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Office of
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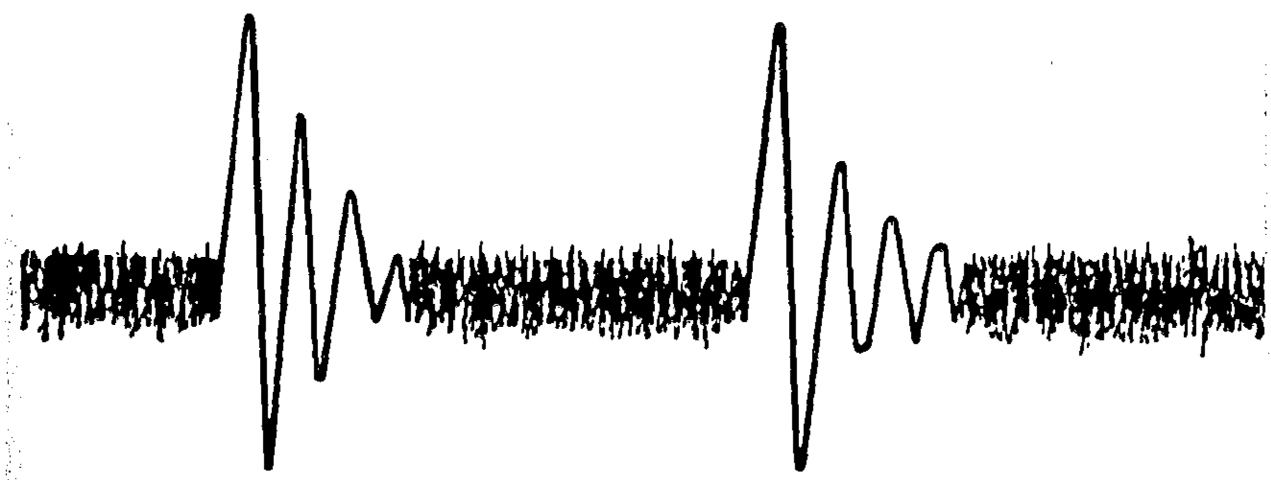
Annoyance, Loudness, and Measurement of Repetitive Type Impulsive Noise Sources



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ANNOYANCE, LOUDNESS, AND MEASUREMENT OF REPETITIVE TYPE IMPULSIVE NOISE SOURCES

NOVEMBER 1979

Prepared by:

L. C. Sutherland

R. E. Burke

WYLE RESEARCH
El Segundo, California 90245

Prepared for:

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Noise Abatement and Control
Washington, D.C. 20460

PREFACE

The United States Environmental Protection Agency (EPA) was charged by Congress in the Noise Control Act of 1972, as amended by the Quiet Communities Act of 1978, to conduct or finance research to investigate "...the psychological and physiological effects of noise on humans and the effects of noise on domestic animals, wildlife, and property, and the determination of dose/response relationships suitable for use in decision making..." (Section 14(b)(1)).

Pursuant to and as part of this mandate, EPA has undertaken investigations to determine and quantify subjective reactions of individuals and communities to different noise environments and sources of noise. A specific series of studies has been initiated to determine the best methods for evaluating subjective magnitude and aversiveness to noise on the basis of spectral and temporal properties, and to ascertain the importance of and means for including nonacoustical factors in the evaluation of general aversion to noise. The overall purpose of this line of research is to derive a more solid basis for assessing the aversiveness of noise and the benefits of noise control.

The aim of the investigation described in this report was to perform a detailed analysis of data pertaining to potential annoyance responses that may be attributed to repetitive type impulsive noise. Specifically, a program was undertaken (1) to review and evaluate the literature on human subjective response to repetitive impulsive noise, and (2) to assess the need for and relative order of magnitude of a subjective impulse adjustment factor that would better define effective level in terms of annoyance reactions.

The report provides much useful information on the annoyance and loudness of repetitive impulsive noise. Moreover, it is expected that the results of the investigation will form the basis of future experimental psychoacoustic work to derive, if appropriate, more precise corrections factors or noise prediction methods to effectively account for the inherent annoyance associated with impulsive noise. EPA believes that further research and evaluation of data on the subjective effects of noise will foster the development of techniques to demonstrate additional benefits of noise control beyond that exhibited by currently used procedures. Fulfillment of this objective awaits further study within this series. The results published in this report, however, do provide an important step toward a more complete understanding of the phenomena of human subjective response to noise.

The conclusions reached in this report regarding moderate level impulsive noise are the authors' and do not necessarily reflect the opinions of the individuals listed above. Moreover, the U. S. Environmental Protection Agency does not endorse the findings of this investigation for use as a "correction factor" applicable to impulsive type noise, nor have similar correction factors been used by the Agency in past or current noise impact analyses.

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U. S. ENVIRONMENTAL PROTECTION AGENCY

ABSTRACT

This study was undertaken to evaluate subjective and objective aspects of moderate levels of noise from impulsive sources. The study excluded evaluation of hearing damage risk or annoyance from building vibration by high level impulsive noise, which were covered by recent recommendations of the National Research Council, Committee on Hearing Bioacoustics and Biomechanics, Working Group 69. While the study included original investigations into some of the objective aspects of impulsive noise, a detailed review of the literature on the subjective aspects was emphasized. Based on this available literature, the annoyance and loudness from a wide variety of repetitive impulse noises were evaluated These results were applied to the evaluation of impulsive noise from a number of specific noise sources. Based on the most pertinent literature, it is tentatively concluded that a subjective impulse correction factor of +7 dB applied to the A-weighted equivalent sound levels of these types of repetitive impulsive noise sources would better define their effective level in terms of annoyance reactions. No additional correction is identified at this time for crest level or repetition rate. Research on subjective correction factors for helicopter blade slap is also reviewed and potential reasons for the smaller subjective correction factors (i.e., 0 to 6 dB) for annoyance response to this type of sound are discussed. It is recommended that refinements to this subjective correction factor be based on the use of standard loudness calculation methods (Stevens Mark VII or Zwicker) modified to include provision for a shorter time constant to reflect subjective response to short duration impulsive sounds.

The study also included a brief experimental evaluation of the measurement of a wide variety of simulated repetitive impulsive-type signals varying in duty cycle, repetition rate, pulse frequency, and ratio of peak impulse signal level to continuous background noise level. When repetitive impulses are measured using maximum values of A-weighted (slow) readings on an Impulse Sound Level Meter, no objective correction is necessary in order to measure, with an accuracy of ±1.5 dB, the equivalent sound level (L_{eq}) of the wide variety of impulsive signals investigated.

ACKNOWLEDGMENTS

A program to develop techniques for evaluating the noise from selected impulsive noise sources was initiated in December 1975 for the Office of Noise Abatement and Control, U.S. Environmental Protection Agency. Mr. Jeff Goldstein served as technical monitor.

The problems addressed in this study encompass areas in psychoacoustics and acoustical measurement technology which have received intensive study by many investigators for many years. The authors wish to thank the following individuals who, during the conduct of this study, provided much helpful information from research which they or their colleagues have conducted.

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The valuable contributions which were made to Appendix A by Dr. Mark Lee, presently of the Jet Propulsion Laboratory, Pasadena, California, and to Appendix B by Mark Montroll, are also appreciatively acknowledged.

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1.0 INTRODUCTION

Under the mandate of the Noise Control Act of 1972, the Environmental Protection Agency is charged with taking steps to abate sources of noise potentially, detrimental to the public health and welfare. Implicit in this is the need to establish the means for evaluating and monitoring the noise from impulsive noise sources.

This report excludes consideration of human response to and measurement of high level impulsive sounds such as sonic booms, weapons fire, or quarry blasts. The latter topic has been the subject of recent recommendations to the Federal Government by Working Group 69 of the National Research Council, Committee on Hearing, Bioacoustics and Biomechanics (CHABA). With this limitation in mind, a research study was carried out to develop an interim method for the evaluation of moderate levels of impulsive noise below hearing damage risk levels. The method was to be compatible with the existing methodology currently in use by the Environmental Protection Agency (EPA) for evaluating community noise impact. The investigation was divided into three basic elements:

1. Selection of a baseline metric for evaluating impulsive noise to which subjective and objective correction factors* could be applied as necessary.
2. Review and evaluation of the literature on subjective effects of impulsive noise with emphasis on data relating to annoyance, noisiness, or loudness of repetitive types of impulsive noise.

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*Throughout this report, the term "subjective correction factor" is used as a convenient label for the difference between the subjectively effective and objectively measured value of loudness, noisiness or annoyance as defined in the text. It is not intended to imply that the values cited for these "correction" factors can be used without careful consideration of their validity and applicability for practical evaluation of real impulsive sounds.

3. Based on this review, the development of a suitable method to account for subjective (annoyance) effects of impulsive noise utilizing suitable measurement methods and currently available instrumentation.

This report presents the results of this investigation in the following sequence:

- Section 2 discusses the selection of the baseline noise metric used throughout the study.
- Section 3, the heart of the report, reviews the literature in detail on loudness, noisiness, and annoyance responses to impulsive sounds. Other subjective effects are also briefly covered.
- Section 4 summarizes the overall findings in terms of the differential subjective response between impulsive and nonimpulsive sounds.

Three appendices are also included, covering:

- Appendix A - Objective factors involved in the measurement of impulsive noise. This includes presentation of results of a laboratory test of various noise metrics obtained from a precision impulsive sound level meter when applied to a wide range of artificially-generated impulsive sounds.
- Appendix B - Summary of the results of an international Round Robin test on response to and measurement of impulsive sounds recently conducted by the International Standards Organization.
- Appendix C - Frequency spectra of repeated time bursts. This appendix briefly illustrates the spectral content of various ideal repetitive tone bursts which roughly approximate some impulsive sounds.

2.0 SELECTION OF A BASELINE METRIC

2.1 Definition of Impulsive Noise

Sounds can be defined as impulsive when they exhibit some form of rapid and substantial variation in the envelope of the time history of the instantaneous peak pressures. This envelope can be visualized as a line connecting the instantaneous peaks of a noise signal as measured on a high-speed oscillograph. Examples of envelopes of impulsive and nonimpulsive sounds, illustrating this qualitative definition, are shown in Figure 1. Figure 1a shows the envelope of peak pressures for fairly steady sounds from a stationary noise source such as an electric motor running at constant speed. Figure 1b shows a noise with a noticeable fluctuation of the envelope. This may simply be called an unsteady or fluctuating noise such as from a stream of highly variable traffic.

The first step in defining a baseline metric for the impulsive sounds considered in this report was to classify all types of impulsive-like sounds into categories. As illustrated in the figure, most types of impulsive sounds fit into two basic categories. Figures 1c and 1d show envelopes of the time history for sounds in these two categories that are clearly impulsive – Figure 1c illustrates a single impulse such as from a quarry blast and Figure 1d shows a repetitive impulsive noise source such as from an unmuffled rock drill or drop hammer.*

There are clearly other examples which fall somewhere in between the time history characteristics shown here. For example, the envelope representing the time history of an aircraft may look quite similar to that of the single impulsive sound except that the time scale is stretched out to many seconds instead of hundredths of a second. However, in order to take advantage of any useful research that could be related to impulsive noise, investigations on subjective reactions to all of the last three examples illustrated in Figure 1 were grouped into three categories according to the type of sound as follows:

*The latter is a wheeled vehicle equipped with a hydraulically operated drop hammer and is used for demolition of road surfaces.

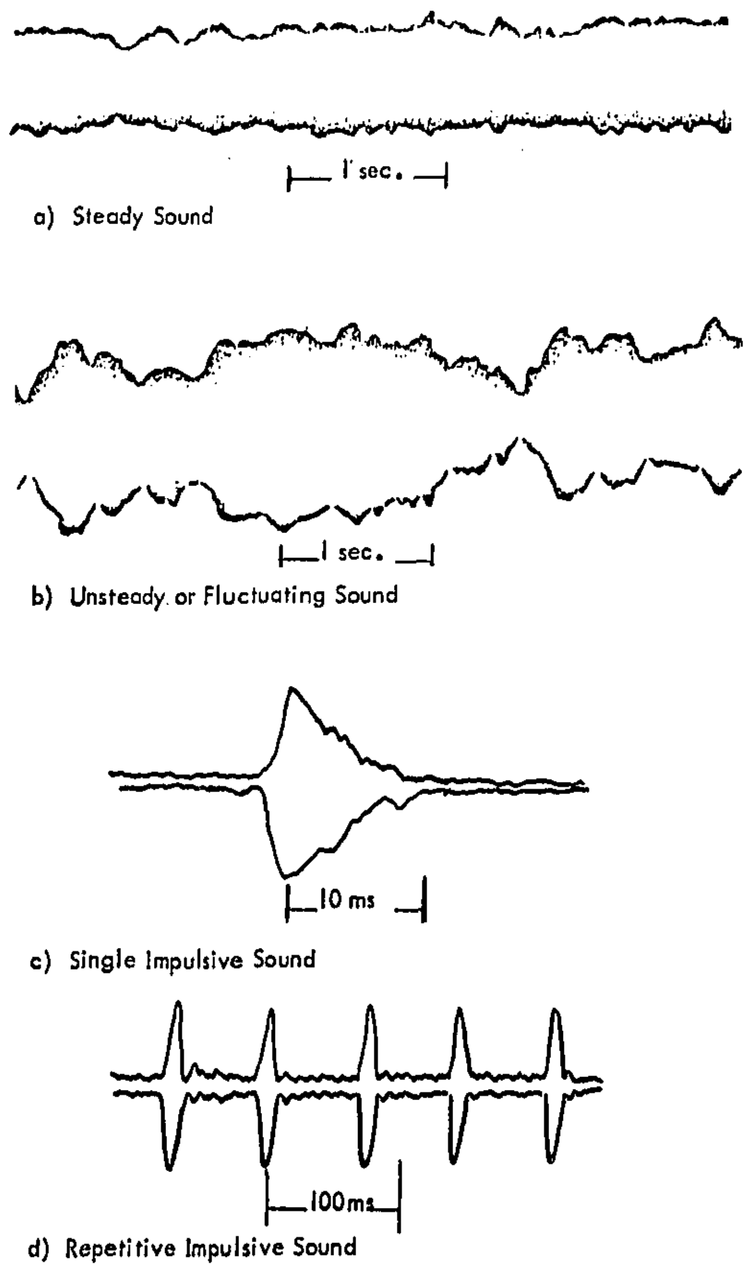


Figure 1. Examples of Time History Envelopes of Nonimpulsive (see a, b) and Impulsive (see c, d) Sounds

I – Repetitive Impulsive Sounds

II – Single Impulsive Sounds

III – Unsteady Sounds

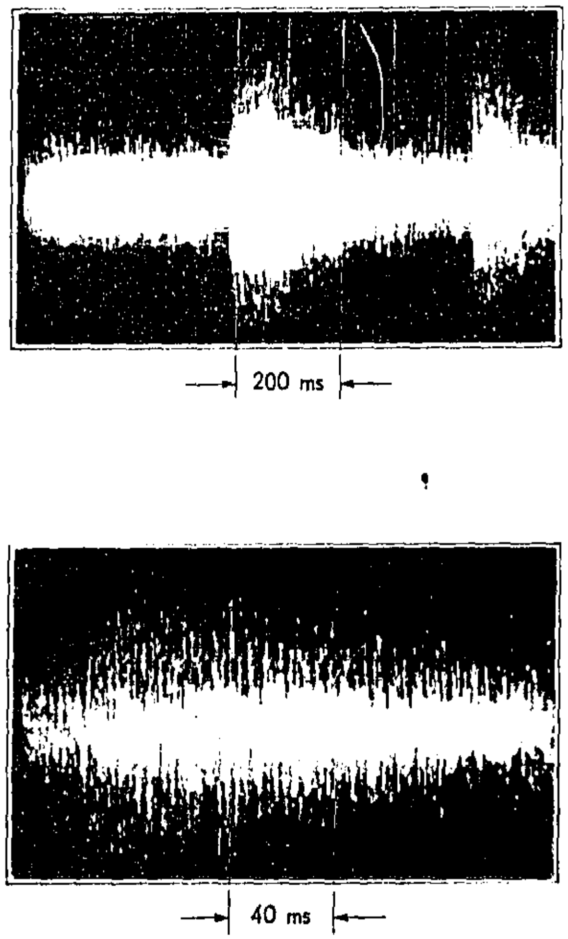
This review of impulsive noises is necessarily broad and potentially applicable to a wide range of moderate to low level impulsive sounds. To illustrate the concepts presented in this report pertaining to loudness and annoyance of repetitive impulsive noises, four particular sources were selected as typical of impulsive community noise. These are:

- Truck-Mounted Garbage Compactors
- Drop Hammers
- Two-Cycle Motorcycles
- Rock Drills

Clearly, some of these sources can generate impulsive noise levels which may represent a hearing damage risk to the equipment operator or an immediately adjacent bystander. However, hearing damage aspects of impulsive noise are not considered in any detail in this review. Under certain operating conditions or with suitable noise control features, these noise sources may not emit what would be called impulsive noise according to our qualitative definition (i.e., rapid and substantial variation in the envelope of the peak pressure time history). However, according to our three categories above, all four of these sources, when generating impulsive sound, will fall into Category I, i.e., sources of repetitive impulsive sounds.

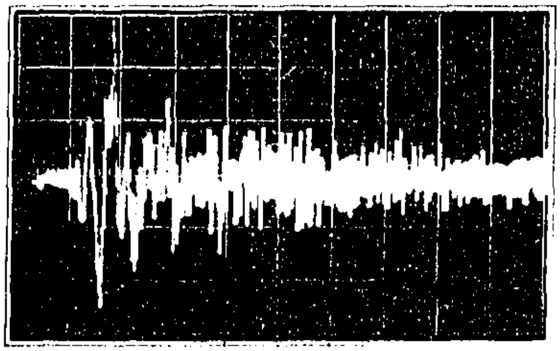
Typical time histories of the instantaneous signals for each of the above sources are illustrated in Figure 2.* For garbage compactors, ignoring the steady noise of the power source used for its operation, the impulsive nature of compactor noise will consist of random or irregular impacts of metal against metal so that the term "repetitive" must, in this case, be interpreted as including such an aperiodic or random repetition. For the other three sources, however, one can expect that under any given operating condition, the repetition rate will be fairly constant so that the envelope will exhibit a definite periodicity. It should be pointed out that repetition rates of concern in this report will fall below the auditory range, that is, below about 20 Hz.

*The time histories shown in Figure 2 were obtained from a small sample within each source category. They are not necessarily representative of all equipment that fall within those categories.

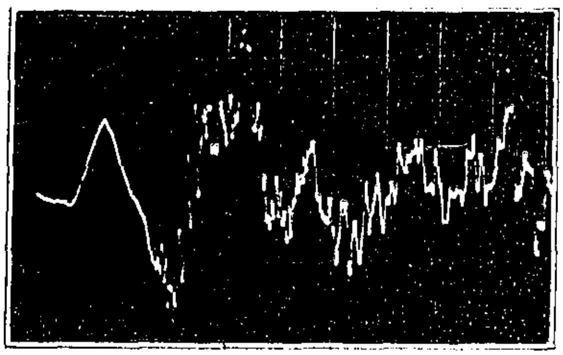


a) Commercial Garbage Truck with Compactor

Figure 2. Examples of Time Histories of the Instantaneous Pressure from Impulsive Sources



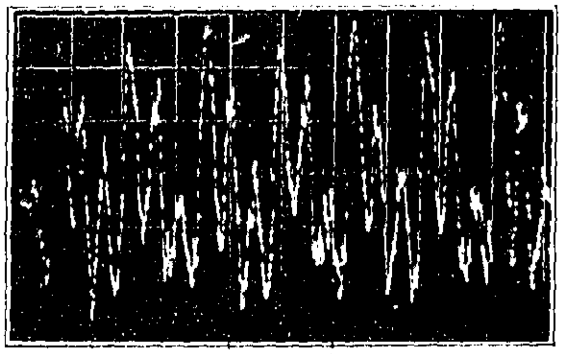
25 ms



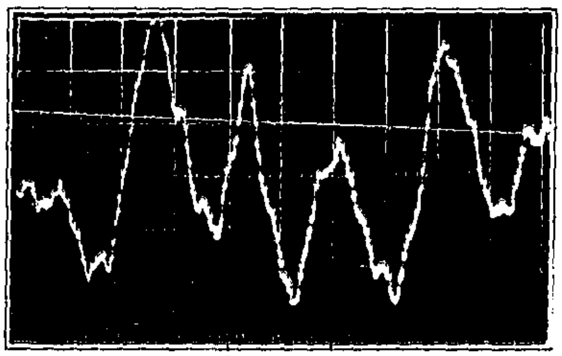
5 ms

b) Drop Hammer

Figure 2 (Continued)



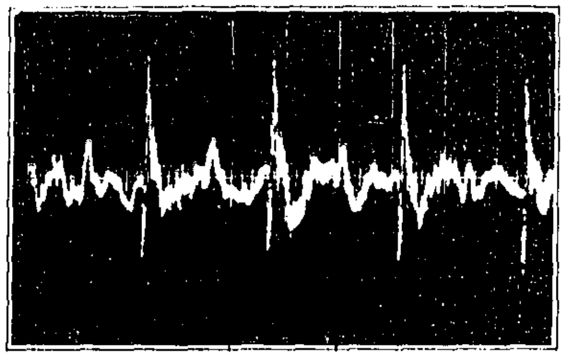
10 ms



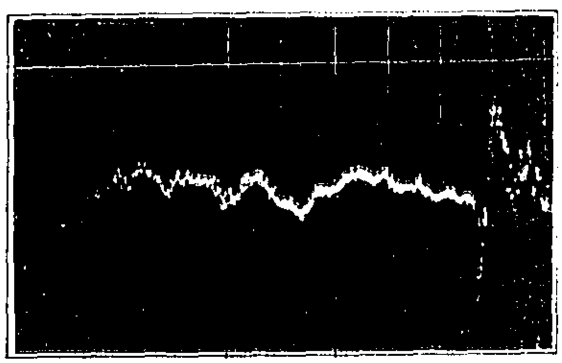
2.5 ms

c) Two-Stroke Motorcycle

Figure 2 (Continued)



—→| 40 ms |←—



—→| 10 ms |←—

d) Rock Drill

Figure 2 (Concluded)

A typical train of impulsive sounds is illustrated in Figure 3. The five physical parameters important for describing impulsive sound are defined for purposes of this report as follows:

- Crest Level - The difference in sound pressure level between the peak and rms level of the noise. For a background noise with a normal (Gaussian) distribution of instantaneous pressure, the peak pressure may be considered as the value at about three standard deviations above the rms value. This peak, which ideally is exceeded only 1 percent of the time for Gaussian noise, will be about 10 dB higher than the rms value. Thus, the crest level should normally exceed about 10 dB before a noise is considered impulsive.
- Duration - The amount of time that the envelope of the instantaneous pressure exceeds the rms value.
- Period (if repetitive) - The time duration between two successive impulses in a train of impulses.
- Spectrum - The frequency distribution of acoustic energy in the impulse.
- Rise Time - The time required for the impulse to rise from the background noise to the peak.

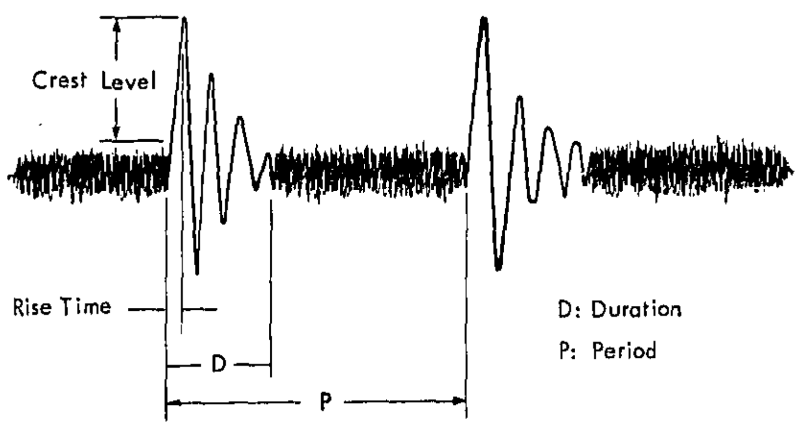


Figure 3. Physical Parameters of a Typical Impulsive Sound

Representative values for these impulsive noise parameters for the two-stroke motorcycle, the drop hammer, rock drill, and truck-mounted garbage compactor are listed in Table 1.* For these sources of impulsive noise, the crest level lies between 13 and 30 dB, the duration varies from several milliseconds to half a second, and the period varies from 10 milliseconds to 1-1/2 seconds. A frequency range of 200 Hz to 2 kHz covers most of the acoustic energy of the impulsive noise. This table provides a general indication of the magnitude of the parameters which define the general physical characteristics of the impulsive noise sources considered in this report. However, this range of parameters, in fact, includes many other impulsive noises so that research into subjective response to all of these can be applied, in part, to the evaluation of subjective response to the four particular sources identified in Table 1.

Table 1

Typical Physical Parameters of Four Real Sources of Impulsive Noise

Impulsive Noise Source	Crest Level dB	Pulse Duration ms	Repetition Period ms	Peaks in Frequency Spectrum kHz	Typical Rise Times ms
Two-Stroke Motorcycle	13	2 - 20	30 - 100	0.30 - 2	2
Drop Hammer	30	300	1500	0.25 - 1	10
Rock Drill	19	10	50	0.040 - 0.400	2
Truck-Mounted Garbage Compactor	19	500	5000	0.200 - 1	50

*The values listed in Table 1 were measured from a small sample within each source category. Although there is no reason to suspect that the values listed are atypical, the reader should apply caution in generalizing the conclusions of this study as necessarily representative of all equipment that fall within each source category.

**Although selected as a repetitive impulsive noise source for purposes of this analysis, recent information as presented in EPA Report No. 550/9-79-257, Regulatory Analysis of the Noise Emission Regulation for Truck-Mounted Solid Waste Compactors, indicates that this feature may not be necessarily characteristic of the majority of truck-mounted solid waste compaction units.

2.2 Baseline Noise Metric

Some sort of baseline noise metric is necessary for evaluating these various impulsive sounds. This baseline metric should be: (1) reasonably unambiguous, (2) measurable with precision laboratory equipment, (3) measurable with standard sound level meters in the field with suitable correction factors, (4) compatible with the day-night sound level (L_{dn}) or the equivalent (energy average) sound level (L_{eq}) metric, and (5) able to provide a foundation for application of subjective impulsive noise corrections to allow comparison of the subjective response to impulsive and nonimpulsive sounds. The baseline metrics applicable to the Category I impulsive sounds could take one of the following alternate forms.

- Sound Exposure Level - The time-integrated measure of the A-weighted sound level is identified by the symbol L_S.
- Equivalent Sound Level - The equivalent sound level is the energy-average of the integrated A-weighted sound level over a specified observation time T and is identified by the symbol L_{eq}.
- Peak Sound Level - The maximum instantaneous A-weighted sound pressure level during a given observation time is identified by the symbol L_{Apk}.
- Peak Sound Pressure Level - The maximum instantaneous unweighted (linear) sound pressure level during a given observation time is identified by the symbol L_{pk}.

All of these metrics are essentially unambiguous quantities measurable in the laboratory and potentially measurable by some of the advanced integrating sound level meters. Measurement of the peak levels (L_{Apk} or L_{pk}) with sound level meters equipped with a peak-hold position is straightforward, providing the rise-time of the signal is greater than 50 μsecs. This corresponds to an upper frequency limit of 20,000 Hz for significant energy in the spectrum of the impulsive sound.

Intentionally excluded from the candidate baseline metrics are the other quantities measurable on a sound level meter. Those which will be considered later for application to measurement of impulsive sounds include:

- Slow Sound Level - The exponential-averaged A-weighted sound level measured with a nominal effective (squared pressure) time constant of 1 second, identified, for this report, by the symbol L_{AS}.
- Sound Level or Fast Sound Level - The exponential-averaged A-weighted sound level measured with a nominal effective time constant of 125 ms, identified, for this report, by the symbol L_{AF}.
- Impulse Sound Level - The exponential-averaged sound level measured with a nominal effective time constant of 35 ms, identified by the symbol L_{AI}.

Other noise metrics could have been considered, such as measures of statistical distribution, L_x, where x is the percent exceedence level, or noise pollution level (L_{NP}) which attempts to account for subjective reaction to fluctuation of a noise. These were rejected as not being directly compatible with current EPA noise metrics and are not readily measurable on standard sound level meters.

Returning to the four candidate baseline metrics, the last two measures of peak level may be rejected at the outset as unsuitable because they fail to fit directly into EPA's time integrated measures of noise, namely, day-night sound level L_{dn} and equivalent level (L_{eq}). In order to make a final choice, it is necessary to consider the general nature of the noise signatures that may be involved. For example, the typical noise exposure of an individual at any one place to garbage compactor noise might consist of several minutes of exposure to a relatively random series of impulses generated by the clanking together of garbage materials as they are compacted, superimposed over the rising and falling hum of noise from the engine which drives the compactor.

The duration of the exposure can only be roughly estimated and will vary widely from one site to another and from one day to the next. The sound exposure level of such a varying noise exposure would also vary accordingly, making it difficult to utilize for realistic noise evaluation or certification unless one observation time were arbitrarily fixed. In this case, however, an equally useful measure would simply be the equivalent (or energy average) sound level (L_{eq}) during the measurement period.

In contrast, during a passby of a motorcycle, the only unambiguous energy-related measure of the noise signature received by a nearby observer would be the sound exposure level (L_S). It would be possible to normalize the sound exposure level by a standard duration of, say 10 seconds to provide what would amount to the equivalent sound level over 10 seconds (i.e., L_{eq} (10 sec)) with the same energy as the actual event. On the other hand, if noise certification tests of motorcycles were to be applied to stationary vehicles, the equivalent sound level (L_{eq}) during the observation period would be a logical baseline metric.

For the drop hammer or rock drill, a typical noise signature could consist of a relatively long period of exposure, on the order of an hour or more with many periods of more or less continuous exposure to the repetitive impulsive sound. In this case, again, the equivalent sound level (L_{eq}) during the observation period appears suitable as the baseline metric.

Thus, with the one exception of noise exposure to single events, which are conveniently defined by the sound exposure level, it appears that the equivalent sound level (L_{eq}) is the logical choice for a baseline metric for the impulsive sources considered in this study.

The A-weighting inherently incorporated in this metric is expected to provide a more accurate or a more consistent correlation with human response to <u>low level</u> impulsive sounds than would be provided by a nonweighted (linear) sound pressure level. As will be discussed later, this observation is also consistent with the observed loudness or noisiness of <u>low level</u> sonic boom sounds. These have been shown to correlate best with frequency-weighted measures (i.e., loudness in phons) of the sonic boom energy spectrum which deemphasizes the low frequencies as does A-weighting.*[46, 55, 60]

It remained only to define the observation time upon which the average sound level will be based. For the general case, the equivalent sound level (L_{eq}) over an observation time T will be defined as

$$L_{eq} = 10 \log_{10} \left[\frac{1}{T} \int_0^T \left(P_A^2 (t) / P_o^2 \right) dt \right] \quad , \text{dB} \tag{1}$$

where

$P_A(t)$ = instantaneous A-weighted sound pressure at time t, Pa

P_o = reference pressure (20 μPa), and

T = observation period, sec

For prediction of the day-night sound level (L_{dn}), the L_{eq} for the impulsive sound is evaluated for the daytime (L_d) - 0700-2200, and for nighttime (L_{dn}) - 2200 to 0700 hours. The normal 10 dB penalty factor would be imposed on L_{dn} for the baseline metric, but the possibility of increasing this for the potentially even greater annoyance at night of impulsive sounds can be left as an option to be defined upon the basis of examining the available information on sleep interference from impulsive sounds.

For application to defining the L_{eq} of repeated single events, the same technique employed for specifying aircraft sound exposure will be used in the form

$$L_{eq} = L_S + 10 \log N - 10 \log [T/t] \quad , \text{dB} \tag{2}$$

*Note that for high level impulsive sounds, such as from quarry blasts or artillery, C-weighted levels appear to predict community response quite well.[21, 147]

where

L_S = sound exposure level of one event, dB re 20μPa · sec

N = number of events during the time T

T = observation period in seconds

t = reference time of 1 second

The observation time T to apply in the measurement of the equivalent sound level will depend on the application, ranging from a minimum of 1 second (corresponding to the duration of reference sounds often used in laboratory evaluation of impulsive sounds), to 1 hour for an hourly equivalent sound level (L_{eq}(h)), to 15 hours for the day sound level (L_d) - the energy average during the hours 0700 to 2200.

In summary, then, the baseline metric used in this study for evaluation of impulsive noise will be the A-weighted equivalent sound level (L_{eq}) measured over a time to be specified as appropriate for each source. This provides a baseline noise metric that is compatible with the existing methods developed by EPA for evaluation of noise impact.* By providing adjustment factors (nominally identified herein as correction factors) to the L_{eq} to account for any subjective effects and measurement errors for impulsive noise, it will be possible to properly include impulsive noises in EPA's evaluation of environmental impact of impulsive noise sources. This metric is also considered appropriate for application to each of the three categories of sounds defined earlier: (a) Category I - Repetitive Impulsive Sounds, (b) Category II - Single Impulsive Sounds, and (c) Category III - Unsteady or Fluctuating Nonimpulsive Sounds.

*U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety." EPA Report No. 550/9-74-004, March 1974.

3.0 SUBJECTIVE RESPONSES TO IMPULSIVE NOISE

Subjective responses of people to noise can be conveniently grouped into three general (and overlapping) categories:

- Health-Critical Responses
  - Hearing damage
  - Long-term medical or psychological effects other than hearing damage
- Activity or Behavioral-Influence Responses
  - Speech interference
  - Sleep interference
  - Task interference
- Attitudinal or Judgment-Influence Responses
  - Annoyance responses
  - Loudness (or noisiness) judgments

The primary concern for subjective responses in this report is in the last category (i.e., attitudinal or judgment responses), and therefore that category is the only category that has been reviewed in depth. An extensive bibliography has been compiled, however, on most of the above categories and is included in the Reference section at the end of this report. For convenience, the bibliography is arranged chronologically within each of five general subjects: Part A, Annoyance of Impulsive or Fluctuating Sounds; Part B, Loudness or Noisiness of Impulsive or Fluctuating Sounds; Part C, Detection or Perception of Impulsive Sounds; Part D, Speech Interference; Part E, Sleep Interference; and Part F, Hearing Damage. An additional subdivision Part G, for the references on measurement of impulsive sound, is also included in this bibliography. While all of the sources are listed in the bibliography, for convenience, only the principal ones of concern for this report are cited as references in the main body of the text.

3.1 Loudness or Noisiness of Impulsive Sounds

As will be shown later in Section 3.2, a correction to L_{eq} to account for the annoyance of impulsive sounds can range from approximately 5 to 15 dB, depending on the correction method. Clearly, such a wide range of correction factors is of little value so that a more precise method for selecting a subjective correction factor is desired. The extensive literature on loudness or noisiness of impulsive sounds was therefore reviewed emphasizing experimental results as a more reliable basis, at this point, for assisting in the selection of a subjective correction factor. In addition, these basic experimental results on response to transient sounds are expected to assist in defining optimum ways to monitor impulsive noise. Following the review in this section of the available experimental results on loudness and noisiness of impulsive sounds, information related to the annoyance of such sounds and comparison of annoyance and loudness or noisiness is considered in the next section. First, however, it is helpful to consider a simplified model for the auditory process as a framework for examining the data relative to impulsive noise response.

3.1.1 A Model for the Hearing Process

A simplified conceptual diagram of the auditory system is illustrated in Figure 4 to assist in defining the principal features significant in this study. As indicated in the figure, characteristic response times for the "acoustic" parts of the auditory chain (i.e., up to the point in the inner ear where spectrum analysis occurs) are much less than the "RC" time-constant inside the last box where the overall detection, integration, and recognition of sound signals is assumed to occur.[146] Even considering the lowest reported value for this time-constant, it is still more than two orders of magnitude greater than for the earlier parts of the auditory chain which must be able to respond to instantaneous pressure changes at rates up to 20,000 times per second ($\tau = 50$ μsec). The "RC" time-constant, on the other hand, only limits the ability to track the envelope of a sound. Thus, experimental studies on response of humans to transient sounds have focused more attention on this part of the hearing process and have utilized the RC smoothing filter concept illustrated as one of the ways to empirically model the results. We will consider the implications of the model illustrated in

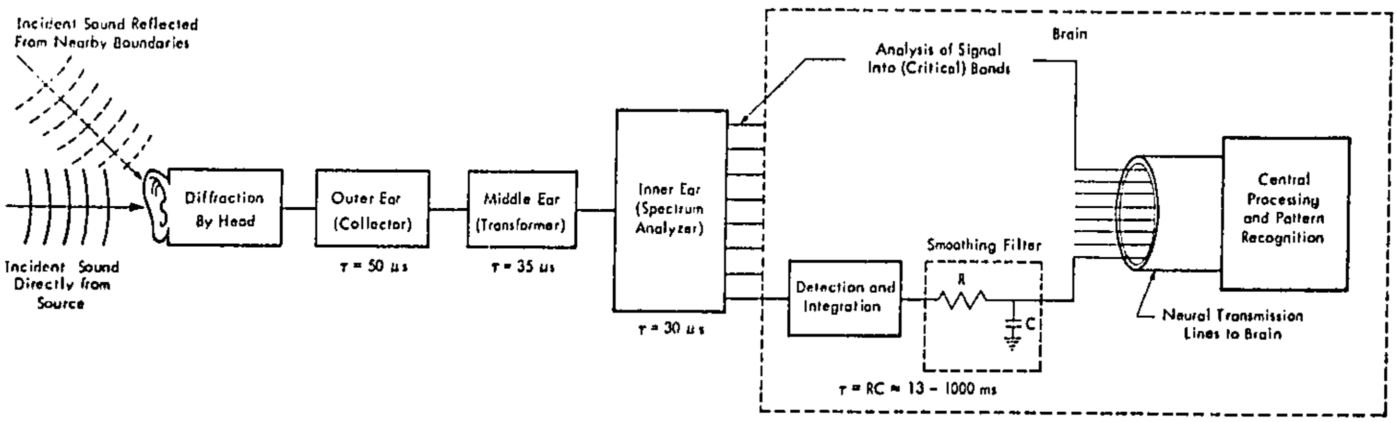


Figure 4. Conceptual Illustration of Auditory Process to Show Characteristic Response Times (τ) in Various Elements Which Govern the Dynamic Response of the Ear to Transient Sounds. Note: the Range for the Value of "RC" Time-Constant Reflects the Extreme Range of Observed Values. (After Bruel, Reference 146)

Figure 4 again later, but first let us examine the experimental data on loudness and noisiness.

3.1.2 Experimental Data

The independent and dependent variables involved in the noisiness of impulsive sounds may be categorized as follows:

Independent Variables (The Stimulus)

- Signal Format
  - Repetition, Single or Multiple Impulses
  - Signal Spectrum Tone, Narrow Band Noise, Complex or Wide Band Impulsive Noise (the complex impulse includes the type of real impulsive sounds of concern in this report)
- Signal Characteristics Varied
  - Pulse Duration
  - Pulse Frequency
  - Pulse Repetition Rate (for Repeated Impulse)
  - Spectrum of Total Signal
  - Rise and Decay Time of Pulse
  - Phase of Signal Components
  - Ratio of Pulse Signal Level to any Background Noise
  - Duration of Total Exposure
  - Method of Signal Presentation (including sound field characteristics for loudspeaker presentation)

Dependent Variables (The Response)

- Thresholds
  - Absolute Detection (absence of noise)
  - Masked Detection (in presence of noise)
  - Flutter or Fluctuation Detection
- Magnitude
  - Loudness
  - Noisiness

Although noisiness and loudness are listed as separate dependent variables for subjective response to impulsive sounds, it will be shown that they may be taken as essentially identical. However, as shown later in Section 3.2.3, the annoyance response to impulsive sounds may, in some cases, be significantly different from a loudness or noisiness magnitude response.

Utilizing the above framework of independent and dependent variables on loudness or noisiness of impulsive (or fluctuating) sounds, an index of the pertinent available literature is presented in Table 2 which covers most of the major experimental studies of subjective response to impulsive or fluctuating sounds. It will be convenient to briefly review the pertinent findings of these experimental studies by three general groups according to the type of stimulus.

- Pure Tones
- Bursts of Noise
- Complex Sounds (real or simulated impulsive noise including helicopter blade slap)

Table 2

Index of Experimental Studies on Loudness/Noisiness of Impulsive or Fluctuating Sounds Indicating Experimental Variables Investigated

References			Single Impulses (1)					Multiple (Repeated) Impulses (1)				
No.	Author	Year	Tones	Narrow Band of Noise	Complex	Wide Band Noise	Measured (2)	Tones	Narrow Band of Noise	Complex	Wide Band Noise	Measured (2)
25	Hughes	(1946)	D, F				AT					
26	Garner & Miller	(1947)	D, F, L				MT					
27	Munson	(1947)	D, F, L				LL					
28	Garner	(1947)						D, F			D	MT, AT
29	Garner	(1947)						D, F				AT, MT
30	Miller	(1948)				D, L	AT, LL					
31	Garner	(1948)						D, F, R, L				LL
32	Garner	(1949)	D, L				LL					
33	Niese	(1956)	D, F				LL					
34	Green +	(1957)	D				MT					
35	Hamilton	(1957)	D				MT					
36	Pollack	(1958)									D	LL
37	Plomp +	(1959)	D, F				MT					
38	M-Fodor	(1960)	D		D		LL					
39	Niese	(1960)	D, L				LL					
41	Small +	(1962)				D, L	LL					
42	Port +	(1963)		D, L			LL					
43	Sheeley +	(1964)	D				MT					
44	Carter	(1965)								R		LL
45	Zwicker	(1965)						D	D			LL, MT
46	Zepler +	(1965)								SB		LL
47	Garrett	(1965)								D, R	D, R	LL
48	Ekman +	(1966)	D				LL					
50	Stevens +	(1966)				D	LL					
51	Zwicker	(1966)				D	LL					
52	Pearsons	(1967)								AC, HBS		N
53	Pearsons +	(1967)									L	N
54	Dubrovskii +	(1967)									AM, R	FT
55	Johnson +	(1967)			SB, L		LL, A					
56	Bauer +	(1967)		D			LL		D			LL

Table 2 (Concluded)

References			Single Impulses					Multiple (Repeated) Impulses				
No.	Author	Year	Tones	Narrow Band of Noise	Complex	Wide Band Noise	Measured	Tones	Narrow Band of Noise	Complex	Wide Band Noise	Measured
57	Harbert +	(1968)						R, RT			R, RT	FT
58	Shepherd +	(1968)			SB		LL, A					
59	Rothausen +	(1968)								R		LL, A
60	Johnson +	(1969)			SB		LL					
61	Reichardt +	(1970)	D				LL					
62	Reichardt	(1970)	D				LL	D				LL
63 64	Fidell +	(1970)	D		D		N, A		D, R, F	D, R	D, R	N, A
65	Ollerhead	(1971)									L, AC	LL
66	Shipton +	(1971)	D		D		LL	D		D		LL
67	Thompson	(1971)	D		D		LL	D		D		LL
70	Leverton	(1972)								HBS		LL, A
71	Fuchs	(1972)								F		LL, A
72	Carter	(1972)								R, RT		LL
73	Stephens	(1973)	D	D			LL					
74	Carter	(1973)								R, RT		AT
75	Boone	(1973)						D	D			LL
76	Leverton	(1974)								HBS		LL
77	Pederson	(1974)			D		LL					
78	Gustafson	(1974)		•	D, F, R, L		LL			D, F, R, L		LL
79	Terhardt	(1974)						AM, R				FT
80	Fuller +	(1975)								D		A

(1) Independent variable identified by abbreviated code under column headings which define type of signal: pure tone, narrow band of noise, complex signal, or wide band noise.

(2) Dependent variable measured identified by abbreviated code.

Abbreviation Code

Independent Variables

D - Duration
F - Pulse Frequency
L - Signal Level
R - Repetition Rate
RT - Rise (and Decay) Time

SB - Sonic Boom Signal
HBS - Helicopter Blade Slap
AM - Amplitude Modulation
AC - Aircraft Sound

(+: et al)

Dependent Variables

A - Annoyance
AT - Absolute Threshold
FT - Flutter Threshold
LL - Loudness Level
MT - Masked Threshold
N - Noisiness

3.1.3 Subjective Response to Impulsive Pure Tone Sounds

Following pioneering work by Bekesy in 1929 on the effects of duration on loudness of tones, Hughes,[25] Garner and Miller,[26] Munson,[27] and Garner[28, 29, 31, 32] laid the groundwork for subsequent studies on loudness of single or multiple tone bursts. Typical results of this early work are represented by the data of Garner and Miller,[26] shown in Figure 5. Figure 5a shows the measured signal-to-noise ratio at detection threshold for a single tone burst of varying duration presented in the presence of a wide band masking noise. Figure 5b shows these same results normalized according to a simple empirical model for the auditory detection process corresponding to the output of a resistance-capacitance (RC) circuit. The latter is driven by a signal (E_1) which is assumed to represent the detected envelope of the tone burst. If we assume that the tone is just detected when the peak output of the RC network reaches some fixed threshold detection level (E_o), then it can be shown that for burst durations (T), much less than the time constant, $\tau = RC$ (analogous to the ear's time constant), the required signal level increases inversely as the pulse duration decreases, or

$$\text{(Required Signal Level, } E_1) \simeq (\tau/T)\text{ (Detection Threshold, } E_o) \qquad (3)$$

Thus, the product of the signal magnitude E_1 and the pulse duration T is a constant, as given by

$$E_1 \cdot T \simeq E_o \tau = \text{constant} \qquad (4)$$

Since the product of the signal magnitude and pulse duration is a measure of the "energy" in the signal, this relationship is simply another way to define the so-called "constant energy" law normally invoked to explain why, for pure tone bursts with a short duration relative to the ear's time-constant, the required signal level for detection increases 3 dB for every halving of the burst duration. This very same result was also obtained by Munson[27] when a tone burst was adjusted in level to equal the loudness of a fixed duration reference tone longer than about 50 msec. However, as suggested by Munson[27] and many others subsequently, a simple "RC" circuit model for the ear's response to transient sounds has a limited application.

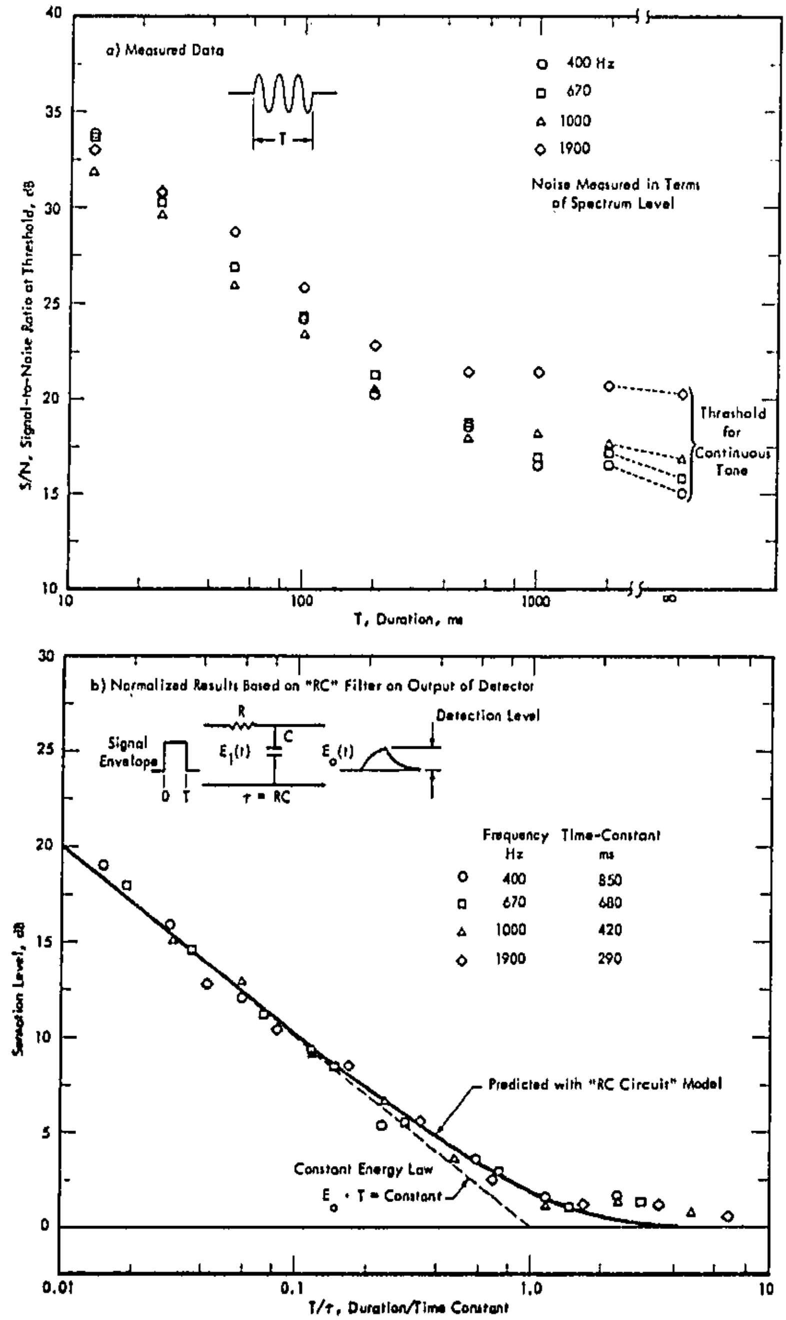


Figure 5. Measured (a) and Normalized (b) Values for Change in Signal-to-Noise Ratio of Single Tone Burst as a Function of Burst Duration (Data from Garner and Miller[26])

The practical implication of this model for impulsive noise is that it could offer a way to select an optimum procedure for measurement of impulsive sounds by duplicating, electronically, the ear's internal time-constant. Such a rationale is the basis for the 35 ms time-constant selected for impulse precision sound level meters (see Appendix A). Unfortunately, there are several complications in this simplistic model which are brought out by the experimental data.

Reichardt and Niese,[61] employing a subject panel of 50 people, found that the loudness matching of a tone burst of variable duration against a fixed duration reference tone, usually of the order of 1 second long, was a very difficult experimental task for the average subject when the two burst durations were substantially different and led to a great deal of data scatter not indicated by the smaller subject panels (four to six) in most other studies. By using reference tone durations near the middle of the range evaluated for the test tone, they found much less scatter in the loudness balances. On the basis of their refined technique, therefore, they measured a time-constant of 30 milliseconds.[61]

These refinements also included a careful selection of the temporal spacing and duration of the test and reference signals to avoid possible masking or memory errors in comparing a test and reference tone or to avoid what they termed "roughness" which was observed when a rhythmically repeated pattern was used for the test or reference signal, particularly at pulse repetition rates on the order of 3 to 50 Hz (Reichardt[62]). This qualitative measure, "roughness," may be important in the evaluation of impulsive noise.

Other factors which can cause variation in the observed trade-off between signal level and duration are: (1) the "energy law" fails either when the signal duration T is so short that a substantial portion of its frequency spectrum falls outside the critical band centered on the pulse frequency (Garner[29]), or the signal duration is much longer than the ear's time-constant, (2) the apparent time-constant increases as the signal level approaches the threshold of hearing (Garner and Miller,[26] Boone[75]), and (3) the time-constant apparently varies with frequency, as implied by the data shown in

Figure 5. It has generally been accepted practice, however, to assume that the time-constant does not vary with frequency.

The lack of agreement between investigators on the time-constant still continues. A recent study by Boone[75] on loudness of repeated short tone bursts in noise, using 20 subjects, produced a value for the time-constant of about 110 ms. Terhardt[79] has suggested an RC time-constant of 13 msec to fit his unique measurements of the detection of periodic sinusoidal modulation (which he calls roughness) of pure tones. In summary, there is substantial evidence to support values for the time-constant ranging from 13 ms to over 200 ms (see Figure 6). Because there is no apparent way to resolve this issue unequivocally for this report, the only practical choice appears to be to work with the existing recommendations or practice for the choice of time-constraints in impulse precision sound level meters.

This lack of agreement on the auditory time-constant is most unfortunate for it implies the potential for conflicting evidence about a subjective correction factor for impulsive sounds. This point is illustrated in Figure 6 which shows the potential range of the time-constant based on the range of experimental data relating perceived loudness of an impulsive sound versus its duration. Thus, for a given duration of an impulsive sound, the potential increase in the signal level to achieve a loudness equal to that of a reference (nonimpulsive) tone can be substantial. Clearly, any correction factor for impulsive noise must be based as much as possible on experimental data for subjective response to real impulsive sounds.

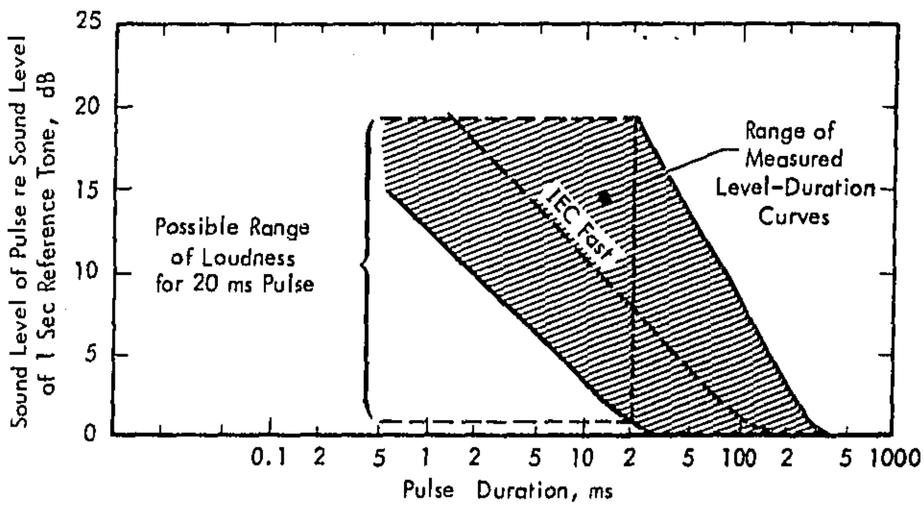


Figure 6. Range of Measured Sound Level - Duration Tradeoff (where the Pulse is Judged to be Equally Loud to the Reference Tone) Reported from Various Studies to Indicate Possible Range of Uncertainty in Predicted Loudness of 20 ms Pulse. (Note that the Time Constant Specified by IEC Sound Level Meter Specifications for "Fast" Would Tend to Fall Near the Middle of the Range of Measured Data — Adapted from P. Bruel, Reference 146.)

Pulse Repetition Rate

Another major variable studied in loudness tests of repeated tone bursts is the repetition rate. A very definitive study in this area was reported by Garner.[31] From these results on repetitive tone bursts, a subjective correction factor for real impulsive noises can be inferred. His experimental procedure consisted of presenting, through monaural earphones to six subjects, a continually repeated pattern of a steady 1 second reference tone, 1/4 second silence, a 1 second cycle of repeated tone bursts, a 1/4 second silence, 1 second reference tone and so on. The repetition rate of the repeated tone burst group was varied from 5 to 100 pulses per second, the pulse duration varied from 1 to 50 ms, the pulse frequency varied from 125 to 8000 Hz and the intensity level of the pulse varied from 20 to 100 dB. The subject varied the intensity of the tone bursts until he obtained equal loudness to the reference tone. In most cases, the energy in each tone burst group was less than that of the equally loud steady reference tone. The subjective correction Δ_s for equal loudness for these tone bursts is simply the positive difference between the sound exposure levels of the reference and test signals. Since the tone burst group and the reference tone each lasts for 1 second, the difference in sound exposure levels is also the difference in equivalent sound levels (L_{eq}). This subjective correction factor is shown in Figure 7 for 1000 Hz tone bursts and covers the repetition rate and pulse duration range indicated. The intensity of the reference level was 80 dB. The typical variation of Δ_s with reference level and frequency is shown in Figure 8.

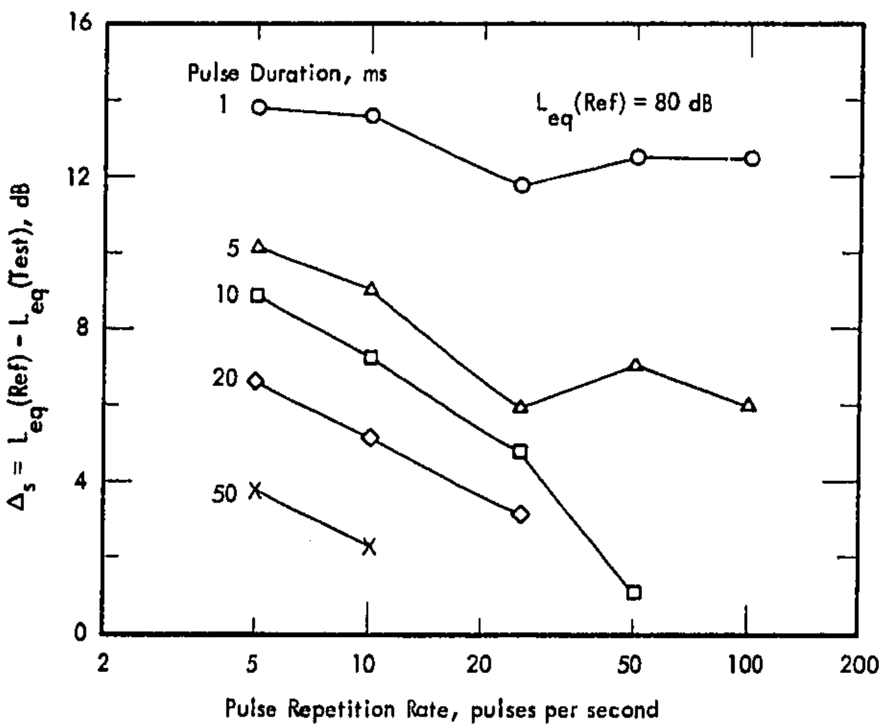


Figure 7. Subjective Correction Δ_s for Repeated 1000 Hz Tone Bursts (from Garner[31])

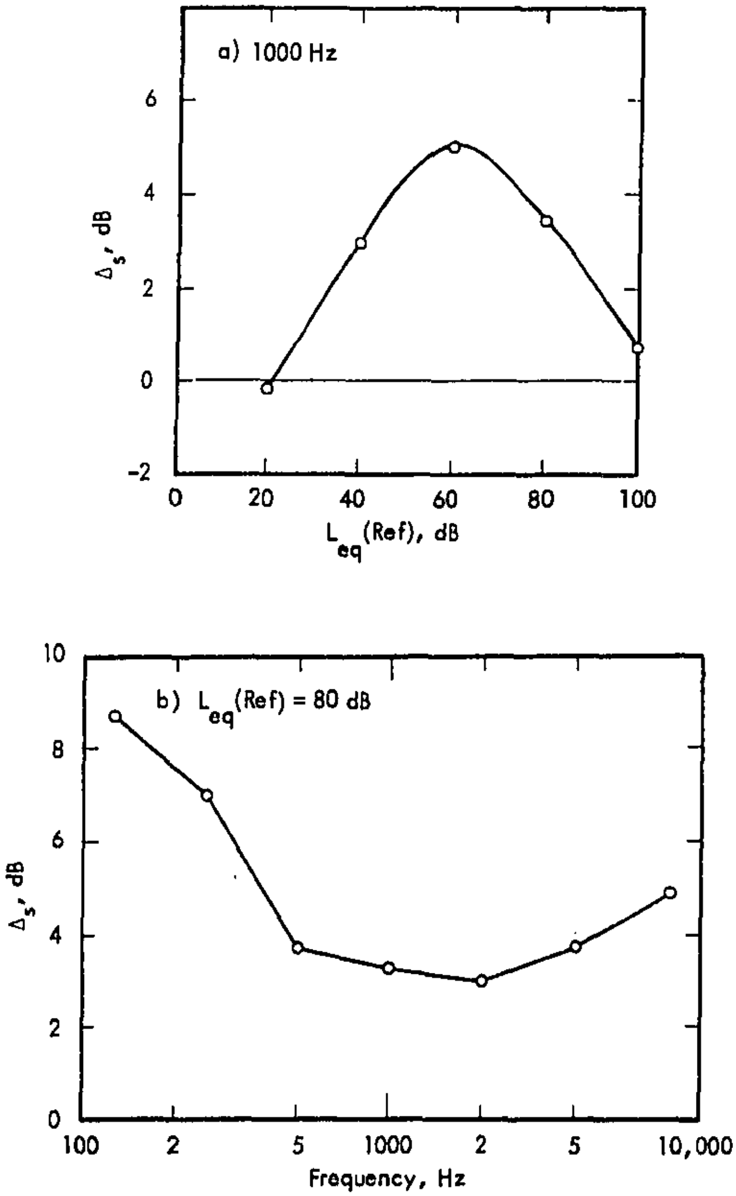


Figure 8. Subjective Correction Δ_s for Repeated Pure Tone Bursts, Pulse Duration 20 ms, Repetition Rate = 25/Second as a Function of a) Reference Intensity, L_{eq} (Ref) at 1000 Hz and b) Frequency for the 80 dB Reference Level (from Garner[31])

As exhibited in Figures 7 and 8, the subjective correction factor behaves in a complex fashion, even for simple tone bursts. These figures indicate the potential difficulty of developing any simple, general method for predicting a subjective correction factor for more complex impulsive noises which have different spectra, rates of attack or decay, or amplitudes. Nevertheless, Garner was able to readily predict his experimental results, such as those illustrated in Figures 7 and 8, on the basis of two basic factors:[31]

1. The spreading out of the frequency spectrum of repeated tone bursts. As a result, the side band frequency components of the repetitive tone burst can fall into critical bands outside the one centered on the tone burst carrier frequency.

2. The shape of the loudness growth function. Due to this unique shape, the loudness of the side band components in each of the several critical bands involved in this broader spectrum of repeated tone bursts can add up to a greater loudness than the sum of their energies because, at noise levels well above threshold, the relative loudness of a sound changes much more slowly than the relative intensity (i.e., 2-to-1 change in loudness for a 10-to-1 (10 dB) change in intensity). That is, the loudness of sounds is roughly proportional to the sum of the loudness in critical bands and the sum of these loudness values in the side band components will not decrease as rapidly at frequencies removed from the tone frequency as the physical energies in these side band frequency components of repeated tone bursts.

There is really nothing new here, of course; it is simply the basic concept of loudness summation of complex sounds which has been developed into a fine art by Stevens,[93], Zwicker,[89] and Niese.[86] However, application of these well-developed concepts for loudness of sounds has had only limited application to impulsive sounds.

It is important to recognize that the concept of "startle" is not involved in a prediction that a weaker impulsive sound can sound louder than a stronger steady-state sound. This simply results from the accepted concepts for simulating the loudness perception of sounds. It remains to be shown that there may indeed be an additional effect that makes impulsive sounds more annoying than indicated by their loudness.

Frequency Spectra of Repetitive Tone Bursts

A brief consideration of the frequency spectra of repeated tone bursts is in order here since this plays such a primary role in the concept just outlined. As Figure 9 shows, repeated tone bursts produce a spectrum centered at the frequency of the tone with side bands above and below this frequency.

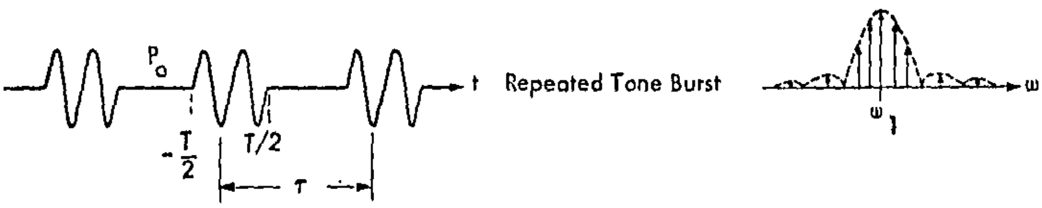


Figure 9. Time History and Fourier Spectrum of a Typical Impulsive Signal

In Appendix C, it is shown that the inverse of the duty cycle of the pulse (τ/T) provides a qualitative indication of the number (N) of side band harmonics within the nominal "1/2 power" spectral bandwidth. The more the repetition rate increases, the louder the pulse train will be, if the total energy stays constant.[31] With a very long duration, and a very slow repetition rate, all the energy of the signal is concentrated in a narrow range of frequencies. If this range falls within a critical bandwidth, then the loudness varies as the signal energy within this band. On the other hand, if this signal spectrum bandwidth is much greater than the critical bandwidth, then loudness of the signal will add approximately as the loudness of energy in each critical band but with emphasis on the loudest band.

The broadening of the spectrum of tone bursts beyond the frequency of the tone itself introduces an inherent complication in evaluating subjective response to intermittent sounds. This complication is overcome, in a sense, by using a test signal - broadband random noise, which already has a broad spectrum. Thus, the spectrum of repeated bursts of wide band random noise differs from the spectrum of the uninterrupted noise only at frequencies, which are generally infrasonic, corresponding to the burst repetition rate. Spectra of single bursts of broadband noise are not significantly different from the spectrum of the steady noise itself.

3.1.4 Subjective Response to Bursts of Noise

Although Garner[28] and Miller[30] carried out initial studies on response to bursts of broadband noise, Pollack[36] presented the first extensive study utilizing pulses of wide band noise. For our purposes, his results may be summarized as showing that the difference between the L_{eq} of a continuous noninterrupted broadband reference noise and the L_{eq} of equally loud pulses of the same noise increased from 0 to +10 dB as the duty cycle of the bursts decreased from 1 to 0.1. For duty cycles below 0.1, the difference remained approximately constant at +10 dB. Thus, the subjective correction factor Δ_s would be +10 dB for duty cycles less than 0.1.

Small, et al,[41] used a more conventional procedure of balancing loudness of repeated bursts of noise of various durations against interspersed 1/2 second bursts of a constant level reference noise. They found that when the sensation level of the reference noise burst was 60 dB (a typical listening level), the level of an equally loud variable duration test burst was constant for durations down to 15 msec and then increased by 12.5 dB for each 10-to-1 decrease in duration for shorter test bursts. For our purposes, this is equivalent to the subjective correction Δ_s increasing linearly, at a rate of +3 dB per halving of test burst duration, from a value of zero for 1/2 second noise bursts to a maximum of 15.2 dB for a 15 ms noise burst, and then decreasing linearly at a rate of -0.75 dB per halving of test burst duration for shorter bursts. This assumes that 1/2 second is the time base for computing the L_{eq} of the variable duration noise burst.

Garrett[47] has repeated the tests of Pollack[36] and Small, et al,[41] with very similar results as shown in Figure 10 where the measured values of Δ_s versus ratio of test signal duration to reference signal duration is plotted. Similar data on loudness of a short burst of 2 to 4 kHz noise from Bauer[56] is also included along with data on relative noisiness of short bursts of noise bands from Fidell and Pearsons.[64] The latter show little agreement with the other data but this may be due to the unique experimental technique employed (free-field presentation, interaction with a computer for signal presentation), and the "noisiness response" instead of loudness. The values for Δ_s in this case are actually differences in measured A-weighted noise levels of the reference and test signals. The effect of A-weighting on the short noise burst levels is not clear.

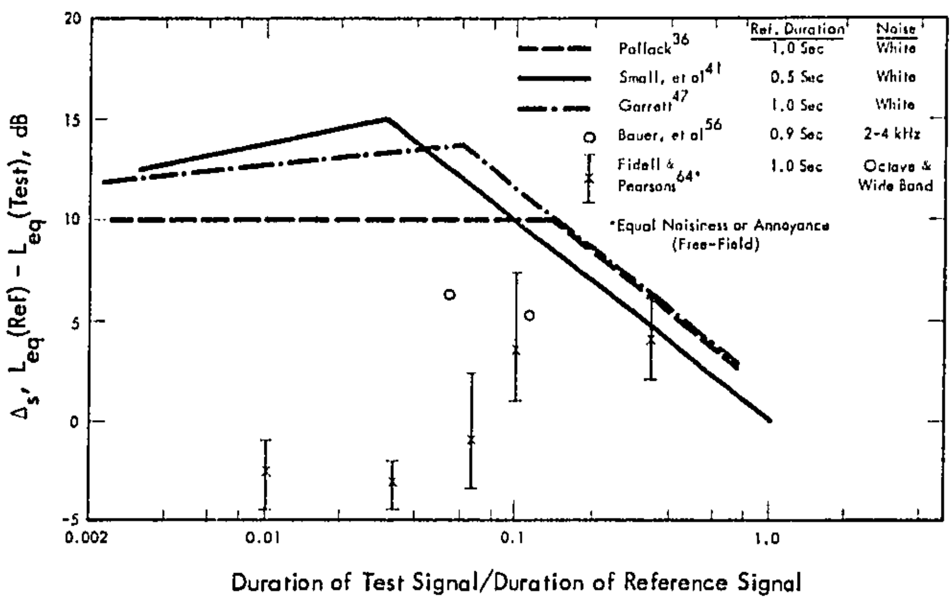


Figure 10. Subjective Correction Factor for Loudness or Noisiness Response to Short Bursts of Noise Bands Relative to a Reference Noise. (Solid and Dashed Lines Identify Mean Lines Through Experimental Data which Vary ~ ±2 dB about Mean).

Finally, returning to Pollack,[36] one particular set of his data provides a good model for examining loudness of more realistic impulsive sounds. These data were obtained on the loudness of partially interrupted noise. This consisted of a continuous background noise with a superimposed periodic increase in noise by amounts varying from

0 to 45 dB. Figure 11 shows the resulting data obtained under one condition of a repetition rate of 1 pulse per second (pps) and a burst duration of 1 ms. The ordinate defines the loudness level of the composite signal relative to the loudness level for continuous noise at the same intensity as the noise peak. The dashed line on the figure shows the computed L_{eq} for this noise signal to illustrate, again, that the equally loud impulsive noise has an L_{eq} substantially less than the L_{eq} of a continuous signal with the same maximum level. The resulting subjective difference factor Δ_s approaches a maximum value of about 10 dB for a ratio of noise burst to background noise greater than 30 dB. Other data by Pollack[36] and Garrett[47] on partially interrupted noise gave similar results as shown in Figure 11.

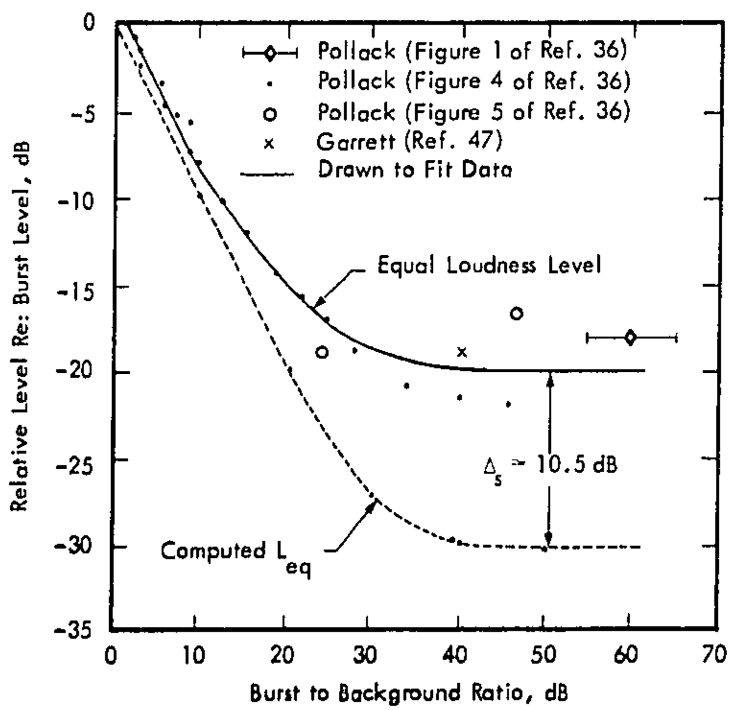


Figure 11. Difference Between the L_{eq} of the Repetitive Noise Burst Superimposed on a Steady Background Noise and the Level of a Continuous Noise which Sounds Equally as Loud as a Function of the Ratio of the Burst Level to the Background Level (Burst Duration = 1 ms, Repetition Rate = 1 pps)

In summary, with the exception of the results of Fidell and Pearsons,[64] the experimental data on loudness or noisiness of short bursts of random noise show consistent trends similar to the tone burst data in terms of order of magnitude values for the subjective difference factor. Limited results on the ear's time-constant from these studies are not inconsistent with the values observed from the pure tone tests. Additional support for the time constant values discussed in Section 3.1.3 is provided by data by Dubrovskii and Tumarkina[54] on subjective perception of the relative loudness of amplitude-modulated noise. They hypothesize a time-constant for the ear of 10 ms to explain their data - a value similar to the 13 ms cited earlier for tests on the modulation threshold of pure tones.

The application of a "time-constant" model again appears convenient to explain experimental results. However, this device may indeed be misleading based on the unique results and resulting hypothesis posed by Miller[30] in his study of the delay in detectability of a low level noise signal following the interruption of a higher level masking noise. Based on his results, Miller suggests that:

> ".... the auditory system as a whole does not have a fixed rate of decay of so many decibels per second independent of intensity. Thus the auditory system cannot be said to have a "time constant" in the sense that this term is generally used, and we have been careful to use the term "critical duration" instead. This is not to say that the mechanism of the ear has no time constant, however. As in all mechanical systems there is a finite time required for the ossicular chain and the cochlear fluids to begin and to stop their motions. The mechanical time constants of this system, however, are far too small to account for the 65 msec periods of perceptual growth and decay.
>
> "It has often been convenient to liken the auditory system to an integrating circuit..... The evidence seems to show that the ear is not so much an integrating device as it is a delaying device.....According to our hypothesis, the growth of the perception of noise is the integral of the

distribution of transmission times of the various pathways from the cochlea to the higher center, and not the integral of the sound intensity."[30]

3.1.5 Loudness Versus Noisiness of Impulsive Noise

None of the preceding studies cited on noise bursts employed standard loudness calculation procedures to predict their results. However, both Pollack[36] and Garrett[47] used different empirical approaches based on weighting their noise burst signals by a function related to the observed level-duration trade-off. Garrett was particularly successful in predicting the loudness of 48 complex transient signals consisting of repeated decaying sinusoids. Other examples of this approach are covered in Section 3.1.6 on response to complex impulsive sounds. However, before considering more complex impulsive sounds, let us examine one final (and very recent) study on the loudness and noisiness of noise bursts.

A new and unique approach to the prediction of human response to impulsive noise is provided by the work of Izumi.[82] In order to examine the possible subjective difference between loudness and noisiness, Izumi conducted a set of two laboratory controlled psychophysical experiments. In the first experiment a periodically intermittent pink noise signal was used to determine if there was indeed any difference between these two subjective parameters. Upon finding a significant difference, the second experiment was conducted so that an effective assessment method could be established.

For the first experiment, consisting of two phases, subjects were asked to compare, using the paired comparison method, the test signal (intermittent pink noise) with a standard signal (continuous pink noise at 70 dBA). The signals were presented in a fade-in, fade-out sequence as shown in Figure 12. In order to overcome any possible error due to sequence bias, the stimuli were presented both signal first and standard first for an equal number of times. The whole procedure was repeated for six different burst-time fractions (BTF); the BTF being defined as the signal-on time divided by the on-plus-off time.

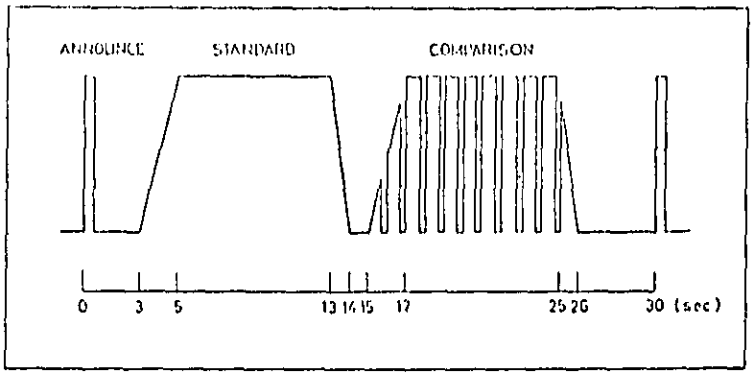


Figure 12. Time-Amplitude Sequence Diagram of the Stimulus Presentation (from Izumi[82])

During Phase I, the subjects compared the pair of signals in terms of their relative loudness, i.e., how much louder (or softer) than the continuous signal is the intermittent signal? During Phase II the same signals were replayed, but this time the subjects compared them in terms of their relative noisiness.

The results of both phases were tabulated and compared with each other (see Figure 13). From these results, Izumi concluded that ".... as far as periodically intermittent sounds are concerned, loudness judgments and noisiness judgments are significantly and systematically different. Therefore, loudness and noisiness shall be considered as different attributes."

Once he determined that the two parameters are indeed different, Izumi set up his second experiment in order to arrive at a model which would accurately predict the noisiness of an intermittent signal.

In this experiment the subjects were presented with signals with 25 different BTFs. They were asked after each trial to rate the relative noisiness of the signals as in the first experiment.

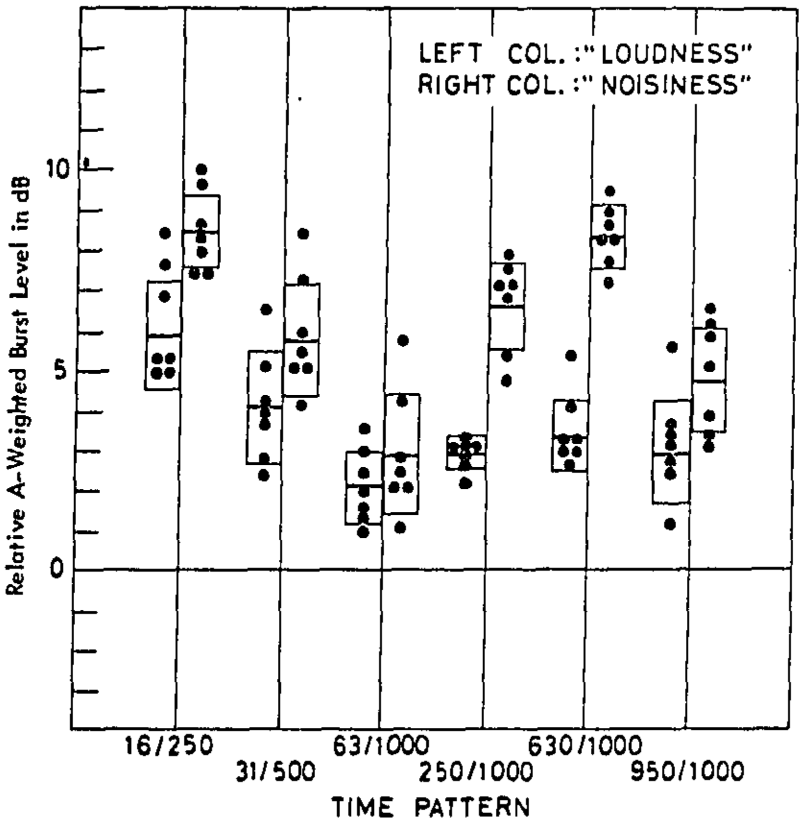


Figure 13. Results of Experiment I. Ȯkisa (Loudness) Data and Yakamashisa (Noisiness) Data are Comparatively Plotted. Filled Circles Represent Mean Relative Burst Levels Judged by Each Subject. Averages and Standard Deviations are Shown by Central Lines and Rectangles on Both Sides (from Izumi [82])

Model

From the results of these trials, Izumi developed what he calls the "Perceived Noisiness Model of Periodically Intermittent Sounds 75-A."

$$L_{RB} = 6 \log_{10} BTF + (10 \log_{10} RR + 10)(1 - e^{-15 T_{off}}) \text{ , dB} \qquad (5)$$

where

L_{RB} = relative A-weighted noise level of burst in dB

BTF = burst time fraction, i.e., on-time/on + off time

RR = repetition rate per second

T_{off} = off time in seconds

In order to test this formula, he predicted the value of L_{RB} for the 25 intermittent noises used in Experiment II. The L_{RB}'s were calculated using nine different methods: peak burst levels in terms of Loudness Level, Stevens LL(S); Loudness Level, Zwicker LL(Z); Perceived Noise Level, PNL; and A-weighted noise level; A-weighted equivalent sound level; Pollack's[36] method; Garrett's[47] method; noise rating number (NRN) as specified by ISO[11a]; and Model 75-A, proposed by Izumi.[82]

The predicted levels were then compared with the experimental data. The results are shown in Figure 14.* From these results, Izumi's Model 75-A appears to be the best predictor. The other methods always underestimate the perceived noisiness of the intermittent sounds.

Startle Effect

The major reason, according to Izumi, for the difference between loudness and noisiness is the startle effect created by the intermittence of the sound. The startle effect is based on three physical parameters of the signal: repetition rate, rise time and the burst-to-background ratio.

In these experiments the rise time and the burst-to-background ratio were held constant and only the repetition rate was varied. The contribution of repetition rate to the noisiness-loudness difference was quantified and this information, shown in Figure 13a, was used in the development of Model 75-A. According to Izumi, work is still necessary if the contribution of the startle effect is to be understood.

*Figure 14 is a corrected version of the form published in Reference 82 which was kindly supplied by Dr. Izumi.

It will be pointed out later that one study of subjective response to helicopter blade slap as a function of rate of slap[23] has also shown a trend of increasing apparent noisiness with increasing repetition rate although the range of "pulse rate" explored was well above that (i.e., 10 to 30 pps) explored by Izumi.

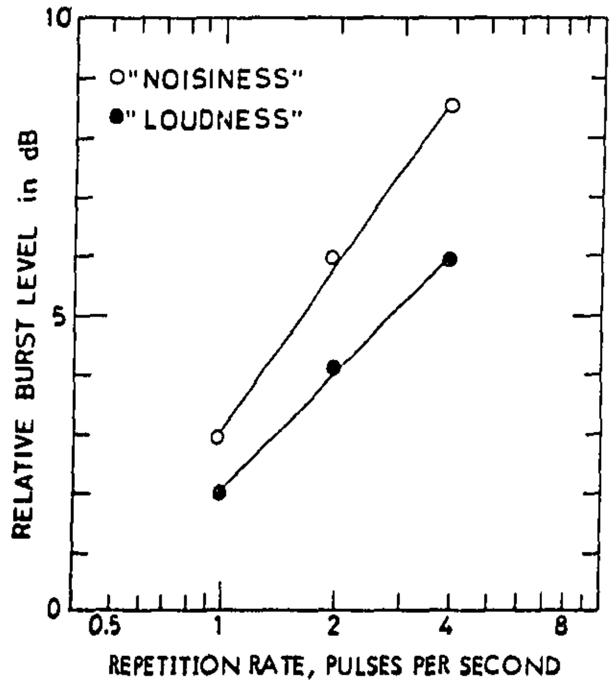


Figure 13a. Comparison of Loudness and Noisiness versus Repetition Rate for a Burst Time Fraction of 0.063 (from Izumi[82]).

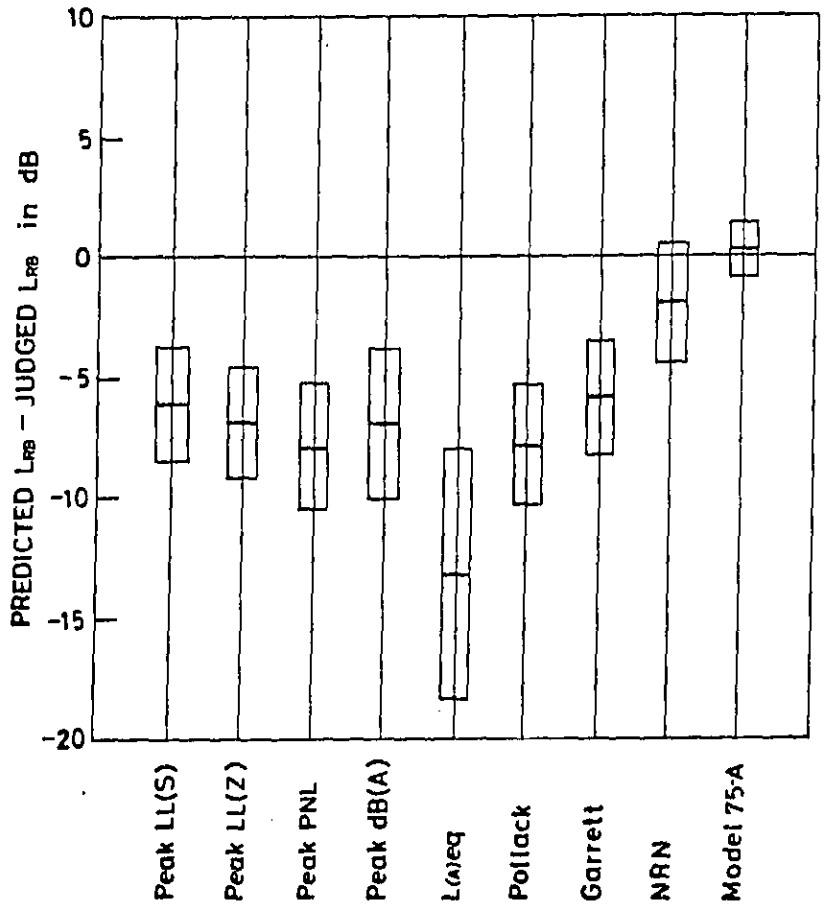


Figure 14. Preliminary Validation of Assessment Methods. Errors of Prediction are Calculated for 25 Intermittent Noises in Experiment II. Mean Errors are Shown by Central Lines and Standard Deviations by Rectangles on Both Sides (from Izumi[82]).

In summary, although this is only one study, Izumi shows quite well that noisiness and loudness are not the same subjective quantities when dealing with intermittent sounds, and that the startle effect of the intermittent sound is a prime cause of this difference.

3.1.6 Subjective Response to Complex Impulsive Sounds

Early work on subjective response to more complex impulsive sounds other than tone or noise bursts involved measuring loudness of short triangular transients such as repeated gun blasts. For example, Carter,[44] Carter,[72] and Carter and Dunlop[74] explored the loudness and threshold levels of this type of transient, which had a pulse duration of 1 ms, for varying rise times (.05 to 0.5 ms) and repetition rates (1 to 256 pps). The effect of repetition rate was adequately covered by a simple energy rule (+3 dB increase in intensity to maintain loudness for each halving of duration). For the highest repetition rate, the ratio of on-time to off-time never exceeded 0.5 and was typically much less. As with all the preceding impulsive noise studies cited so far (except Fidell and Pearsons), earphone presentation was used. The loudness judgments were made by comparison of a 3 second reference (white noise) signal with two impulses separated by 1 second from each other and from the reference noise. For most of the loudness tests, the reference noise was fixed at 15 dB above threshold (sensation level of 15 dB) for each subject.

The principal result from Carter's work is the evaluation of alternate means of predicting loudness of triangular impulsive sounds. For each repetition rate and rise time, the loudness of the reference noise and impulse, at the "equally loud" intensity levels, was calculated from the signal spectra. The spectra were computed from the pressure time history for the impulsive sounds and measured directly for the reference noises.

The four calculation methods analyzed were:

- Zwicker[87, 89]
- Stevens, Mark VI[93]
- Perceived Noise Level[103]
- A-Weighting

The average difference between the calculated loudness (based on the computed spectrum) of the impulsive sound, which was judged equally as loud as the reference sound, and the calculated loudness of the reference sound was measured for all the combinations of rise time and repetition rates (306 cases). The results are summarized in Figure 15 for these four methods in terms of this difference as a function of pulse repetition rate.

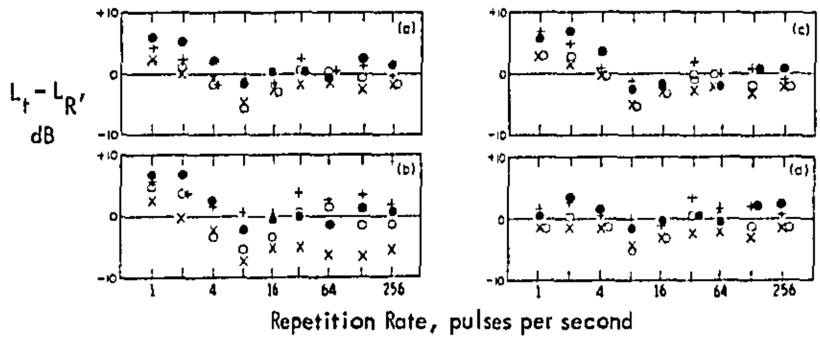


Figure 15. Comparison of Loudness Calculation Methods for Triangular Transients. Variation about the overall mean (within each loudness method) of the mean difference (over subjects) between the calculated loudness (L_t) of the triangular 1 ms impulse and the calculated loudness (L_R) of the reference noise, subjectively judged to be equally loud. Deviation from zero is a direct measure of the error in each loudness calculation method: (a) Zwicker, phons; (b) Stevens Mark VI, phons; (c) Perceived Noise Level; (d) A-Weighted Level. The symbols denote varying rise time (•, 0.5 ms; +, 0.25 ms; o, 0.1 ms; and x, 0.05 ms). (From Carter[72])

Surprisingly, the loudness computed on the basis of the A-weighted levels exhibits the least deviation about an overall mean. The Zwicker method was next in accuracy. There is reason to doubt the general applicability of these results, however, as shall be seen when these loudness calculation methods are applied to other types of impulsive sounds.

Fidell and Pearsons[63] investigated the influence of phase of harmonic components on the judged noisiness of five different simple transient sounds corresponding to (1) an ideal N wave, (2) an N wave with 1 ms rise and decay times, (3) a triangular waveform, (4) a square waveform, and (5) a doublet or positive and negative sharp impulse. Power spectra for each basic waveform were maintained essentially constant while phase was adjusted by a computerized waveform generator. No significant influence of phase on subjective loudness was detected.

They also evaluated the subjective loudness of 12 actual impulsive sounds and eight artificial sounds presented, as were all their signals, over a high quality loudspeaker system. The characteristics of these 12 sounds are listed on Table 3. The difference between a time-integrated objective measure of the sounds and the same measure for the reference sound is shown in Figure 16.

Table 3

Description of Naturally Occurring Impulsive Sounds Employed as Comparison Signals in Evaluation Experiment by Fidell and Pearsons[64]

Impulse	Duration (msec)	Identification	Approximate Spectral Characteristics
1	300	Automobile Door Slam	Peaks at 0.5 kHz
2	150	Paper Tearing	Near flat spectrum to 10 kHz
3	425	Hand Clap	Rises and falls about 0.8 kHz
4	450	Two Bottles Clinking Together	Highly leptokurtic at 4 kHz
5	580	Chain Collapsing on Itself	Near flat spectrum to 1 kHz, falls slowly at higher frequencies
6	480	Nocturnal Animal Noise	Complex spectrum peaked at 0.125 and 2.5 kHz
7	180	Squeaky Release of Air Through a Valve	Peaks at 0.8, 1.6 and 5 kHz
8	400	Balloon Bursting	Peaks at 0.2 kHz
9	600	Balloon Bursting	Peaks at 0.2 kHz
10	180	Automobile Horn	Discrete frequency peaks concentrated between 0.3 and 1 kHz
11	1200	Simulated Sonic Boom	Predominantly low frequency, falling steeply from 0.125 kHz
12	900	Basketball Bounce in Highly Reverberant Environment	Energy concentrated between 0.2 and 1.6 kHz
Standard	1000	White Noise, 1 Second	Octave Band from 0.6 to 1.2 kHz

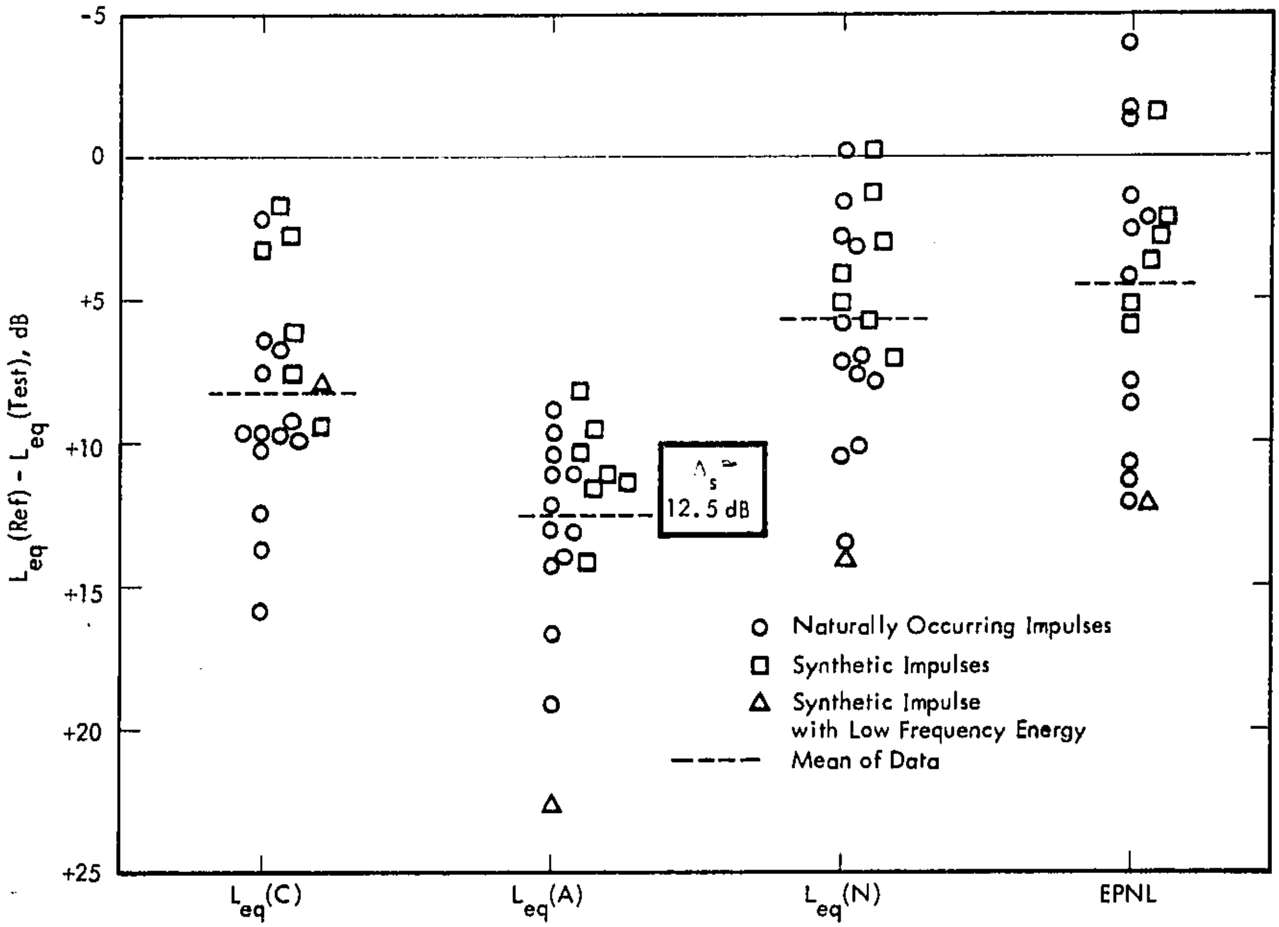


Figure 16. Comparison of Time-Integrated Measures of the Impulsive Noises with the Same Measure of the Equally Noisy Reference Sound (1 Sec of Octave Band Noise, 600–1200 Hz). (From Fidell and Pearsons[64])

The ordinate specifies the difference between the average sound level (computed from a mean square average of the digitized time history of the signal)[64] and the same measure for the equally noisy impulsive sounds. For the A-weighted measure, this difference is identical to our subjective correction factor Δ_s and was equal to 12.5 dB with a standard deviation of 3.5 dB. The standard deviations for the other measures were slightly greater, thus indicating the A-weighted average sound level was slightly more reliable as a predictor of noisiness of these impulsive sounds. Note that these impulsive sounds vary substantially in their characteristics; some may not be very impulsive. However, they are all essentially single events and not repetitive. The average value of Δ_s observed, in this case, has considerably more validity than the values given up to now for the following reasons:

1. It was measured with a loudspeaker presentation thus insuring that realistic head diffraction effects are included.
2. The objective measurement of the average sound level should be very accurate – they were performed by digital analysis of a recording of the actual sound reproduction.
3. The sounds cover a variety of actual impulsive noises to which the subjects can relate.
4. The instructions to the subjects asked for a judged noisiness but prompted an annoyance response as well (i.e., the test instructions defined a noisy sound as annoying, unacceptable, objectionable, and disturbing if heard in the home during the day and night).[64]

Loudness measurements of decaying sinusoidal transients similar to those used by Garrett were carried out by Gustafsson[78] but at sound levels from 95 to 117 dB. While the results tend to substantiate those given earlier, the high noise levels used place these data outside the area of interest for this study.

3.1.6.1 ISO Round Robin Tests

The most complete set of data on loudness of impulsive noises is provided by the final results of an international cooperative Round Robin test program organized under the auspices of the International Standards Organization, ISO/TC 43/SC-1, Study Group B, "Loudness of Impulsive Sounds." The final report, prepared by Pedersen, et al,[77] represents results from 22 laboratories and "close to 400 subjects." Additional detailed supporting data were reported by Shipton, Evans, and Robinson, from the National Physical Laboratory,[66] on the specific results from their tests with the ISO Round Robin data tapes. Detailed information on findings of the ISO Round Robin Tests, drawn from these two sources, is presented in Appendix B.

Although the tests consisted of an evaluation of subjective and objective correction factors for the following three types of impulsive sounds, results for only the subjective correction factors for the first group are considered here.

Group I	Nine quasi-steady impulsive noises recorded from actual sources such as a teletype, pneumatic hammer, outboard motor.
Group II	Five single impulse noises, such as from a gun or mechanical ram.
Group III	Six 1 kHz tone pulses of 5 to 160 ms duration.

The sounds were presented to the subjects via loudspeaker in repeated A-B sequences and matched, in loudness, with reference signals presented at three sound levels (55, 75, and 95 dB re 20 μ Pa). The overall grand average subjective correction factor, Δ_s, for all reporting laboratories, nearly 400 subjects, and for the nine repetitive noises in Group I, is 12.5 dB. The standard deviation over the nine average values for each noise is 0.9 dB. This is a highly smoothed statistical result since the variation between subjects for any one level and test sound can be 10 to 15 dB. However, it is estimated that the final result is reliable within ± 1.5 dB. No estimate could be made of subjective correction factors for the five single impulse sounds since the equivalent noise levels for these sounds were not available.

3.1.6.2 Loudness of Sonic Booms

The evaluation of the loudness of sonic booms provides additional information pertinent to the subjective response to impulsive sounds. Zepler and Harel[46] successfully predicted the relative loudness of sonic boom sounds by applying a loudness frequency weighting to the Fourier energy spectrum of the simulated N waves. Johnson and Robinson[55, 60] have extended this type of approach to successfully correlate the annoyance response from explosive blasts and sonic bands as well as conventional aircraft sounds on the same loudness scale. They utilized the S.S. Stevens, Mark VI, loudness calculation method[93] with a modification to extend its low frequency range to encompass the strong, very low frequency energy inherent in sonic booms. This low frequency deficiency in the loudness calculation methods has been observed by others.[64, 67] However, this may not be a significant problem for the type of impulsive sources of concern in this report.

A key element in Johnson and Robinson's approach is the use of a specific 70 ms integration time for measuring the signal spectrum. This was intended to duplicate the ear's integration time.[60] Note that this is twice the value of the time-constant specified for the impulse precision sound level meter. This is obviously a critical point that will require careful consideration in the selection of an optimum impulsive noise monitoring technique.

Johnson and Robinson applied a loudness calculation scheme to the prediction of annoyance for impulsive sources. Are these two forms of human response (loudness and annoyance) really synonymous? The answer, based on available data is that they are not necessarily the same. This point is fundamental to describing impulsive noise and deserves the more careful review taken up in the next section.

3.2 Annoyance and Other Subjective Responses to Impulsive Noise

Review of the existing literature dealing with annoyance due to impulsive noise yields a wide range of approaches and results. These results from available studies, excluding those on helicopter blade slap, are briefly summarized in Table 4. Annoyance of helicopter blade slap is considered later. Annoyance due to aircraft sonic booms were of primary concern in about half of the studies cited in Table 4. While most studies attempted to measure annoyance, the terms "unpleasantness"[1] and "unacceptability"[12] were also used. It was assumed that these terms represented a similar measure of subjective response. The qualitative descriptor "annoyance" is not well defined but may be assumed to represent an overall subjective reaction to an impulsive noise stimulus. This reaction may very well integrate not only the loudness or noisiness sensation but also the response to other non-acoustic factors such as startle, emotional content or intrusive noise level relative to the existing background ambient level.

3.2.1 Annoyance Response to Impulsive Noise

A division of the references on annoyance responses into the three categories of impulsive noise studies defined earlier helped in selecting only those applicable to this effort. Category I, which is the principal concern of this report, covers the "repetitive impulses" produced by two-stroke motorcycles, rock drills, pavement breakers, helicopter blade slap, and other repetitive impulsive noise sources. Category II, "single impulse," includes sonic booms and artillery blasts. Category III, "unsteady noise," covers traffic and subsonic aircraft noise and is actually more concerned with noise "events" rather than with "impulses." In one sense, however, the first and last categories are similar, differing basically in the time scale of and between "events" and in the crest factor or ratio of maximum peak pressure to rms pressure.

In the studies cited, correction factors were developed to account for annoyance on the basis of one or more features of the impulsive sounds: number or frequency of impulses, amplitude, fluctuation (rate of change in amplitude), and duration. Some investigators proposed correction factors which were applicable to impulsive noise in general, independent of its characteristics.[11, 11a, 11b] Thus, Eldred[11] and ISO R1996[11a] propose a 5 dB correction should be added to any community noise which is

Table 4

A Summary of Literature on Annoyance Responses to Impulsive Noise (Excluding Studies for Helicopter Blade Slap)

Noise Type	Author	Date	No. of Subjects	Noise Source		Parameters		Measurements		Results		
				Test	Reference	Varied	Constant	Subjective	Objective	Base Scale	Impulse Correction(b)	Response Scale
I Repetitive Pulses	Plutchik[1]	1957	4	Tone Burst	None	Frequency Repetition Rate, dB	Duration	Just Noticeable Unpleasantness	Attenuation in dB	-	-	-
	Keighley[8]	1970	1902	Live Office	None	-	-	Acceptability	Peak Index (PI) Average dBA	Average L_A	$3.52(PI)^{1/2}$, dB(c)	Acceptability
	Anderson, Robinson[10]	1971	24	Recorded Road Drill	None	Duration and Number of Bursts	Bkgd Level Exposure Duration	Adjective Pair (11 Point Comparison)	L_{eq}	L_{eq}	4σ, dB(d)	Annoyance
	Eldred ISO-R 1996[11a]	1971	-	Community Noises	None	Source, Level, Site	-	Community Complaints	L_{eq}	L_{eq}	5 dB	Community Noise Equivalent Level
	Fuchs[13]	1972	100	Recorded Handclap	Tone Burst	Handclap SPL Tone Burst Duration	Handclap Duration	Annoyance	L_A	L_A	-	Annoyance
II Single Impulse	Broadbent, Robinson[2]	1964	79	Jet, Prop A/C Sonic Boom	Jet	Level Source	Duration	Annoyance Rating	L_{PN}	L_{PN}	(e)	Annoyance
	Borsky[3]	1965	3000	Live Sonic Boom	None	Overpressure (psf)	-	Annoyance	Overpressure Probability of psf	-	-	-
	Kryter[7]	1970	-	Sonic Boom	Subsonic Jet	-	-	Unacceptability	L_{PN}	EPNL	$\frac{25}{70}(\Delta L_{PN})$, dB(f)	Unacceptability
	Schomer[16]	1973	-	Artillery, Surface Blasts, Sonic Boom	None	-	-	Annoyance Complaints	CNR	EPNL	$10 \log_{10} N$, dB	Community Response
	CHABA WG #69[21]	1975	-	Artillery, Blasts, Sonic Boom	-	-	-	Annoyance	L_{Cdn}	L_C	0 for C-weighted Levels	Community Response & Structural Vibration

Table 4 (Concluded)

Noise Type	Author	Date	No. of Subjects	Noise Source: Test	Noise Source: Reference	Parameters: Varied	Parameters: Constant	Measurements: Subjective	Measurements: Objective	Results: Base Scale	Results: Impulse Correction[b]	Results: Response Scale
III Unsteady Noise	Robinson[6, 9]	1969	-	Traffic/ Aircraft	-	-	Theory		-	L_{eq}	2.56 σ, dB	Annoyance
	Parry, Parry[12]	1972	-	Aircraft	-	-	Theory		-	PNL	0 (Duration)	Acceptability
	Fuller, Robinson[15]	1973	24	Traffic	None	L_A(max)	Event Duration, Frequency	Annoyance	L_{NP}	L_{eq}	2.56 σ, dB	Annoyance
	Matschat, Muller, Zimmerman[14]	1973	352	Live Aircraft	None	Level, Duration, and Frequency of Events	-	Tolerability, Activity Disturbance, Annoyance	L, L_{eq}, NNI, L_{NP}	L_{eq}	$\int\left(\frac{dL(t)}{dt}\right)^2 dt$ [g]	General Subjective Reaction to Noise

(a) Based on concepts by Rosenblith and Stevens as cited in Reference 11.

(b) Except as noted, equal to subjective correction factor Δ_s, in dB, to correct for subjective response to impulsive noise.

(c) PI, the Peak Index, is the sum of number of impulses which are 5, 10, 15 and 20 dB above L_{eq} in 1 minute sample.

(d) σ = Temporal Standard Deviation.

(e) Sonic boom, with L_C = 116 dB indoors equally annoying as jet noise outdoors with L_{PN} = 110 PNdB.

(f) ΔL_{PN} = Difference in L_{PN}, in PNdB, between impulsive sound and background noise, respectively.

(g) Correction proportional to mean square rate of level fluctuation.

deemed impulsive, while ISO R 1999[11b] recommends a fixed 10 dB correction be applied to assess the hearing damage risk of impulsive noise.

In most cases, as noted in Table 4, the various subjective correction factors developed from the referenced studies are added to the measured L_{eq} of an impulsive noise in order to obtain the effective L_{eq} of a nonimpulsive noise that will produce the same annoyance. For one method, however, the correction is not to be added to L_{eq} but rather to the Effective Perceived Noise Level (EPNL).[7] It might be assumed that this correction factor proposed by Kryter could also be applied to the L_{eq} scale. Another correction method (developed by CHABA Working Group 69)[21] involves the prediction of annoyance that may, in part, be due to building vibration induced by impulsive sounds. Since this response is potentially quite important for large amplitude impulsive sounds and since it is not treated in any of the other studies, it is also included in the table. However, as clearly pointed out by the CHABA Working Group, the concept, based on the use of a C-weighted L_{eq} without further correction, was designed to be applicable only to single high intensity impulsive sounds with a peak sound pressure level above 100 to 110 dB – well above the peak sound level range of concern in this report.

In investigations of repetitive impulses, Category I, much of the emphasis has been on how the level of the impulses fluctuates over time, or equivalently, what is the probability density function of the impulsive noise. Two correction factors, based on fluctuation, identified in Table 4, are the peak index (PI), proposed by Keighley[8] for rating acceptability of office noise, and a measure proportional to the temporal standard deviation, σ, proposed by Anderson and Robinson[10] for application to impulsive noises superimposed on steady random background noise. The peak index (PI) measures the number of impulses in the sampling period at various peak levels while the standard deviation measures only the rms variation about the mean – the rate of impulses is not accounted for.

For investigations of single impulses, Category II, the number of impulses in the sampling period[16] and the level of impulses above the background level[7] are the main considerations. A scale which incorporates both types of corrections into one number may be needed for general application to Category II type impulsive sounds.

In investigations of unsteady noise (i.e., Category III noise), the primary concern appears to be in the degree and rate of noise level fluctuation. Matschat, et al,[14] use a time-averaged measure of the rate of change of level while Robinson, et al,[6, 9, 15] use the average standard deviation of the level. These are not unrelated since the former can be considered an approximate measure of the mean frequency of the latter. The duration of fluctuating or repeated single noise events (specifically aircraft noise) was found to be inconsequential by Parry and Parry[12] contrary to the conclusions of Kryter[7] and others. Although these conflicting conclusions about the effect of duration have never been fully resolved, the currently accepted practice is to assume that an energy summation of noise events should be employed in rating their noise impact. Thus, for Category III noises, this is equivalent to a rule that the effective noise level will increase directly as the duration (or more exactly as 10 log (duration)). For multiple events of fixed effective duration t_e, the equivalent duration correction is $10 \log t_e + 10 \log N$, where N is the number of events.

To summarize so far, the previous studies on impulsive correction factors for annoyance of other than helicopter blade slap lead to several choices for the form and magnitude of subjective correction factor. The form varies from a constant value to a variable dependent upon, for example, the relative magnitude, rate of occurrence, or rate of fluctuation of the impulsive sound.

The magnitude of the correction factor for annoyance will vary widely according to these concepts covering a range of as much as 30 dB. A more definitive evaluation of the magnitude of Δ_s for annoyance for the four impulsive sources of concern for this report is developed in section (4). It is shown that, based on several of the concepts summarized in Table 4, the value of Δ_s varies from 0 to 28 dB; the latter value is based on the use of Keighley's[8] peak index concept and is probably too high. More reasonable values of Δ_s are shown to fall in the range of 5 to 13 dB.

3.2.2 Helicopter Blade Slap Noise

Helicopter blade slap is a troublesome impulsive noise source which has received a great deal of attention as to causes and effects.[81] This attention has focused, most recently, upon the practical problems associated with noise certification of helicopters. It is, to a large extent, this more recent work which is briefly reviewed here. Major aspects of 14 studies involving measurements of subjective response to helicopter noise are summarized in Table 5.

The first study, by Pearsons,[3a] did not consider blade slap per se but only attempted to rate various momentary noise descriptors as to their accuracy for predicting the relative noisiness of helicopter sounds. As indicated in the last column of Table 5, the Perceived Noise Level metric appeared to be superior over others. Leverton[11c] made, perhaps, the first attempt to quantify a blade slap correction factor for helicopters and found that the A-weighted noise level from nonslapping helicopters had to be increased 4 to 8 dBA above the A-weighted noise level from helicopters with blade slap to achieve the same annoyance in a simulated living room listening situation. This would imply an average subjective correction for annoyance from blade slap of +6 dB.

Munch and King[17] found a subjective correction factor to the sound exposure level to predict annoyance of blade slap that increased linearly from +6 dB to +13 dB as the crest level of the recorded helicopter noise signature increased from 14 to 21 dB. The correction factor did not increase beyond 13 for higher crest levels.

Berry, Rennie and Fuller[18] evaluated methods of measuring relative impulsiveness of blade slap and found the following typical crest levels for varying degrees of impulsiveness.

Slightly Impulsive	Crest Level = 5-10 dB
Moderately Impulsive	Crest Level = 10-15 dB
Very Impulsive	Crest Level $\simeq$ 20 dB

Table 5

Summary of Recent Studies of Helicopter Blade Slap Noise Including Summary of Subjective Correction Factor For Impulsiveness

Investigator	Date (Ref)	No. of Subjects	Helicopter Noise Source	Parameters		Measurements		Results	
				Base Scale	Parameters Varied	Subjective	Objective	Correction	Human Response
Pearsons[a]	Jan. 1967 (3a)	21	Recorded Comparison w/Jet Noise	Reference Jet Noise	L_C, L_A, L_N, L_{PN}, Dur_{10}, Dur_{20}	Noisiness Comparisons	L_C, L_A, L_N, L_{PN}, Dur_{10}, Dur_{20}	-	Order of Appropriateness: L_{PN}, L_N, L_A, L_C. Duration and pure-tone corrections did not improve prediction.
Leverton	Mar. 1972 (11c)	?	Recorded	L_A	L_A	Annoyance Comparisons	Measured[b] Comparisons	4-8 dB (Subjective)	Impulsive helicopters, subjectively 4-8 dB more annoying than nonbanging helicopters.
Munch and King	1974 (17)	?	Recorded	L_s	L_s Crest Level	Extent of Blade Slap	L_s Crest Level	6-13 dB (Varies with Crest Level)	No reliable correction between annoyance and impulsiveness.
Berry, Rennie, Fuller	Oct. 1975 (18)	20	Recorded	L_{PN}	Time Constraints (used in Integrals)	Degree of Impulsiveness	L_{PN} Impulsiveness	-	Impulsiveness was <u>not</u> overriding factor in judging annoyance. Less impulsive signals frequently judged rougher, more irregular and less predictive.
Man-Acoustics	July 1976 (18a)	12 24	Simulated Simulated	L_A, L_s L_{PN}, EPNL	$L_{A(max)}$, Impulsiveness Rate Level Impulsiveness	Annoyance Annoyance	L_s Corrected) EPNL	<0 1 to 4 dB	Pilot study showed negative correction (Not statistically significant). Correction increased with degree of subjectively judged impulsiveness.
Lawton	Dec. 1976 (19)	40	Acoustical Simulation w/Continuous and Impulse Noise	L_C, L_A, L_{PN}	No. of Sine Waves per Single Impulse, Frequency of Sine Waves, Impulse Repetition Frequency, SPL Continuous and Crest Factor	Annoyance	L_C, L_A, L_{PN}	Approximately 2 dB	Three base scales underestimate annoyance 2 dB.

Table 5 (Concluded)

Investigator	Date (Ref)	No. of Subjects	Helicopter Noise Source	Parameters		Measurements		Results	
				Base Scale	Parameters Varied	Subjective	Objective	Correction	Human Response
Patterson, Mozo, Schomer, Camp	May 1977 (22)	25	Real	L_s, EPNL, L_B, L_C, L_{D2}	Base Parameters	Annoyance	Base Parameters	0 dB	No correction for blade slap required. No substantial penalty for helicopters compared to fixed wing aircraft. SEL is equivalent predictor to L_{D2} and EPNL.
Galloway[d]	Dec. 1977 (23)	20	Recorded Sound Simulation	EPNL	Components of the Simulated Sound	Relative Annoyance	EPNL per FAR Part 36, EPNL plus High Sample Rate, Crest Level	4-5 dB	EPNL underestimates annoyance by 4 to 5 dB. Impulsiveness plus repetition rate adjustments give good prediction of correction factor.
Galanter, Popper, Perera	Dec. 1977 (24)	40	Recorded Comparison with Recorded Fixed Wing Aircraft	EPNL	EPNL, L_A Crest Level	Annoyance	EPNL, Crest Level	4-5 dB	Helicopters were rated 4 to 5 dB more annoying than commercial jet aircraft. Crest level correlated better with EPNL than A-Wtd. SPL.
Leverton, Southwood, Pike	1978 (24b)	?	Recorded Sound Simulation	EPNL	EPNL, Crest Level	Annoyance	EPNL, Crest Level	0-6 dB Depending on Crest Level	Corrections are needed for both main rotor blade slap and tail rotor.
Powell	July 1978 (24c)	91	Real Comparison with Real Fixed Wing Aircraft	EPNL	EPNL, Crest Level	Noisiness in Terms of Unwanted Objectiveness, etc.	EPNL, Crest Level L_A at High Sample Rate	None established (-2 dB for EPNL, +2 dB for $L_{A(max)}$)	Neither ISO proposal nor A-weighted crest level correction adequately predicted noisiness. More impulsive helicopter was judged less noisy than less impulsive helicopter.
F. d'Ambra, A. Damongeot	1978 (24d)	60	Recorded Sound Simulation	L_{PN}	Mix Broadband Noise with Real Helicopter Impulse Signals	Annoyance	L_{PN}, L_A at High Sample Rate	$\Delta_s = 2.8$ dB[e]	The ISO method of correction (defined in Ref. 24a) is considered best annoyance descriptor.
Klump, Schmidt	1978 (24e)	28	Recorded Sound Simulation	L_A	$L_{A(max)}$, Degree of Blade Slap	Annoyance	L_A, Crest Level	1.5-2.5 dB	Correction based on relative annoyance of 7 sec Samples in lab setting.
Sternfeld, Doyle	June 1978 (24f)	25	Simulated Broadband + Recorded Helicopter Impulses - By Earphones	L_A	L_A, Relative Impulsiveness	Annoyance	L_A, $L_C - L_A$, Crest Level	2.5-5 dB	Correction based on Wyle interpretation of authors' method of adjustment data.

Footnotes:

(a) No blade slap data.
(b) Between impulsive and nonimpulsive helicopters.
(c) A "Blade Slap Factor" (BSF) is defined to rate blade slap strength.
(d) This report attempts to close the gap between simulated and real helicopter noise.
(e) An equation is given for EPNL correction that is related to a digitized set of samples. A high sample rate is used. See text of reference.

Their data relating crest level and judged relative degree of impulsiveness are compared in Figure 17 with similar data from Leverton[76] and Munch and King.[17] A consistent trend is apparent indicating crest level is a reasonably good predictor of relative impulsiveness. However, Berry, et al,[18] found quite a different story when they attempted to predict relative annoyance of blade slap noise with the same objective measure. Figure 18 shows the relative rank order rating of judged annoyance of two groups of helicopter noises with varying degrees of objectively and subjectively observed "blade slap." The experimenters found that there was not a reliable correlation between them; in fact, the subjects seemed more responsive to the "roughness" quality of the sound than to blade slap per se as a measure of its annoyance. As was pointed out earlier, Reichardt and Niese observed a similar problem relative to subjective response to repetitive impulsive sounds.[61] Thus, according to this limited set of data, crest level may not be a reliable predictor for rating annoyance of impulsive noises.

Mabry, et al,[18a] measured the relative annoyance of simulated and recorded real helicopter sounds with varying degrees of blade slap in a laboratory setting and found that duration corrected noise level (using the Perceived Noise Level or A-weighted noise metrics) correctly measured the annoyance response with little or no additional correction required for blade slap. However, simulated helicopter sounds with subjectively judged "light," "moderate," and "heavy" blade slap were about 1, 2, and 4 dB more annoying, respectively, in terms of EPNL values, than a reference nonslapping helicopter simulation.

Lawton,[19] in an extensive laboratory investigation of continuous noises and simulated helicopter sounds, found that Perceived Noise Level, A-weighted level and overall sound level measures of simulated blade slap noise all underestimated the levels that would produce the same annoyance as a steady sound by about 2 dB. Patterson, et al,[22] using real helicopters, found that no correction factor was required to correct for blade slap when helicopter sounds were measured in terms of time-integrated A-weighted level (Sound Exposure Level, L_s) or comparable metrics such as EPNL.

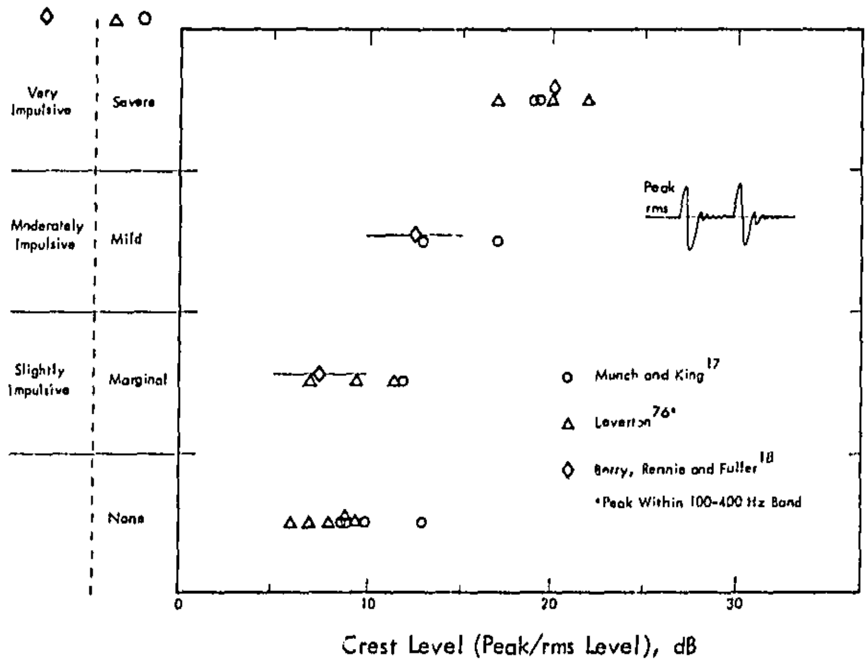


Figure 17. Correlation of Judged Degree of Helicopter Blade Slap Versus Crest Level

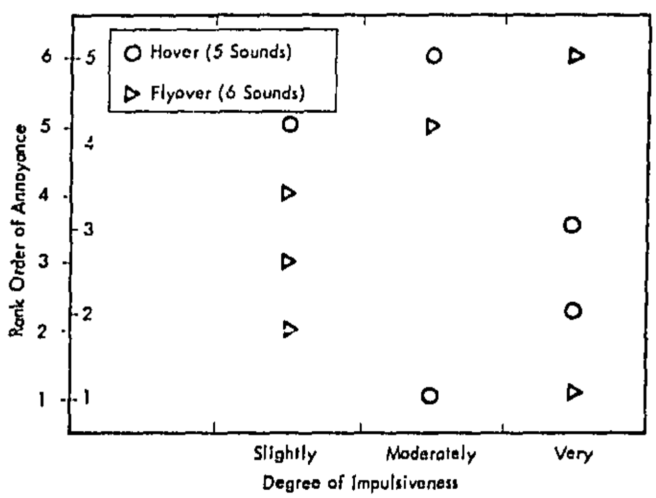


Figure 18. Illustration from Two Groups of Helicopter Blade Slap Data That Rank Order of Annoyance Does Not Correlate with Judged Impulsiveness (From Berry, Rennie and Fuller)[18]

Galloway,[23, 24a] using both recorded and real helicopter sounds, evaluated tentative proposals by the British, French and the U.S.A. to the International Civil Aviation Authority (ICAO) and the International Standardization Organization (ISO) for blade slap penalty factors for helicopter noise certification. These are intended to account for subjective response to blade slap and were proposed to correct measured Effective Perceived Noise Levels of helicopter noise. The observed penalty factors for equal annoyance for eight real helicopter sounds was 4 dB and 2 to 5 dB respectively for two different types of simulated helicopter sounds. When each of the objective correction methods proposed by ISO, which provided a measure of signal impulsiveness only, were adjusted by Galloway[23] according to the rate of blade slap impulses, they predicted the observed subjective correction factors quite well.

Galanter, et al,[24] found subjective correction factors of 4 to 5 dB to equate annoyance of helicopters with conventional jet aircraft when both are measured in terms of EPNL. In other words, the EPNL of the helicopter sound would have to be about 4 to 5 below that of the CTOL aircraft for equal annoyance. In more recent studies, Leverton, et al,[24b] have explored both blade slap correction factors and a potential additional subjective correction factor to account for the pseudo-impulsive nature of tail rotor noise. For the former, a correction factor varying linearly from 0 to 6 dB as "crest level" varies from 11 dB to 20 dB is recommended to explain results of subjective tests for blade slap annoyance. (Crest level, in this case, is measured by the difference between the peak level in the 250 Hz octave band and the A-weighted, Slow level.)

An extensive series of field tests by Powell[24c] using 90 subjects exposed indoors and outdoors to two different real helicopters and a small fixed wing propeller aircraft demonstrated that:

1. No significant improvement in noisiness predictability of EPNL was provided by either an ISO-proposed correction factor or an A-weighted crest level correction for impulsiveness.

2. For equal EPNL, the more impulsive helicopter was consistently judged less noisy than was the less impulsive helicopter (i.e., Δ_s was negative).

The latter anomalous result might be attributable to the fact that the subjects were asked to rate relative noisiness instead of relative annoyance although their instructions implied unwantedness, objectionability, etc. as measures of noisiness. Based on Powell's data, a blade slap penalty factor to be applied to EPNL would actually be negative. (The actual value was about -2 dB; however, the penalty, or subjective correction, factor was about +2 dB when applied to maximum A-weighted levels.)

In contrast, the study, by d'Ambra and Damongeot,[24d] carried out to validate the latest ISO proposal for computing a blade slap correction factor, shows a small but finite subjective correction factor for annoyance of 2.8 dB based on the average result for 20 flights and 60 subjects.

In the study by Klump and Schmidt,[24e] subjective responses to short recorded (17 sec) samples of helicopter sounds, presented in a laboratory setting, were measured and consistent evidence was found for an impulse correction factor, when applied to A-weighted levels, of about +2 dB.

For the last study considered, by Sternfeld and Doyle,[24f] a subjective correction factor could only be estimated due to the unique experimental (method of adjustment) and data analysis techniques employed so the results are not included in the following summary. However, the values of Δ_s estimated from their study do agree very well with the average of the other studies.

The findings from these helicopter noise studies, which are pertinent to this report, can be summarized as follows:

- The mean <u>observed</u> blade slap correction or penalty factor (assumed roughly equivalent to the subjective correction factor Δ_s) was 3.3 dB ±2.7 dB for the 11 studies which measured this quantity directly. However, three of these 11 studies found essentially a zero or negative correction. The maximum correction for moderate blade slap (i.e., crest level of 10 to 15 dB) was about 6 dB. The maximum correction for severe blade slap (i.e., crest level about 20 dB) was 13 dB, comparable to the values measured for a variety of nonhelicopter sounds.

- The methods recently proposed to objectively compute a blade slap correction factor do not appear to agree consistently with the correction factors measured subjectively to account for annoyance of blade slap. Galloway shows that improved results are obtained if some modification is made to account for variations in the frequency of the blade slap.[23] He shows results from one series of tests indicating Δ_s can change from about 2 dB for a slap repetition rate of 10 Hz to 7 dB for a rate of 30 Hz. This effect may explain part of the wide range in measured correction factors. This dependency on repetition rates in this frequency range also suggests that the "correction factor" may, in part, arise from inherent errors in perceived noise level computations for signals with significant energy below 50 Hz.

- The proposed objective means for predicting a subjective correction factor depend on some means of measuring the relative impulsiveness. The proposed methods vary from a simple measurement of the crest level of the A-weighted noise level[23, 24a] to more complex procedures involving sampling the detected signal (e.g., instantaneous A-weighted level) at a high rate (~5000 Hz) and computing a measure of mean square fluctuation level from these samples.

- Finally, it is desirable to attempt some degree of resolution of the differences in blade slap correction factors that evolved from the various studies summarized in this section. Any attempt in this direction must first recognize the substantial differences in experimental techniques involved in the studies. Perhaps most important of all was the variation in signal presentation. It varied from presentation to subjects in a laboratory setting of simulated or recorded real helicopter sounds lasting for only a short period or for a complete flyby, to exposing subjects in the field to actual helicopter flyby noise. A review of the various results seems to indicate that any "impulse" correction factor may be partially masked or substantially reduced in real field tests where subjects were exposed to the relatively long duration of the helicopter flyby. Thus, larger duration corrections which are, in fact, characteristic of helicopter noise, may serve to partially mask out the potentially added annoyance of blade slap. Thus, results of those studies on subjective response to helicopter blade slap probably cannot be used directly to accurately define the magnitude of a correction factor for impulsive noise alone.

So far, results have been presented on measured subjective correction factors to account for either the relative annoyance or loudness of impulsive sounds. The next section attempts to show how these potentially different responses may be related.

3.2.3 Loudness Versus Annoyance of Impulsive Sounds

The limited data dealing with comparison of annoyance versus loudness responses to impulsive noises come from controlled laboratory tests. In an early laboratory study, Reese, Kryter, and Stevens[83] found some evidence, shown in Figure 19, that high frequencies, above 2000 Hz, were somewhat more annoying than indicated by their loudness. However, the data are limited and exhibit considerable scatter. Parnell, et al,[88] found no such indication in their studies of response to bands of noise. Niese[86] also found no distinction between loudness and annoyance response for a wide variety of steady-state sounds but did find a difference between loudness and annoyance when one-third octave bands of noise were presented as impulses. Shepherd and Sutherland[58] found that judged loudness and annoyance responses to simulated sonic booms were the same for all cases except for the highest values of rise time investigated (i.e., 10 ms). In this case, a slight decrease in annoyance was noted relative to the loudness response. This can be interpreted to support Reese, Kryter and Stevens' data

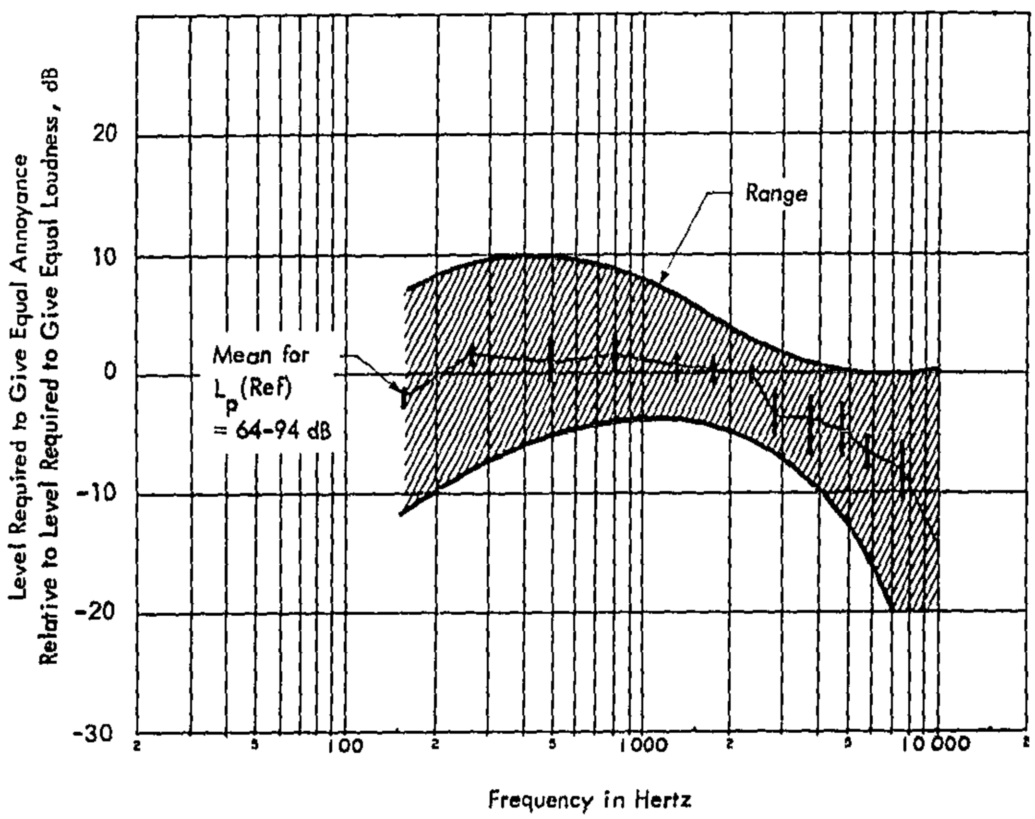


Figure 19. Comparison of Noise Levels for Equal Annoyance Versus Equal Loudness (From Reese, Kryter, and Stevens[83])

indicating high frequencies are more annoying at the same loudness. An increase in sonic boom rise time would tend to reduce high frequency content and hence reduce annoyance more rapidly than loudness.

Rothauser, et al,[4a] investigated both annoyance and loudness judgments of a panel to recorded typewriter sounds. They found that for keystroke rates less than 10 per second, a typewriter noise that was adjusted to be equally loud as a reference wideband noise with a similar spectrum, had to be decreased in level about 2 dB to be judged equally annoying. This would indicate a +2 dB correction to loudness criteria for repetitive impulsive sounds like typewriters at repetition rates less than 10 per second.

Fuchs,[13] in a brief study of response to single handclap sounds, observed that his subjects rated the claps about 5 to 6 dB more annoying than an equally loud tone burst of comparable duration.

To summarize, laboratory data do not clearly support a significant difference between loudness and annoyance of nonimpulsive sounds, but there appears to be a consistent indication that there is a small positive difference between the annoyance and loudness of many typical impulsive sounds. An annoyance correction of +3 dB to a loudness-based subjective correction factor appears reasonable for repetitive impulses with a rate less than 10 pps with zero correction at higher repetition rates.

<u>Summary</u>

So far, several possible approaches to the development of a subjective correction factor Δ_s to be added to L_{eq} to account for annoyance effects have been suggested:

- Computation from previously developed impulsive noise - annoyance correction factors as outlined in this section.

- Estimation from data on loudness of impulsive noise in terms of the impulse signal parameters such as duty cycle and ratio of pulse amplitude to background noise (see Figure 10).
- Application of the ISO Round Robin or Fidell and Pearsons' data to define Δ_s (see Section 3.1.6.1 and Appendix B).
- Application of existing loudness computation methods (i.e., Stevens, Mark VI or VII, or Zwicker), possibly modified for an annoyance (startle) effect of impulsive noise to compute Δ_s.
- Application of the new approach suggested by Izumi (see Section 3.1.5).

To a large extent, the data for subjective correction factors for impulsive noise are based on artifical listening situations in a laboratory and are thus subject to certain limitations. First, subjects who rated "annoyance," loudness or noisiness of impulsive sounds normally did so only while concentrating on the listening task and were not burdened with other stimuli or tasks. Secondly, no objective (e.g., physiological) measures of the subjects' response were made. Nevertheless, sufficient information appears to be available to provide the basis for a subjective correction for evaluation of impulsive noise. Before developing this, however, it is desirable to briefly outline the other effects of impulsive noise which have not been discussed and which could conceivably influence the selection of a subjective correction.

3.2.4 Other Subjective Effects of Impulsive Noise

3.2.4.1 Impulsive Noise and Models for the Hearing Process

Returning briefly to our conceptual model for hearing illustrated earlier in Figure 4, there are other features to this model related to audition of impulsive noise which have not been mentioned. The significant effect of head diffraction on modifying the pressure-time history on an incident sound field that reaches the ear has been clearly reviewed by Shaw.[95] Related models for acoustic resonances, in the external ear, analyzed by Teranishi and Shaw,[92] identify the major resonances which will further modify the pressure signature transmitted to the middle ear. The combined transmission response of all of these elements, including the middle ear, add up to a major factor which shapes the spectrum of the pressure signal processed in the inner ear. As shown in Figure 20, this influence will be dominant in the high frequency range (above 1000 Hz) where many impulsive noises tend to have their dominant spectral content. Thus, subject-to-subject variation in these elements of the auditory process will be more significant in considering measurement and evaluation of impulsive noise than is the case for most other major noise sources which tend to have their energy concentrated at low frequencies.

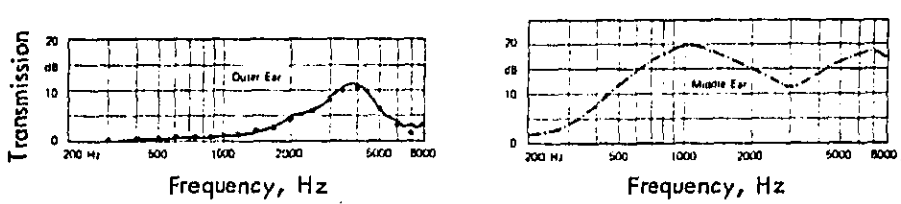


Figure 20. Typical Transmission Response of the Outer and Middle Ear (Adopted from Bruel)[146]

The simplistic elements for the detection and processing of auditory signals, illustrated earlier in Figure 4, do not really represent the more advanced approaches to this subject such as represented by the more detailed studies on auditory detection theory.[84, 85, 90, 91, 94] This work has potential bearing on the selection of an optimum "time constant" model for application to optimum methods for measuring impulsive noise. For example, the choice of the same "time constant" for both build-up and decay of transient sounds is not necessarily well-founded by either theory or observation (e.g., References 30, 56 and 91).

3.2.4.2 Speech Interference From Impulsive Sounds

Reference materials for the interference of speech from impulsive sounds are listed in References 96 to 106.

An empirical analysis of speech interference from intermittent sounds, presented in the EPA "Criteria" document,[106] indicated that for steady and intermittent sounds of the same Energy Equivalent Level (L_{eq}) the speech interference of intermittent sound could be greater than that for steady sound under certain conditions. A more detailed analysis of speech interference of intermittent sounds using ANSI Standard methods[100] indicates that intermittent sounds should always exhibit substantially less speech interference than a non-intermittent sound with the same L_{eq}. This is due, in part, to the fact that the ANSI Standard includes a positive noise on-time correction to the articulation index obtained from a steady-state masking noise. Thus, speech interference effects do not appear to be the basis for any positive impulsive noise correction factor.

3.2.4.3 Sleep Interference From Impulsive Sounds

The effects of acoustic stimulation on sleep depend on several factors:[106]

1. The nature of the stimulus.
2. The stage of sleep.
3. Instructions to the subject and his psychophysiological and motivational state.
4. Individual differences, e.g., sex, age, physical condition, and psychopathology.

Due to the complex nature of the effects of noise on sleep, no attempt will be made to elaborate on the sleep interference from impulsive sounds. However, pertinent material on this subject can be found in References 107 to 111. It should only be mentioned that the current use of a 10 dB penalty for assessing noise exposure at night[21, 105] may not be entirely adequate for evaluating nighttime exposure to impulsive noise due to the potential for greater disturbance to sleep.

3.2.4.4 Hearing Loss Due to Impulsive Sounds

Both the energy principle and TTS_2 (temporary threshold shift 2 minutes after cessation of noise exposure) have been utilized to derive damage risk criteria for impulsive noise exposure.[121, 130] Any discussion on the divergence of opinion on these two methods is beyond the scope of this report. However, the topic is covered in References 112 to 130. The CHABA damage risk criterion (1968)[119] and its later modified version[130] are shown in Figure 21 to indicate the general magnitude of the acceptable pressure level as a function of impulse duration for a normal incidence condition at a normalized repetition rate. Therefore, the evaluation of hearing damage due to impulsive sounds involves the measurement of the peak sound pressure level and its time history. So far as is known, no attempt has been made to relate the type of predictive information concerning hearing damage risk of impulsive sounds, contained in Figure 21, to nontraumatic responses such as annoyance or loudness.

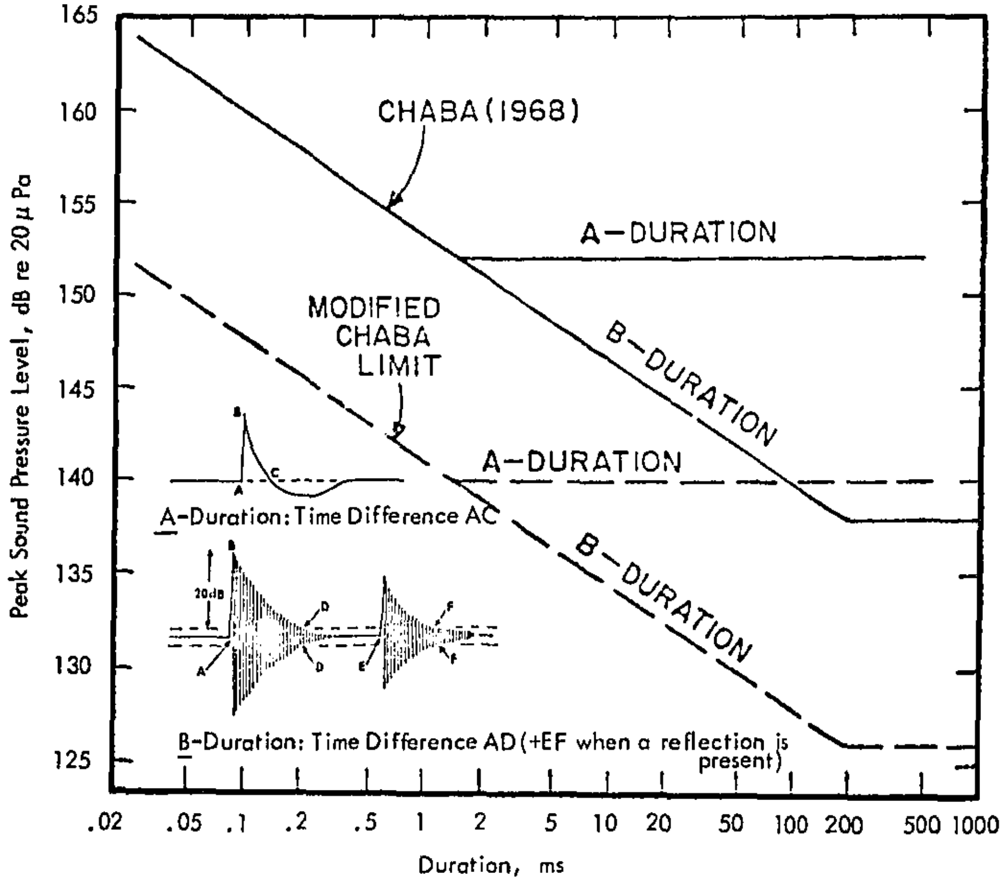


Figure 21. The 1968 CHABA Damage-Risk Criterion for Impulsive Noise Exposure (Solid Lines) and a Proposed Modification (Dashed Lines) for a Nominal Exposure of 100 Impulses Per Day at Normal Incidence. Peak Sound Pressure Level is Expressed as a Function of A- or B-Duration in the Range 25 Microseconds to 1 Second (Adopted from Reference 130)

4.0 CONCLUSION: SUBJECTIVE CORRECTION FACTORS FOR EVALUATION OF IMPULSIVE NOISE

The approaches toward the development of subjective correction factors for evaluation of impulsive noise are reviewed in this section and conclusions are drawn concerning a method to account for the difference in subjective response between impulsive and nonimpulsive sounds. The method is necessarily based on the type of psychoacoustic response data available for impulsive sounds and does not necessarily include other aspects of the subjective response due to factors such as startle effects or emotional reaction to impulsive sounds.

4.1 Subjective Correction Factor Δ_s

The various approaches considered in Section 3 for the development of Δ_s were based on: (1) computation from previously proposed annoyance correction factors; (2) estimation from data on loudness response to impulsive noise; (3) application of the ISO Round Robin[66, 67, 77], Fidell-Pearson[64] or Izumi[82] data; or (4) application of some form of loudness computation method. These candidate approaches are compared in this section.

4.1.1 Subjective Correction Factors Based on Loudness Response Data for Tone and Noise Bursts

The laboratory data on tone and noise bursts can be used only for rough estimates of the subjective correction factor due to the large difference between the test signals employed and the real impulsive sounds of concern here. Nevertheless, based on the limited information on the impulsive noise sources in Section 2, the following rough estimate for Δ_s can be made. These estimates do not include any consideration of a possible increase in annoyance response over loudness response.

Noise Source	Basis for Correction	Δ_s, dB
Motorcycles	Repeated Tone Bursts (Figure 7)	4-12
Drop Hammers	Repeated Tone Bursts (Figure 7)	4-6
All Sources	Repeated Noise Bursts (Figure 10)	4-14
All Sources	Repeated Noise Bursts (Figure 11)	3-9
	Mean of Range	4-10 dB

Attempting to estimate values of Δ_s from these data necessarily involves considerable uncertainty and seems to indicate lower values than expected. However, it should be recalled that in one case (Gamer[31]), the observed values of loudness for repeated tone bursts were very well predicted by loudness calculations.

4.1.2 Subjective Correction Factors Based on Measured Loudness of Real Impulsive Noise Sources

ISO Round Robin Data

The extensive ISO Round Robin data on Δ_s summarized in Appendix B lead to an average value for Δ_s of 12.5 ±0.9 dB over all of the nine real impulsive sound tests. Based on selecting values of Δ_s from the specific ISO sources that relate, approximately, to the sources considered in this study, the following estimates are obtained. The values of Δ_s are rounded values from the ISO data in Table B-2 of Appendix B.

ISO Impulsive Source	This Report	Estimated Δ_s, dB
Outboard Motor	Motorcycle	13
Compressed Air Drill	Rock Drill	14
Cement Mill	Garbage Compactor	11-12
Mechanical Ram	Drop Hammer	11-12

There is little justification for this attempt to pair-off the ISO and the four specific sources identified in Section 2, since differences in noise signature may be extensive. Thus, a single average number of 12.5 dB for Δ_s is considered a representative result from the ISO data applicable to the sources considered for this report.

Fidell-Pearsons Data

From Figure 16, the average Δ_s for the 12 impulsive noise sources listed in Table 3 was 12.5 dB with a standard deviation of ±3.5 dB. Most of the 12 sources studies differed substantially from those of concern here so that the direct applicability of this value to the source in this report is questionable.

Izumi Data

As discussed in Section 3.1.5, Izumi has proposed a method for predicting an effective burst level according to a noisiness response which seems to agree well with subjective judgments (see Figure 14). Unfortunately, the parameters required by his predictive model defined in Eq.(5) were not available with sufficient accuracy to permit application of the model for this report. However, as noted in Figure 14, his data do show that the average difference (Δ_s) between the subjectively effective and measured L_{eq} for his 25 intermittent noises was 13.5 dB. This number may be compared to the value of 12.5 dB from Fidell and Pearsons.

4.1.3 Subjective Correction Factors Based on Annoyance

Several methods to directly account for the annoyance effect of impulsive noise were outlined in Section 3.2. To determine both the applicability and the validity of the various correction schemes proposed for repetitive impulses – shown earlier in Table 4 – corrections were calculated with some of these procedures for the four sources of repetitive impulsive noise of concern for this report and for which data were available.

Three correction schemes, considered in Section 3.2, were applied to the real impulsive noise sources: (1) Crest Factor (or Crest Level when expressed in decibels); (2) Peak Index; and (3) Standard Deviation.

Crest Level Method

The first correction scheme, based on the Crest Level (C.L.), has been previously proposed to predict a helicopter blade slap (subjective) correction factor by Munch and King[17] and Galloway[23], as discussed earlier in Section 3.2.2. For Munch and King, Δ_s was given by:

From Munch and King,

$$\Delta_s = \begin{cases} 0 \text{ dB for C.L.} < 14 \text{ dB} \\ \text{C.L.} - 8 \text{ dB for C.L.} = 14 - 21 \text{ dB} \\ 13 \text{ dB for C.L.} > 21 \text{ dB} \end{cases} \quad (6)$$

where C.L. = Crest Level = L_A (peak) - L_A (rms), dB

Galloway's[23] results can be used to define two different predictive models for Δ_s. The first is based on only the Crest Level (C.L.) for A-weighted levels. The second is based on the addition of a pulse repetition rate (ν_0) modifier. Both of these "models" are based on the psychoacoustic tests conducted by Galloway and on his regression analysis. Acknowledging the preliminary nature of these results as pointed out by Galloway, they can be used to predict values of Δ_s as follows:

From Galloway

(Crest Level only) $\quad \Delta_s = -4 + 0.54\,(\text{C.L.})$, dB (7)

(Crest Level + Repetition Rate) $\quad \Delta_s = -5.9 + 0.46\,(\text{C.L.}) + 0.19\,(\nu_0)$, dB (8)

where C.L. = Crest Level = L_A (peak) - L_A (rms), dB

and ν_0 = pulse repetition rate, Hz.

Based on Galloway's rather limited data, which covered a range of 13.5 to 16 dB for C.L. and about 11 to 25 Hz for ν_0, his first expression could be replaced, for all practical purposes, by a simple linear equation, $\Delta_s = \text{C.L.} - 11$, dB, similar to that of Munch and King. Galloway also points out that the additive correction term for repetition rate is expected to reach a maximum value at 30 to 40 Hz and then decrease at higher repetition rates.

The Crest Level for the impulsive sources considered in this report was measured in the following manner. The tape-recorded test noise was fed into an impulse precision sound level meter (B&K 2204/5) and the highest value of the A-weighted SLOW response was read to define the maximum rms level (L_A (rms)) of the impulsive sound. The same signal was monitored on an oscilloscope and the maximum peak level L_A (peak) determined. The repetition rate was estimated from oscillographic records of the four noise sources (see Table 1, Section 2.1). The preceding expressions were then used to compute values of Δ_s. No attempt was made to apply the other impulsive noise correction method proposed by ISO for helicopter noise,[24] which requires that the A-weighted noise signal be sampled at a rate of 5000 samples per second.

Peak Index Method

The Peak Index correction method, proposed by Keighley[8] for office machine noise, was applied to each of the sample impulsive noise sources, with the exception of the motorcycle. The value of the Peak Index (PI) was derived by examining the time histories of the impulsive sounds on a graphic level recorder set to a writing speed of 125 dB/second. The number of peaks in 1 minute, which were at least 5, 10, 15, and 20 dB above the average graphic level reading, were tabulated and summed. The square root of this number, when multiplied by the constant 3.52, gives the value of Δ_s for this scheme. Motorcycle noise was not evaluated with this method because the time variation of the noise level was such that true peaks were not registered by the graphic level recorder at the pen-speed setting used.

Standard Deviation Methods

The Standard Deviation correction, proposed by Anderson and Robinson[10] for general impulsive noises, was also obtained using the graphic recorder, and again motorcycle noise was excluded because of its rapid time variation. Using a sampling period less than the duration of typical impulses for the other sources, the average levels for up to 100 successive periods were manually compiled from the graphic level recordings and tabulated in a histogram. From the histogram, the Standard Deviation of the A-weighted level was then calculated and multiplied by 4 to give the value of Δ_s as prescribed in Reference 10.

ISO R 1996 Method

The ISO R 1996[11a] correction of 5 dB is considered as a fourth method to be considered for predicting Δ_s.

Results

Table 6 provides a comparison of the results of applying the preceding schemes for predicting Δ_s for annoyance. For each impulsive noise source, the various values of Δ_s allow comparison between the various methods, even though their absolute validity remains dependent on direct psychophysical experiments involving the noises themselves.

It has already been pointed out in Section 3.2.2, that some of the studies on helicopter blade slap demonstrated that crest level was a reliable predictor of subjectively judged impulsiveness[18] but an unreliable predictor of annoyance.[18, 24c] Hence, values of Δ_s based on this parameter alone may not be reliable. However, when repetition rate is included, Galloway's data show a substantial improvement in the ability to predict a value of Δ_s in agreement with the observed value. His correlation coefficient increased from 0.42 (Δ_s predicted by crest level only) to 0.88 when the repetition rate correction was added, thus indicating the potential significance of this parameter for subjective response to impulsive sounds.

The fact that the Peak Index correction scheme necessitates a 1 minute sample may make it inapplicable for many passby or intermittent impulsive sounds. A similar correction based on a 10 to 20 second sample may be more practical in such cases. However, in the absence of any other supporting data, this method for predicting Δ_s is not considered further in this report.

For the remaining methods for predicting Δ_s, based on an annoyance response, the values of Δ_s ranged from 0 to 13 dB. The average over all the four sources and the three remaining prediction methods (i.e., Crest Level method with or without repetition rate adjustments, the Standard Deviation Method, and the ISO R 1996 method) is 7.2 dB.

Table 6

Comparison of Several Predicted Subjective Correction Factors for Annoyance Applied to the Four Impulsive Noise Sources

Correction Method	Impulsive Noise Source			
	Motorcycle	Drop Hammer	Truck-Mounted Garbage Compactor	Rock Drills
Crest Level - Value, dB[(d)]	13	30	19	19
Repetition Rate -Value, Hz[(d)]	10-40[(a)]	0.7	0.2	1
Δ_s, dB Munch & King[17] (Eq. 6)	0	13	11	11
Δ_s, dB Galloway[23] (Eq. 7)	3	12[(b)]	6	6
Δ_s, dB Galloway (Eq. 8)	2-8	8	3	3
Peak Index[8] Value	- (c)	63	21	-
Δ_s, dB	-	28	16	-
Standard Deviation[10] Value, dB	-	2.97	1.26	1.09
Δ_s, dB	-	12	5	4
ISO R 1996[11a] Δ_s, dB	5	5	5	5

(a) Assumed maximum repetition rate of 10-40 Hz for purposes of estimating maximum Δ_s according to Eq. 8.

(b) Computed value beyond range of Crest Level for Galloway's data.

(c) Data not available for computing Δ_s.

(d) Estimated from data in Table 1, page 2-9.

4.1.4 Summary of Methods for Computing the Subjective Correction Factor Δ_s

The values for Δ_s derived from most of the preceding methods are summarized in the following table. It was feasible to break down the comparison by the four noise sources only for methods based on annoyance.

Table 7

Summary of Subjective Correction Factor (Δ_s) Estimated from Existing Methods or Data, dB

Impulsive Noise Source	Annoyance[a]			Noisiness		Loudness	
	Crest Level[b]	Crest Level[c] Plus Repetition Rate	Standard Deviation	Fidell-Pearsons	Izumi	Tone/ Noise	ISO Round Robin
Motorcycle	0-3	2-8	-				
Drop Hammer	12-13	8	12	12.5 ±3.5	13.5 ±5.5	7 ±2.5	12.5 ±0.9
Truck-Mounted Garbage Compactor	6-11	3	5				
Rock Drill	6-11	3	4				
Average	6.7±4.1			13.0		7	12.5

(a) See Table 6.
(b) Based on Munch and King (Eq 6) and Galloway (Eq 7).
(c) Based on Galloway, Eq 8).

The average values for Δ_s summarized in Table 7 seem to fall into two groups. The average values of Δ_s, based on the methods which involve direct measurement of noisiness or loudness response with real impulsive noise sources in a laboratory setting, are essentially identical (i.e., Δ_s = 12.5 to 13.5 dB). In contrast, the predicted values of Δ_s for real impulsive sound based on annoyance criteria or measured values of tone or noise bursts are lower (about 7 dB).

The data in Table 7 do not provide the basis for an unequivocal choice for a means of predicting a subjective correction factor. However, the lower group of values observed for the annoyance response has one basic point in their favor -

the values are generally based on more realistic test data in terms of the test signals. For example, the results from the helicopter tests in many cases stem from real fly-overs for which the observed value of Δ_s was generally low or, in at least one case (Powell[24c]), actually negative. Thus, the actual temporal setting of the impulsive noise signal may tend to decrease the observed value of Δ_s below that observed for quasi-steady state sounds evaluated in a laboratory setting.

In an attempt to resolve the differences in these average results, an effort was made to reexamine the use of Crest Level (Crest Factor in dB) to discriminate between various degrees of impulsiveness and hence, presumably, annoyance. Thus, dis-counting, for the moment, the negative result by several investigators regarding a relationship between judged impulsiveness and judged annoyance, the ISO Round Robin data were reviewed to see if such a relationship might be evident. By pooling the information on the peak and rms values of the ISO impulsive noise samples numbers 1-9 from two specific ISO Round Robin Tests (Shipton, et al,[66] and Thompson, et al),[67] it was possible to estimate the Crest Level for these sources. The subjective annoyance correction factor Δ_s was then plotted as a function of this Crest Level. The results are shown in Figure 22 along with the estimated value of Δ_s based on the methods proposed for helicopters by Munch and King[17] and Galloway[23] and Kryter's method. For the latter, it was assumed that his level, $L_{PN}(i) - L_{PN}(b)$, defined as the perceived noise level of the impulse minus the perceived noise level of the background noise, would be roughly comparable, to a first approximation, to the Crest Level as defined in Figure 22. This comparison seems to again indicate that Crest Level alone is not a valid basis for predicting Δ_s. The potential improvement in a prediction model for Δ_s by including repetition rate is certainly an avenue to pursue. In any event, in the absence of more definitive data, the following conclusions are drawn concerning an interim method to estimate a subjective correction factor for impulsive noise sources.

1. For the type of impulsive sources of concern for this report (this excludes helicopters), a constant subjective correction (Δ_s) of +7 dB added to the true A-weighted equivalent sound level for an impulsive

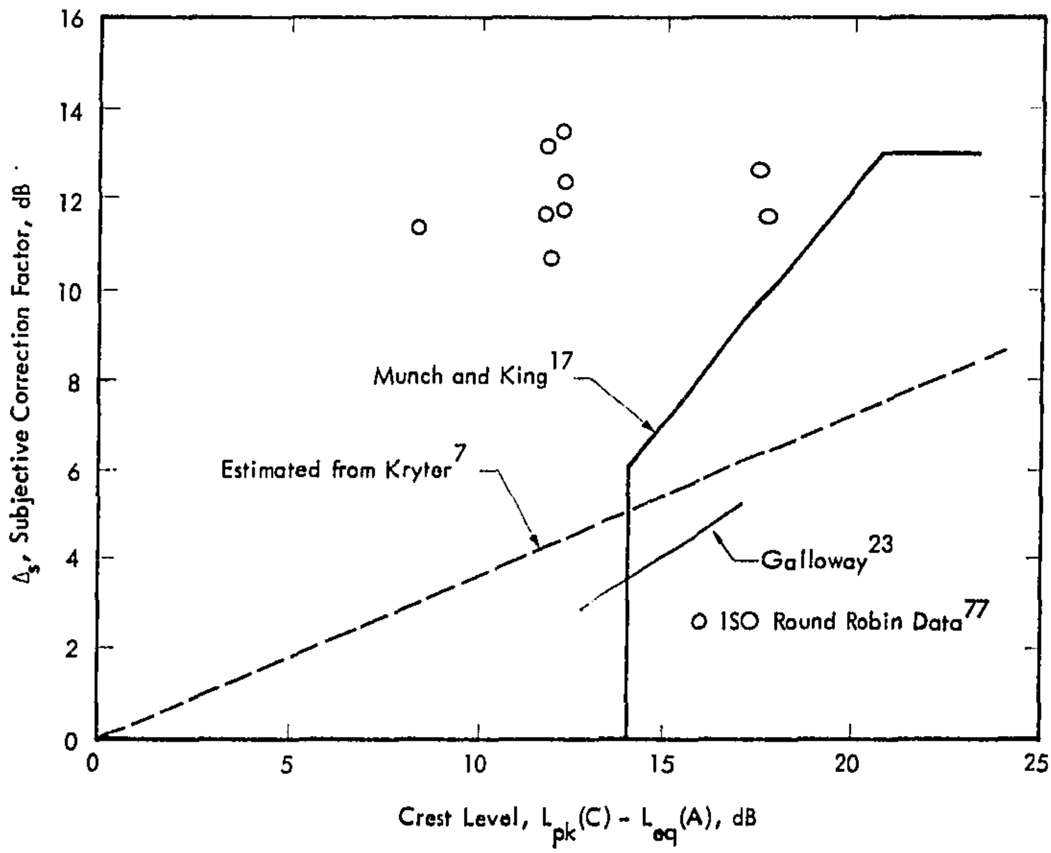


Figure 22. Comparison of Measured and Estimated Values of the Subjective Correction Factor Δ_s As a Function of Crest Level (based on C-weighted peak level minus A-weighted rms level) (Note that Galloway defines Crest Level in terms of the difference in Peak and rms A-weighted levels)

noise source would better define its effective L_{eq}, that is the L_{eq} of an equally annoying nonimpulsive reference sound. No additional correction is identified at this time for the possible change in Δ_s as a function of Crest Level or repetition rate.

This first approximation leaves much to be desired in developing a more discriminating correction factor. Indeed, the strong evidence of the potential validity of improved methods for calculating loudness of impulsive sounds suggests just such an approach. According to Reichardt,[62] improved accuracy in predicting loudness of impulsive sounds would be provided by adding a secondary correction to the Stevens or Zwicker loudness level equal to $\Delta_I = L_{AI} - L_{AS}$ where L_{AI} and L_{AS} are the A-weighted "impulse" and "slow" readings taken on an impulse precision sound level meter. Alternatively, Johnson and Robinson[55] have computed loudness directly, using Stevens Mark VI and a 70 ms integrating time for acquisition of spectral content data. Neither of these approaches were able to take advantage of the latest model (Stevens Mark VII) for loudness calculation. The need to select an optimum loudness calculation method applicable to the type of impulsive sources considered here leads to the following recommendation.

2. A comparative evaluation should be made of alternate forms of existing loudness calculation methods based on either the Stevens Mark VII[93] or Zwicker[87, 89] models when applied to existing or new data on subjective response to impulsive noises. Particular attention should be given to the selection of an optimum time-constant or time-averaged measures of level for the spectral analysis data required. Alternatively, the methods proposed by Izumi[87] may offer an improved procedure for predicting Δ_s and should be explored further.

It is anticipated that values of Δ_s computed with such improved models will show more discrimination as to the magnitude of Δ_s versus one or more signature characteristics of the impulsive source such as Crest Level or peak to background noise levels. A valid data base for computing the subjective correction factor for any one category of impulsive noise sources is required. This data base of one-third octave spectra must be acquired for a sufficient number of units to ensure a valid sample of the total population.

Finally, the evidence that repetition rate is potentially significant in the development of valid subjective correction factors leads to the final recommendation:

3. Further research is needed to explore, in more detail, the significance of repetition rate on the subjective response to impulsive sounds. This research should also consider the potential need to extend or refine estimates of loudness or noisiness contours to lower frequencies where spectral peaks due to repetition rate may be significant.

Other areas for improvement in understanding subjective response to impulsive noise also exist. These include such areas as developing a better understanding of hearing damage risk to impulsive sound, correlating annoyance versus loudness or noisiness responses and evaluating sleep disturbance due to impulsive noise. This report has attempted to provide an overview of most of these problems and, hopefully, provide a basis for practical steps to be taken now for evaluating the environmental impact of impulsive noise sources. Problems related to the objective measurement of such sounds are addressed in Appendix A to this report.

APPENDIX A
OBJECTIVE MEASUREMENT OF IMPULSIVE NOISE

A.1 Introduction

A measurement of impulsive sounds which accurately represents their annoying quality has clearly presented a major challenge to acousticians. This difficulty is mainly derived from the inability of a piece of electronic hardware to faithfully reflect the way the human ear detects, processes, averages, interprets, stores and finally discards complex incoming acoustical signals of widely varying physical parameters. An impulse precision sound level meter (ISLM) which attempts to approach this ideal in one instrument has several meter settings: PEAK HOLD, IMPULSE, FAST, and SLOW which can be combined with the various weighting networks: A, B, C, D, and LINEAR. Any one of these settings can be applied to only a limited range of physical parameters. For impulsive sounds, for instance, the reading cannot be expected to be within the accuracy limit of the instrument unless the characteristic period of the impulsive sound is substantially greater than the overall response time-constant of the electronics for that particular setting. Thus, the task of monitoring impulsive sounds involves both the problem of finding a procedure which will accurately reflect the physical phenomena, as well as the even more difficult problem discussed in Section 3 of predicting the subjective response to impulsive sounds. We shall be concerned in this Appendix with the first task - the measurement problem for which References 131-148 are pertinent.

The goal for evaluation of the objective correction factor was to define the difference between the true and measured L_{eq}* for a variety of impulsive sounds. Based on laboratory experimentation, the A-weighted SLOW meter setting was selected to most closely approximate the L_{eq} of impulsive sounds. An objective correction factor is then defined to add to readings from this meter setting to give the corrected baseline metric,

*See page 2-10 in Section 2 for definition of L_{eq}.

viz. A-weighted L_{eq}. Various physical parameters of the impulsive sounds, such as the crest level, pulse duration, period, spectrum content, and rise time of impulsive sounds are presumably parametric to the objective correction factor. The difference between the calculated L_{eq} and the A-SLOW meter reading will be plotted against various important physical parameters of the signals.

A.2 Current State-of-the-Art of Impulsive Noise Measurement

With laboratory measurement of impulsive noise, using sophisticated electronic equipment, a majority of the important physical parameters of an impulsive signal can be studied in detail. This provides a more accurate evaluation of impulsive noises than analyses made in the field with simple equipment. However, if on-site evaluation is required, the measuring instrument must be portable, compact and easy-to-operate. The Impulse Sound Level Meter is such an instrument. Although it is constructed in conformance with established standards, it may give only a crude assessment of the annoying quality of the noise.

A.2.1 Laboratory Methods

- Time History

One of the most powerful tools in a laboratory for investigation of transient signals is the Cathode Ray Tube (CRT) Oscilloscope. With it the time history of the instantaneous sound pressure can be displayed visually and a photograph taken for a permanent record. Such photographs were shown in the main body of this report (see Figure 2) for noise from a two-stroke motorcycle, a pavement breaker, a rock drill, and a commercial truck-mounted garbage compactor. The rise time, amplitude, duration, and period of impulsive noise are easily read using this method. If a significant pure tone is present in the noise, its frequency can also be estimated.

If the time history of the detected level is of interest, a high speed graphic level recorder can be employed with suitable writing and paper speed settings to measure the envelope of the rms or peak value of the instantaneous level. Figure A-1

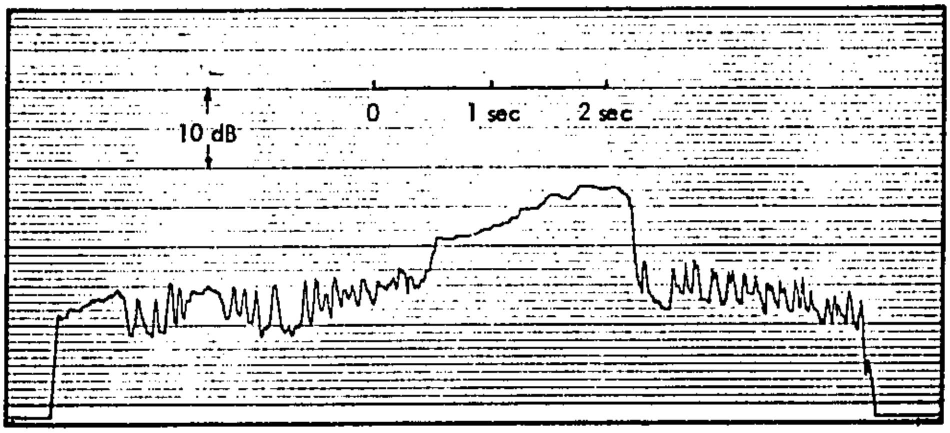


Figure A-1. (a) Time History of a Two-Stroke Motorcycle

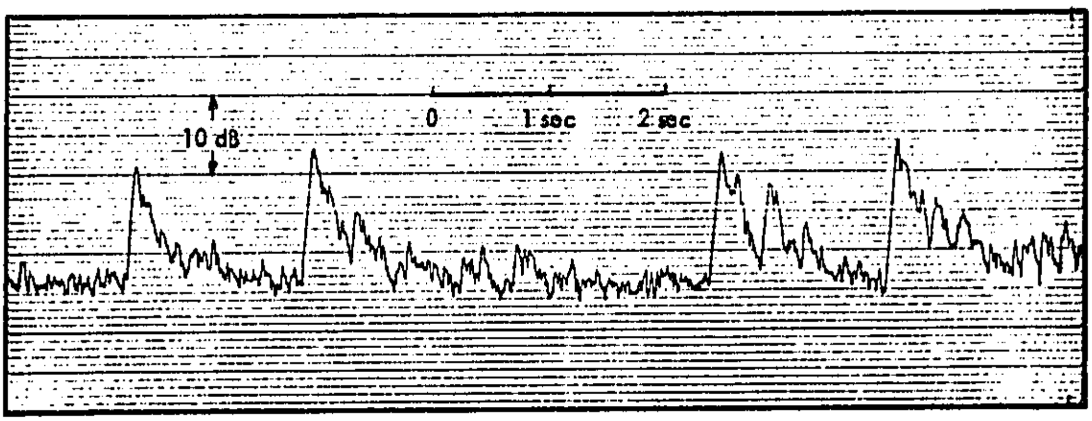


Figure A-1. (b) Time History of a Drop Hammer

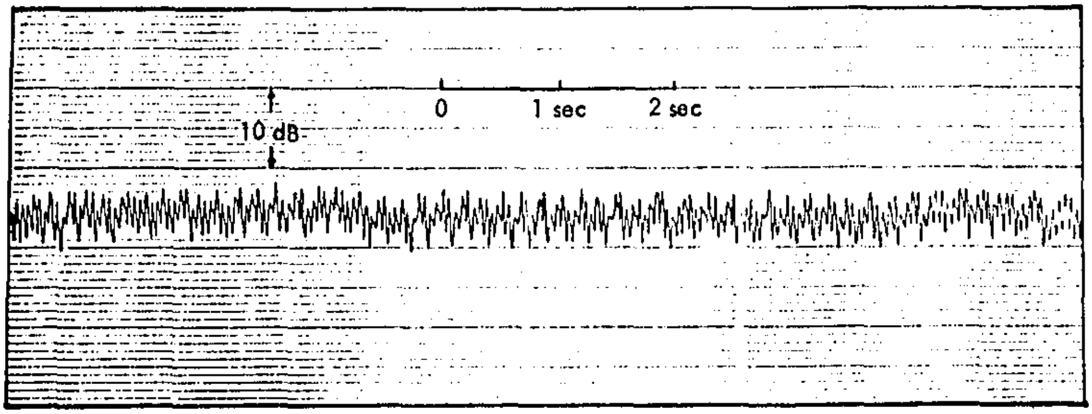


Figure A-1. (c) Time History of a Rock Drill

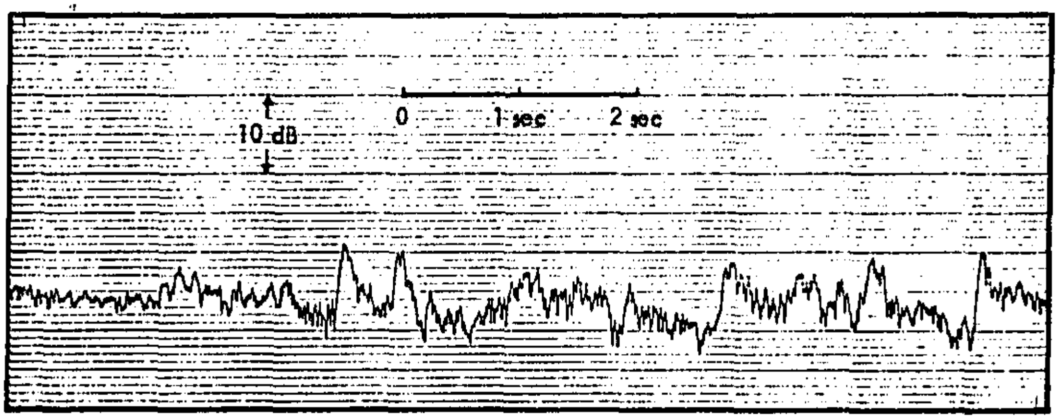


Figure A-1. (d) Time History of a Commercial Trash Truck with Compactor shows the time histories of the rms magnitude of the four impulsive sound sources mentioned above. For very short duration impulsive sounds, an oscilloscope driven by a log amplifier can also be used to portray the time history of the signal envelope.

- Spectrum Analysis

Another powerful tool in the laboratory is the Real Time Analyzer (RTA) which can be used to determine the detailed spectral content of impulsive sounds over the audible frequency range. Figure A-2 shows the frequency spectrum from the four impulsive sound sources mentioned above. However, the spectral analysis measurements of short transient sounds is subject to appreciable error unless due consideration is given to the transient response of the filters and to the use of an adequate integration time-constant.[142]

- Digital Analysis and Computation

A Fourier analyzer coupled to a high-speed digitizer and an electronic computer provides the most powerful, state-of-the-art approach for analysis of impulsive sounds.

A.2.2 Field Method

- Sound Level Meter (SLM)

Generally, the SLM is designed to conform with one or more internationally-recognized standards. Therefore, the built-in specifications for any given SLM will not vary significantly from manufacturer to manufacturer. Thus, an important general observation may be made regarding the four RC-integrating and averaging time-constants in the so-called "Impulse Sound Level Meter (ISLM)."[137]

At the "PEAK HOLD" position, the RC-network has a time-constant of 50 μs. At settings of IMPULSE, FAST, and SLOW, the nominal effective time-constants are 35 ms, 125 ms, and 1 sec respectively.[136, 137] These time-constants, in general, do not include the magneto-mechanical inertia effect of the analog indicating device which tends to

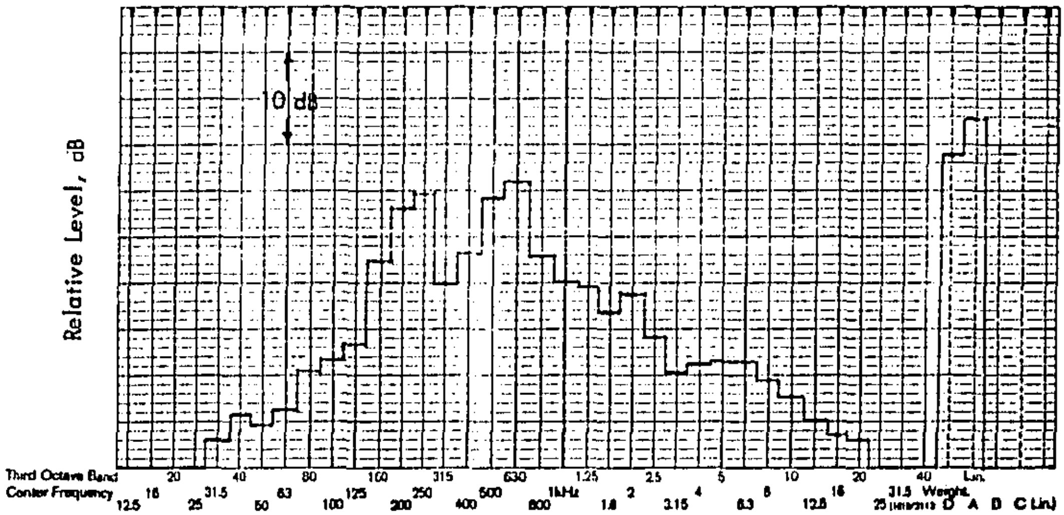


Figure A-2. (a) One-Third Octave Spectrum of a Two-Stroke Motorcycle

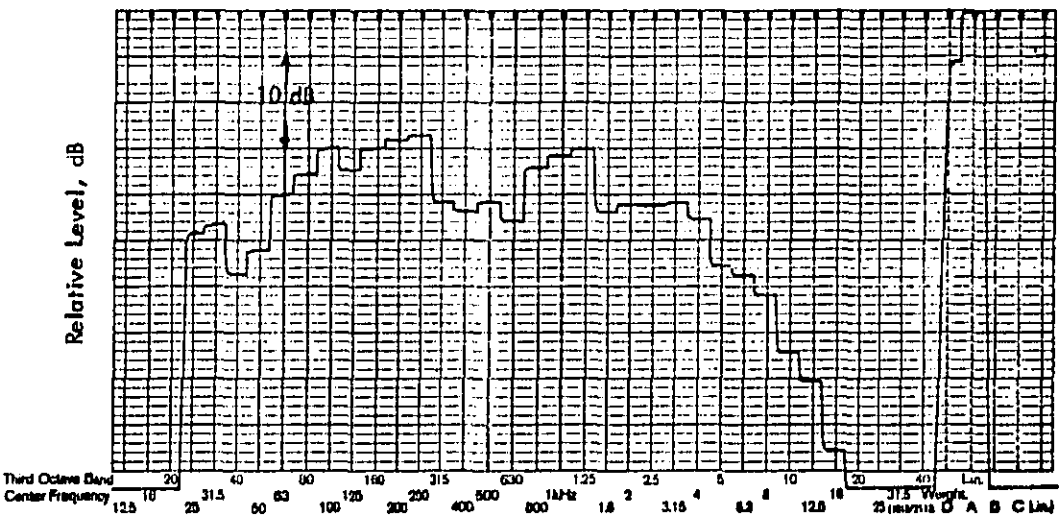


Figure A-2. (b) One-Third Octave Spectrum of a Drop Hammer

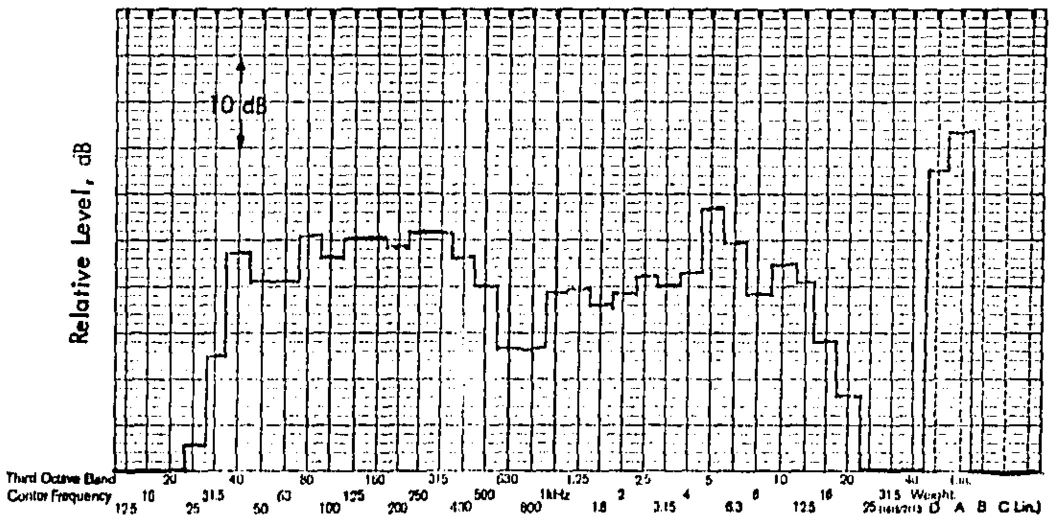


Figure A-2. (c) One-Third Octave Spectrum of a Rock Drill

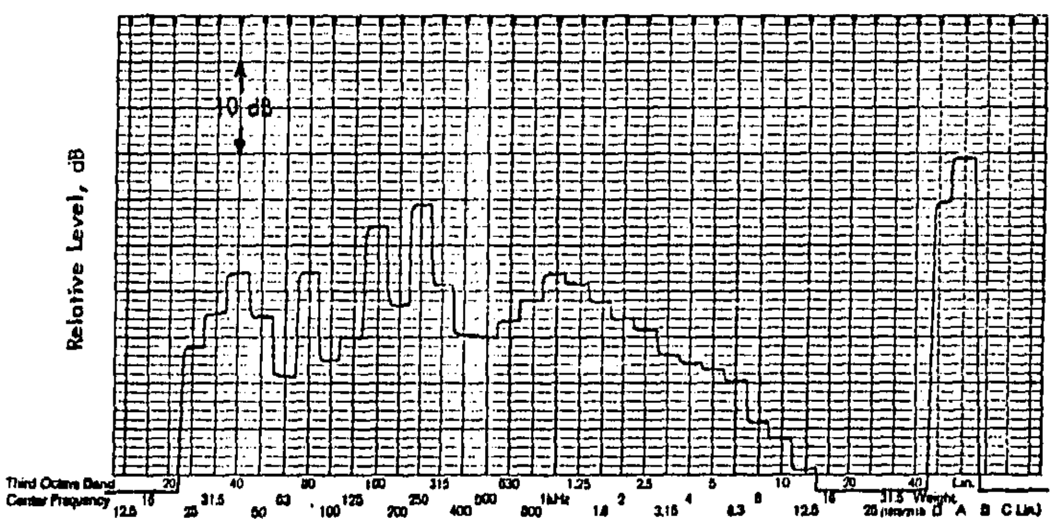


Figure A-2. (d) One-Third Octave Spectrum of a Commercial Truck-Mounted Garbage Compactor increase the overall end-to-end time-constants of the ISLM.* It is possible to roughly identify the characteristic period of repetitive impulsive sounds according to the degree of fluctuation which occurs in the read-out device as a result of these different time-constants. For instance, with a SLOW meter setting and an impulsive signal of very short duration and period, the amount of signal charging and discharging through the integrating capacitor on the output of the meter detector would be minimal, resulting in a steady reading of the ISLM. For an impulsive signal of very long duration and period, on the other hand, the capacitor is fully charged and discharged during each cycle and a large fluctuation in the meter reading would result. Therefore, from the degree of the fluctuation of the reading, a rough idea of the combined duration and period of the impulse can be roughly estimated (see Figure A-3).

In addition to the effect of internal time-constants of the ISLM, another important parameter which reduces the accuracy of the ISLM is the crest level of the input signal. By carefully adjusting the position of the ISLM input and output attenuators to avoid saturating the amplifier of the ISLM, the reading accuracy can be improved. However, the inherent uncertainty in the meter reading for maximum crest level signals that can be handled by the ISLM is approximately ± 1 dB.[141] The orientation of the ISLM with respect to the impulsive sound source, the distance from it, and the general physical environment surrounding the sound source will also influence the reading obtained from the ISLM.

- Spectrum Analysis

An octave band filter can be used in conjunction with the ISLM to determine the approximate frequency distribution of an impulsive noise; however, the accuracy is necessarily limited by the transient response characteristics of the filter.

*A decay time constant of 3 sec is provided for the ISLM to partially compensate for this meter sluggishness.

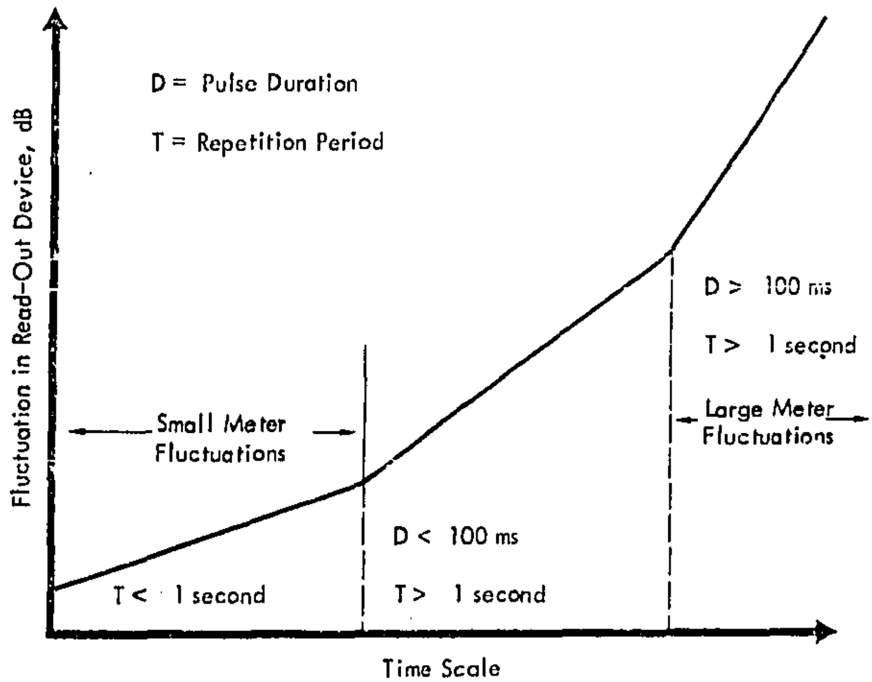


Figure A-3. Fluctuation of the Sound Level Meter Readings Versus Pu P~riod and Duration

A.3 Experimental Procedure

In order to systematically investigate the output of an Impulse Sound Level Meter due to impulsive signals, a wide range of synthesized signals was used to cover the three regions of meter fluctuation. Readings fluctuated the least, of course, for the SLOW meter setting. The most steady conditions were obtained for impulse durations less than 100 ms and periods less than 1000 ms (see Figure A-3). Thus, the SLOW meter setting was used to define an objective correction factor, Δ_o, for impulsive sounds as follows:

$$\Delta_o = L_{eq} - L_{AS} \tag{A-1}$$

where L_{AS} is taken to be the maximum reading of the fluctuating meter needle and L_{eq} is the equivalent sound level based on the duty cycle and sound levels of the tone-burst and background noise. The variation of Δ_o with respect to various physical parameters of impulsive signals was then examined. Since the A-weighted equivalent sound level (L_{eq}) was selected as the baseline metric, the A-weighting network was chosen in conjunction with the SLOW meter setting to read impulsive sounds in order to minimize the variation of the objective correction factor as much as possible. However, the objective correction factor was expected to be meaningful only for impulsive signals which produced a small meter fluctuation or produced a definitive trend of Δ_o based on the maximum meter reading for signals with larger fluctuation (see Figure A-3).

The reason for choosing the maximum meter reading for signals with other than small fluctuation is based on the fact that any fluctuation of more than 10 dB will be difficult to observe with the same attenuator settings of the ISLM. Consequently, only either the maximum or the minimum reading can be read at any one time, and the maximum value was considered much more informative.

The physical parameters of the impulsive signals used in this experiment are listed in Table A-1. Three types of background noise are used: none, pink, and USASI.[149]

Table A-1

Range of Physical Parameters of the Synthesized Impulsive Signals Used in This Study

Duration	Period	Frequency	Crest Level	Signal-to-Noise Ratio, dB
.4-400 ms	2-4000 ms	20 Hz-10 kHz	15-35 dB	10-50

A block diagram of the instrumentation is shown in Figure A-4. The measurement procedure is as follows: The level of the background noise is first set to a given SPL as read by the ISLM.* With the background noise off, a continuous sinusoidal signal of a given frequency is similarly set to a different level to provide a given "signal-to-noise" ratio. This continuous signal is then changed in temporal pattern only to a tone-burst with a preset duration and period which is then superimposed on top of the background noise. Finally, the combined signal is fed into the ISLM and readings are taken.

A.4 Results

All the observed and computed data have been tabulated in Table A-2. The computations for the values in columns 10 and 11 are explained in the footnotes at the end of the table. The master index in Table A-2 is the pulse duration (PD), given in the first column, which ranges between 0.4 ms to 400 ms. The next sorting is on the period (T) in the second column, which varies from 2 ms to 4 seconds. The duty cycle is not listed, but is equal to 100 (PD)/T, %. It varies from 0.1 percent to 50 percent. The next sorting is on the center frequency of the tone burst in the third column, which ranged from 20 to 10,000 Hz. The final sorting was usually on the signal-to-noise ratio, defined in the table, and listed in column 10, which varied from 5 dB to 50 dB. The measured crest level, which is defined as $L_{pk} - L_S$, varies from 10 dB to 35 dB. The range of these parameters is considered large enough to embrace most of the impulsive sounds

*The ISLM (B& K Model 2204/S) performed according to the manufacturer's specifications on single and repeated tone bursts.[137]

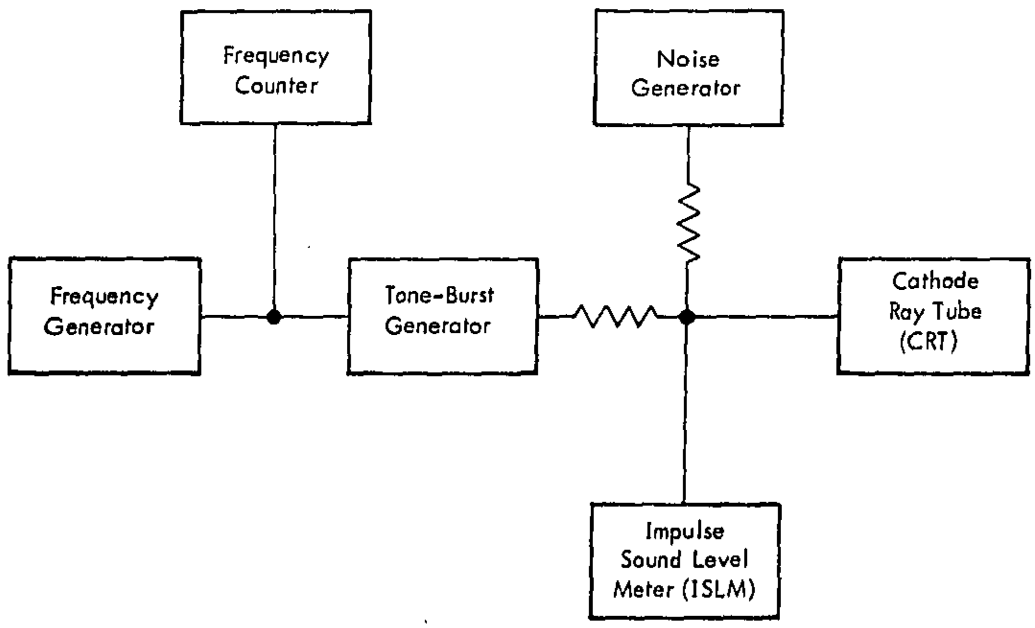


Figure A-4. Block Diagram of the Instrumentation Used in Generating and Measuring Objective Correction Factors for Artificial Impulsive Sounds which are of particular interest. The objective correction factor, $\Delta_o = L_{eq} - L_{AS}$, is listed in the fourth column.

In studying the table, several points are of interest. First, note that when L_{AF} starts to fluctuate for a particular pulse duration and period, L_{AS} remains steady.* The second point to be noted is that when both the duration and period become longer, L_{AS} starts to fluctuate also. The greatest fluctuation in L_{AS} occurs when the pulse duration (PD) is on the order of 100 ms and the period exceeds 2 seconds. Impulsive signals for which the duration is over 500 ms and the period is over several seconds have not been included in the measurements since no real sounds which were analyzed fall into this range.

In Figure A-5 the objective correction factor, $\Delta_o = L_{eq} - L_{AS}$, has been plotted for a constant frequency and pulse duration against the measured crest factor $L_{pk} - L_S$ for several values of the duty cycle. The correction factor remained nearly constant in the range of 0 to +2 dB. The average objective correction factor is 0.78 dB with a standard deviation of 0.45 dB. The correction factor is plotted against S/N in Figure A-6. The scattering of the data points is small, but no definitive trend with varying parameters was observed. The mean and standard deviation of Δ_o is given on the figure. In the plot of Δ_o versus frequency (Figure A-7), the data scatter has increased but still no definitive trend resulted. From Figures A-8 to A-13, the objective correction factor has been plotted versus period (T) (for constant pulse duration), pulse duration (PD) (for constant period), and duty cycle, for impulsive signals with little or no fluctuation in the SLM (Figures A-8 to A-10) and for signals which cause substantial fluctuation in the SLM reading (Figures A-11 to A-13). For the latter, the data are based on the maximum meter reading. The scatter of the data ranges between +2.0 dB to -3.0 dB. A gross downward trend is evident in Figures A-8, A-9 and A-12. Although this trend is not clearly defined by the data, it would seem to suggest a significant decrease in the average value of Δ_o (accompanied by an increase in data scatter) when the pulse duration substantially exceeds 100 ms or the period exceeds 1 second.

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*Significant meter fluctuation for any condition is signified in Table A-2 by two values for the SLM reading (i.e., the maximum/minimum reading).

Table A-2

Summary of Experimental Data Obtained from Laboratory Synthesized Impulsive Sounds

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq}(4)	L_{AS}(5)	L_S(6)	L_{AF}(7)	L_{AI}(8)	L_{pk}(9)	S/N(10)	C. L.(11)	Remark
.4	40	5000	+1.2	115.5	114.3	113.5	114.3	117.3	137.2	50	23.7	U.A. 82.1 dB*
1	2	1000	-0.4	89.1	89.5		88.8/89.4**	89.9/89.5		1.5		P.A. 85 dB***
			0.7	92.8	92.1		92.2/92.0	92.4/92.1		6.5		
			0.8	97.3	96.5		96.6/96.4	96.7/96.6		11.5		
			0.8	102.1	101.3		101.4/101.2	101.6/101.3		16.5		
	10		-0.5	86.2	86.7		86.8/86.4	37.3/86.9		1.5		
			0.5	88.0	87.5		87.7/87.3	88.3/87.7		6.5		
			0.6	91.2	90.6		90.8/90.5	91.4/91.3		11.5		
			-0.2	95.4	95.6		95.6/95.4	96.2/95.9		16.5		
	100		1.7	82.9	81.2	83.5			102.0	10	18.5	U.A. 82.1 dB
			1.0	86.8	85.8	86.5			109.2	20	22.7	
			1.0	95.2	94.2	95.2			117.8	30	22.6	
			1.1	105.0	103.9	104.8			128.6	40	23.8	
			1.0	115.0	114.0	114.8			137.6	50	22.8	
	200		0.4	82.5	82.1	84.5			102.0	10	17.5	
			0.8	85.1	84.3	86.2			109.4	20	23.2	
			0.4	92.4	92.0	93.0			117.8	30	24.8	
			0.6	102.0	101.4	102.4			128.8	40	26.4	
			0.6	112.0	111.4	112.3			137.5	50	25.2	
	500		0.5	82.3	81.8	84.3			101.4	10	17.1	
			0.5	83.5	83.0	85.2			109.2	20	24.0	
			0.8	90.0	89.2	90.5			117.8	30	27.3	
			0	98.1	98.1	99.2			128.7	40	29.5	
			-0.1	108.0	108.1	109.1			137.5	50	28.4	

Table A-2 (Continued)

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq} (4)	L_{AS} (5)	L_S (6)	L_{AF} (7)	L_{AI} (8)	L_{pk} (9)	S/N(10)	C. L.(11)	Remark
1	1000	1000	0.7	82.2	81.5	84.3			101.3	10	17.0	U.A. 82.1 dB
			0.9	82.9	82.0	84.5			109.2	20	24.7	
			0.8	86.8	86.0	87.8			117.6	30	29.8	
			1.2	95.2	94.0	95.0			128.6	40	33.6	
			1.6	105.0	103.4	104.2			137.5	50	33.3	
2	4	500	0.5	89.1	88.6		88.8/88.4	89.0/88.7		4.7		P.A. 85 dB
			0.7	92.8	92.1		92.2/91.9	92.4/92.1		9.7		
			0.8	97.3	96.5		96.6/96.4	96.8/96.6		14.7		
			0.9	102.1	101.2		102.2/101.1	104.4/101.3		19.7		
	20		0.5	86.2	85.7		85.6/85.9	86.4/85.9		4.7		
			0.6	88.0	87.4		87.5/87.2	88.4/88.0		9.7		
			0.9	91.2	90.3		90.4/90.1	91.5/91.0		14.7		
			0.3	95.4	95.1		95.0/95.2	95.9/96.1		19.7		
	200		-2.0	81.8	83.8	87.6			109.4	8.2	21.8	P.A. 81.5 dB
			+0.6	92.2	91.6	95.4			118.6	30	23.2	
			+0.4	101.8	101.4	105.2			128.5	40	23.3	
			+0.5	111.8	111.3	115.2			137.6	50	22.4	
	2000		+.5/-1.4	81.5	81.0/80.1	84.4/83.5			109.4	0	25.0	
			+.2/-5.7	84.7	84.5/79.0	88.5/82.5			118.6	30	30.1	
			-.3/+∞†	92.2	92.5/<90	96.8/<90			128.6	40	31.8	
			-.7/+∞	101.8	102.5/< 100	106.5			137.4	50	30.9	
			+0/+.5	82.5	82.5/82.0	85.5/84.8			108.5	20	23.0	U.A. 82.1 dB
			+.5/+3.8	85.0	85.5/81.2	89.0/84.0			117.3	30	28.3	
			-.3/+∞	92.2	92.5/<-∞††	96.5/<90			127.4	40	30.9	

Table A-2 (Continued)

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq}(4)	L_{AS}(5)	L_S(6)	L_{AF}(7)	L_{AI}(8)	L_{pk}(9)	S/N(10)	C.L.(11)	Remark
2	2000	500	-.2/+∞	101.8	102.0/< -∞	106.3/< -∞			137.4	50	31.1	U.A. 82.1 dB
4	400	500	-.5/-.4	111.8	112.3/112.2	115.9/0.8	112.2/109.5	121.4/121.3	137.7	50	21.8	
		1000	-.8/-.7	115.0	115.8/115.8	116.0/115.9	115.6/112.9	125.2/125.0	137.5	50	21.5	
		5000	-.9/-.8	115.5	116.4/116.3	115.6/115.5	116.3/113.0	125.7/125.5	137.2	50	21.6	
5	10	200	0.4	91.6	91.2	102.0			110.4	20	8.4	
			0.5	101.2	100.7	111.8			119.2	30	7.4	
			0.5	111.1	110.6	121.8			128.2	40	6.4	
	25		1.0	88.3	87.3	97.4			110.2	20	12.8	
			1.2	97.2	96.0	107.2			119.3	30	12.1	
			1.2	107.0	105.8	117.1			128.1	40	11.0	
	50		0.9	86.2	85.3	94.7			110.3	20	15.6	
			1.0	94.1	93.1	104.2			119.3	30	15.1	
			1.1	104.0	102.9	114.2			128.1	40	13.9	
			0.7	86.2	85.5		85.7/85.3	86.7/86.4		20		
			0.9	88.0	87.1		87.2/86.9	89.1/88.8		22.6		
			1.0	91.2	90.2		90.3/90.1	92.6/92.4		26.5		
			1.1	95.4	93.3		93.2/93.5	96.6/96.3		31.1		
	100		0.6	84.6	84.0	92.3			110.2	20	17.9	
			0.7	91.5	90.8	101.7			119.2	30	17.5	
			0.7	101.0	100.3	111.6			127.4	40	15.8	
			-1.3	71.1	72.4	82.1	72.3/72.1	77.1	98.5	∞	16.4	No BN†††
		400	-.2/.1	77.2	77.4/77.3	82.5/82.3	77.3/77.0	82.9/82.8	98.3		15.8	
		1000	0.6	82.0	81.4	81.7	81.3/81.1	87.2/86.6	98.7		17.0	

Table A-2 (Continued)

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq} (4)	L_{AS} (5)	L_S (6)	L_{AF} (7)	L_{AI} (8)	L_{pk} (9)	S/N(10)	C.L.(11)	Remark
5	100	2000	0.6	83.2	82.6	81.6	82.4/82.3	87.6	98.5	∞	16.9	No BN
		4000	0.6	83.0	82.4	81.6	82.2/82.1	87.4	98.3		16.7	
		10,000	0.8	79.5	78.7	81.4	78.5/78.3	83.6	98.1		16.7	
	250	200	0.2	83.3	83.1	90.3			110.0	20	19.7	U.A. 82.1 dB
			-0.4	88.2	88.6	99.3			119.4	30	20.1	
			-0.6	97.1	97.7	108.0			128.0	40	20.0	
8	800	500	1.1/1.6	118.8	111.7/111.2	115.1/114.5	114.8/-∞	124.3/123.0	137.6	50	22.5	
		1000	0.1/0.5	115.0	115.1/114.5	115.1/114.6	118.3/-∞	128.0/126.5	137.5	50	22.4	
		5000	-.2/.4	115.5	115.7/115.1	115.0/114.5	119.4/-∞	128.8/127.3	137.3	50	22.3	
10	20	100	0.9	89.1	88.2		88.3/88.0	89.0/88.7		20.6		P.A. 85 dB
			0.1	92.8	92.9		93.0/92.8	93.5/93.3		25.6		
			-0.3	97.3	97.6		97.7/97.5	98.2/98.1		30.6		
			-0.3	102.1	102.4		102.4/102.3	102.9/102.8		35.6		
	100		0.4	86.2	85.8		85.9/85.6	87.7/87.4		20.6		
			0.3	88.0	87.7		87.8/87.5	90.6/90.2		25.6		
			0.1	91.2	91.1		91.1/90.8	95.0/94.7		30.6		
			1.0	95.4	94.4		94.5/94/2	99.3/99.1		35.6		
	1000			96.1	98.0	118.2/117.2	103.5/-∞	111.9/110.0	137.9	50	19.7	U.A. 82.1 dB
		500	-.7/.1	111.8	112.5/111.7	115.8/115.0	116.8/-∞	126.1/124.0	137.9	50	22.1	
		1000	-.5/.4	115.0	115.5/114.6	115.0/114.6	120.2/-∞	128.7/126.7	137.4	50	22.4	
		5000	-.4/.6	115.5	115.4/114.9	115.2/114.2	120.4/-∞	129.2/127.0	137.3	50	22.1	
20	200	50	-.08	86.2	87.0		87.1/86.8	90.0/89.7		20.6		P.A. 85 dB
			-1.7	88.0	89.7		89.8/89.4	94.2/94.0		25.6		
			-2.4	91.2	93.6		93.5/93.1	98.3/98.0		30.6		

Table A-2 (Continued)

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq}(4)	L_{AS}(5)	L_S(6)	L_{AF}(7)	L_{AI}(8)	L_{pk}(9)	S/N(10)	C.L.(11)	Remark
20	2000	50	1.2/1.3	81.5	80.3/80.2	89.0/83.0			109.4	40	20.4	P.A. 81.5 dB
			1.6/2.6	81.6	80.0/79.0	97.1/84.0			117.8	30	20.7	
				82.3	****	106.8/91.0			127.7	40	20.9	
				85.9	****	116.8/100.5			137.8	50	21.0	
			-4.8	86.7	91.5	120.3/100.0	****	103.0/98.0	137.9	50	17.6	U.A. 82.1 dB
		100	-3.9	96.1	100.0/-∞	119.2/~100	105.5/-∞	113.2/106.2	137.8	50	18.6	
		500	-2.7	111.8	114.5/<100	117.8/~100	120.3/-∞	128.5/122.5	137.4	50	19.6	
		1000	-2.8	115.0	117.8/~100	117.8/~100	123.4/-∞	131.6/126.0	137.5	50	19.7	
		5000	-3.2	115.5	118.7/~100	117.9/~100	124.0/-∞	132.2/126.6	137.2	50	19.3	
		50	+0.8	82.1	81.3	89.0/83.0			109.3	20	20.3	
			+1.8	82.2	81.0	97.2/84.0			118.0	30	20.8	
				82.8	****	106.8/90.0			127.8	40	21.0	
				86.2	****	116.7/110.0			137.8	50	21.1	
50	500	1000	-2.4	86.2	88.6		89.6/86.2	94.8/94.3		15		P.A. 85 dB
			-1.1	88.0	89.1		90.0/87.0	95.1/94.6		20		
			-1.2	95.2	96.4	96.6			110.5	20	13.9	U.A. 82.1 dB
			-0.8	105.0	105.8	105.9			119.3	30	13.4	
			-0.8	115.0	115.8	115.8			128.9	40	13.1	
			-1.3	125.0	126.3	126.3			137.9	50	11.6	
	1000		-.3/+.4	92.4	92.7/92.0	93.1/92.3			110.2	20	17.1	
			-.4/+.5	102.0	102.4/101.5	102.4/101.5			119.2	20	16.8	
			-.3/+.6	112.0	112.3/111.4	112.3/111.4			128.9	40	16.6	
			-.3/+.5	122.0	122.3/121.5	122.4/121.5			137.8	50	15.4	

Table A-2 (Continued)

PD (ms)[1]	T (ms)[2]	F (Hz)[3]	$L_{eq} - L_{AS}$	L_{eq}[4]	L_{AS}[5]	L_S[6]	L_{AF}[7]	L_{AI}[8]	L_{pk}[9]	S/N[10]	C.L.[11]	Remark
50	2500	1000	-1.7/+∞	89.6	92.3/< 80	92.6/82.7			110.1	20	17.5	U.A. 82.1 dB
			-3.7/+∞	98.1	101.8/< 80	102.1/< 80			119.2	30	17.1	
			-3.8/+∞	108.0	111.8/< 90	111.8/< 90			128.7	40	16.9	
			-4.0/+∞	118.0	122.0/< 100	122.0/< 100			137.7	50	15.7	
100	1000	20	-.7/-1.0	86.2	87.5/87.2		90.6/88.2	94.9/92.9		52		P.A. 85 dB
			-5.2	88.0	93.2		93.4/92.7	97.0/96.8		57		
	2000	1000	-2.7/+12.2	92.4	95.1/80.2	95.2/82.8			109.7	20	14.5	U.A. 82.1 dB
			-2.8/+∞	102.0	104.8/< 90	104.8/< 90			119.2	30	14.4	
			-2.7/+∞	112.0	114.7/< 100	114.7/< 100			128.8	40	14.1	
			-2.8/+∞	122.0	124.8/< 100	124.8/< 100			137.8	50	13.0	
		200	-2.5/+∞	71.1	73.6/-∞	84.7/-∞	79.4/-∞	83.5/77.5	99.1	∞	14.4	No BN
		400	-2.3/+∞	77.2	79.5/-∞	84.5/-∞	85.3/-∞	89.5/83.0	99.2		14.7	
		1000	-2.5/+∞	82.0	84.5/-∞	84.5/-∞	90.3/-∞	94.5/88.5	99.2		14.7	
		2000	-2.6/+∞	83.2	85.8/-∞	84.5/-∞	91.5/-∞	95.8/90.0	99.0		14.5	
		4000	-2.5/+∞	83.0	85.5/-∞	84.5/-∞	91.3/-∞	95.6/89.8	99.3		14.8	
		10,000	-2.5/+∞	79.5	82.0/-∞	84.3/-∞	87.8/-∞	92.1/86.2	98.8		14.5	
200	1000	20	-1.2/.-6	87.1	88.3/87.8		91.4/83.0	94.8/93.0		52		P.A. 85 dB
	2000		-1.7/+1.7	86.2	87.9/84.5		91.9/83.0	95.1/90.3		52		
				88.0	89.4/85.0		94.0/84.0	96.8/92.0		57		
400	800		-0.9	89.1	90.0		91.4/86.8	94.6/92.3		52		
			-0.2/0.1	92.8	93.0/92.7		95.0/87.5	96.8/95.4		57		

Table A-2 (Concluded)

PD (ms)(1)	T (ms)(2)	F (Hz)(3)	$L_{eq} - L_{AS}$	L_{eq}(4)	L_{AS}(5)	L_S(6)	L_{AF}(7)	L_{AI}(8)	L_{pk}(9)	S/N(10)	C.L.(11)	Remark
400	2000	20	-1.8/+1.8	87.1	88.9/85.3	92.0/83.6	94.7/90.9			52		P.A. 85 dB
			-2.2/+2.5	88.8	91.2/86.3	94.8/84.0	96.8/93.0			55.4		
			-3.0/+3.2	86.2	89.2/83.0	92.0/83.0	94.8/83.0			52		
			-3.6/+4.0	88.0	91.6/84.0	94.8/83.5	97.1/85.0			57		

(1)PD: Pulse duration, ms

(2)T: Period of the impulse train, ms

(3)F: Center frequency of the synthesized pulse, Hz

(4)L_{eq}: Computed A-weighted equivalent continuous sound pressure level, dB

(5)L_{AS}: Impulse Sound Level Meter reading at "SLOW" meter setting with A-weighting network, dB

(6)L_S: ISLM reading at "SLOW" with no weighting, dB

(7)L_{AF}: ISLM reading at "FAST" with A-weighting network, dB

(8)L_{AI}: ISLM reading at "IMPULSE" with A-weighting network, dB

(9)L_{pk}: ISLM reading at "PEAK HOLD" with flat weighting, dB

(10)S/N: Difference between the unweighted rms levels of the background noise and the continuous sinusoidal tone (prior to tone bursting), dB

(11)C.L.: Crest Level. Defined as $L_{pk} - L_S$, dB

*: Background noise, USASI, A-weighted (U.A.), 82.1 dB (see Reference 148 for description of spectrum)

**: A virgule separates upper and lower readings from the same meter setting

***: Background noise, pink, A-weighted (P.A.), 85 dB

†: $+\infty$ means that the difference is more than 10 dB

††: $-\infty$ means that the SLM reading is too small to be registered for a particular setting of attenuators

†††: No background noise (BN)

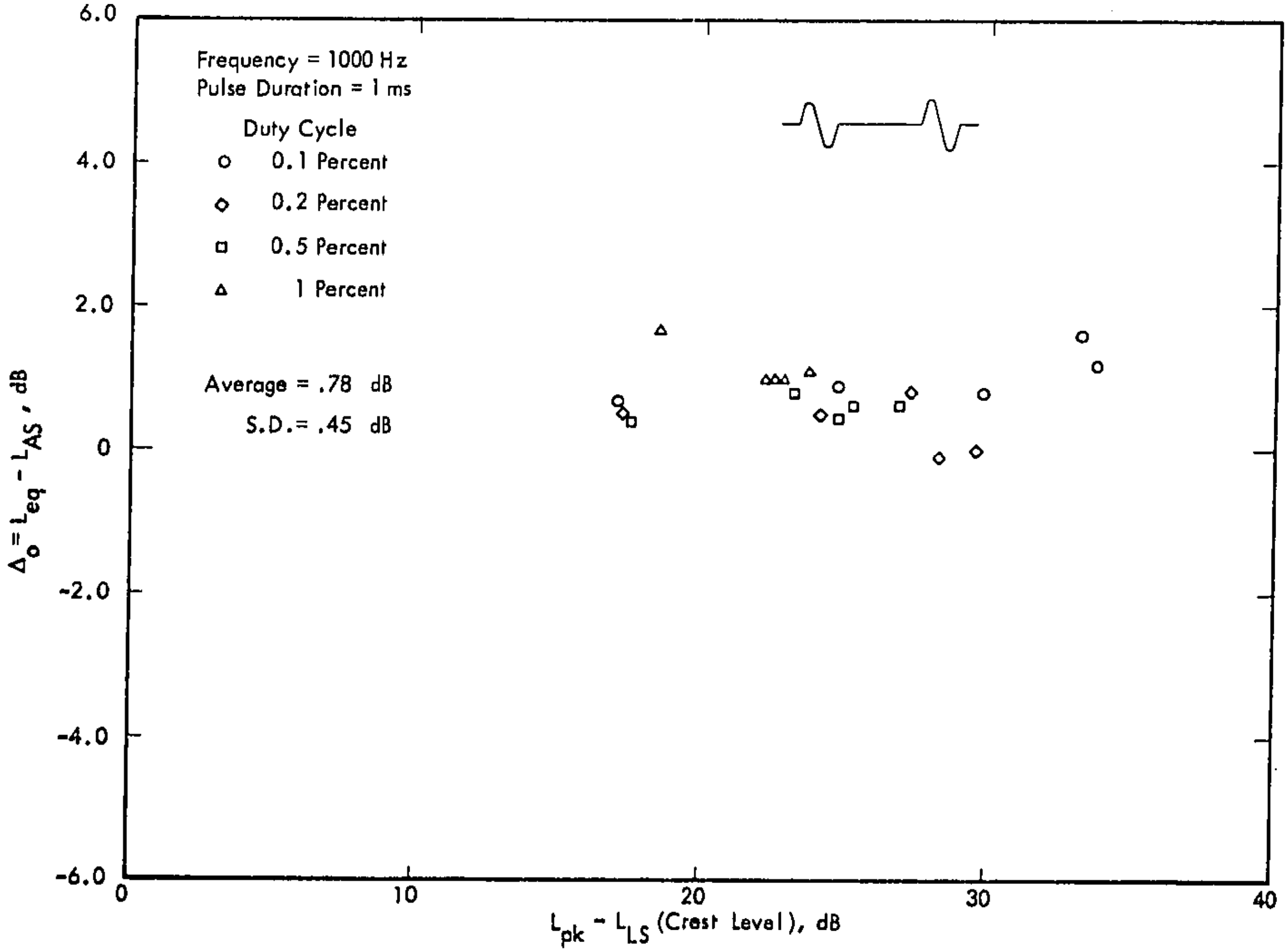

Figure A-5. Correction Factor for a Constant Frequency and Pulse Duration Versus the Measured Crest Level

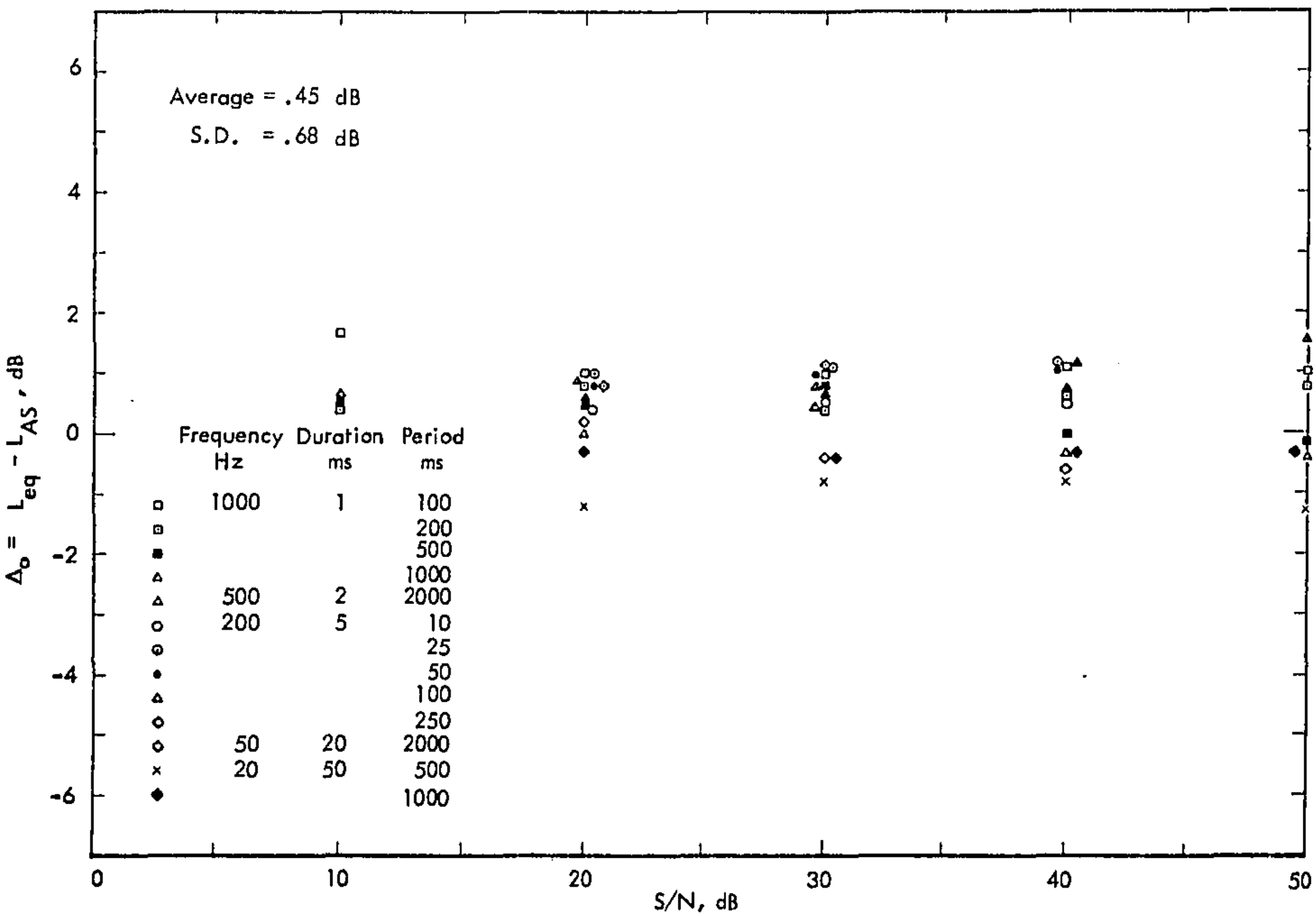

Figure A-6. Correction Factor Versus Signal-to-Noise Ratio for Steady Readings

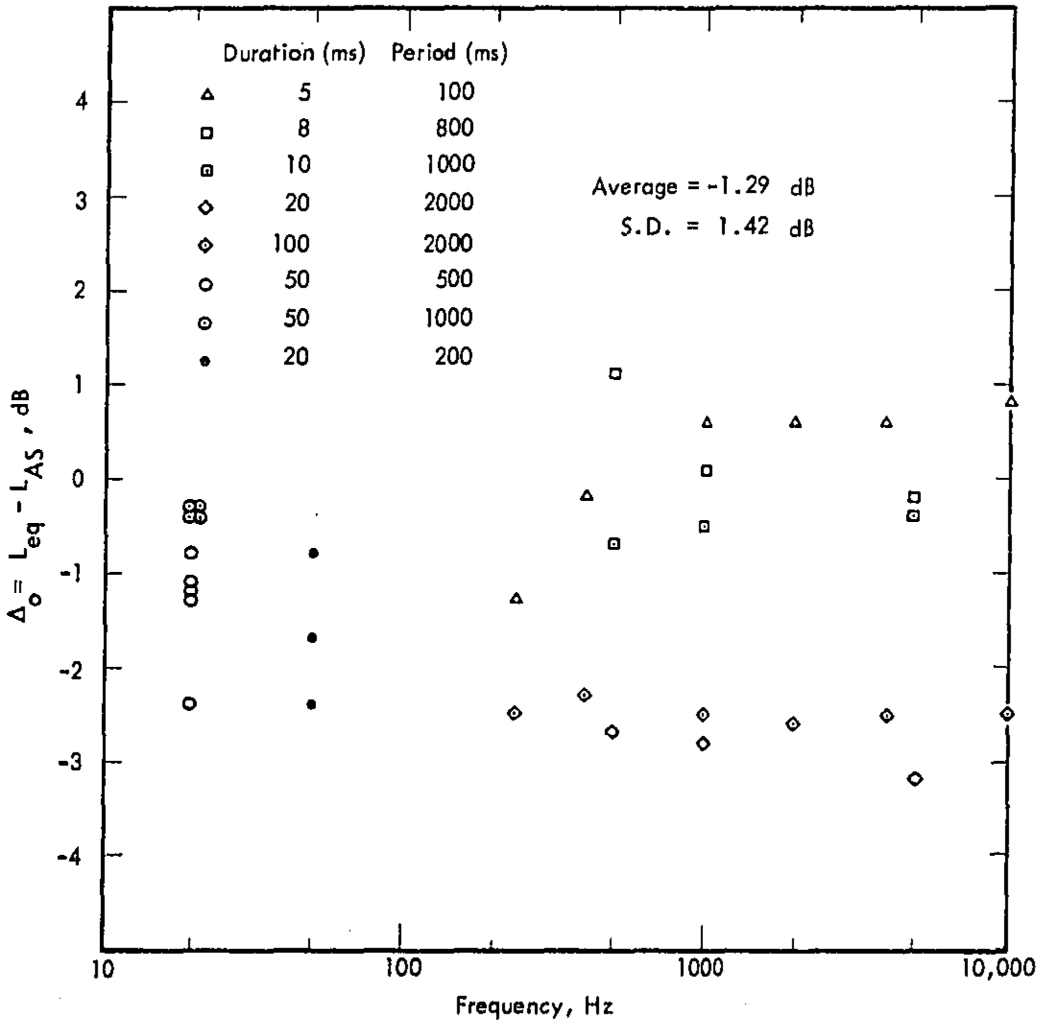

Figure A-7. Correction Factor Versus Pulse Frequency for Steady Readings

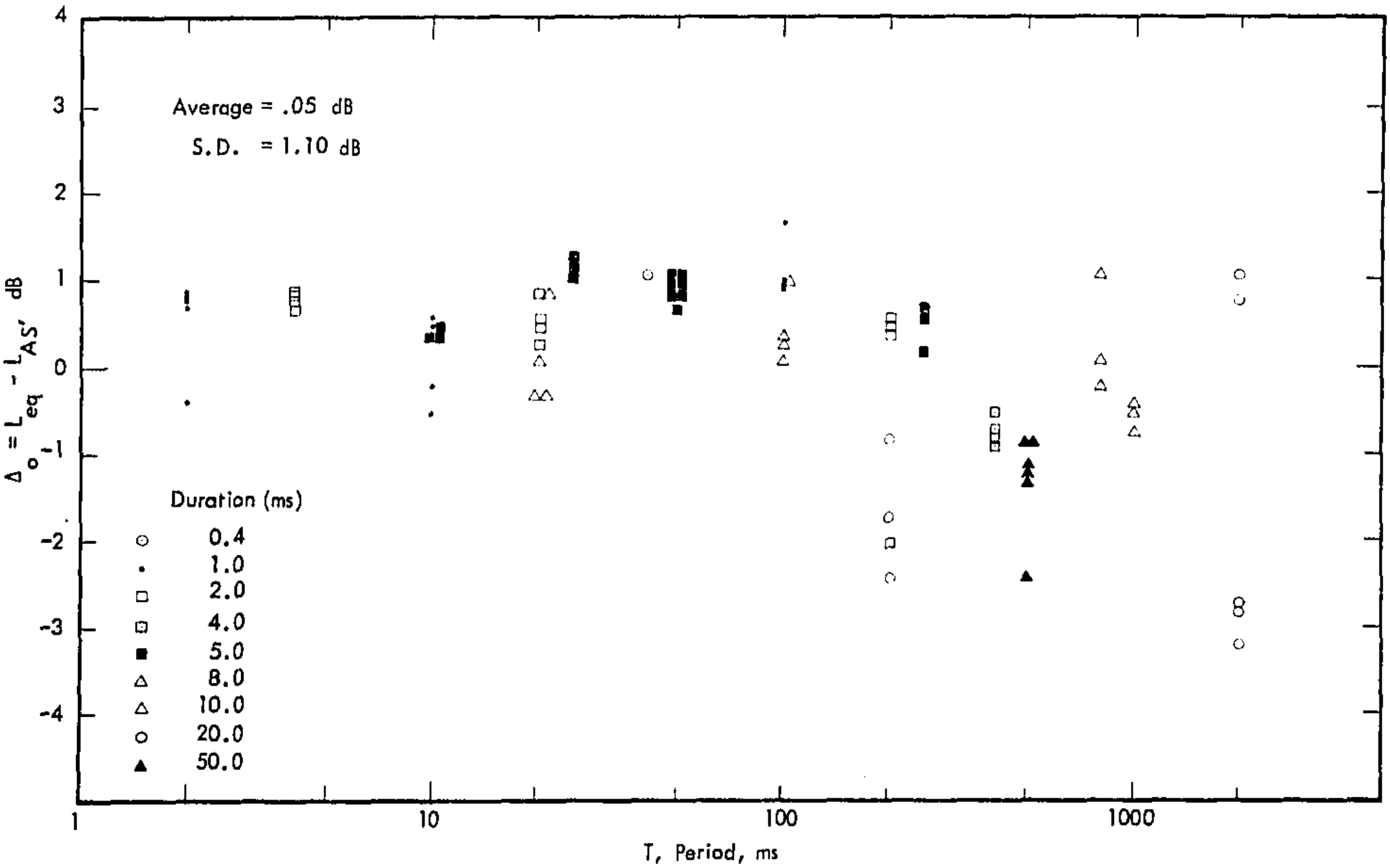

Figure A-8. Correction Factor Versus Period for Steady Readings

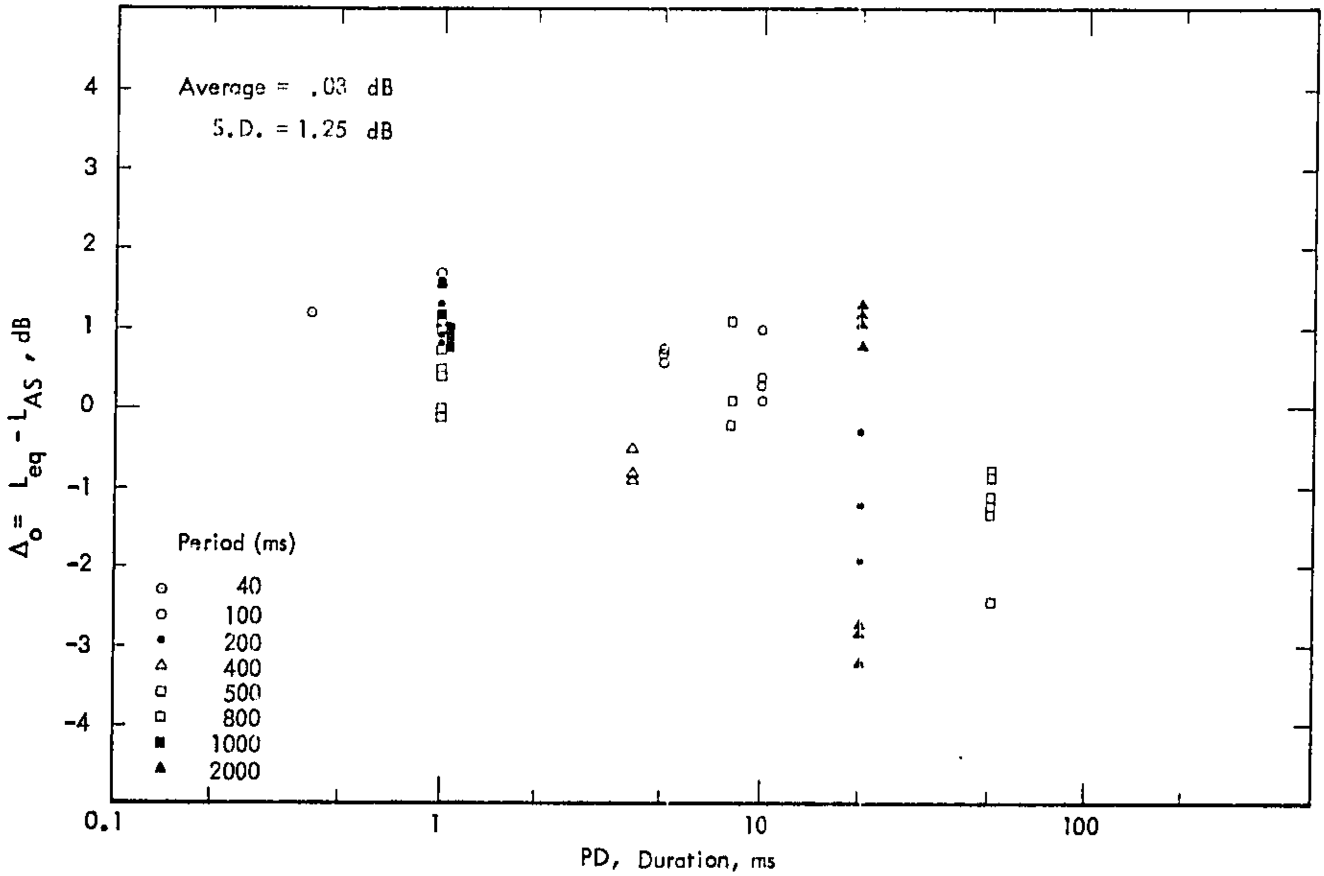

Figure A-9. Correction Factor Versus Impulse Duration for Steady Readings

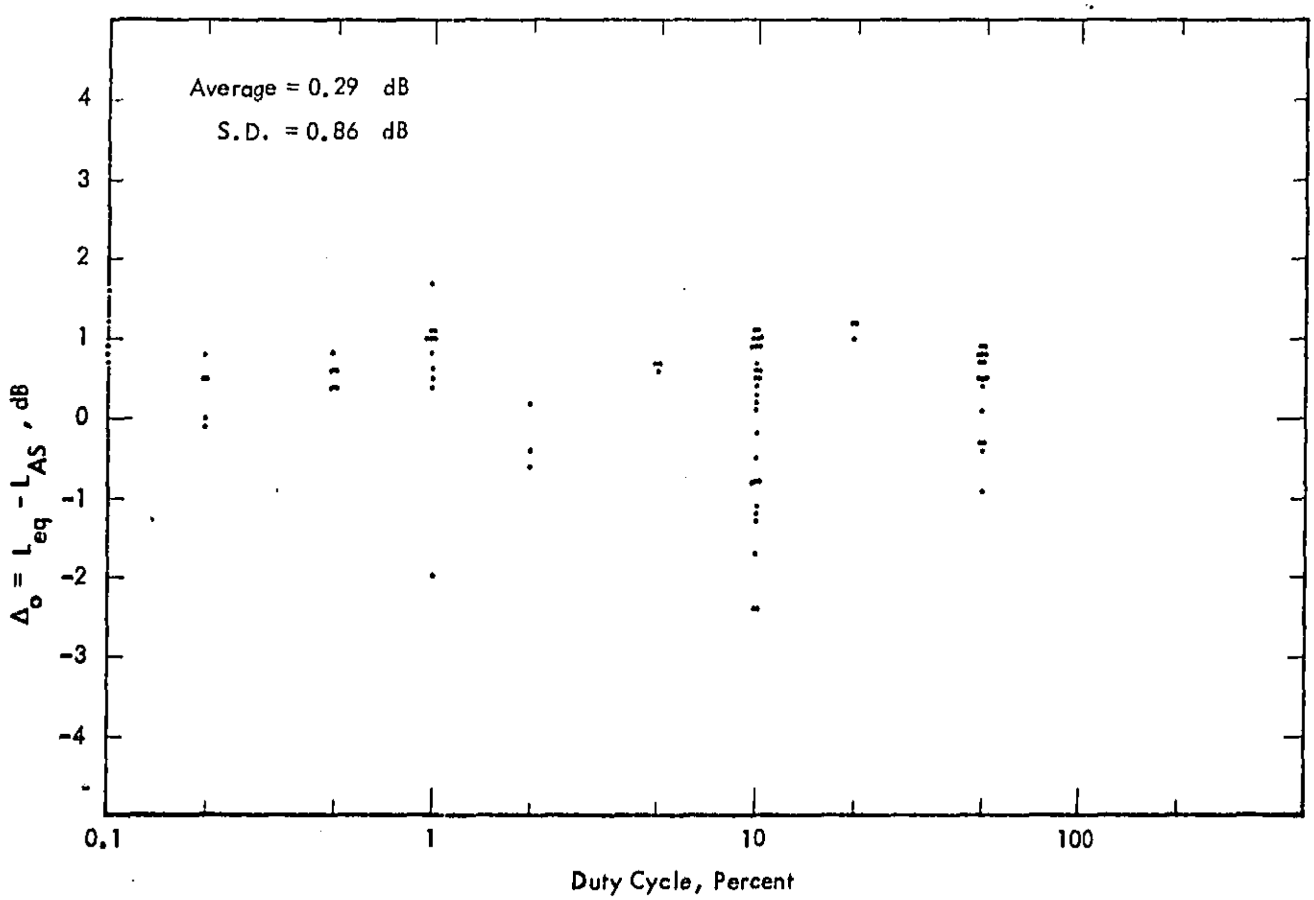

Figure A-10. Correction Factor Versus Duty Cycle for Steady Readings

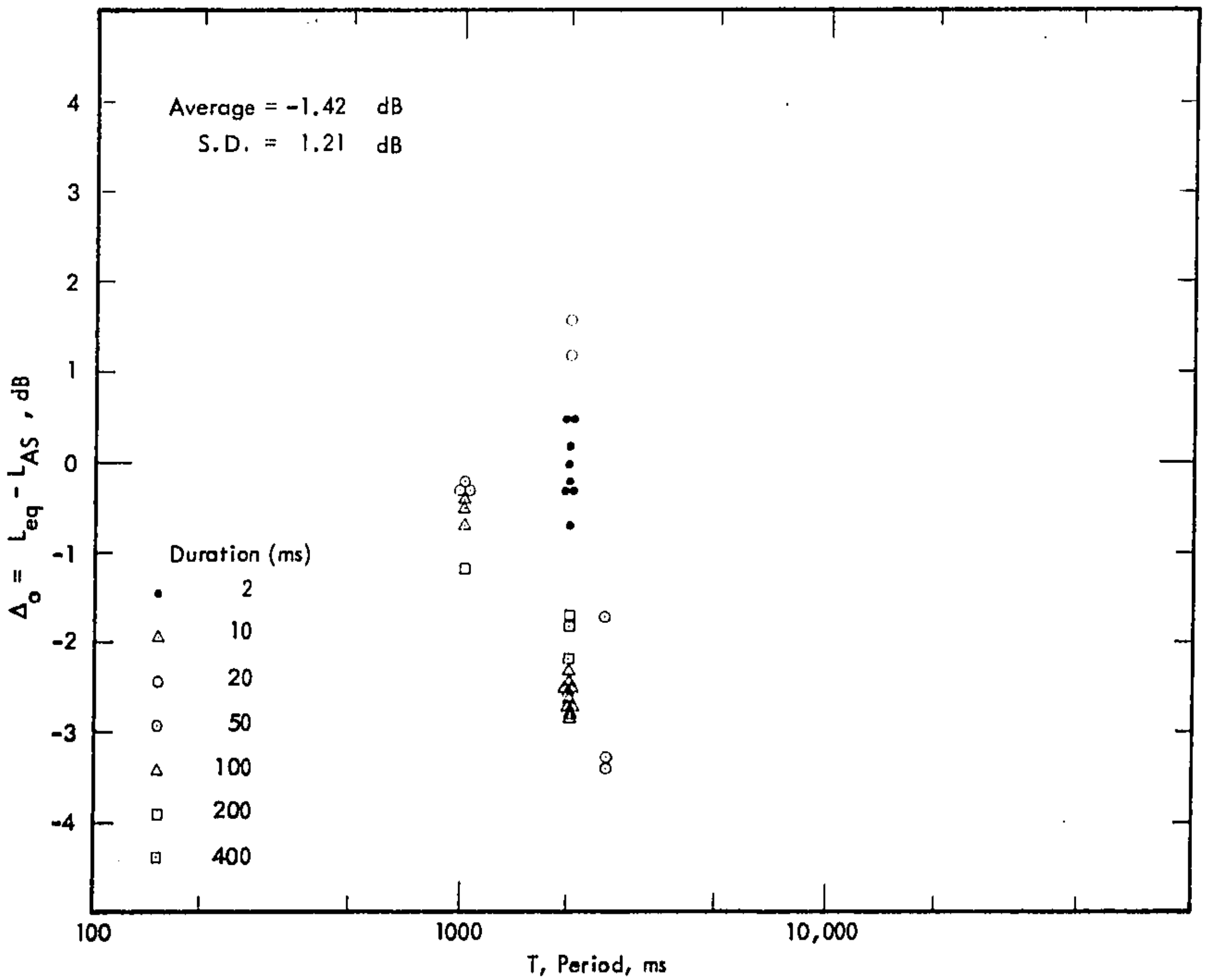

Figure A-11. Correction Factor Versus Period for Fluctuating Readings

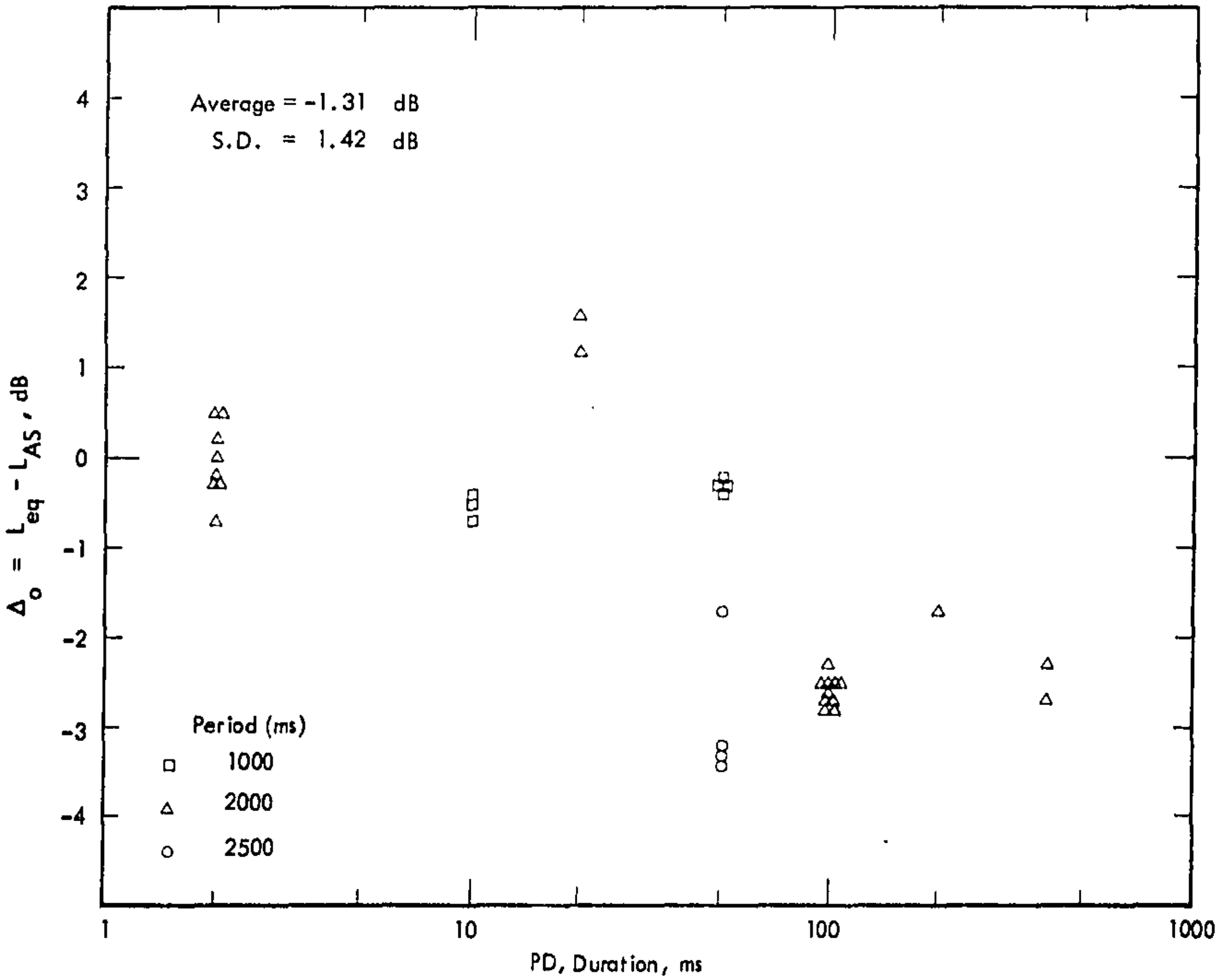

Figure A-12. Correction Factor Versus Duration for Fluctuating Readings

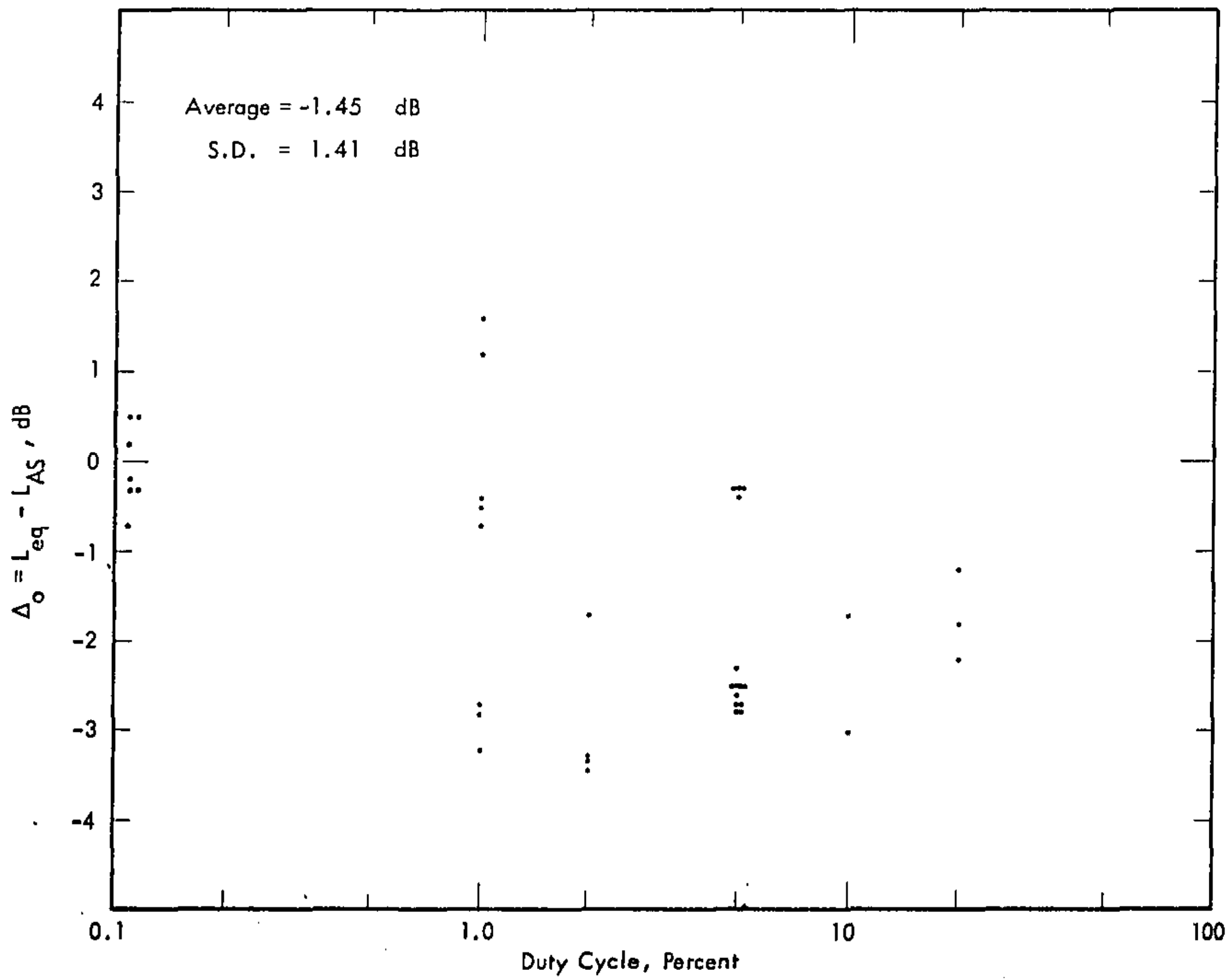

Figure A-13. Correction Factor Versus Duty Cycle for Fluctuating Readings

A.5 Conclusions - Objective Measurement of Impulsive Sounds

The ISLM readings have been divided into two categories: those obtained from the signals with a repetition rate greater than 1 pulse per second (pps) small fluctuation region and those with a repetition rate from 0.4 to 1 pps. The average value and standard deviation of the objective correction factor for these two regions are:

	Average Δ_o	Standard Deviation
When repetition rate > 1 pps	+0.1 dB	1.3 dB
When repetition rate = 0.4 to 1 pps	-1.4 dB	1.4 dB

The objective correction factor has also been studied for various temporal parameters of the impulsive signals, viz. signal-to-noise ratio, crest level, pulse duration, period and duty cycle. The average value of Δ_o falls within ±1.5 dB over the full range examined for each of the above parameters. However, except for the decrease in Δ_o for repetitive rates < 1 pps (period > 1 sec), no definitive trend in Δ_o with any of the other parameters was evident.

It was mentioned previously that a broadband noise with normally distributed instantaneous pressures had a crest level of about 10 dB. Thus, any impulsive signal evaluated with an ISLM must have a crest level greater than 10 dB before it can produce meaningful test data. This, in turn, implies directly that the accuracy in reading the meter is limited by the high crest level of the synthetic signals used in the data acquisition. Manufacturers of impulse sound level meters estimate this inaccuracy in the meter reading as ±1.0 dB for the highest crest levels employed in this study. These readings had to be made on the lower part of the ISLM scale. Any objective correction factor which is not greatly different than this inherent ±1 dB scale reading error cannot be considered as significant. It is concluded, therefore, that the A-weighted "SLOW" meter setting can be used to measure directly the A-weighted equivalent sound level (L_{eq}) to within an accuracy of ±1.5 dB for an impulsive signal with a repetition rate greater than 0.4 pps. However, caution must be exercised on two factors concerning this conclusion. First, for Impulse Sound Level Meters with a conventional (-10 to +10 dB) meter scale, it is necessary to use the lower portion of the scale for data acquisition and to use the maximum reading of the sound level meter for reading fluctuating levels. Secondly, the conclusions do not necessarily apply to the latest state-of-the-art Sound Level Meters which may employ even more accurate impulse measuring characteristics and digital readouts or true integration features for measuring an equivalent level (L_{eq}) directly. It is anticipated, however, that the latter type of instruments would, in fact, exhibit even less error when measuring the true equivalent level (L_{eq}) of impulsive sounds in terms of the A-weighted, slow reading.

Pulse repetition rates lower than 0.4 Hz were not measured in this study. However, at this pulse rate, the maximum sound level meter reading for each pulse will tend to approximate the reading obtained on a single isolated pulse with the same characteristics as each of the repetitive pulses. Young and Cohen[144] have shown that for single cycle sine bursts with burst frequencies greater than 100 Hz (i.e., pulse durations less than 10 ms), the A-weighted sound exposure level for such a pulse can be obtained quite accurately by the maximum reading on a sound level meter set to A-weighting, SLOW. (For lower pulse frequencies, this sound level meter reading will tend to exceed the true sound exposure level reaching a maximum error of about +8 dB for a single 20 Hz sine burst.) However, the type of impulsive noise sources of concern for this study are not expected to involve significant sine pulse components as low as this. For example, the one-third octave band spectra of the ISO single event impulsive sounds shown later in Figure B-4 of Appendix B have peak frequencies well above 100 Hz. If spectral content of an impulse is, in fact, dominant at low frequencies (below 100 Hz), then, according to the results of Young and Cohen[144] the A-weighted sound exposure level can also be obtained within a maximum error of about 1 dB for pulse frequencies down to 20 Hz by using the maximum reading on the C-weighting scale. Thus, for the objective correction factor, an interim recommended procedure is as follows:

RECOMMENDATION

Until more definite data are available, the objective correction factor for the measurement of the equivalent (energy average) sound level of impulsive noise sources shall be assumed equal to zero when the L_{eq} is based on the maximum reading on the A-scale (SLOW) of an Impulse Precision Sound Level Meter. For single isolated pulses, the corresponding equivalent sound level for N such single events, over a time T (seconds) can be approximated by

$$L_{eq} \simeq L_{AS}(e) + 10 \log N - 10 \log T \qquad \text{(A-2)}$$

where

$L_{AS}(e)$ = the energy mean value of the maximum A-weighted (SLOW) noise level over the N events

When the dominant pulse frequency is below 100 Hz, the C-weighting scale should be used instead of the A-weighting.

This interim procedure is equivalent to setting the objective correction factor (the difference between the L_{eq} of the test signal and the L_{eq} of the reference signal for the same instrument reading) equal to zero. In any event, a correction factor would not have been required at all if sound level measurements of transient events were obtained with a true rms time-integrating meter which measured sound exposure level.

APPENDIX B

ISO Round Robin Tests

The most complete set of data on loudness of impulsive noises is provided by the results of an international cooperative Round Robin test program organized under the auspices of the International Standards Organization, ISO/TC 43/SC-1, Study Group B (Secretariat-15) 23, "The Round Robin Test on Evaluation of Loudness Level of Impulsive Noise." The final report from the organizers, O. Juhl Pedersen, et al, provides summary data from a portion of the results from over 22 laboratories covering "close to 400 subjects."[77] More detailed results, from the National Physical Laboratory (NPL), included in the summary report, have been reported by Shipton, Evans and Robinson.[66] Pertinent results from these reports are summarized here.

The test signals employed for these round robin tests consisted of the following three groups:

Group I: Nine quasi-steady impulsive noise signals recorded from practical noise sources, e.g., teletype, pneumatic hammer, outboard motor. Each noise sample has a duration of approximately 1 second and is recorded repeatedly alternating with the reference signal (1/3 octave band of noise at 1 kHz). Intuitively judged, the noises of this group form a continuum ranging from highly impulsive to almost steady noises. (Their relative 1/3 octave band spectra are shown in Figures B-1 to B-3).

Group II: Five noises basically consisting of a single pulse, e.g., from a gun or a mechanical ram. These noises are recorded as for Group I with reference signals (1 kHz tone pulses) of approximately the same duration as the pulse. (Their relative frequency spectra are shown in Figure B-4).

Group III: Six 1 kHz tone pulses of durations from 5 ms to 160 ms. The reference signals are 1 kHz tone pulses of durations 10-320 ms.

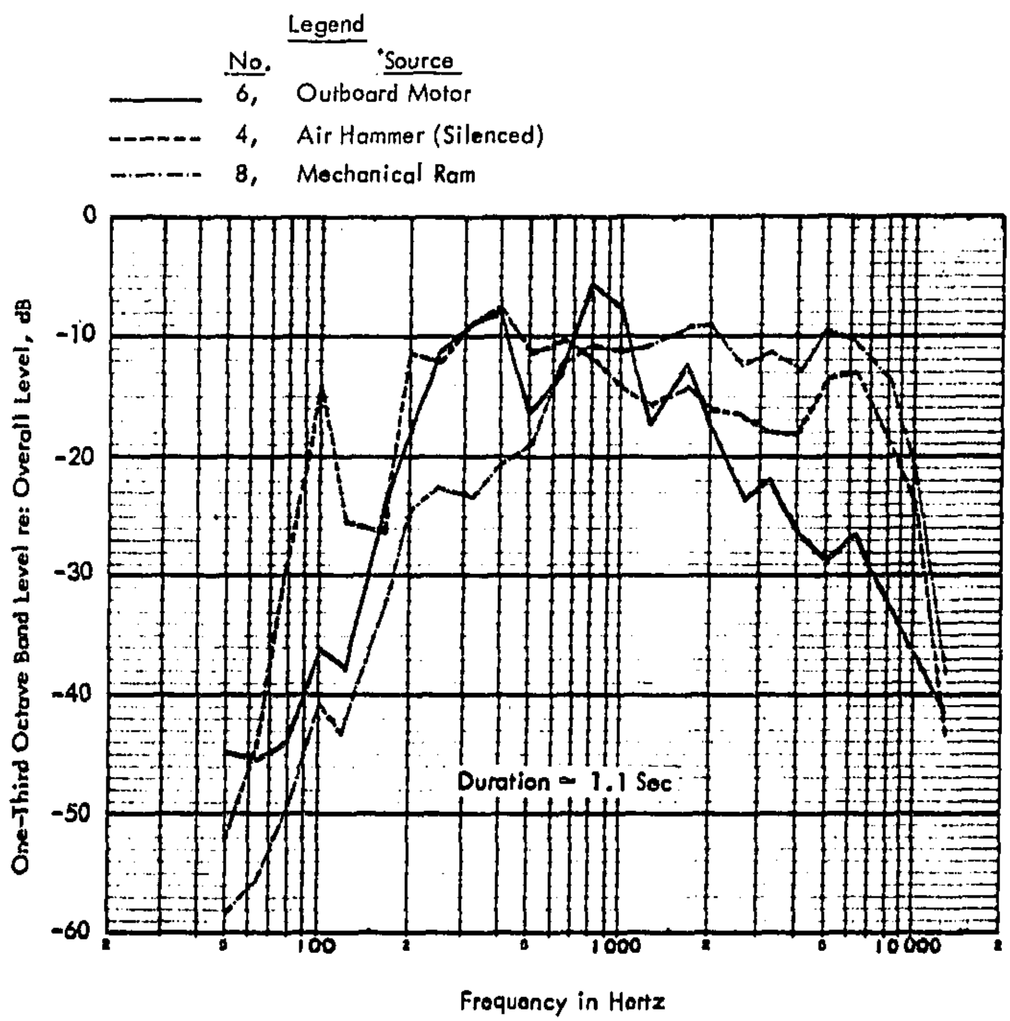

Figure B-1. Relative One-Third Octave Band Spectra of ISO Round Robin Impulsive Noise Samples, Numbers 6, 4, 8 (as Measured By NPL)[66]

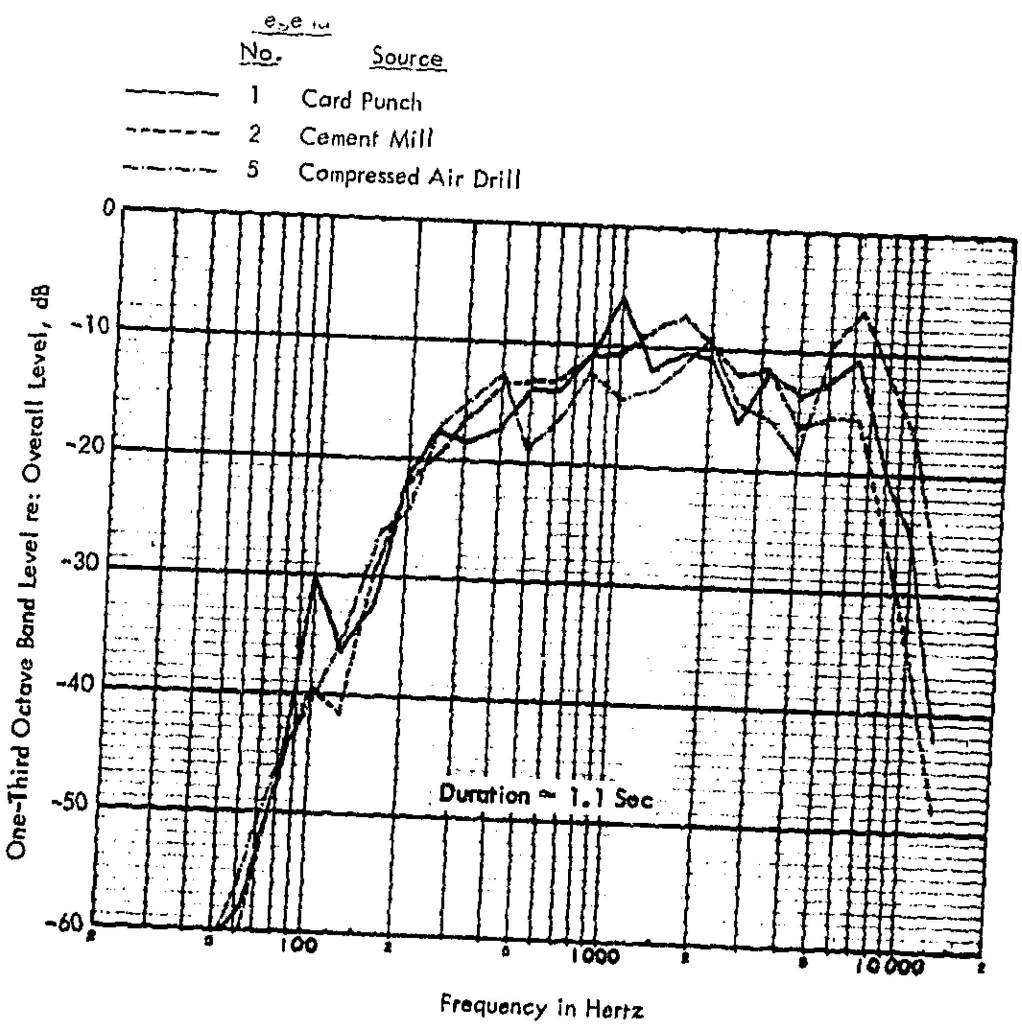

Figure B-2. *One-Third Octave Band Spectra of ISO Round Robin Impulsive Noise Samples 1, 2, 5 (As Measured by NPL)[66]*

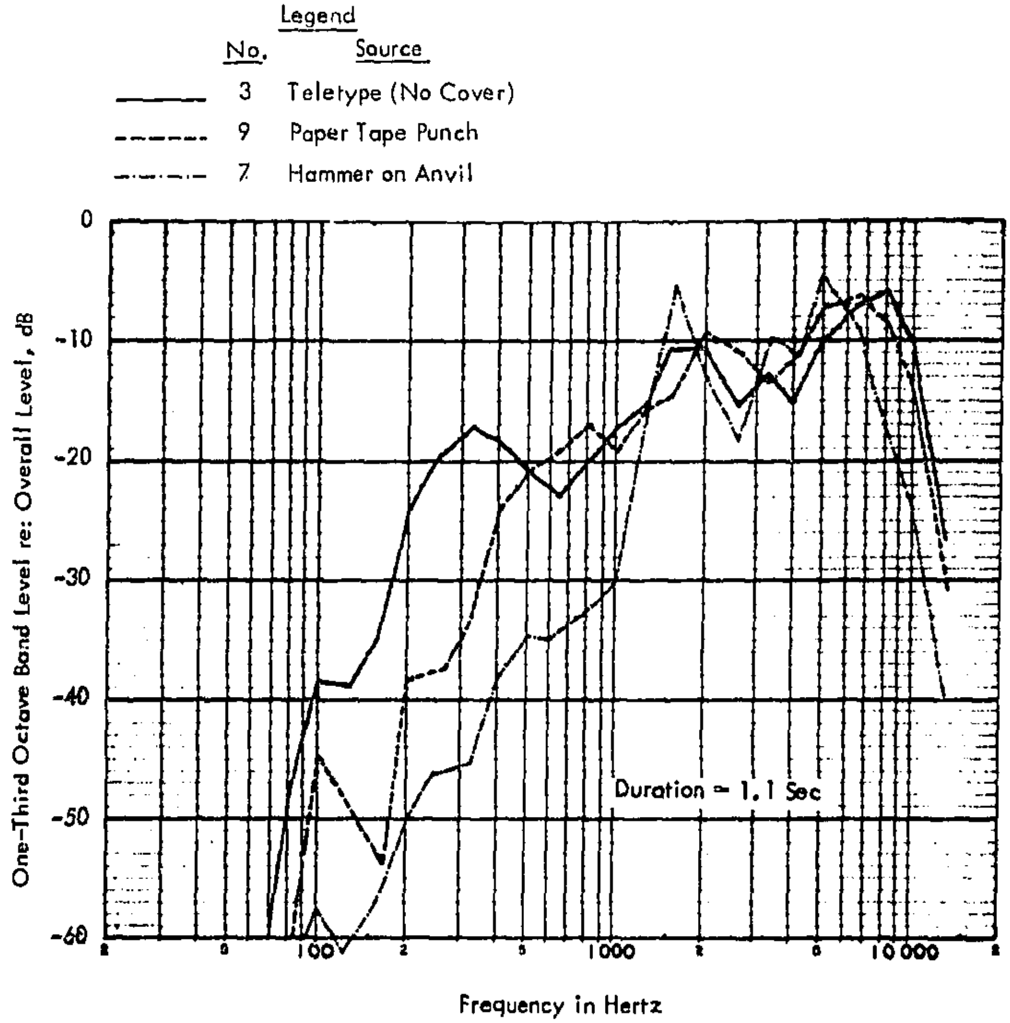

Figure B-3. Relative One-Third Octave Band Spectra of ISO Round Robin Impulsive Noise Samples 3, 9, 7 (as Measured by NPL) [66]

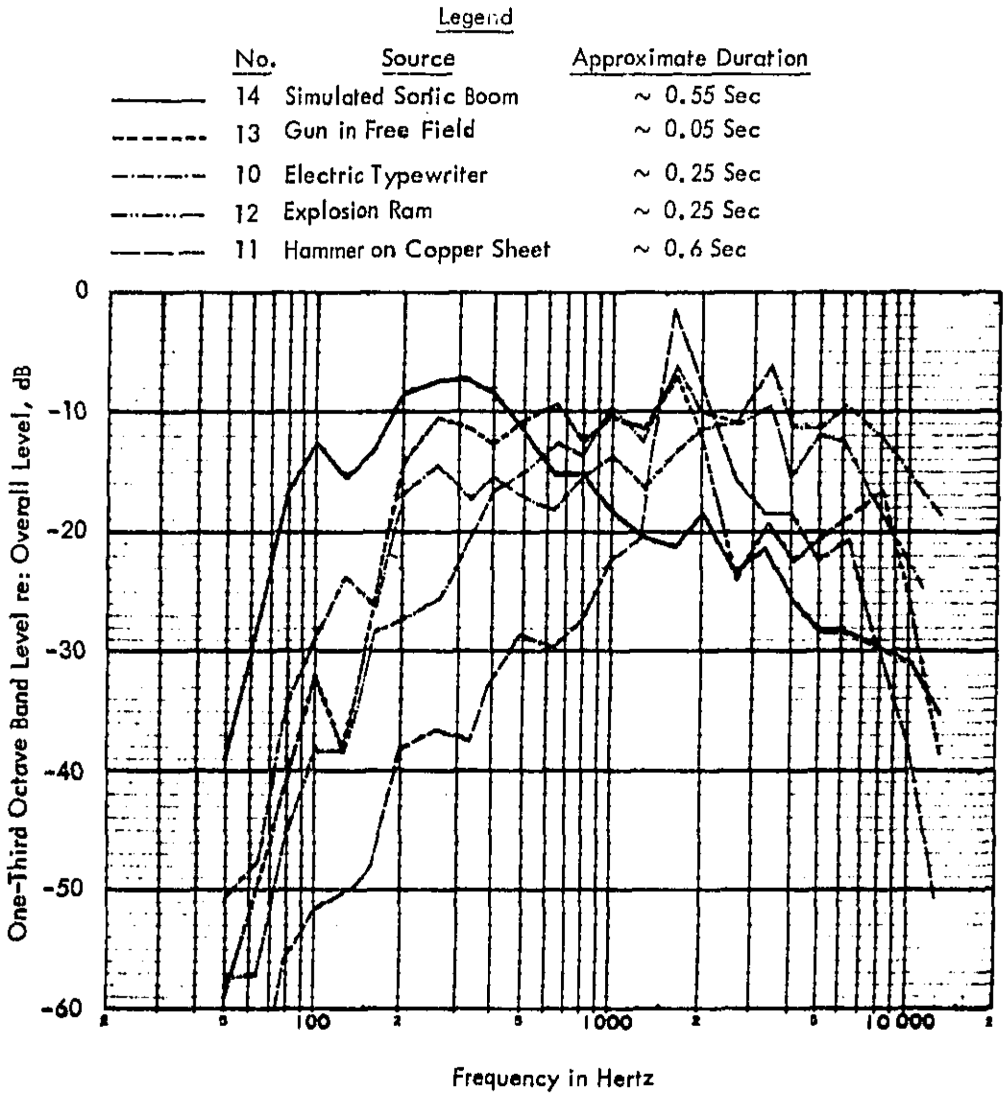

Figure B-4. Relative One-Third Octave Band Spectra of ISO Round Robin Impulsive Noise Samples 10 to 14 (As Measured by NPL)[66]

The source of the first 14 impulsive sounds is identified on the preceding Figures. The sounds were presented in repeated A-B sequences at 3 sound levels (55, 75, and 95 dB re 20 μ Pa) to the subjects using, in each case, loudspeaker presentations in presumably free-field or nearly free-field conditions. The subjective data which will be reported here consist of average values (over subjects) of the difference in settings of attenuators placed in the test and reference signal channels (i.e., attenuation of test signal minus attenuation for reference signal) required to achieve equal loudness between the two signals. This "Equal Loudness Attenuation" for the subject tests (called ELA_{subj} by Pederson) provided a basic raw measurement of the relative subjective loudness for each of the test sounds. In order to determine a subjective correction factor Δ_s from these tests, it was necessary to utilize the additional detailed data from Shipton, et al,[66] to correct these attenuator settings for the additional relative difference in the test signals before any relative attenuation was applied. Thus, as illustrated in Figure B-5, an additional small deviation Δ_t accounts for the difference in L_{eq} of the reference signal and the test signal before the additional (ELA_{subj}) attenuation is applied. Thus, as illustrated in the figure below, Δ_s can be defined by

$$\Delta_s = ELA_{subj} + \Delta_t \tag{B-1}$$

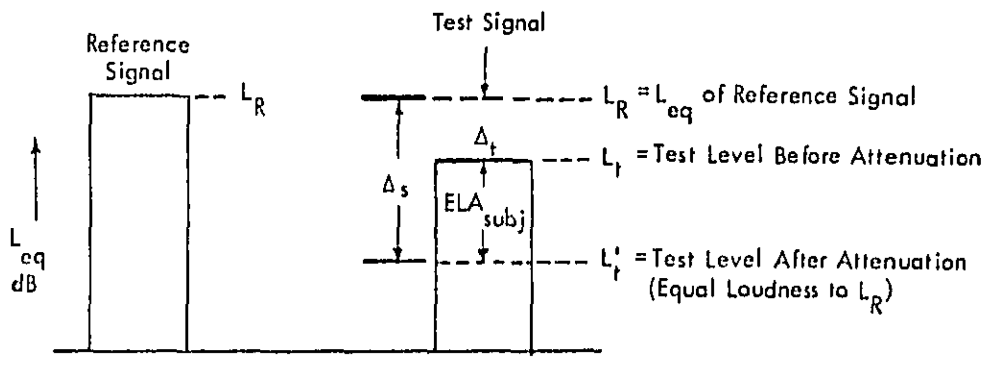

Figure B-5. Computation of the subjective Correction Factor Δ_s From the ISO Data.[77]

The values for Δ_t were computed from the detailed data on the reference and unattenuated test signal levels in Table 2 of Reference 66. It was assumed that these data apply universally to the ISO average values for ELA_{subj} for the corresponding sounds. In other words, it was necessary to assume that the relative unattenuated signal levels from one noise to another were essentially fixed on the Round Robin tapes and would be reflected in identical variations in each laboratory. This clearly is an approximation but is not considered unreasonable considering the expected care each laboratory would take to provide a "flat" reproduction of the (uniform) test tapes provided by ISO to each laboratory. Table B-1 summarizes the reported values of ELA_{subj} from the ISO report for the nine Group I sounds.

Table B-1

ISO Round Robin Comparisons for ELA_{subj} (dB)

Parameters	Sounds (Group I)									Average	Std. Dev.
	1	2	3	4	5	6	7	8	9		
Mean	12.2	8.9	7.0	7.5	8.4	11.5	8.2	8.7	11.4	9.31	1.90
Std. Dev.	3.5	3.5	4.9	3.9	3.7	3.2	3.3	4.1	3.5		

The computations for Δ_t from the NPL data and the corresponding values for Δ_s are given in Table B-2. The overall grand average of Δ_s (including all laboratories in the ISO figures, all 3 levels, nearly 400 subjects, and for the 9 Group I impulsive noises) is 12.5 dB. The standard deviation over the 9 average values for each noise is 0.9 dB. It must be recognized, of course, that this is a highly smoothed statistical result for, as pointed out in the ISO report, variation in ELA_{subj} values from subject to subject for any one level and test sound can be 10 to 15 dB.[77] Nevertheless, the central tendency of the data is clearly indicated by the above values. Considering the necessary assumptions required to compute Δ_s from these data, it is estimated that the values given in Table B-1 are reliable within better than $\pm$ 1.0 dB.

Table B-2

Summary of Computation of Δ_s from ISO Round Robin Data for First Nine (Repetitive) Impulsive Sounds

Row	Data Source	Impulsive Sound 1	2	3	4	5	6	7	8	9	Ref. Signal
	NPL (66)										
1	L_{AI}(Ref)[b]	79.1	77.6	77.3	77.6	78.3	78.6	78.4	78.3	78.2	78.4[a]
2	ΔL_{AI}[c]	+0.7	-0.8	-1.1	-0.8	-0.1	+0.2	0	-0.1	-0.2	0
3	L_{eq}(Ref)[d]	(77.1)	(75.6)	(75.3	(75.6)	(76.3)	(76.6)	(76.4)	(76.3)	(76.2)	76.4[a]
4	L_{eq}(Test)[e]	75.6	73.4	69.7	69.9	70.9	75.6	77.8	72.9	75.9	
5	Δ_t[f]	1.5	2.2	5.6	5.7	5.4	1.0	3.6	3.4	0.3	
	ISO (77)										Avg
6	$ELA_{(sub)}$ (g)	12.2	8.9	7.0	7.5	8.4	11.5	8.2	8.7	11.4	9.3
7	Δ_s[h]	13.7	11.1	12.6	13.2	13.8	12.5	11.8	12.1	11.7	12.5[i] ±0.9

(a) Level of Calibration Tone for Reference Signal.

(b) L_{AI}(Ref) = Impact Sound Level from Table 2b, Reference 66 (same as dB(A_I)).

(c) $\Delta L_{AI} = L_{AI}$(Ref) - 78.4 (where 78.4 = L_{AI} of Calibration Tone on Reference Channel.

(d) L_{eq}(Ref) = 76.4 + Row 2, Estimated Values of L_{eq} for Reference Channels. (76.4 = L_{eq} of Calibration Signal on Reference Channel.)

(e) From Table 2a, Reference 66 (same as dB(A) Integrated).

(f) $\Delta_t = L_{eq}$(Ref) - L_{eq}(Test), Row 3 - Row 4.

(g) From Table 3.3.3.2, Reference 77.

(h) $\Delta_s = ELA_{subj} + \Delta_t$, Row 5 + Row 6.

(i) Overall Mean Δ_s for all 9 Sounds.

Not considered here is the fact that the values of ELA_{subj} reported by Shipton et al,[66] show a variation with presentation level due to the so-called mid-level bulge in loudness growth.* The effect was relatively small, however, and has been averaged out in the above figures. Since L_{eq} data were not available for the 5 single impulsive sounds (Group II), Δ_s values for these sounds could not be established.

Combined Subjective and Objective Corrections From ISO Round Robin Tests

Analogous to the Equal Loudness Attenuation (ELA_{subj}) to achieve subjective equality of the reference and test signals, there is also an objective Equal "Loudness" Attenuation (ELA_{obj}) - again adopting Pedersen's terminology - which is the attenuation of the test signal required to achieve the same response on the objective measuring instrument as for the reference signal. The comparable objective correction factor Δ_o which we seek will be the difference in L_{eq} between the test and reference signals to achieve the same "instrument reading." As with Δ_s, there is the same initial difference in level Δ_t between the reference signal and the unattenuated signal and it can be shown that, for the procedures employed in the 150 tests,

$$\Delta o = -(ELA_{obj} + \Delta_t) \quad , \text{dB} \tag{B-2}$$

Thus, the quantity $ELA_{subj} - ELA_{obj}$, reported for the ISO tests, is the same as the sum of our objective and subjective correction factors ($\Delta_o + \Delta_s$). This quantity can be shown to be equal to the equivalent level of the reference signal, when it is adjusted to the same loudness as the test signal, minus the equivalent level of this same reference signal, when it is now adjusted to have the same "instrument" reading as the test signal.**

An ideal "instrument" would have a zero value for $\Delta_o + \Delta_s$ so that it would correctly measure the loudness of an impulsive sound. However, a fixed but consistent "error", represented by a constant non-zero value of $\Delta_o + \Delta_s$ could be considered as a fixed "instrument" error to be corrected out. The critical parameter, therefore, for

* At presentation levels of 55, 75, and 95 dB, the average values of ELA_{subj} from Reference 66 were 9.3, 11.2, and 9.5, respectively.

** When $\Delta_s + \Delta_o$ is added to the "instrument" reading of the test signal the resulting level is the equivalent sound level, L_{eq} of an equally loud reference signal.

evaluating the ability of any "instrument" to measure impulse noise, be it an actual sound level meter (SLM) or a loudness calculation method, would be the standard deviation of the values of $\Delta_o + \Delta_s$ about the mean.

Table B-3 summarizes the comparable values of $\Delta_o + \Delta_s$ from the ISO data. The table defines the mean and standard deviation, over noise sources, subjects, and levels for $\Delta_o + \Delta_s$ for each of the ISO data sources and for the variety of objective measurement "instrument" indicated. It appears from these data that A-weighted sound level, slow (L_{AS}) equivalent sound level (L_{eq}), or some form of loudness calculation using, preferably, time-integrated measures of the spectral content, would all have potentially higher utility and validity than other "instrument"/metric combinations. For the single event impulsive sounds (Group II), all the measures with the exception of B-weighted peak impulse or C-weighted peak-hold indicate substantial variation about the mean.

The results of this Round Robin Test can also be compared, in terms of the mean objective correction factor $\overline{\Delta}_o$ with the results from Appendix A. From Table B-2, the mean sum $\overline{\Delta_o + \Delta_s}$ for A-weighted slow levels is + 11.6. Subtracting the mean subjective correction factor $\overline{\Delta}_s$ of 12.5 from Table B-2 gives a mean objective correction factor $\overline{\Delta}_o$ of - 0.9 dB. That is, the average A-weighted slow ISLM reading of the 9 impulsive sounds tested would be 0.9 dB above the average L_{eq} of these sounds. This average objective correction factor from the ISO round robin tests of - 0.9 dB compares well with the average of Δ_o of + 0.1 and - 1.4 dB from the two categories of impulsive signals (repetition rate > 1 pps or 0.4 to 1 pps respectively) reported in Appendix A.

Table B-3

Evaluation of ISO Round Robin Data for Optimum "Instrument" to Evaluate Impulsive Noise[f]

"Instrument"	Metric	Sounds 1-9 (Group I) $\overline{\Delta_o + \Delta_s}$ dB[e]	Sounds 1-9 (Group I) σ dB	Sounds 10-14 (Group II) $\overline{\Delta_o + \Delta_s}$ dB[e]	Sounds 10-14 (Group II) σ dB
Sound Level Meter	L_{AS}[a]	+11.6 (6)	1.5	+13.4 (6)	3.6
	L_{AF}[a]	+12.1 (8)	1.8	+12.5 (7)	4.9
	L_{AI}[a]	+11.2 (11)	2.3	+ 8.3 (11)	3.3
	L_{eq}[a]	+10.8 (1)	1.3	+10.5 (1)	2.6
	$L_B(PI)$[c]	+11.9 (1)	2.4	+ 4.5 (1)	1.7
	$L_{PK}(4)$[d]	+11.8 (1)	2.4	+ 3.6 (1)	1.6
Stevens Mk. VI	L_{CS}	+ 4.1 (3)	2.2	---	
	$L_{eq(C)}$[b]	- 0.5 (1)	1.4	+ 1.6 (1)	1.8
Stevens Mk. VII	$L_{eq(C)}$[b]	- 1.5 (1)	1.2	- 0.2 (1)	1.8
Zwicker	L_{CS}	- 0.8 (3)	2.6	+ 8.4 (3)	7.3

(a) Maximum peak reading.

(b) One second integration time.

(c) B-weighted peak impulse.

(d) C-weighted peak impulse.

(e) Number in parentheses signifies number of laboratories who provided data for this value.

(f) $\overline{\Delta_o + \Delta_s}$ defines absolute accuracy of loudness prediction, σ is standard deviation about this mean (see text).

APPENDIX C

FREQUENCY SPECTRA OF REPEATED TONE BURSTS

Four basic cases for the frequency spectra of transient sounds are illustrated in Figure C-1. The corresponding Fourier spectra for each of these cases, where the peak amplitude of the pulse is P_o, can be given as follows:[135]

Single Square Pulse

$$|P(j\omega)| = P_o T \left| \frac{\sin \omega T/2}{\omega T/2} \right| \tag{C-1}$$

Repeated Square Pulse

$$|P(\omega t)|_{max} = P_o \frac{T}{\tau} \left[1 + 2 \sum_{n=1}^{\infty} \left| \frac{\sin(n\omega_o T/2)}{n\omega_o T/2} \right|^2 \right]^{1/2} \tag{C-2}$$

Single Tone Burst

$$|P(j\omega)| = P_o T \left| \frac{\sin(\omega - \omega_1) T/2}{(\omega - \omega_1) T/2} \right| \tag{C-3}$$

Repeated Tone Burst

$$|P(\omega t)|_{max} = P_o \frac{T}{\tau} \left[1 + 2 \sum_{n=1}^{\infty} \left| \frac{\sin(n\omega_o - \omega_1) T/2}{(n\omega_o - \omega_1) T/2} \right|^2 \right]^{1/2} \tag{C-4}$$

where

T = Pulse duration

τ = Pulse repetition period

ω_1 = Pulse frequency

ω_o = $2\pi/\tau$, the pulse repetition frequency

n = Order of harmonic

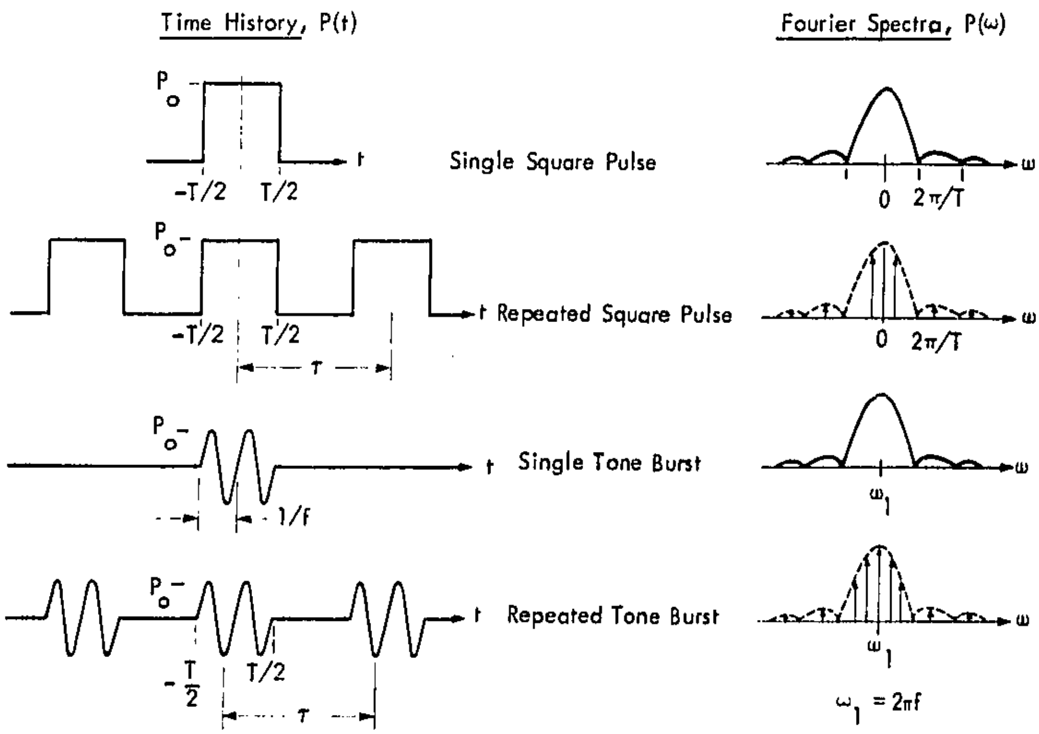

Figure C-1. Time History and Fourier Spectra of Four Common Impulsive Wave Forms

The general shape of the envelope of the frequency spectra is the same in all cases $\sim \sin x/x$. For the single or repeated tone bursts, the spectrum is the same as for the corresponding case of a single or repeated square pulse but with the peak frequency shifted to the right to the frequency (ω_1) of the pulsed tone. The 1/2 power bandwidth (Δf) of the spectrum for the case of the single tone burst can be expressed as $\Delta f = 1/T$. Thus, for a single pulse with only one cycle, $T = 2\pi/\omega_1$ and the 1/2 power bandwidth is equal to the frequency of the pulse itself. Then, a single impulse with only one cycle will have a very broad spectrum so that its loudness will correspond to the summation of loudness over many critical bands in the ear. For a repetitive version of such an impulsive signal, the frequency separation of the sidebands is equal to the pulse repetition frequency $\omega_1 = 2\pi/\tau$. The number (N) of harmonics within the same "1/2 power" point on the spectral envelope would be

$$N \simeq \frac{\tau}{T} = 1/\text{duty cycle}$$

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16. ABSTRACT

This study was undertaken to evaluate subjective and objective aspects of moderate levels of noise from impulsive sources. The study excluded evaluation of hearing damage risk or annoyance from building vibration by high level impulsive noise, which were covered by recent recommendations of the National Research Council, Committee on Hearing Bioacoustics and Biomechanics, Working Group 69. While the study included original investigations into some of the objective aspects of impulsive noise, a detailed review of the literature on the subjective aspects was emphasized . Based on this available literature, the annoyance and loudness from a wide variety of repetitive impulse noises were evaluated. These results were applied to the evaluation of impulsive noise from a number of specific noise sources. Based on the most pertinent literature, it is tentatively concluded that a subjective impulse correction factor of +7 dB applied to the A-weighted equivalent sound levels of these types of repetitive impulsive noise sources would better define their effective level in terms of annoyance reactions. No additional correction is identified at this time for crest level or repetition rate. Research on subjective correction factors for helicopter blade slap is also reviewed and potential reasons for the smaller subjective correction factors (i.e., 0 to 6 dB) for annoyance response to

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this type of sound are discussed. It is recommended that refinements to this subjective correction factor be based on the use of standard loudness calculation methods (Stevens Mark VII or Zwicker) modified to include provision for a shorter time constant to reflect subjective response to short duration impulsive sounds.

The study also included a brief experimental evaluation of the measurement of a wide variety of simulated repetitive impulsive-type signals varying in duty cycle, repetition rate, pulse frequency, and ratio of peak impulse signal level to continuous background noise level. When repetitive impulses are measured using maximum values of A-weighted (slow) readings on an Impulse Sound Level Meter, no objective correction is necessary in order to measure, with an accuracy of ± 1.5 dB, the equivalent level (L_{eq}) of the wide variety of impulsive signals investigated.