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Hearing Protector Performance in Impulsive Noise
(Part I: Study on Impulsive Noise Sources in the workplace)

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1. INTRODUCTION

European Communities Directive 86/188/EEC [1] sets advisory and mandatory limits, called action levels. These limits set both the daily personal noise exposure of employees and the maximum unweighted sound pressure to which employees may be exposed. The daily exposure action levels are currently 85 and 90dBA and the peak limit is 200 Pascal (140dB SPL). In order to assess the protection provided by hearing protector devices information is needed which describes the resultant pressure level underneath hearing protectors when subjected to impulse noise. To do this the characteristics of the impulse noise people are subjected to must be determined, however only those impulses above the 140dB action level need be addressed.

To fully define the acoustic performance of a hearing protector to any specified impulse would require a detailed knowledge of the dependence of any non-linearity on the peak level, rise time, and duration of the impulse. In other words, a full parametric analysis of the protector's attenuation performance as a function of these variables would be needed.

It is often impracticable to measure the attenuation of hearing protectors at a working location. Therefore, laboratory impulse sources need to be developed whose characteristics are similar to those found at the workplace to facilitate laboratory attenuation measurements.

The first of these two papers describes the characteristics of impulse noise and gives an indication of the peak levels and durations of many industrial and military impulse sources. In order to make modelling in the laboratory simpler, the impulses have been split into four categories which encompass all the possible impulses in the military and industrial environments.

The second paper will discuss the performance of various types of hearing protector on the market today and give some indication of their nonlinear behaviour. Secondly a review of the laboratory producible impulse sources will be presented together with the categorization in which they fall.

2. CHARACTERISTICS OF IMPULSE NOISE

Impulse noise is produced by a number of different phenomena giving the impulse its own characteristics. The nature in which the impulse is developed determines the time history characteristics of the impulse. For example the impulse produced by an explosion in free air produces a single spike type overpressure whereas the impulse of a drop forge has a characteristic ringing time history due to various resonance effects. Because of the differing time histories different describers are used to define the impulse characteristics. The types of time histories and their describers are shown below.

2.1 Classical Friedlander (A-Wave) Impulse

A single explosion or electrical discharge in free air will generally produce the classical Friedlander wave, shown in Figure 1.
The ideal impulse, for which the risetime (t_1 - t_0) is zero, is described by equation 1.

$$p(t) = p_{max}\begin{cases} 0 & , -\infty < t < t_0 \\ 1-\dfrac{t}{(t_2-t_1)}\, e^{-\frac{t}{(t_2-t_1)}} & , t_0 \le t < \infty \end{cases} \qquad (1)$$

The time taken for the pressure to first return to zero (at t_2) is called the A-duration. The tail of the impulse extends for approximately six times the A-duration before the pressure again returns to zero - in practice to less than 1% of the peak level - at t_3.

The spectral distribution of the energy in the impulse is controlled by both the A-duration

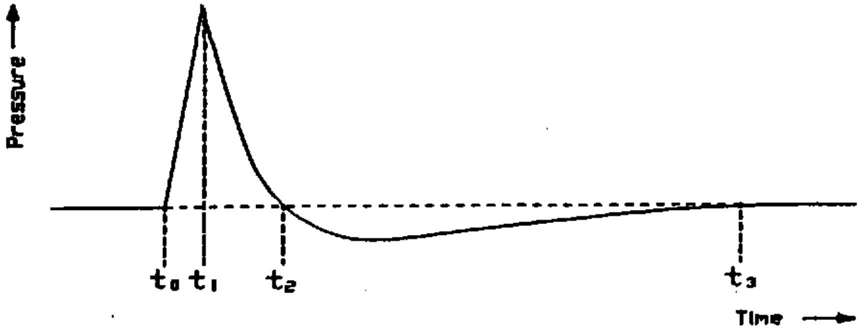


Fig 1 Friedlander Waveform

(T_D) and the rise time (T_R), as shown in Figure 2.

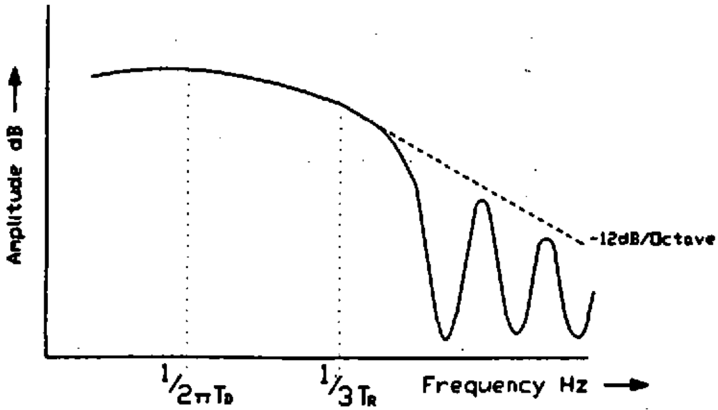


Fig 2 Spectrum of Friedlander Impulse

Peak level, rise time, and duration all depend on the type of source - in the case of explosives, the charge weight, design and containment. Gunfire noise (in free space) also resembles these simple Friedlander waves.

2.2 Reverberant Impact Pulse

The impulse produced by two metal objects colliding, as in drop-forging and stamping processes, is a far more complex transient decay of energy which is distributed across the many possible modes of mechanical vibration of the objects in question. It is likely, at its simplest level, to take the form shown in Figure 3.

The decay of the ringing time history is described in terms of its B-Duration - the time taken for the pressure to fall 20dB from its peak value. (An alternative term, the D-duration, is sometimes used. This is the time taken to fall 10dB from the peak level). The spectral distribution of energy in this impulse is determined both by its overall envelope decay and by the complex "ringing" infrastructure.

It is worth describing briefly the different mechanisms which produce the ringing time history. Akay [2] describes the five fundamental noise generating mechanisms associated the impact of two bodies.

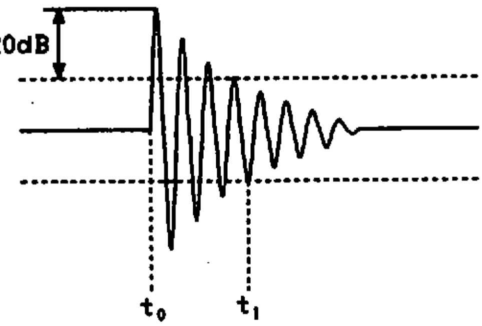


Fig 3 Reverberant Impact Pulse Waveform.

2.2.1 Air ejection: When two surfaces approach each other air is ejected from the space between them. When this gap is rapidly narrowed just prior to contact the flow becomes compressible and a pressure gradient is developed in the gaps between the surfaces. Upon rebound the newly created gap between the surfaces becomes a low pressure area and air flows inward generating another pressure pulse. The inflow also sets the trapped air in the cavity between the surfaces into resonance, causing oscillations in the acoustic field.

2.2.2 Rigid body radiation: One element in the sound field resulting from the impact of two bodies is due to sudden velocity changes of two bodies on impact. Rigid body radiation is the predominant source of sound when a ball strikes a massive plate. Radiation from the flexural vibrations of the thick plate is negligible.

2.2.3 Radiation due to rapid surface deformations: The deformation of a surface results in the generation of an initial peak sound pressure pulse before the natural mode of radiation of the plate is set up.

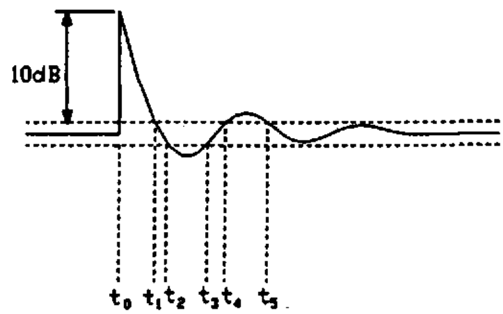
2.2.4 Pseudo-steady-state radiation: Impact processes are generally employed to convert a vast amount of energy into useful work in a very short time. The time span is often too short for the applied energy to be wholly converted to work. The excess energy is absorbed by the mechanical structure. The resulting damped harmonic radiation is referred to as ringing, this generally dominates the total radiation field from forging machinery. This is called pseudo-steady-state radiation in order to distinguish it from harmonically excited steady-state acoustic radiation.

2.2.5 Radiation from material fracture: The noise resulting from fracture of materials is a consequential source in punch presses and some other impact forming machines.

2.3 Effect of Environment
In the presence of any reflecting surface, such as the ground, or in a reverberant space, such as in a factory, there will be additional components in the impulse, produced by reflections.

If the path lengths involved are short enough, the reflections may interfere with the original pulse, producing a complex temporal pattern.

The term C-duration is used to describe the total time for which the pulse level exceeds the (peak - 10dB) criteria - see Figure 4.



$$\text{C-duration} = (t_1 - t_0) + (t_3 - t_2) + \ldots$$

Fig 4 Definition of C-duration.

Within a reverberant space such as a factory, a machinery impact noise may now comprise a series of pulses, possibly overlapping - see Figure 5. In such cases, the B-duration relates to the total time for which the level exceeds the peak -20dB criterion.

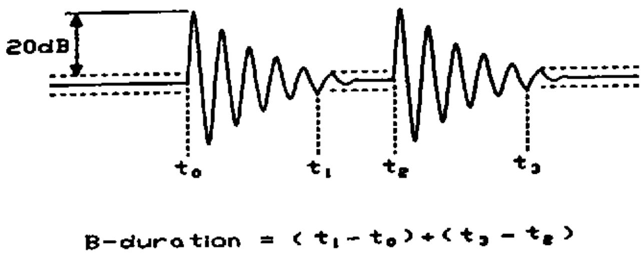


Fig 5 Definition of B-duration of multiple impulses.

3.0 WORKPLACE IMPULSE NOISE

Impulse noise is generated in the workplace from sources associated with metal forming and cutting, fabrication and material-dressing, air exhausts, and pyrotechnic devices.

Although many noise sources to which employees may be exposed in the workplace might be classified as "impulsive" in nature, in the vast majority of cases the peak sound pressure effective to the employee's ear is less than 200Pa. Such cases need not be considered within the scope of this study.

3.1 Industrial Impulse Sources

A project undertaken by Bolt Beranek and Newman Inc. and reviewed in [3] involved the measurement of a number of impact and impulsive noises commonly found in industry. Information regarding the peak levels of noise are listed in table 1. No information on the temporal and spectral characteristics were presented in this report. Other studies of impulse noise are included in the table.

Source	Duration (mS)	Peak level (dB)
[3] Bolt setting Gun		140
[4] Hammer on metal plate	B=25	125
[3] Carpenter's Hammer (0.45Kg)		147
[3] Pile Driver		130
[3] Plastic Forming Press		128
[3] Board Hammer (29000N)		145
[5] Drop Forge	B=60	133.4
[6] Drop Forge	B=50-100	160
Drop Forge (12 Tonne)	B=80	143
[3] Drop Hammer (11000N)		138
[7] Pneumatic Hammer		140
[3] Hand Hammering (2Kg on anvil)		130
[8] [9] [10] Punch Press	B=40	135
[3] Punch Press		118
[3] Transistor lead preformer		128
[11] Nail Shooting	B=15	140
[4] Nail Shooting		148
[12] Stapler	B = 35	130
Impact Welder	B=10	155
[3] Staple Gun		127
[3] Power Shear		117
[3] Pneumatic nailing machine		148

Table 1.

This table enables us to outline several major sources of impulse noises found in industry.

3.2 Military Impulse Sources
Military impulses have in general shorter duration, lower repetition rate and higher peak levels than industrial impulse noise. The temporal and spectral characteristics of impulses produced by military weapons can be broadly categorised under two different classes, that produced by light weapons and that from heavy artillery weapons both exhibiting Friedlander type waveforms.

Light weapons such as pistols and rifles have very short rise times (typically 30μs) and short durations (typically 300μs). This sharp time history produces a spectrum which has a very large bandwidth.

Medium and heavy weapon (cannon type weapons) impulses have longer rise times and duration, therefore producing spectra with large low frequency components and less energy in the upper frequency ranges. Impulses produced from blasting, quarrying and explosive testing are also characterised in the same manner.

Impulses commonly found in military environments have been studied considerably to try and relate the impulse characteristics to hearing loss. The characteristics of many weapons are described below in table 2.

NOTE:- The duration data presented from Hodge and Soderholm[15] is calculated using the time of 20dB below (before) the peak to the time when the pressure envelope has decreased to 20dB below the peak.

Weapon	Peak	Duration	Ref.
Howitzer 105mm	181 dB 167-183 dB 175-187 dB 158-165 dB	2.5 ms A 2.2-3.5 ms A 8.9-13.3 ms B 2.4-5.6 ms A 2.5 ms A	[13] [14] [15] [16]
Rifle Self Load. RK 7.62 M16 7.62 M14	159 dB 154-158 dB 155 dB 154-156 dB 155 dB	 0.4 ms A 0.3 ms A 0.3 ms A	[17] [18] [16] [19] [15]
Bazooka Light Heavy	165-180 dB 172-175 dB		[20]
Mortar	166-176 dB		[20]
Antitank Panzerfaust	182.8 dB	2 ms A - 10msB	[21]
Pistol .38 Rev. M/08 9mm P6 9mm 9mm	172 dB 150 dB 152 dB 159 dB	2.7 (Hodge) 0.3 ms A 	[15] [22] [23] [19]
Cannon (130mm)	176 dB		[19]
Machine Gun (7.65mm) M60	 164 dB 149-161 dB	 4ms (Hodge)	 [23] [15]

Table 2.

3.3 Categorization of Industrial and Military Impulse Noise.

To ensure the attenuation of hearing protectors in impulse noise environments is calculated correctly, the impulse source used in the laboratory has to resemble the impulse for which the hearing protector is to be used against. To do this one must be able to describe the impulses found at the workplace and relate laboratory impulse sources to common industrial and military impulses. To simplify the discussion, the impulse noises described in this chapter have been categorised into four different types.

Type 1.
These are high amplitude, long B-duration impulses which have most of their acoustic energy distributed in lower frequency ranges (ie. below 2 kHz). Noises that fall into this category include Drop Forges, Punch Presses and Stamping. Peak levels range from 125dB to 160dB, with B-durations greater than 30ms.

Type 2.
Type two noises are typified by Hammer Noise, Nail Shooting, Impact Welder and Staplers and have high peak level, short B-durations and most of the acoustic energy distributed in the higher frequency ranges (ie. above 2kHz). Peak levels range from 125dB and 150dB, with B-durations of between 2.5 and 30ms.

Type 3.
These are Friedlander type waves produced by large calibre weapons such as large howitzers, cannons and explosives. Peak levels can reach 190dB with A-durations between 2 and 6ms. The majority of the acoustic energy is concentrated into the lower frequencies.

Type 4.
Again these are Friedlander type waves produced this time by small calibre weapons such as pistols and rifles. Peak levels range from 150 to 172dB with A-durations between 0.2 and 2ms. The acoustic energy is predominantly in the high frequency end of the spectrum.

4.0 CONCLUSIONS

The purpose of this study is to facilitate the comparison of typical industrial and military impulse noise to that reproducible in a laboratory by means of categorisation of the different types of impulse noise. This categorization enables us to define laboratory impulse noise sources which can then be used to study the non-linear attenuation characteristics of hearing protectors in a laboratory environment.

A literature survey on the characteristics of impulse noise in the workplace (both industrial and military) has outlined four categories of impulse noise. These categories are briefly described below.

Type 1 sources are long B-duration impulses which have most of their acoustic energy distributed in lower frequency ranges (ie. below 2 kHz).

Type 2 sources have short B-durations with most of the acoustic energy distributed in the higher frequency ranges (ie. above 2kHz).

Type 3 sources are Friedlander type waves with long A-durations between 2 and 6ms, with the majority of the acoustic energy concentrated in the lower frequencies.

Type 4 sources are Friedlander type waves with short A-durations between 0.2 and 2ms, with the majority of the acoustic energy in the high frequency part of the spectrum.

Type 1 and 2 sources are commonly found in industry whereas type 3 and 4 sources are most commonly encountered in a military, mining and quarry environments.

Part II of this paper will discuss the non-linear behaviour of hearing protectors and laboratory impulse noise sources that can be used to assess the attenuation characteristics of such hearing protector devices. Using the categories of impulse noise defined in this paper the suitability of the laboratory impulse sources to determine the attenuation of hearing protectors will be discussed.

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