1	.3	6.0	8.4	5.2	316
5	25	73.0	77.5	77.1	83.1	75.1	82.5	.6	6.0	9.2	5.6	316
6	25	73.6	77.3	77.0	83.3	76.3	83.6	.9	6.0	9.8	6.2	316
7	25	74.5	77.7	77.5	83.6	76.1	83.7	3.7	6.0	10.1	6.5	500
1	40	64.2	73.9	72.1	77.3	68.3	77.4	1.3	3.5	3.5	2.5	125
2	40	67.1	75.2	73.7	78.8	70.5	78.5	1.3	5.3	5.3	3.0	250
3	40	72.6	77.7	77.1	82.7	74.5	81.6	1.2	6.0	7.2	3.5	400
4	40	74.0	77.9	77.7	83.7	75.7	82.9	1.1	6.0	8.1	4.6	400
5	40	75.6	78.2	78.0	84.0	76.5	84.1	1.1	6.0	9.1	4.6	500
6	40	77.2	78.5	78.1	84.4	77.0	84.8	1.3	6.0	9.3	5.0	800
7	40	76.1	78.5	77.7	84.7	76.9	84.8	2.9	6.0	9.9	6.0	1250
1	60	67.6	75.4	73.9	79.3	70.5	78.6	1.9	4.0	4.0	1.4	125
2	60	70.8	77.1	76.1	81.9	73.0	80.4	1.8	4.9	4.9	1.5	316
3	60	75.1	78.5	78.3	83.9	76.0	83.4	1.6	6.0	7.0	3.3	500
4	60	76.2	78.8	78.4	84.5	76.8	84.5	1.6	6.0	8.1	4.2	500
5	60	76.8	79.5	78.4	85.8	77.3	85.2	1.5	6.0	8.5	4.5	1600
1	85	70.4	77.0	75.9	81.2	72.3	79.5	3.2	4.0	4.0	.8	250
2	85	73.2	78.1	77.5	82.8	74.4	81.4	3.2	4.8	4.8	1.2	316
3	85	76.3	78.8	78.3	84.7	76.8	84.3	3.1	6.0	6.9	2.9	630
4	85	77.2	80.2	78.8	86.3	77.4	85.3	3.0	6.0	7.2	3.1	1600
1	115	74.1	78.8	78.2	83.7	75.1	82.0	3.0	3.6	3.6	.3	316
2	115	75.5	78.8	78.5	84.1	75.6	83.1	3.0	4.6	4.6	.9	316
3	115	77.5	80.5	79.2	86.2	77.5	85.3	2.8	6.0	6.1	2.0	1600

TABLE III.- SUBJECTIVE NOISE LEVELS L_S FOR ROTOR-NOISE STIMULI OF FIRST EXPERIMENT

Impulsiveness condition	Level condition	L_S, dB, for repetition rate, Hz, of -						
		10	15	25	40	60	85	115
1	1	38.0	38.4	47.8	52.1	52.4	57.3	62.9
	2	54.2	53.2	48.9	56.0	54.8	66.9	73.2
	3	55.7	58.4	60.6	68.4	69.4	75.8	80.2
2	1	51.0	48.6	49.6	52.0	53.3	60.9	61.0
	2	58.4	56.6	56.8	60.4	61.1	69.8	72.5
	3	65.0	65.3	64.1	69.1	70.3	78.5	79.9
3	1	63.3	63.1	61.3	62.0	59.7	63.2	62.8
	2	64.9	66.5	68.3	70.0	69.1	71.5	74.3
	3	73.4	70.4	73.3	75.1	74.9	77.2	79.9
4	1	62.4	63.2	63.8	65.0	64.8	68.6	68.1
	2	66.8	69.1	73.0	72.2	71.9	72.8	76.0
	3	74.8	74.9	76.5	77.1	77.8	80.1	81.6
5	1	65.7	67.0	70.9	71.8	70.8	70.6	74.3
	2	69.6	72.3	73.3	76.8	76.0	75.3	79.5
	3	75.6	76.0	78.5	79.1	81.0	82.3	84.2
6	1	70.5	70.9	71.3	70.7	78.0	73.2	76.5
	2	74.1	72.7	76.9	77.4	78.0	77.5	80.5
	3	78.8	77.1	80.2	81.6	82.3	83.9	84.1
7	1	71.9	71.0	73.7	74.0	75.2	76.9	78.5
	2	74.5	75.6	78.0	79.2	79.7	81.1	82.1
	3	79.2	78.8	79.3	82.6	83.3	84.2	85.3

TABLE IV.- SUBJECTIVE NOISE LEVELS L_S FOR ROTOR-NOISE STIMULI OF SECOND EXPERIMENT

Impulsiveness condition	Level condition	L_S, dB, for repetition rate, Hz, of -						
		10	15	25	40	60	85	115
1	1	51.2	50.7	59.2	68.8	67.5	73.8	76.7
	2	50.0	54.0	61.0	71.9	73.4	76.2	80.1
	3	52.5	62.3	69.7	74.6	76.5	80.5	84.4
2	1	49.7	54.0	61.7	70.4	72.1	74.0	76.8
	2	53.9	56.9	66.9	73.9	76.6	77.3	81.7
	3	60.2	64.1	71.5	76.1	78.4	83.9	91.5
3	1	56.0	60.4	68.9	75.9	76.6	79.0	81.7
	2	62.6	68.3	73.8	77.9	80.4	80.5	87.7
	3	68.6	71.4	76.1	78.6	83.7	88.6	92.9
4	1	59.4	67.9	71.3	74.8	78.4	80.4	
	2	66.4	69.8	75.3	77.5	80.6	83.6	
	3	68.3	72.0	77.0	80.1	83.0	89.5	
5	1	61.2	66.7	73.5	76.4	78.8		
	2	67.4	72.2	76.4	78.3	82.4		
	3	72.4	73.3	79.0	80.2	88.0		
6	1	64.8	69.7	74.1	76.9			
	2	68.2	72.1	76.1	77.9			
	3	72.2	76.4	78.2	84.1			
7	1	64.6	71.3	75.7	77.2			
	2	68.8	73.1	76.9	79.6			
	3	73.1	74.6	79.4	73.0			

TABLE V.- FIRST-EXPERIMENT ANALYSIS-OF-VARIANCE SUMMARY

FOR ANNOYANCE PREDICTION ERROR FOR L_A

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio	p
Repetition rate	6	425.517	70.920	22.80	0
Impulsiveness	6	205.252	34.209	11.00	0
Noise level	2	11.518	5.759	1.85	0.1646
Repetition rate × impulsiveness	36	238.276	6.619	2.13	0.0033
Repetition rate × noise level	12	21.140	1.762	0.57	0.8691
Impulsiveness × noise level	12	276.022	23.002	7.40	0
Error	72	223.927	3.110		
Total	146	1401.652			

TABLE VI.- FIRST-EXPERIMENT ANALYSIS-OF-VARIANCE SUMMARY

FOR ANNOYANCE PREDICTION ERROR FOR PNL

Source	Degrees of freedom	Sum of squares	Mean square	F-ratio	p
Repetition rate	6	578.578	96.430	29.94	0
Impulsiveness	6	1765.815	294.302	91.37	0
Noise level	2	16.058	8.029	2.49	0.0900
Repetition rate × impulsiveness	36	240.963	6.693	2.08	0.0042
Repetition rate × noise level	12	19.009	1.584	0.49	0.9142
Impulsiveness × noise level	12	255.383	21.282	6.61	0
Error	72	231.910	3.221		
Total	146	3107.716			

TABLE VII.- SECOND-EXPERIMENT ANALYSIS-OF-VARIANCE SUMMARY

FOR ANNOYANCE PREDICTION ERROR FOR L_A

Source	Degrees of freedom			Sum of squares	Mean square	F-ratio	p
Noise level	2			394.437	197.219	62.709	0
Impulse treatments	39			644.082	16.515	5.251	0
Main factors		12		545.527	45.461	14.455	0
Repetition rate			6	435.282	72.547		
Impulsiveness (adjusted)			6	110.245	18.374	5.842	0
Impulsiveness			6	267.715	44.619		
Repetition rate (adjusted)			6	277.812	46.302	14.72	0
Interaction		27		98.555	3.650	1.16	0.2991
Error	78			245.296	3.145		
Total	119			1283.815			

TABLE VIII.- SECOND-EXPERIMENT ANALYSIS-OF-VARIANCE SUMMARY

FOR ANNOYANCE PREDICTION ERROR FOR PNL

Source	Degrees of freedom			Sum of squares	Mean square	F-ratio	p
Noise level	2			394.437	197.219	62.73	0
Impulse treatments	39			1916.553	49.142	15.63	0
Main factors		12		1848.471	154.039	48.99	0
Repetition rate			6	1720.965	286.827		
Impulsiveness (adjusted)			6	127.506	21.251	6.76	0
Impulsiveness			6	102.887	17.148		
Repetition rate (adjusted)			6	1745.584	290.931	92.54	0
Interaction..........................		27		68.082	2.522	0.81	0.7260
Error	78			245.230	3.144		
Total	119			2556.220			

TABLE IX.- STANDARD DEVIATION OF DIFFERENCES BETWEEN SUBJECTIVE NOISE LEVELS AND NOISE LEVELS OBTAINED WITH SEVERAL NOISE METRICS

Noise metric	Standard deviation, dB, for -		
	First experiment	Second experiment	Combined experiments
L_A	3.10	3.28	3.35
L_D	4.57	5.15	4.89
L_E	4.21	4.64	4.43
PNL	4.61	4.63	4.62
PL	4.59	4.50	4.54
LL	5.11	5.19	5.14

TABLE X.- CORRELATION BETWEEN ANNOYANCE PREDICTION ERROR AND VARIOUS PHYSICAL PARAMETERS

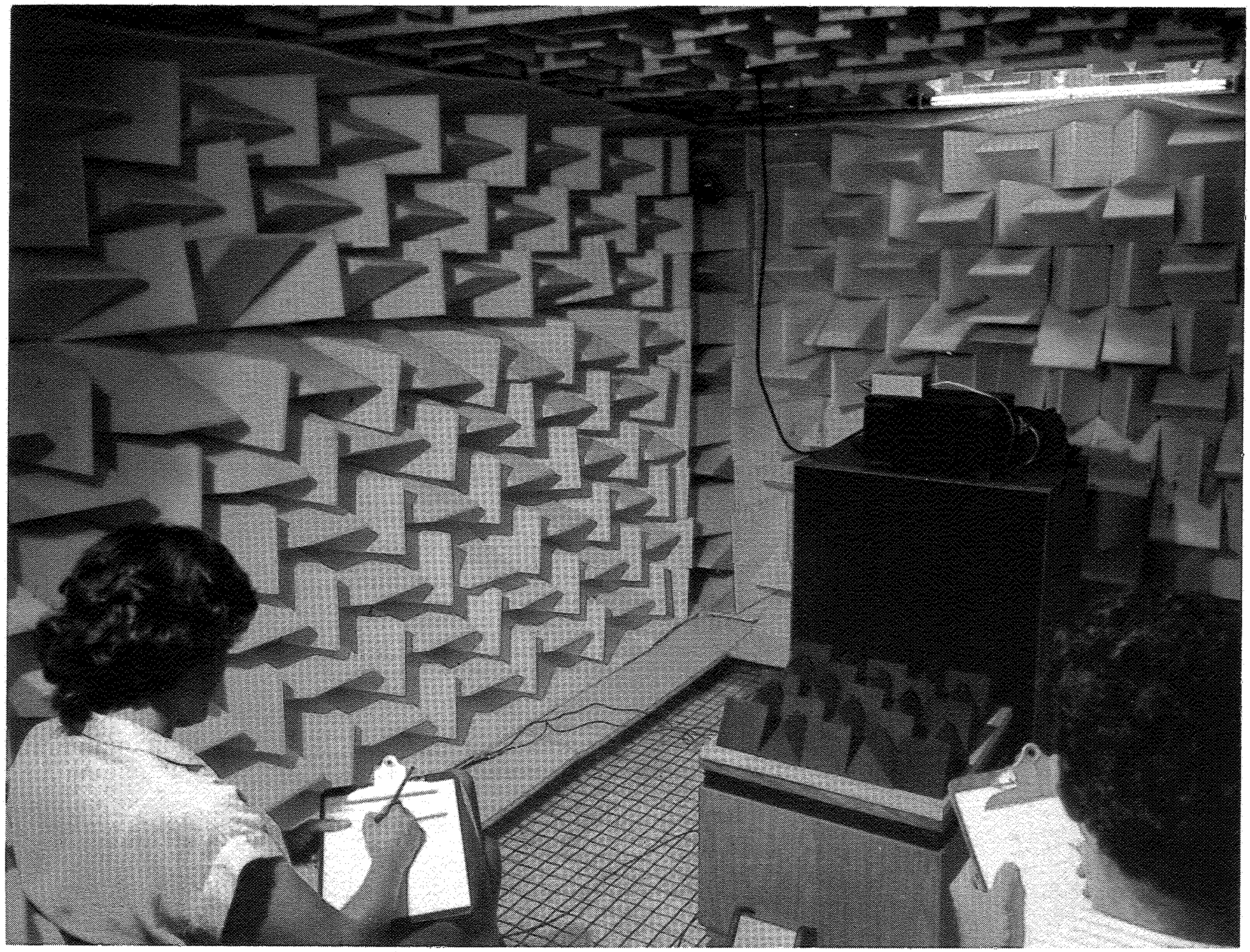
Noise metric	Correlation coefficient for -							
	ΔT	ΔC_1	ΔC_2	ΔC_3	F_R	log F_R	F_M	log F_M
	First experiment							
L_A	0.410	-0.032	-0.120	-0.268	0.487	0.527	0.153	0.249
L_D	.357	.340	.260	.049	.387	.399	.549	.637
L_E	.356	.301	.215	-.008	.393	.410	.505	.593
PNL	.337	.349	.253	.036	.401	.409	.530	.638
PL	.488	.059	.003	-.174	.548	.579	.383	.467
LL	.424	.255	.161	-.052	.513	.518	.518	.624
	Second experiment							
L_A	0.186	-0.121	-0.328	-0.466	0.558	0.567	0.243	0.165
L_D	.449	.452	.264	-.051	.743	.807	.617	.749
L_E	.440	.374	.177	-.124	.748	.800	.623	.701
PNL	.420	.377	.152	.143	.756	.814	.543	.659
PL	.416	.246	.016	-.269	.784	.827	.527	.587
LL	.452	.384	.155	-.155	.791	.845	.541	.676
	First and second experiments							
L_A	0.303	-0.197	-0.319	-0.442	0.509	0.551	0.025	-0.013
L_D	.388	.397	.299	.068	.507	.555	.520	.678
L_E	.388	.328	.221	-.005	.523	.567	.495	.613
PNL	.370	.343	.217	-.011	.531	.571	.421	.589
PL	.458	.092	-.013	-.211	.642	.685	.345	.438
LL	.435	.272	.151	-.080	.618	.653	.401	.572

TABLE XI.- CORRELATION BETWEEN PHYSICAL PARAMETERS

Physical parameter	Correlation coefficient for -						
	ΔT	ΔC_1	ΔC_2	ΔC_3	F_R	log F_R	F_M
First experiment							
ΔC_1	-0.451						
ΔC_2	-.361	0.954					
ΔC_3	-.370	.830	0.943				
F_R	.796	-.572	-.593	-.0637			
log F_R	.723	-.573	-.639	-.729	0.950		
F_M	-.010	.709	.699	.538	-.110	-0.101	
log F_M	.090	.708	.688	.525	.019	.008	0.945
Second experiment							
ΔC_1	0.183						
ΔC_2	.148	0.903					
ΔC_3	-.051	.737	0.915				
F_R	.585	.096	-.168	-0.497			
log F_R	.492	.168	-.092	-.439	0.944		
F_M	.393	.442	.357	.117	.498	0.522	
log F_M	.467	.758	.651	.353	.530	.594	0.859
First and second experiments							
ΔC_1	-0.221						
ΔC_2	-.154	0.944					
ΔC_3	-.225	.825	0.943				
F_R	.708	-.376	-.443	-0.579			
log F_R	.625	-.336	-.426	-.596	0.948		
F_M	.211	.472	.456	.308	.194	0.231	
log F_M	.236	.744	.720	.536	.171	.216	0.833

TABLE XII.- STANDARD DEVIATION OF DIFFERENCES BETWEEN SUBJECTIVE NOISE LEVELS AND NOISE LEVELS PREDICTED BY NOISE METRICS FOR HIGHEST NOISE-LEVEL CONDITIONS

Noise metric	Standard deviation, dB, for -		
	First experiment	Second experiment	Combined experiments
L'_1	2.58	3.52	3.19
L'_2	2.53	3.52	3.05
L_A	2.42	3.03	3.33
L_D	3.10	4.85	3.96
L_E	2.68	4.38	3.55
PNL	3.11	4.37	3.75
PL	3.65	4.30	4.08
LL	3.73	4.90	4.34



L-80-6613

Figure 1.- Anechoic listening room in the Langley Aircraft Noise Reduction Laboratory.

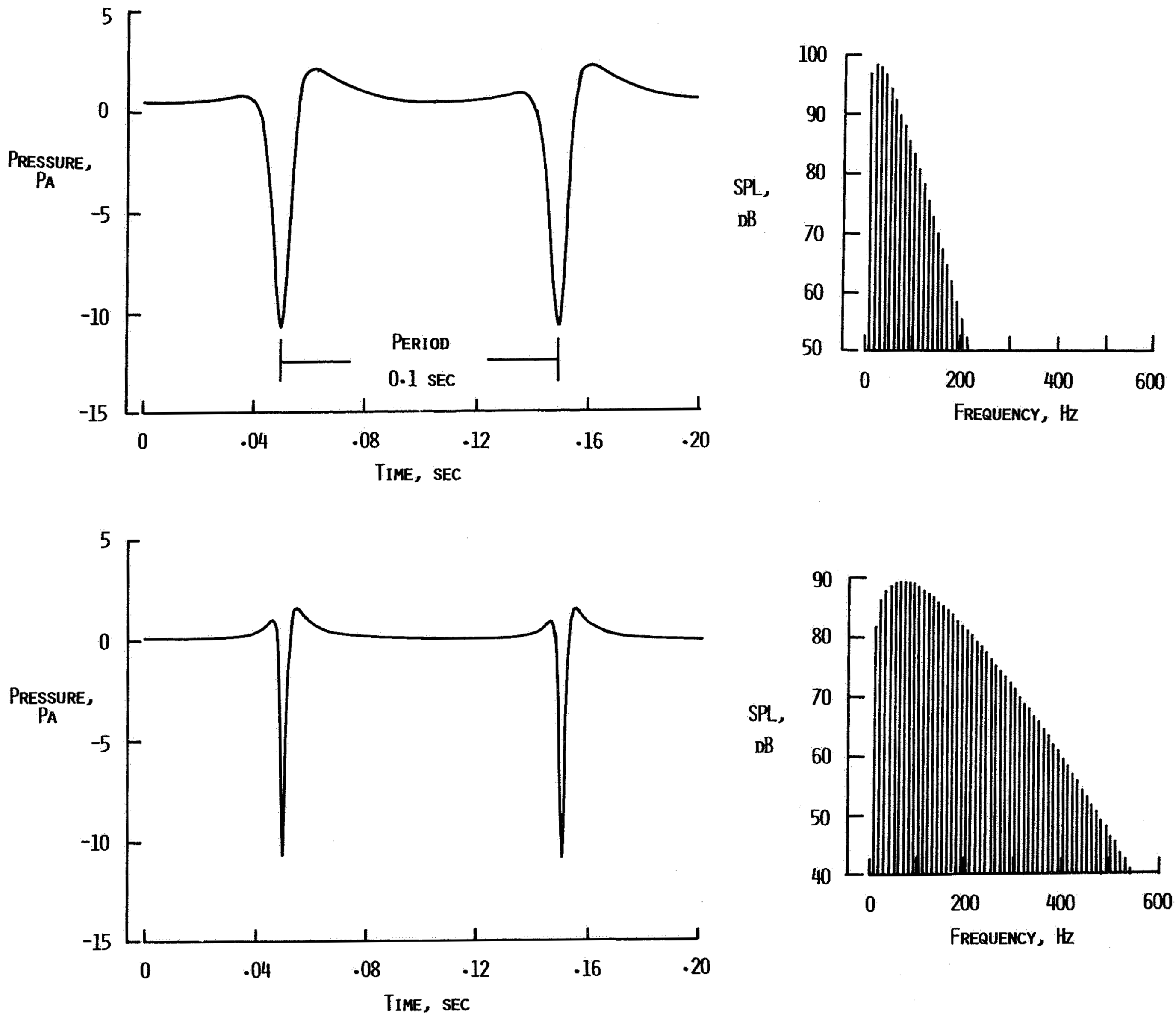
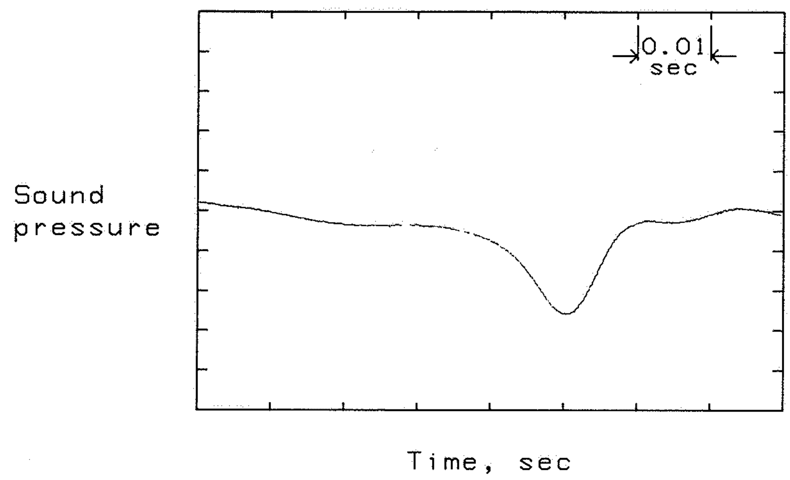
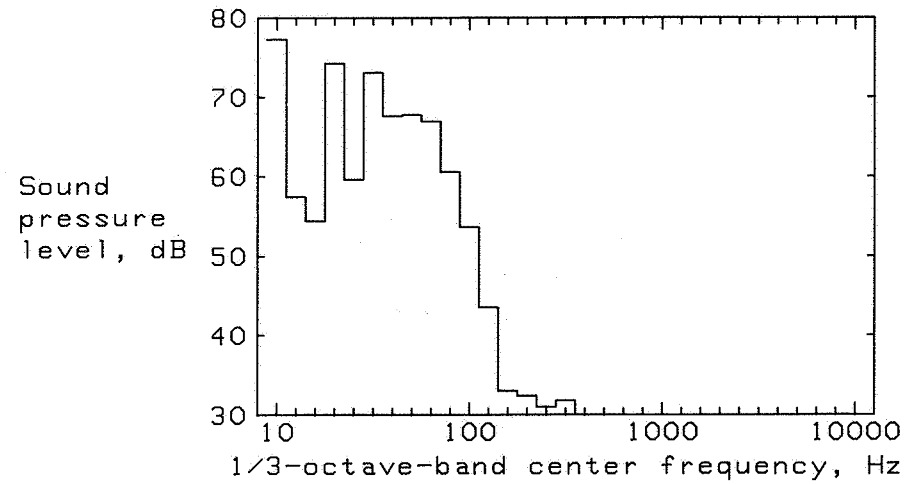


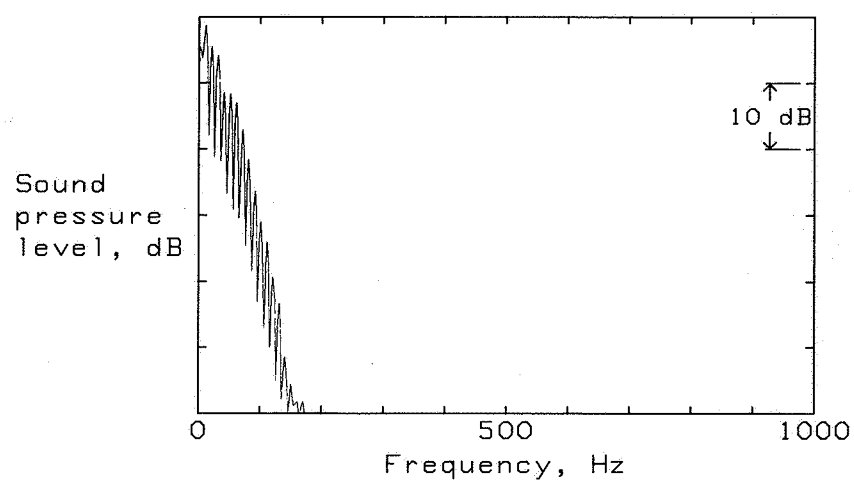
Figure 2.- Examples of predicted thickness noise.



(a) Time history.

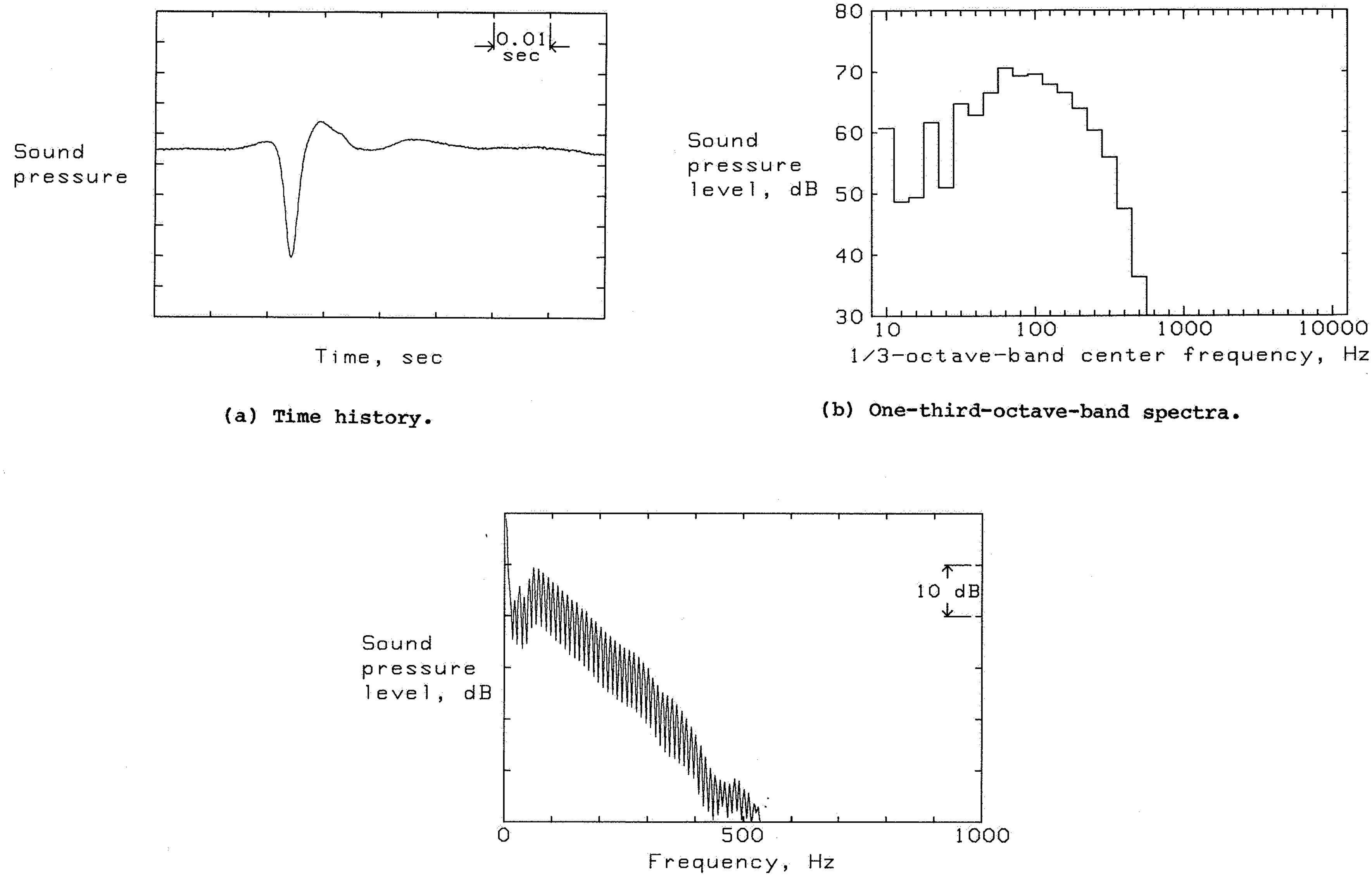


(b) One-third-octave-band spectra.



(c) Narrow-band spectra.

Figure 3.- Characteristics of low impulsiveness with 10-Hz repetition-rate stimulus used in first and second experiments.

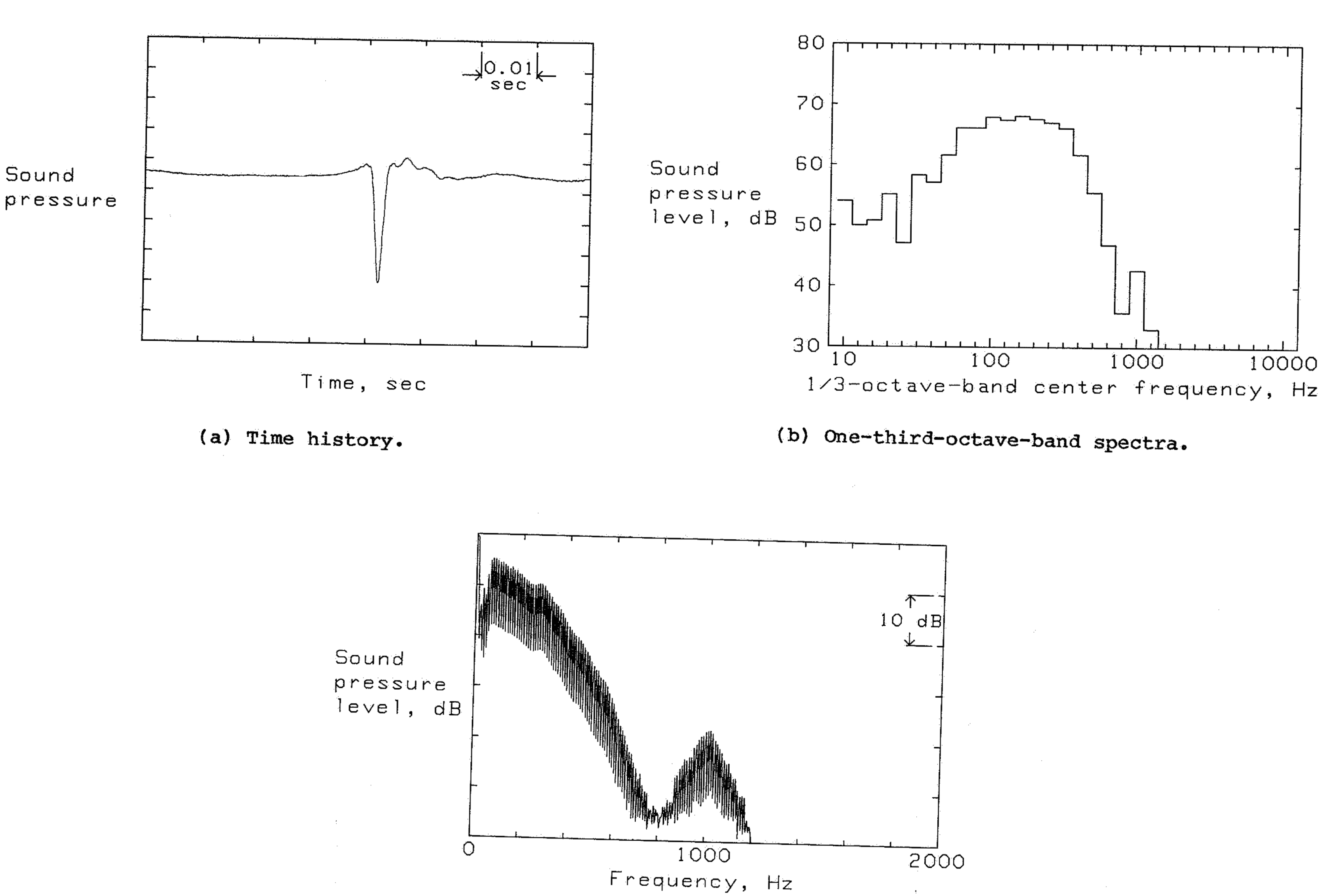


(a) Time history.

(b) One-third-octave-band spectra.

(c) Narrow-band spectra.

Figure 4.- Characteristics of medium impulsiveness with 10-Hz repetition-rate stimulus used in first and second experiments.

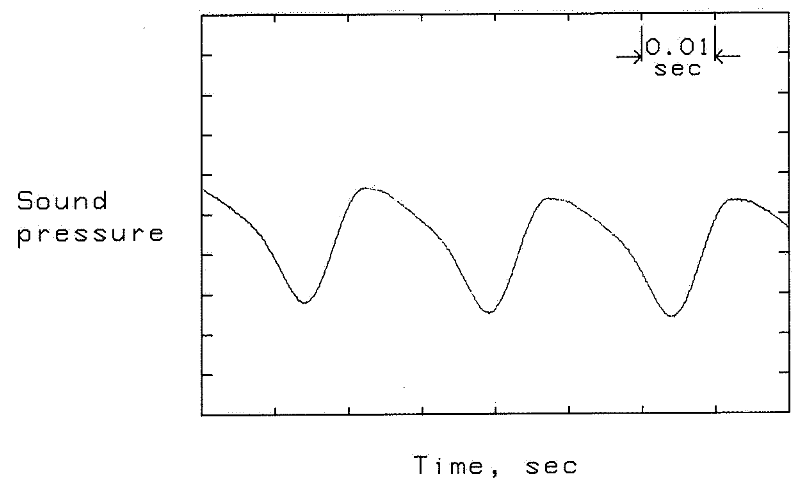


(a) Time history.

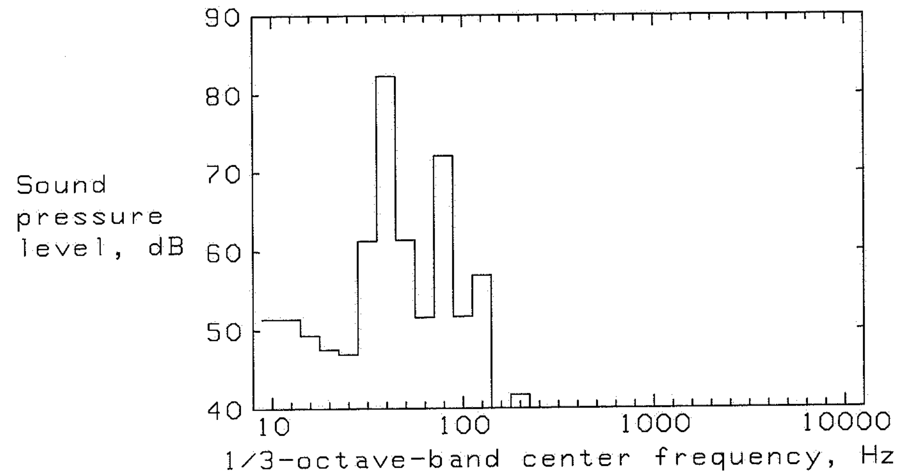
(b) One-third-octave-band spectra.

(c) Narrow-band spectra.

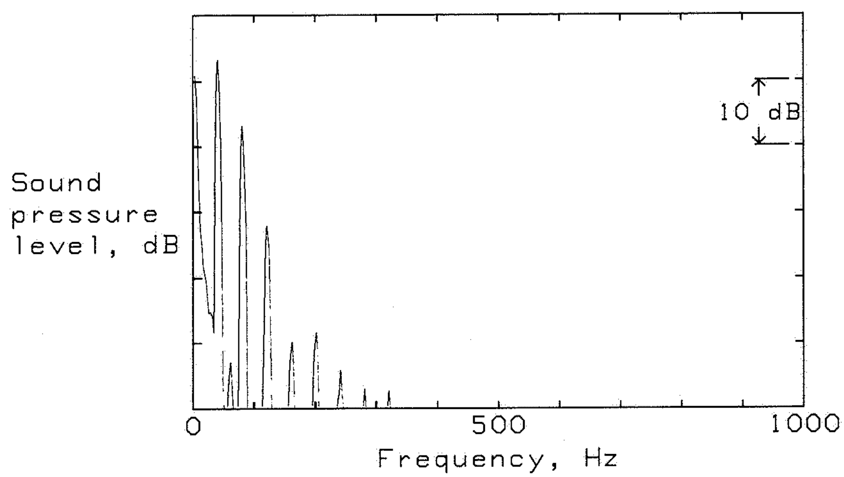
Figure 5.- Characteristics of high impulsiveness with 10-Hz repetition-rate stimulus used in first and second experiments.



(a) Time history.

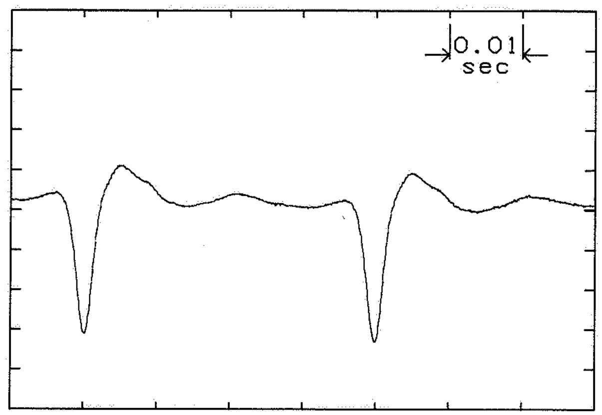


(b) One-third-octave-band spectra.

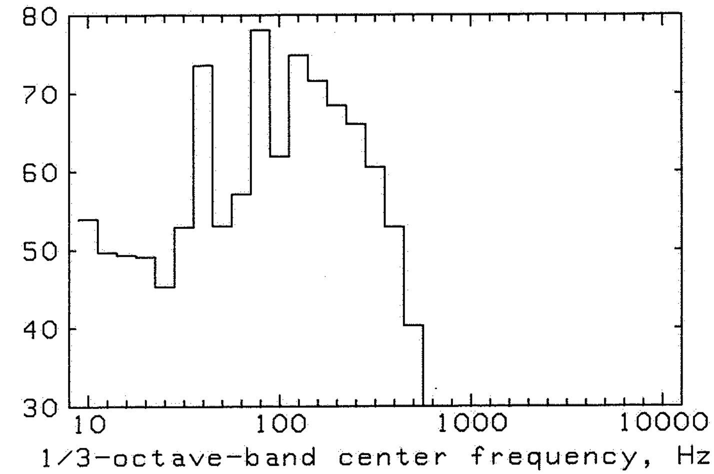


(c) Narrow-band spectra.

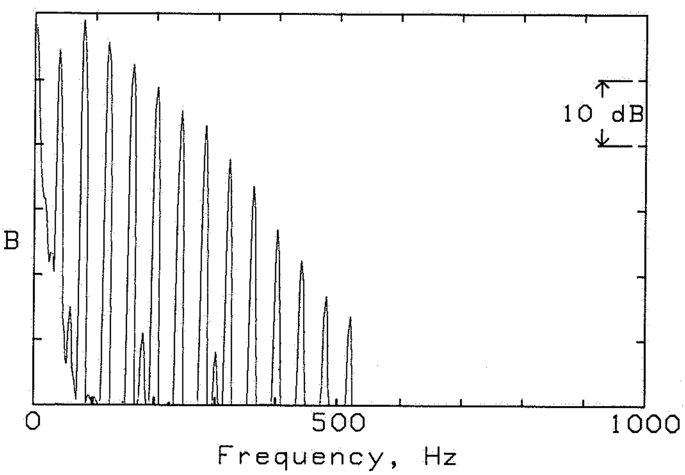
Figure 6.- Characteristics of low impulsiveness with 40-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

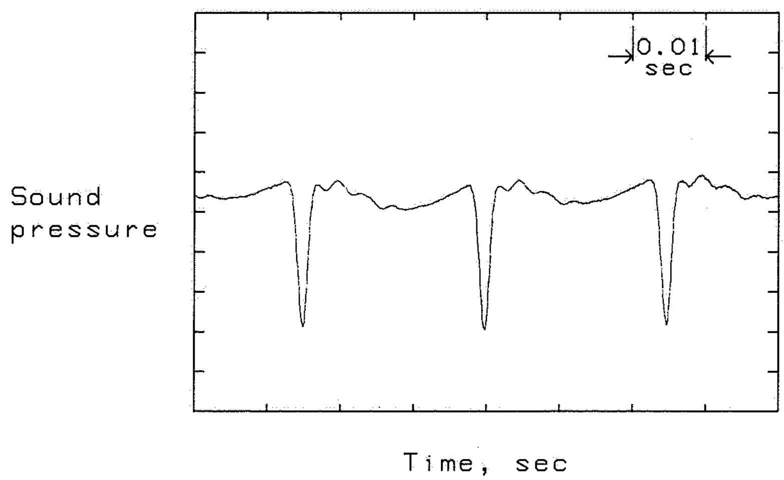


(b) One-third-octave-band spectra.

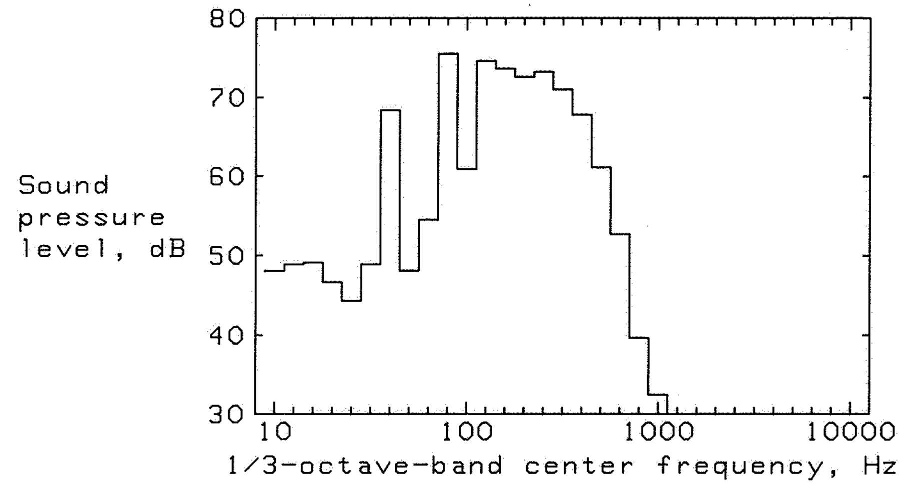


(c) Narrow-band spectra.

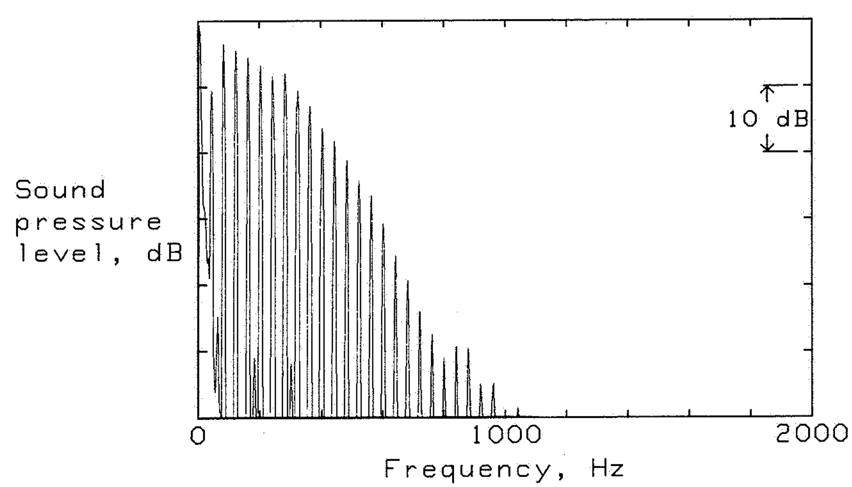
Figure 7.- Characteristics of medium impulsiveness with 40-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

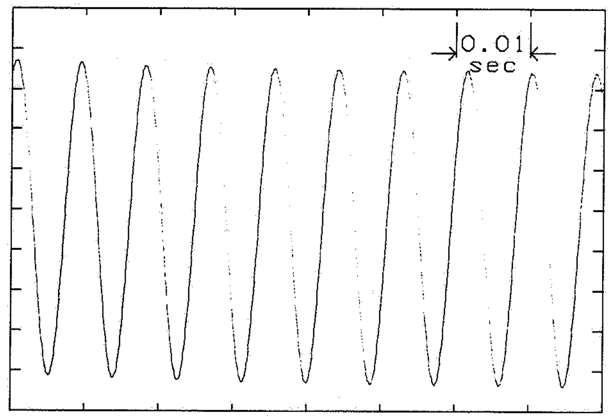


(b) One-third-octave-band spectra.

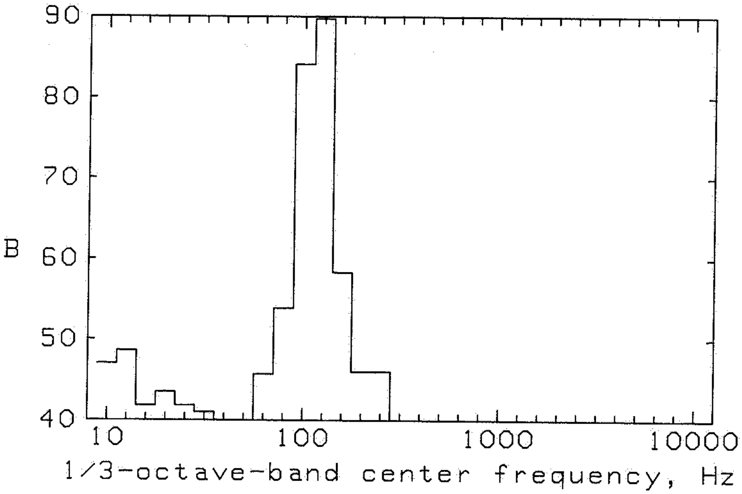


(c) Narrow-band spectra.

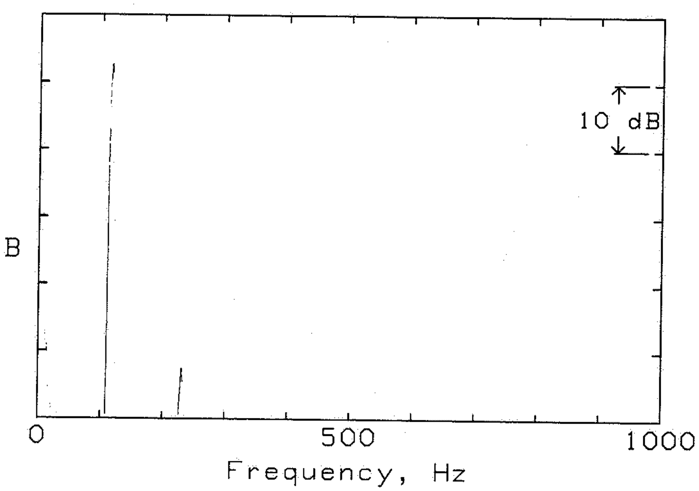
Figure 8.- Characteristics of high impulsiveness with 40-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

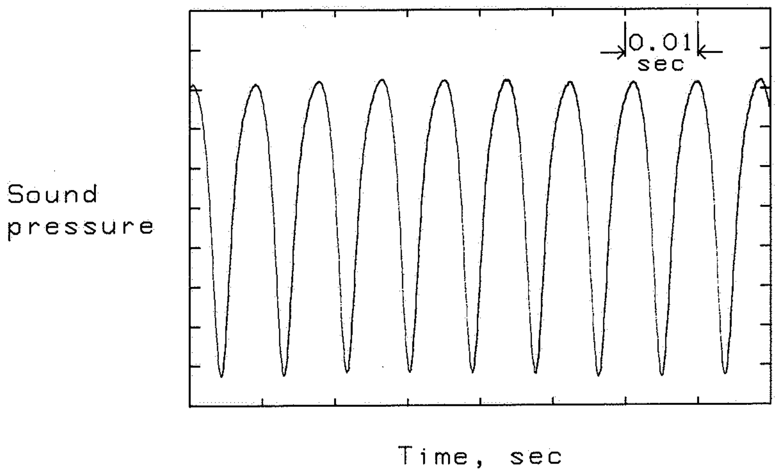


(b) One-third-octave-band spectra.

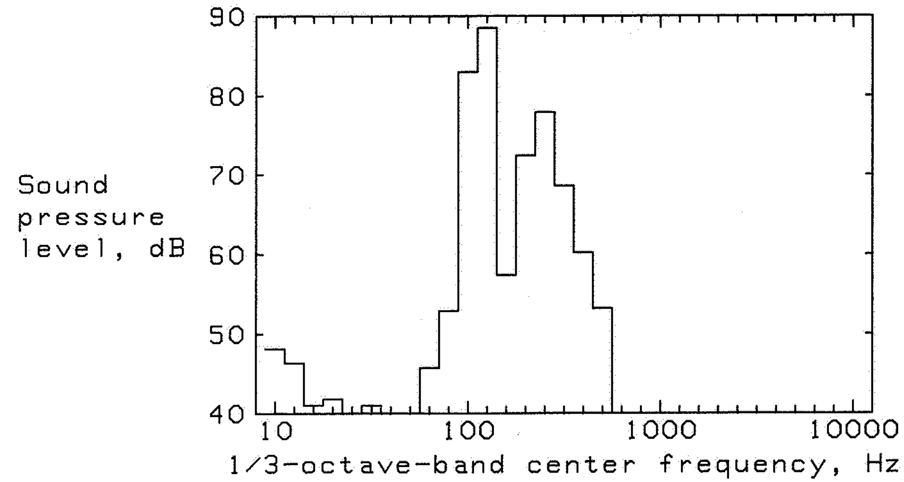


(c) Narrow-band spectra.

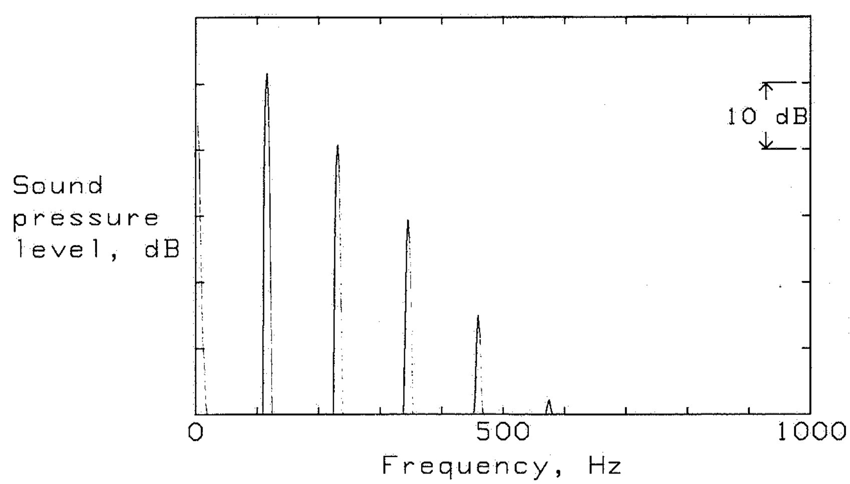
Figure 9.- Characteristics of low impulsiveness with 115-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

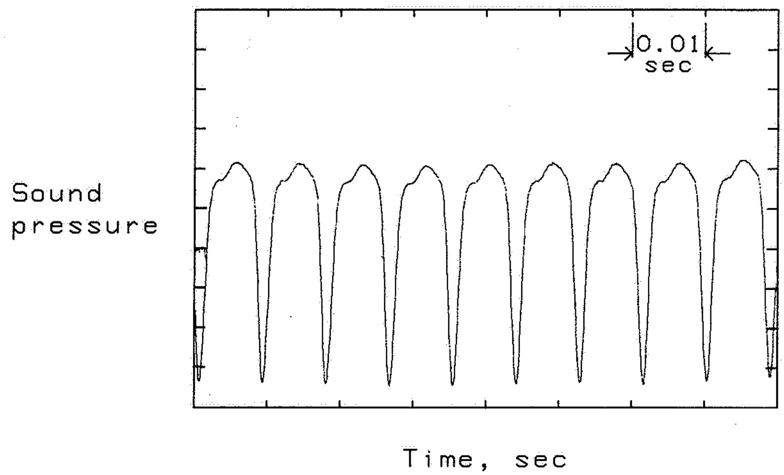


(b) One-third-octave-band spectra.

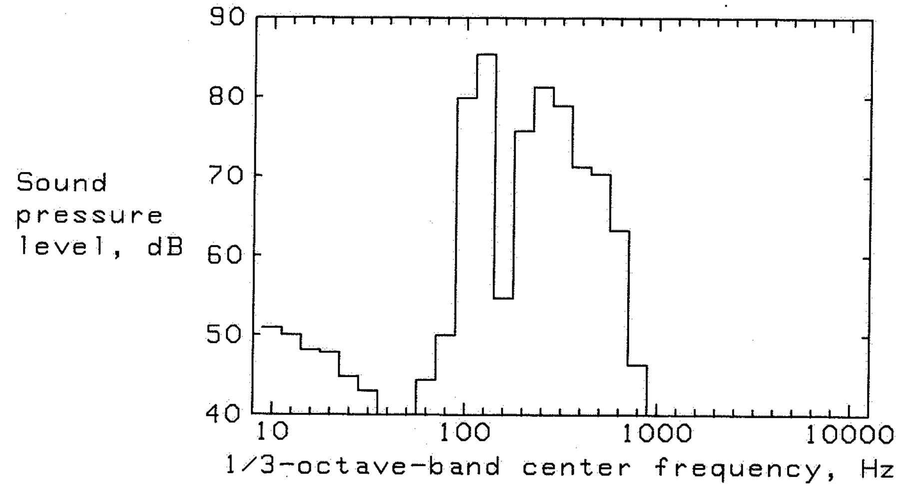


(c) Narrow-band spectra.

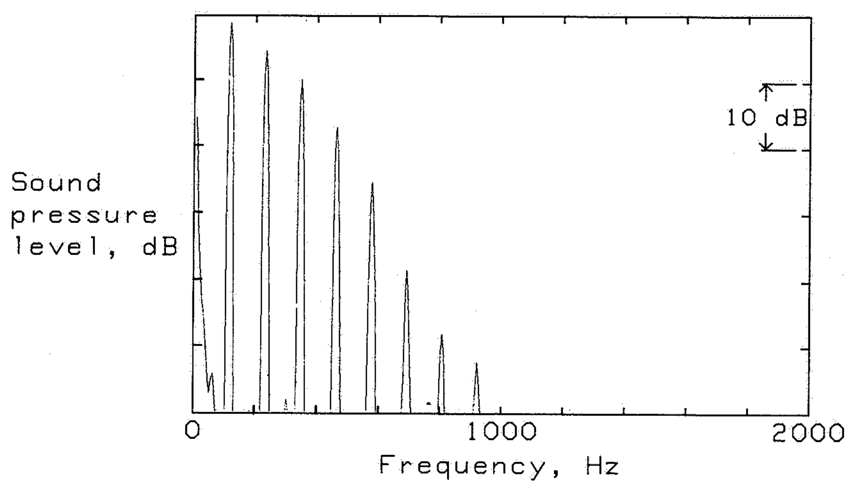
Figure 10.- Characteristics of medium impulsiveness with 115-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

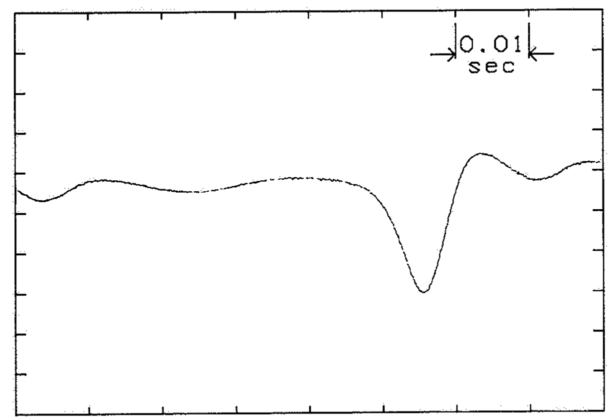


(b) One-third-octave-band spectra.

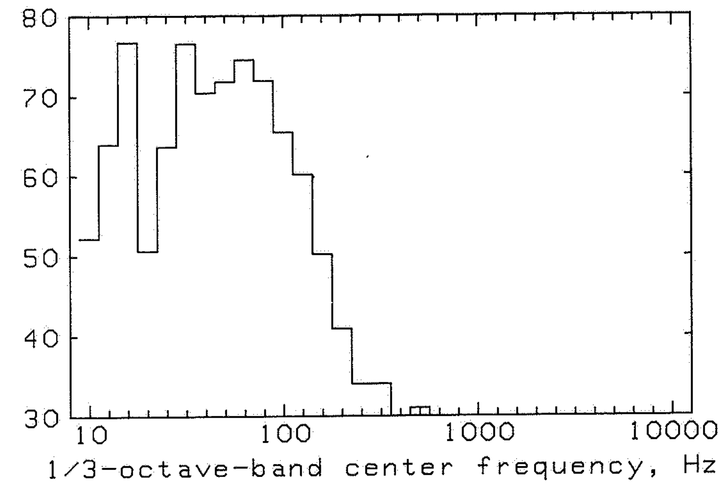


(c) Narrow-band spectra.

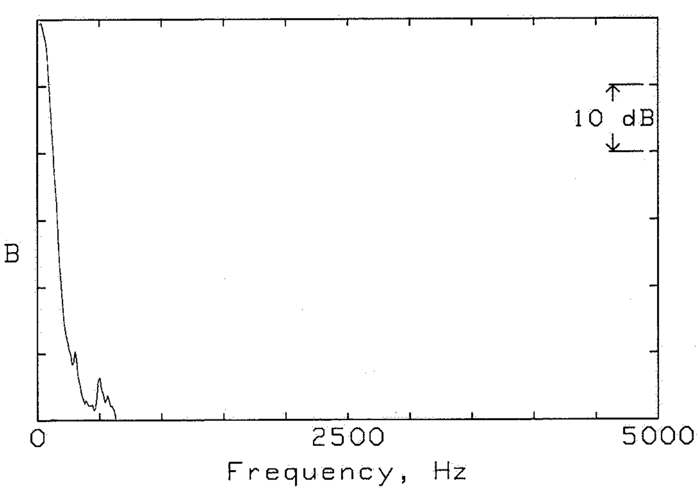
Figure 11.- Characteristics of high impulsiveness with 115-Hz repetition-rate stimulus used in first experiment.



(a) Time history.

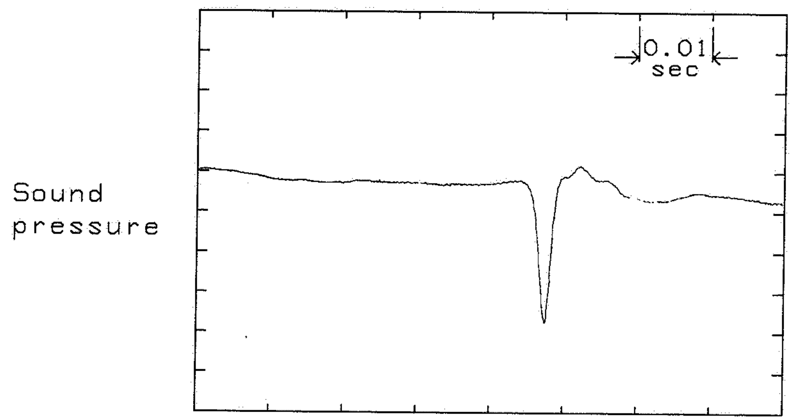


(b) One-third-octave-band spectra.

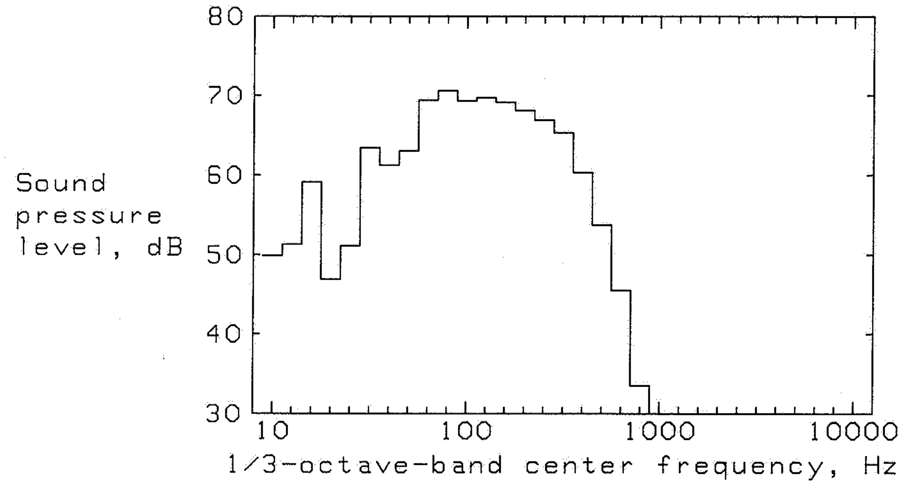


(c) Narrow-band spectra.

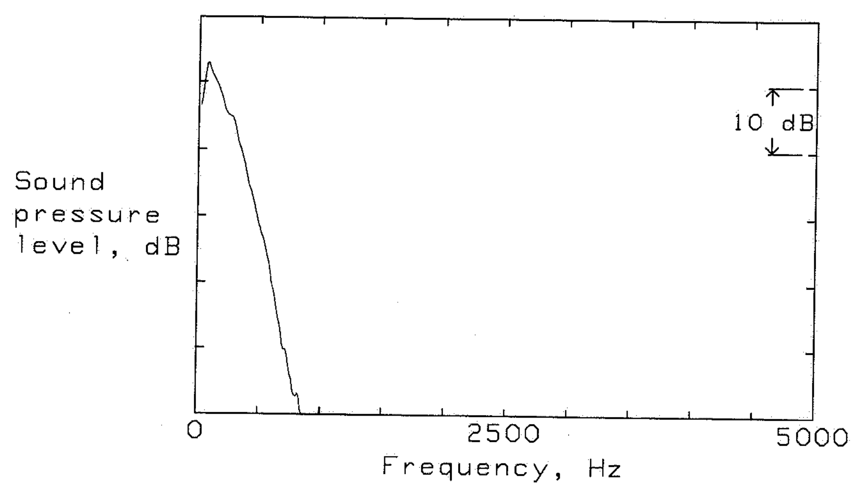
Figure 12.- Characteristics of low impulsiveness with 15-Hz repetition-rate stimulus used in second experiment.



(a) Time history.

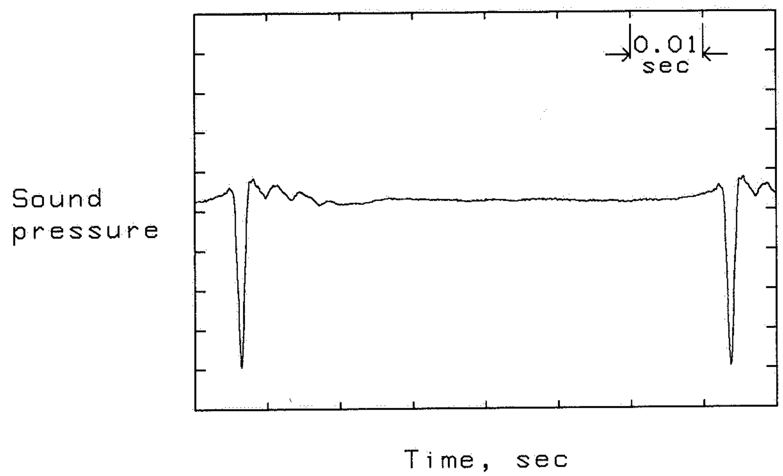


(b) One-third-octave-band spectra.

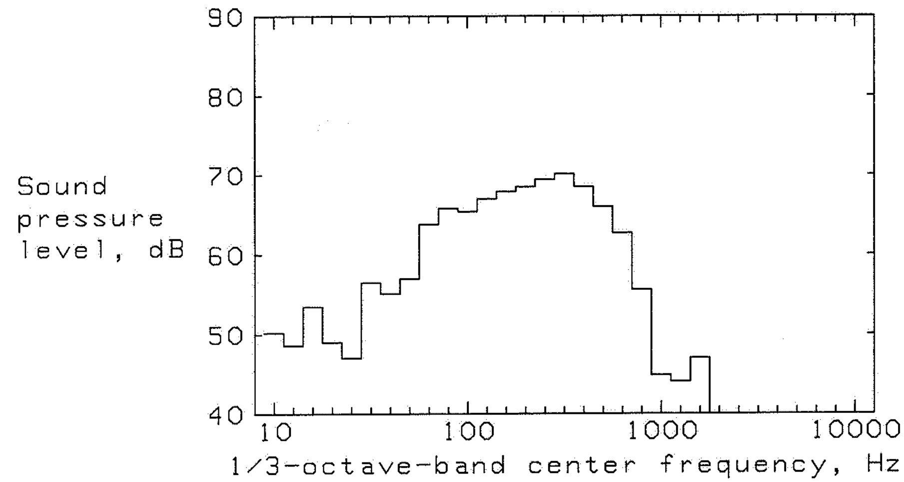


(c) Narrow-band spectra.

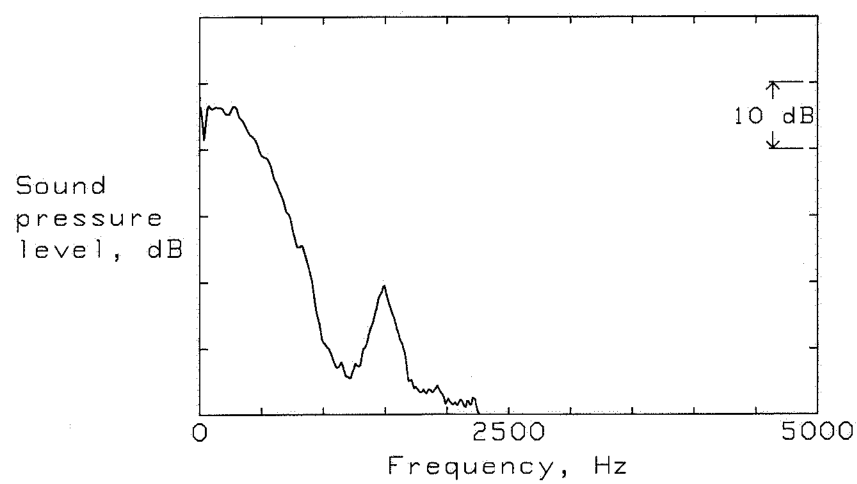
Figure 13.- Characteristics of medium impulsiveness with 15-Hz repetition-rate stimulus used in second experiment.



(a) Time history.

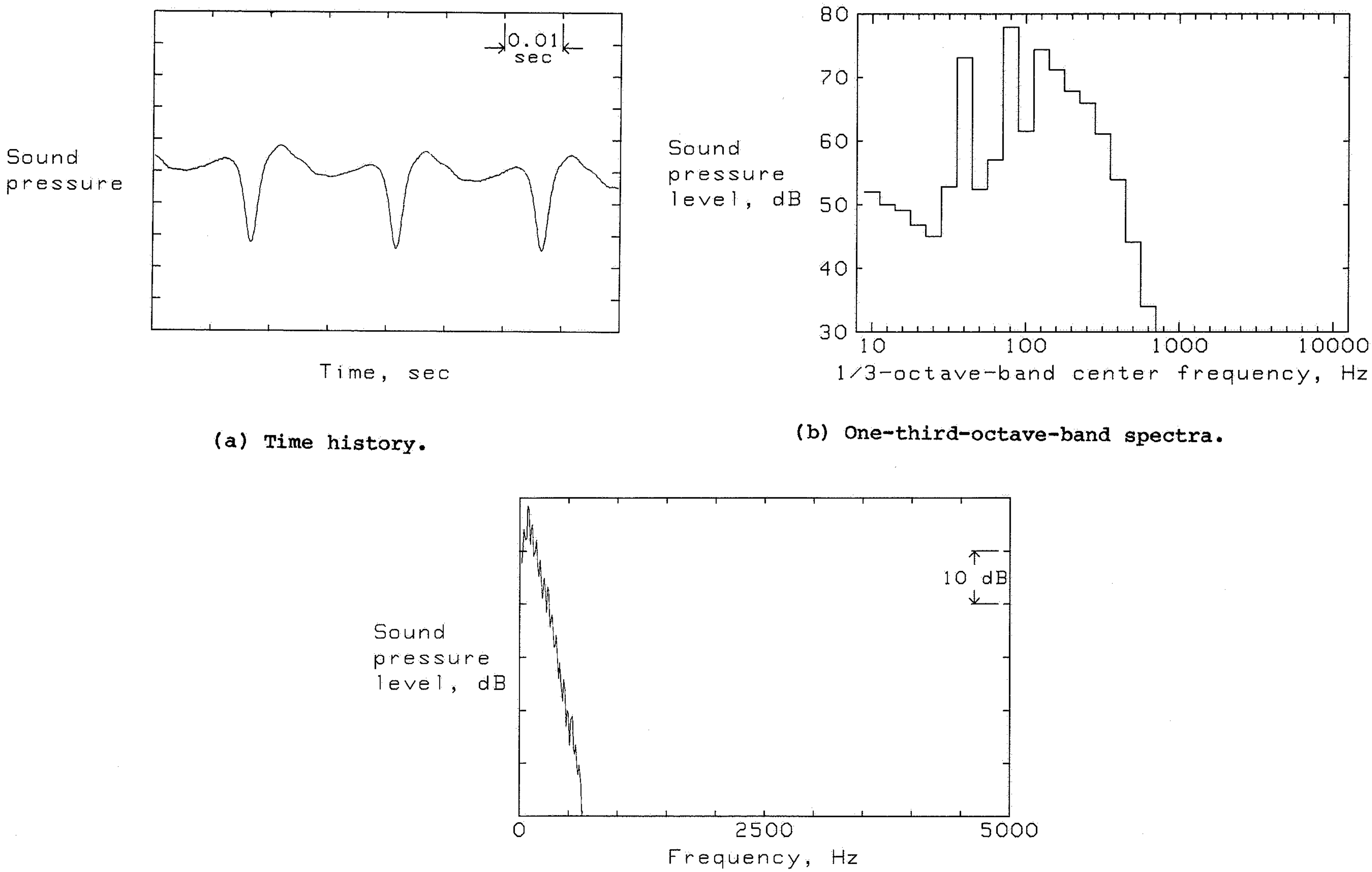


(b) One-third-octave-band spectra.



(c) Narrow-band spectra.

Figure 14.- Characteristics of high impulsiveness with 15-Hz repetition-rate stimulus used in second experiment.

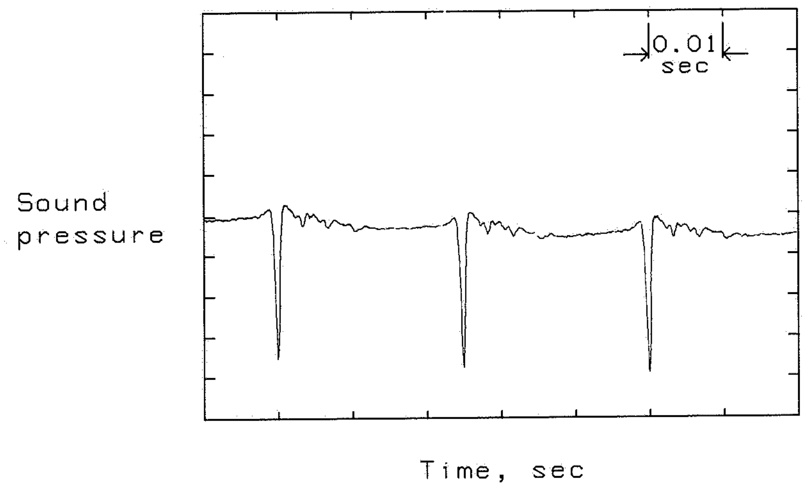


(a) Time history.

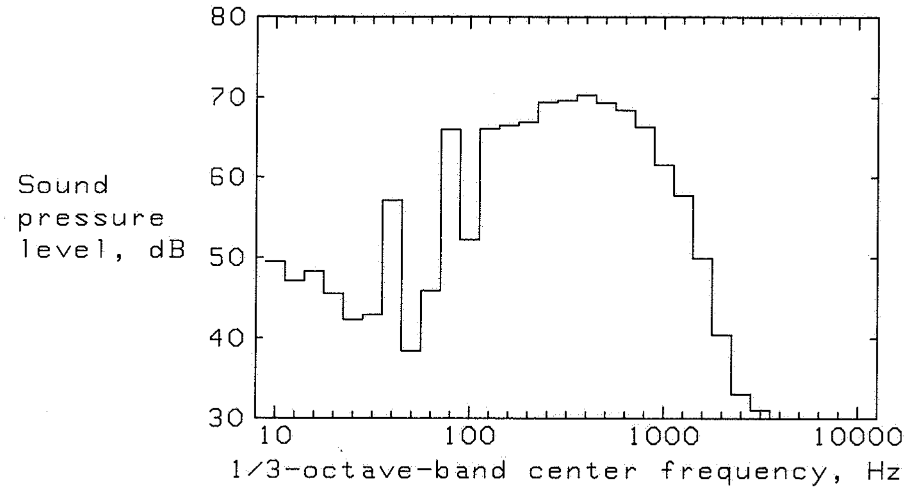
(b) One-third-octave-band spectra.

(c) Narrow-band spectra.

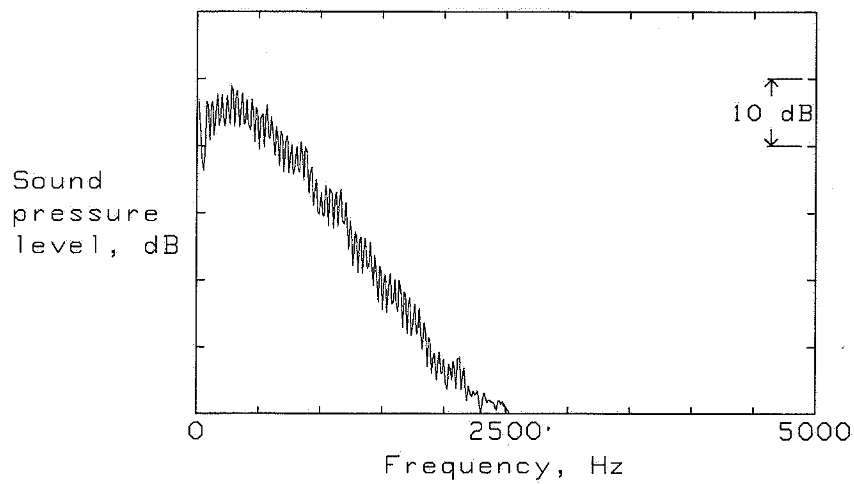
Figure 15.- Characteristics of low impulsiveness with 40-Hz repetition-rate stimulus used in second experiment.



(a) Time history.

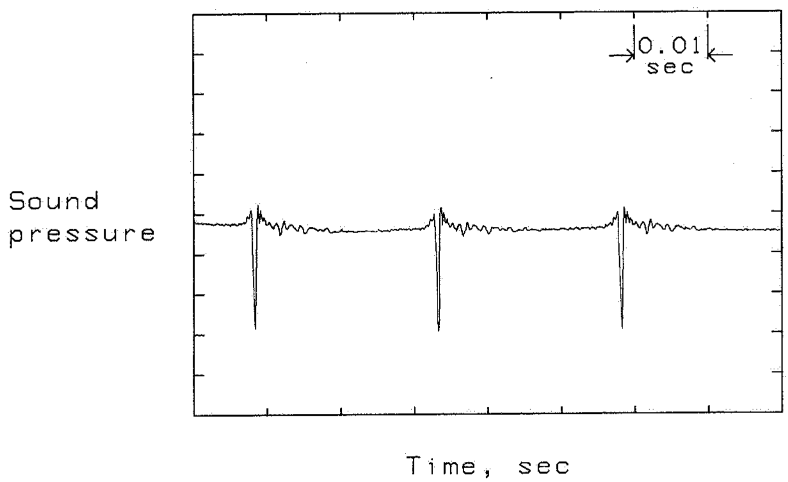


(b) One-third-octave-band spectra.

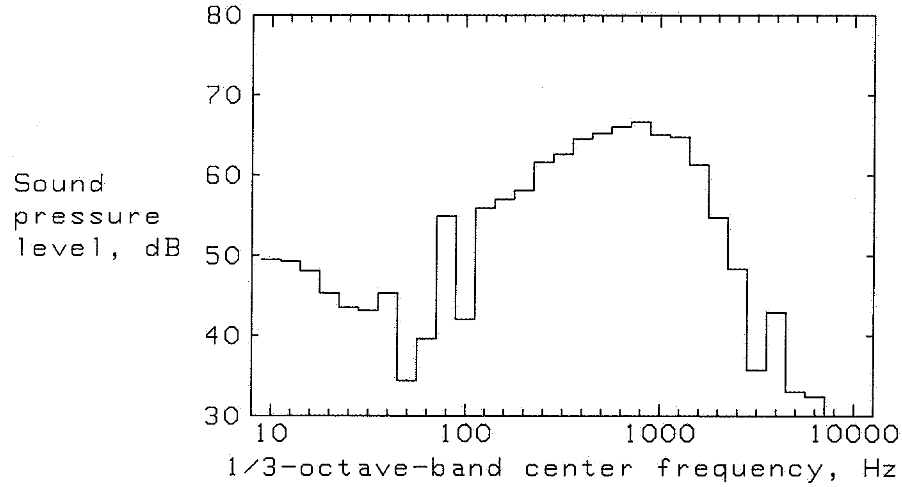


(c) Narrow-band spectra.

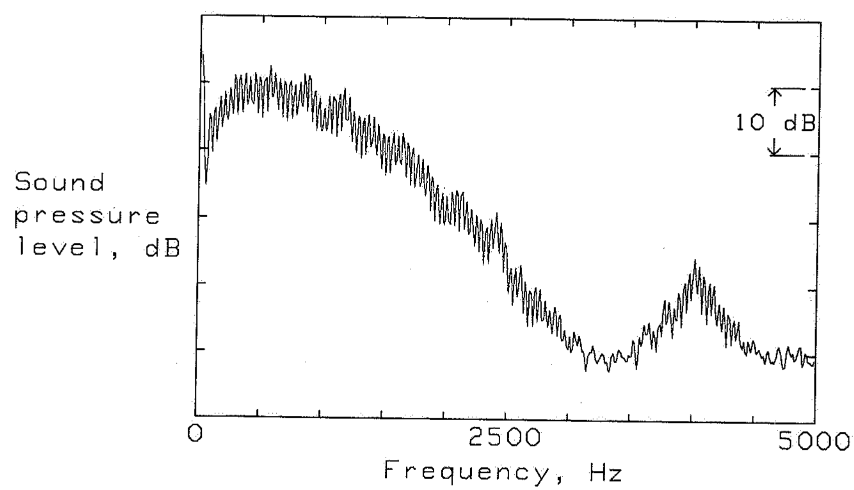
Figure 16 - Characteristics of medium impulsiveness with 40-Hz repetition-rate stimulus used in second experiment.



(a) Time history.



(b) One-third-octave-band spectra.



(c) Narrow-band spectra.

Figure 17.- Characteristics of high impulsiveness with 40-Hz repetition-rate stimulus used in second experiment.

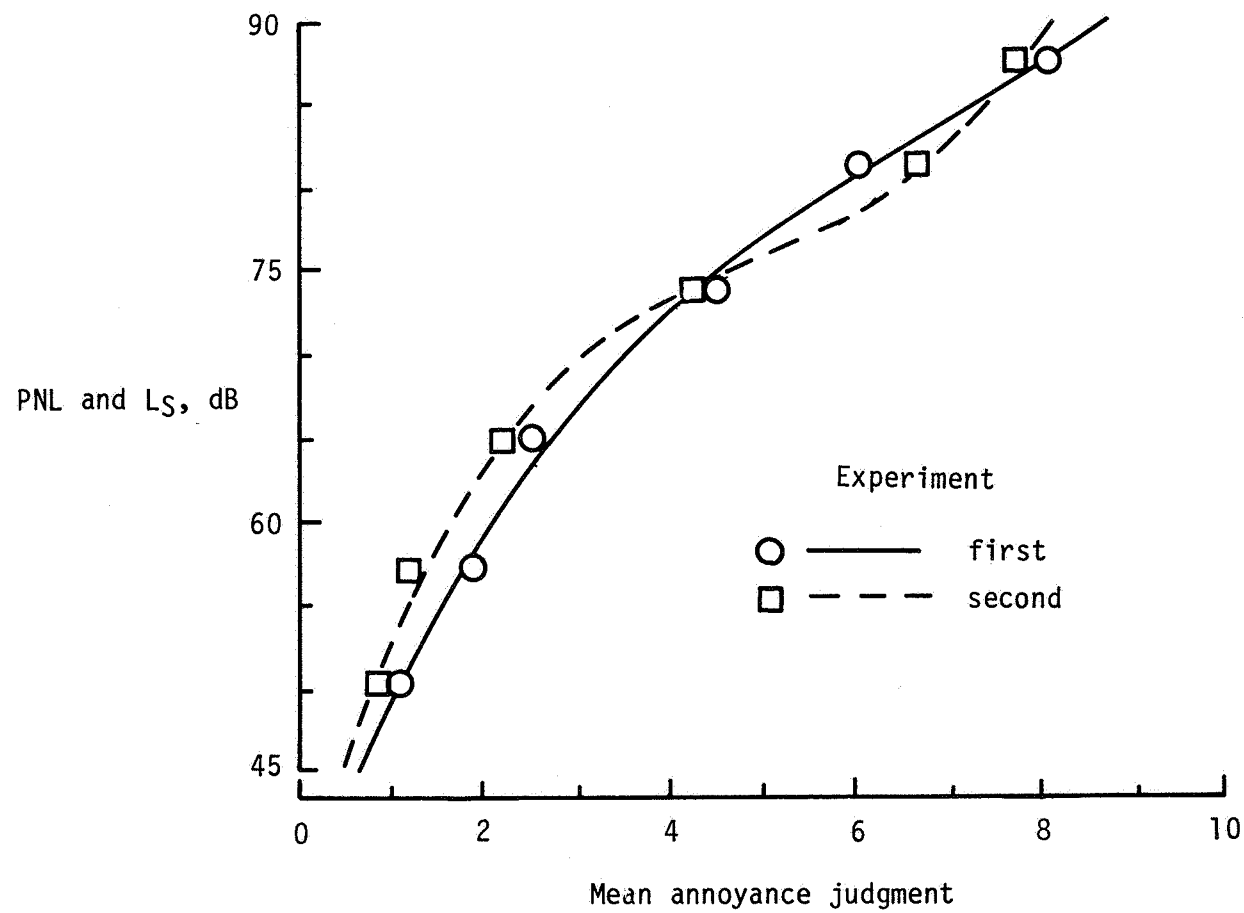
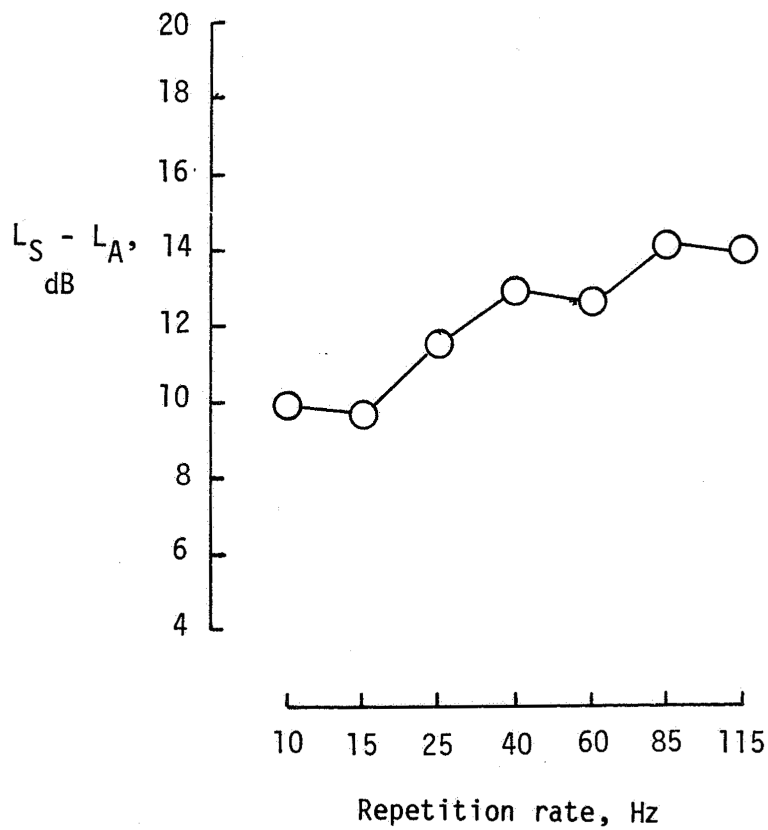
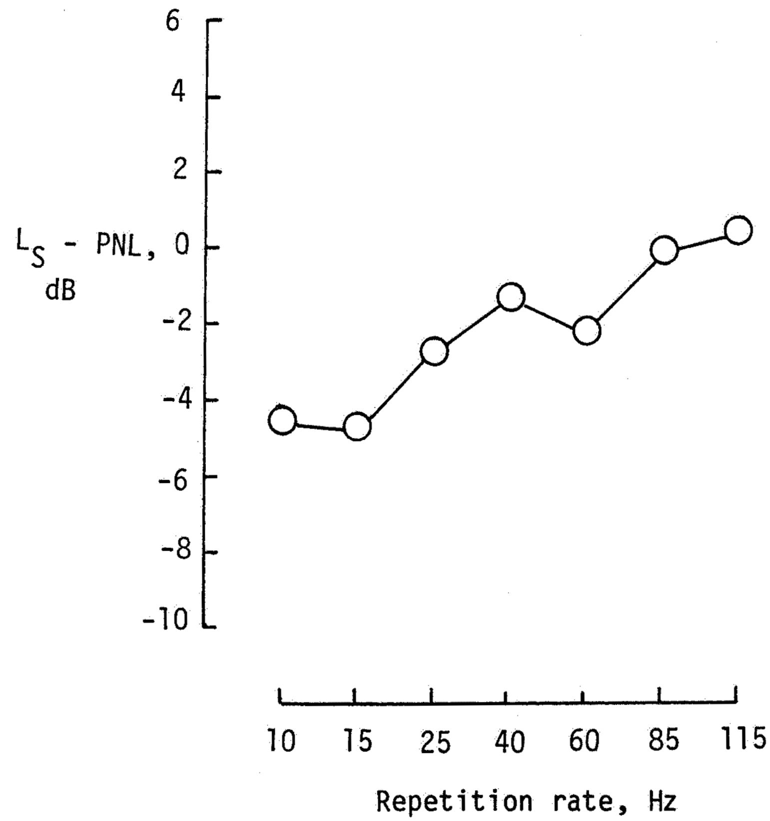


Figure 18.- Regression analysis of PNL on mean annoyance judgments for 115-Hz tone stimuli used to convert annoyance judgments to subjective noise level L_S.

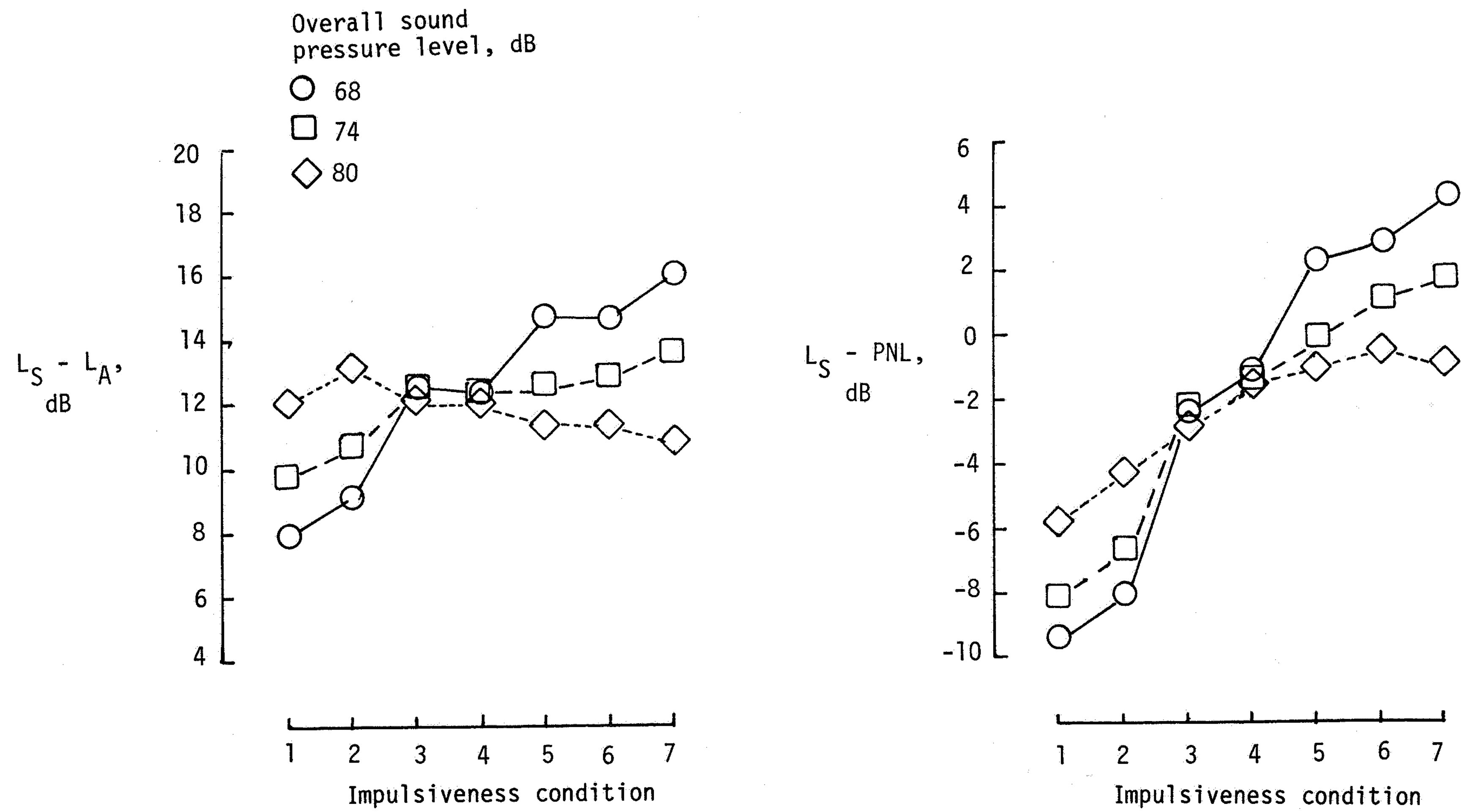


(a) L_A noise metric.



(b) PNL noise metric.

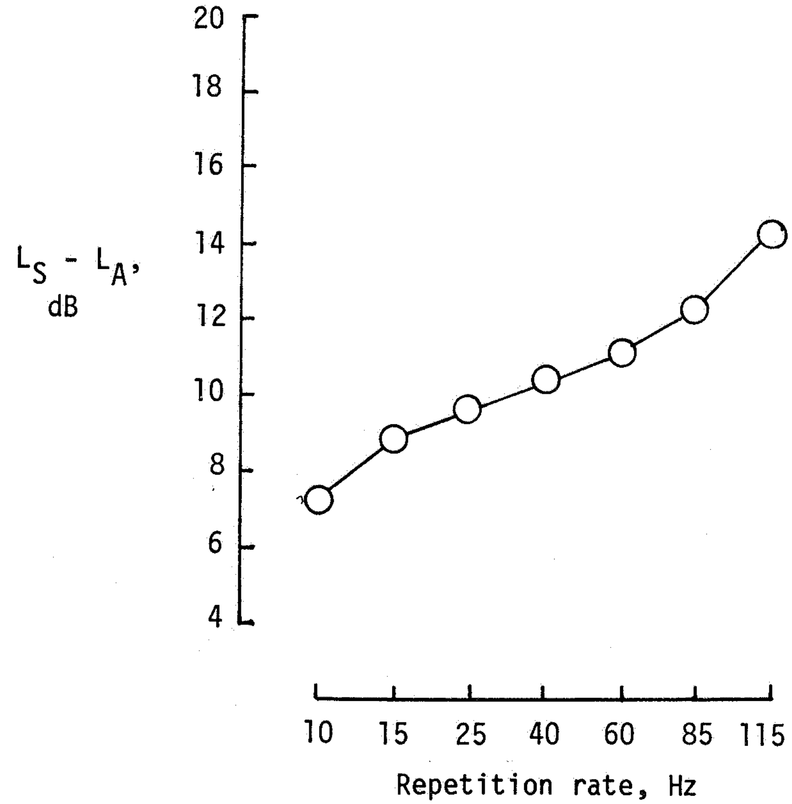
Figure 19.- Effect of repetition rate on annoyance prediction error in first experiment.



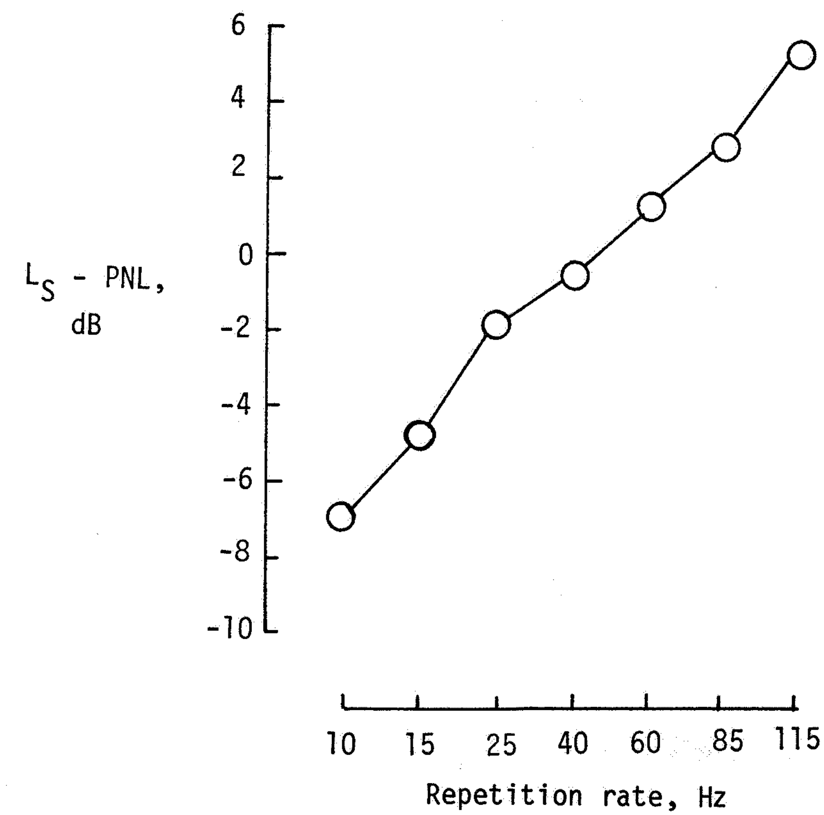
(a) L_A noise metric.

(b) PNL noise metric.

Figure 20.- Effect of impulsiveness condition on annoyance prediction error for different noise levels in first experiment.

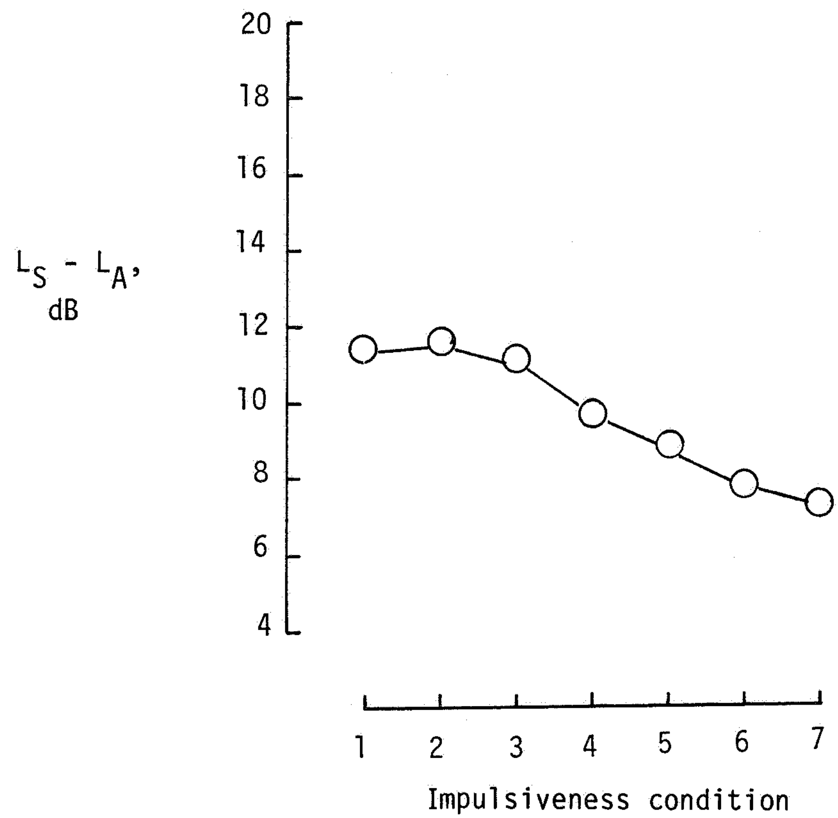


(a) L_A noise metric.

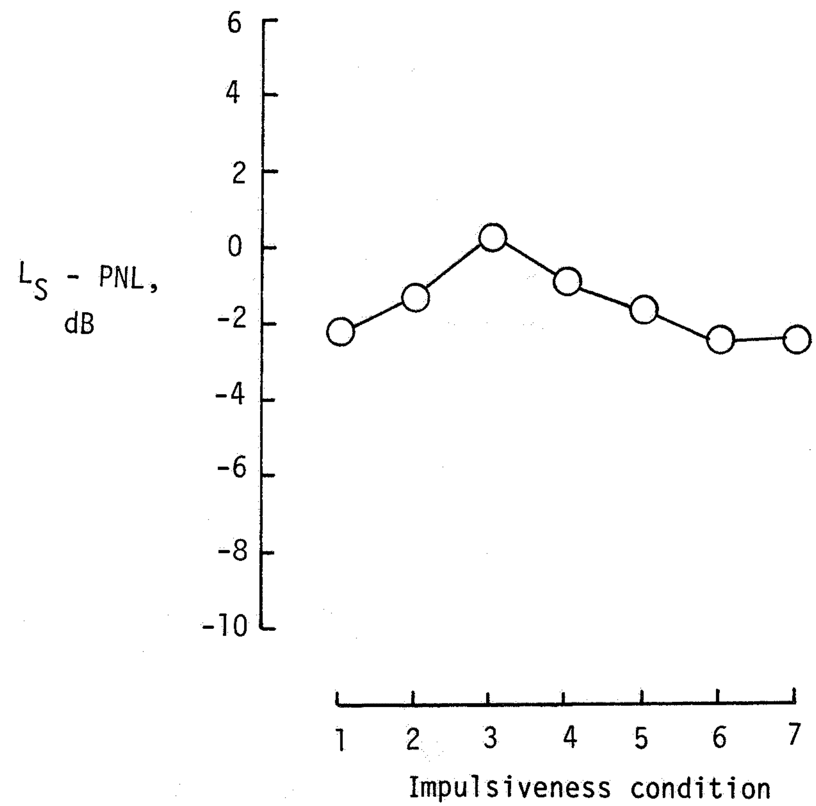


(b) PNL noise metric.

Figure 21.- Effect of repetition rate on annoyance prediction error in second experiment.



(a) L_A noise metric.



(b) PNL noise metric.

Figure 22.- Effect of impulsiveness condition on annoyance prediction error in second experiment.

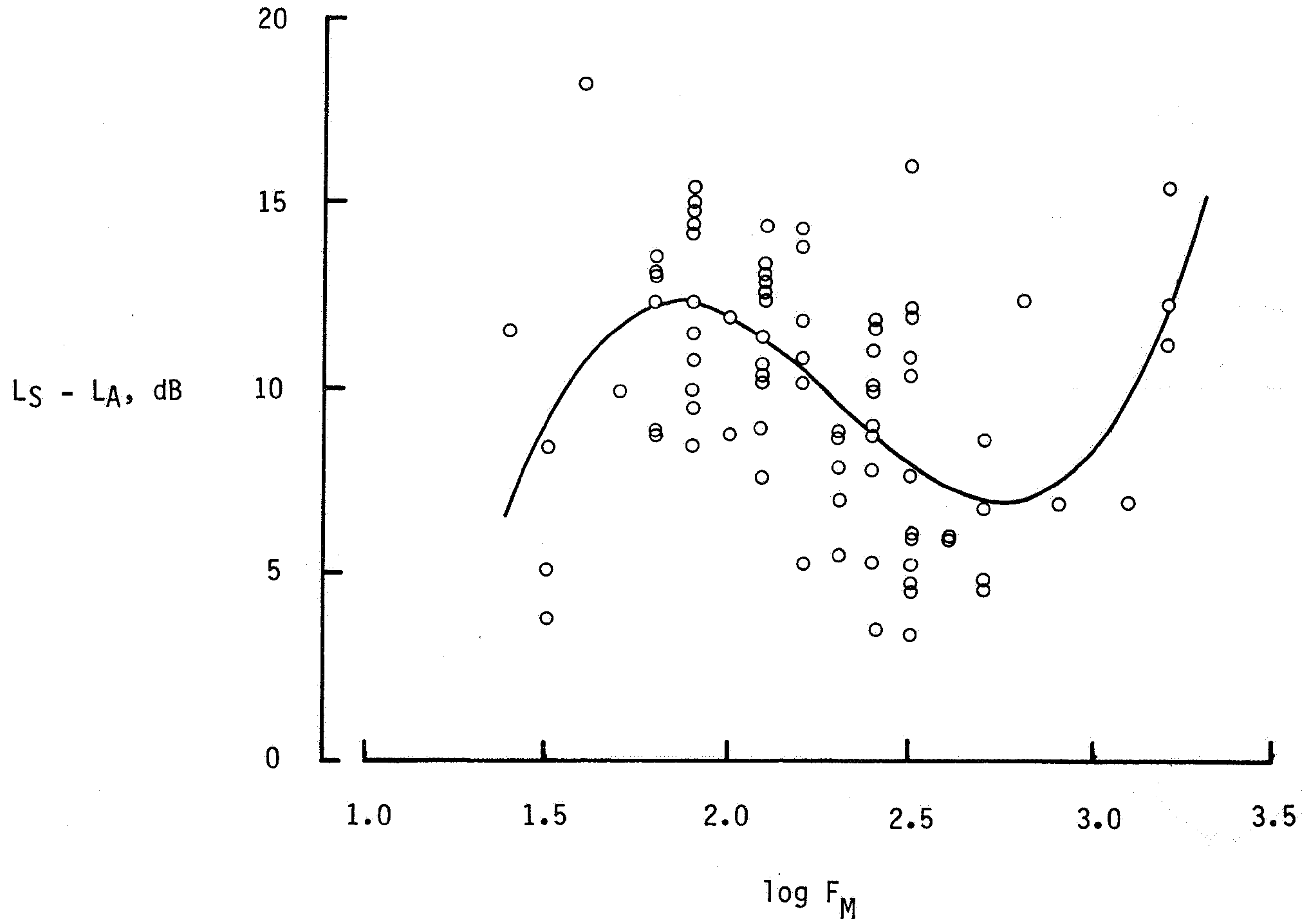


Figure 23.- Effect of subjectively dominant frequency F_M on annoyance prediction error for L_A.

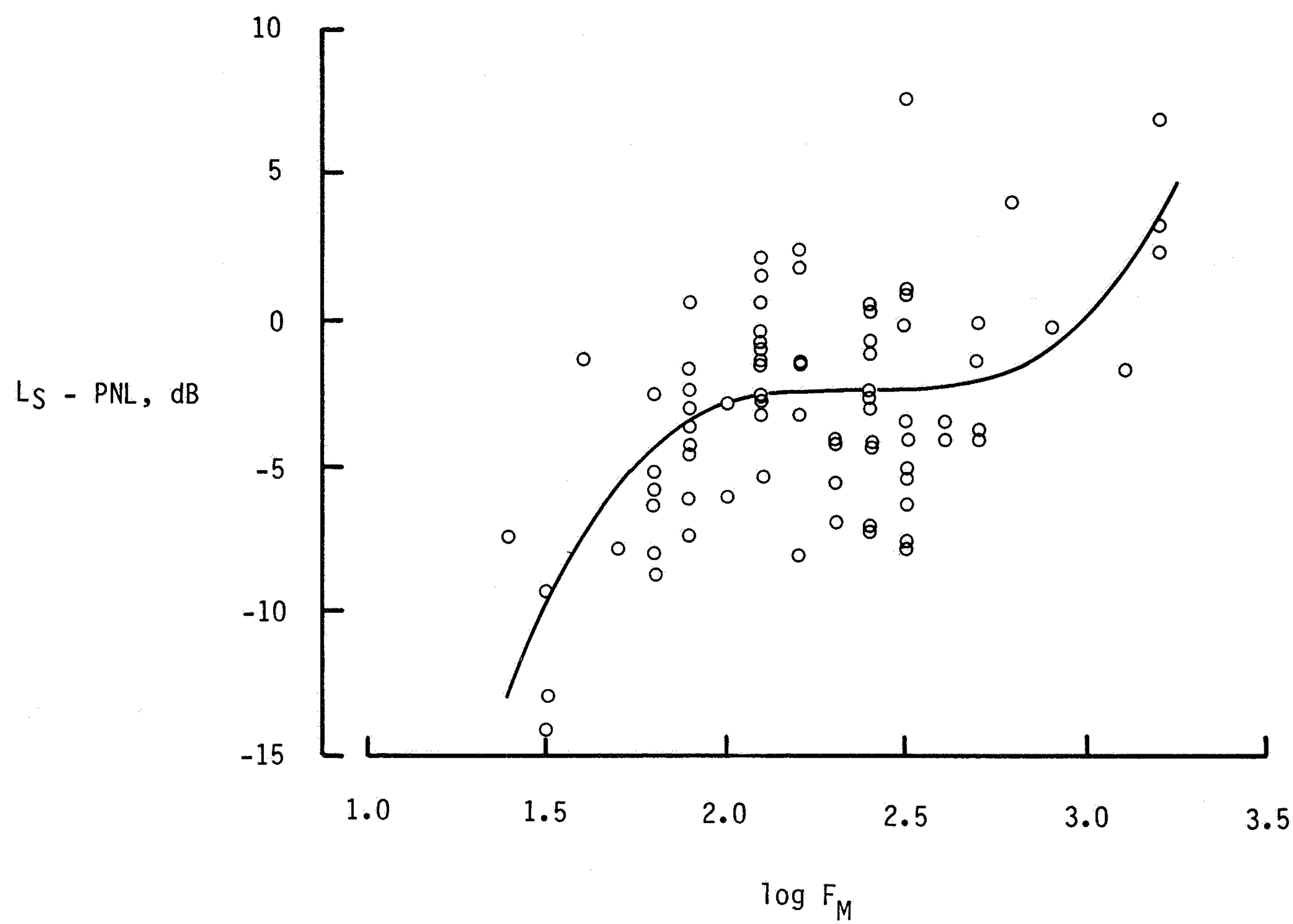


Figure 24.- Effect of subjectively dominant frequency F_M on annoyance prediction error for PNL.

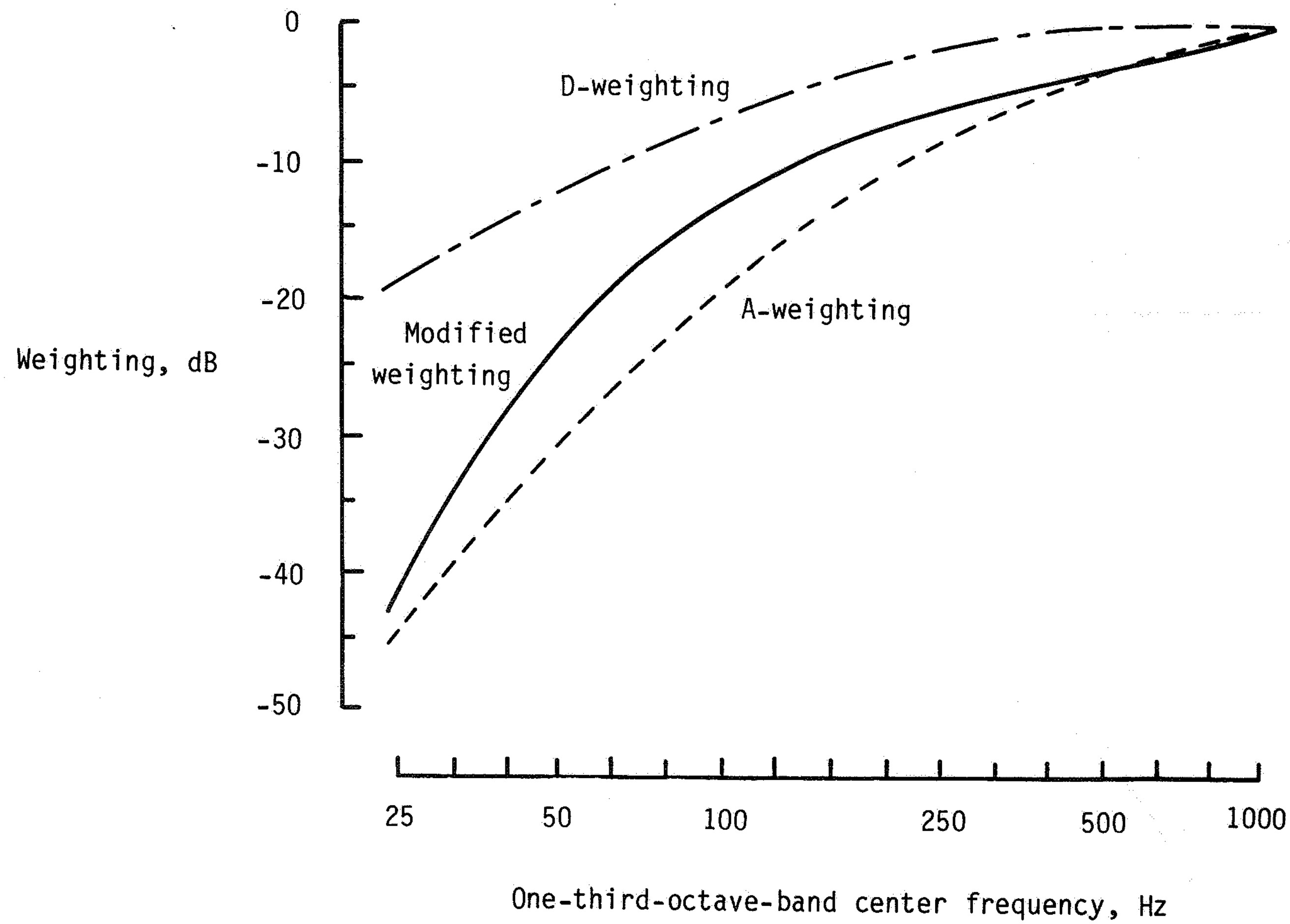


Figure 25.- Modified frequency weighting compared with A- and D-weightings.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-1969		
4. Title and Subtitle EFFECTS OF REPETITION RATE AND IMPULSIVENESS OF SIMULATED HELICOPTER ROTOR NOISE ON ANNOYANCE		5. Report Date February 1982 6. Performing Organization Code 505-35-13-01
7. Author(s) Clemans A. Powell and David A. McCurdy		8. Performing Organization Report No. L-14936
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Paper 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Annoyance judgments were obtained for computer generated stimuli simulative of helicopter impulsive rotor noise to investigate effects of repetition rate and impulsiveness. Each of the 82 different stimuli was judged at 3 sound pressure levels by 48 subjects. Impulse repetition rates covered a range from 10 Hz to 115 Hz; crest factors covered a range from 3.2 dB to 19.3 dB. Increases in annoyance with increases in repetition rate were found which were not predicted by common loudness or annoyance metrics and which were independent of noise level. The ability to predict effects of impulsiveness varied between the noise metrics and was found to be dependent on noise level. The ability to predict the effects of impulsiveness was not generally improved by any of several proposed "impulsiveness corrections." Instead, the effects of impulsiveness were found to be systematically related to the frequency content of the stimuli. A modified frequency weighting was developed which offers improved annoyance prediction.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Psychoacoustic Helicopter noise Rotor noise Annoyance Impulsiveness	Unclassified - Unlimited Subject Category 45

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	57	A04

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1982