RIO 2005 inter-noise **ENVIRONMENTAL NOISE CONTROL**
The 2005 Congress and Exposition on Noise Control Engineering
07-10 August 2005 - Rio de Janeiro - Brazil

New System for monitoring exposure to impulsive noise

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Abstract: The U.S. National Institute for Occupational Safety and Health (NIOSH) developed a measurement and analysis system for accurately capturing and monitoring exposure to impulsive noise. The system consists of a Type 1, high intensity measurement microphone, a 24-bit data acquisition board with 96 kHz sampling rate, and a software tool that uses a graphical user interface (GUI) built in MATLAB to display the time domain waveform, frequency spectrum, and (1/1) and (1/3) octave band spectra of the captured impulse noise event. Additionally, parameters such as peak pressure level, equivalent average level, kurtosis, time duration, number of impulses, and temporal spacing between impulses are also calculated and displayed. An impulse detection routine was developed to aid in the location and analysis of impulsive events. Once the impulsive events have been identified, the program uses the three major damage risk criteria in use today (LeqA-8hr, MIL-STD 1474D, and Price/Kalb Auditory Hazard Units) to determine the limits for exposure to a particular impulsive noise event.

1. INTRODUCTION

Impulsive (impulse or impact) noise is generally considered to be more damaging to hearing than continuous noise.[1,2] Exposure to high-intensity impulse noise can cause acute acoustic trauma, which can be followed by such symptoms as tinnitus and temporary hearing impairment.[3,4] Sudden hearing loss may also occur from exposure to impulses that exceed a critical intensity level by causing direct mechanical damage to the inner ear.[5,6]

The U.S. National Institute for Occupational Safety and Health (NIOSH) recommended guidelines state that no exposure should be permitted above 140 decibels (dB).[7] This criterion is also used by the European Union (EU) directive 86/188, the International

Organization for Standardization (ISO) 1999–1990, and the American National Standards Institute (ANSI) S3.44.[8,9,10] Most of these standards recommend integrating both impulsive and continuous-type noise (using the 3-dB exchange rate of the equal-energy-rule) when calculating sound exposures over any specified time period. However, commercially available dosimeters and sound level meters do not perform properly in impulsive noise environments because they suffer from certain instrumentation limitations and lack measurement parameters that have been associated with characterizing impulse noise and its effect on the auditory system.[11] Current impulse damage risk criteria suffer from a lack of empirical data needed to quantify impulse noise exposures and assess potential damage to hearing.[12,13] Additionally, no universally-accepted standard defines impulse noise accurately nor does a standard method exist to measure impulses.

A new system for monitoring exposure to impulse noise was developed at the U.S. National Institute for Occupational Safety and Health (NIOSH) that addresses the limitation issues of existing instruments, as well as incorporates the application of relevant impulse noise parameters to current damage risk criteria. The system is based on the accurate capture and storage of the impulse waveform using a type 1 microphone, a data acquisition board, and a portable storage device or portable computer. The digitized waveforms are processed and analyzed by software algorithms built on the MATLAB software platform. The system was tested in the laboratory and the field and used to capture and analyze impulse noise exposure of law enforcement personnel at indoor and outdoor firing ranges. The system is shown in Figure 1.

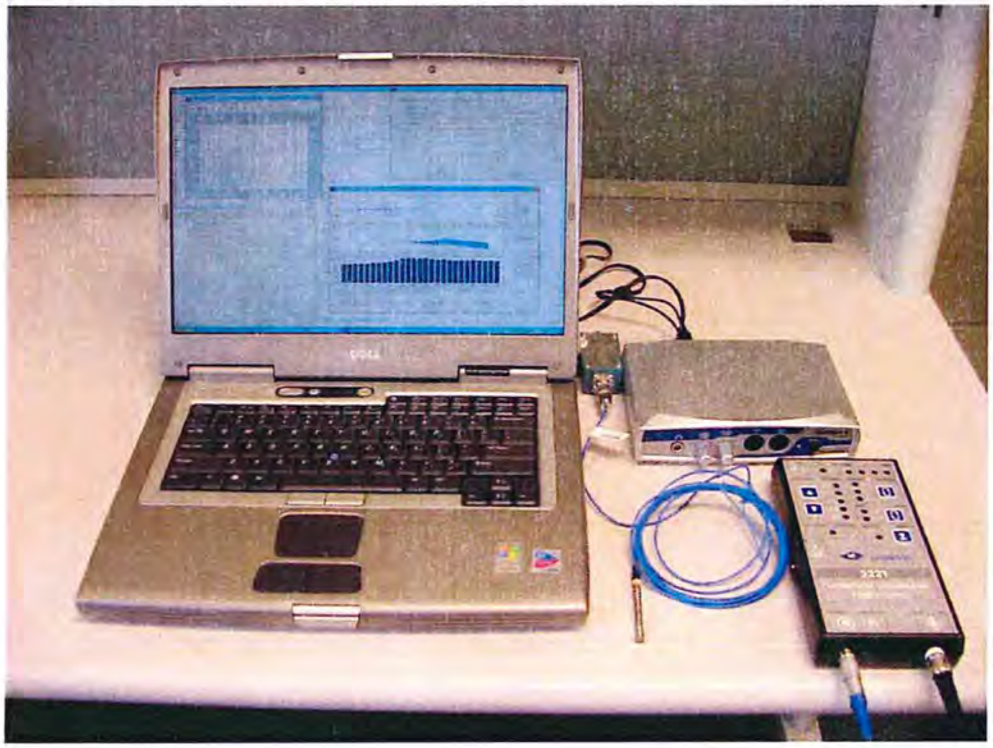


Figure 1: The NIOSH Impulse Noise Measurement System

2. CURRENT INSTRUMENTS LIMITATIONS

Contemporary noise dosimeters and most commercially available sound level meters face three major problems when used in impulsive noise environments. First, microphones and circuitry have been designed to satisfy prevailing regulatory practices and guidelines for monitoring hazardous exposures to limited ranges of noise waveforms and magnitudes. The microphones used in noise dosimeters, for example, are rated Type 2 and have a limited frequency response that significantly deteriorates above 3 kHz. The limited bandwidth also means the instrument is not capable of responding to impulses with fast rise time. Most noise damage risk criteria rely on the accurate measurements of true peak pressure levels to predict hearing damage risk from impulse noise.

The second problem relates to the uncertainty associated with the dose-response relationship in an impulse noise environment. The dose-response relationship as specified in current regulations and guidelines is based on the assumption that halving the exposure time would create the same degree of hazard as reducing the noise level by 3 dB (5 dB is used by the U.S. Occupational Safety and Health Administration). While this might hold true for continuous noise over a specific dynamic range, there have not been sufficient well-controlled studies to conclusively evaluate the equal energy hypothesis with humans when the noise contains impulsive components.

The third problem arises from the existing measurement parameters that cannot properly describe an impulsive event. Current noise dosimeters report noise levels (average, maximum, minimum, and peak), dose and projected dose, and the sound exposure level. Some sound level meters might also provide information about the spectral content in octave or 1/3-octave readouts. However, these parameters are not suitable to describe an impulsive noise environment. Impulsive noise is characterized by a different set of parameters. The Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) suggested in 1992 that to evaluate fully the effect of impulse noise on the auditory system, specific parameters should be considered such as peak pressure, durations, rise time, energy, spectral content, number and mixture of impulses, and temporal spacing.[14] Ear modeling algorithms were developed by Price and Kalb to model the response of the auditory periphery to impulsive and continuous noise. Their goal was to assess the potential Auditory Hazard to impulsive exposures.[15] Johnson and Patterson showed no significant temporary threshold shift (TTS) in 95 percent of their subjects in a blast overpressure study, and that current military exposure limits may be over-protective for humans wearing hearing protection.[16] The French Committee for Weapons Noises advocates the use of the A-weighted energy concept in the form of LAeq8 (8-hour, equivalent A-weighted sound exposure level) with a limit of 85 dB for unprotected ears.[17,18]

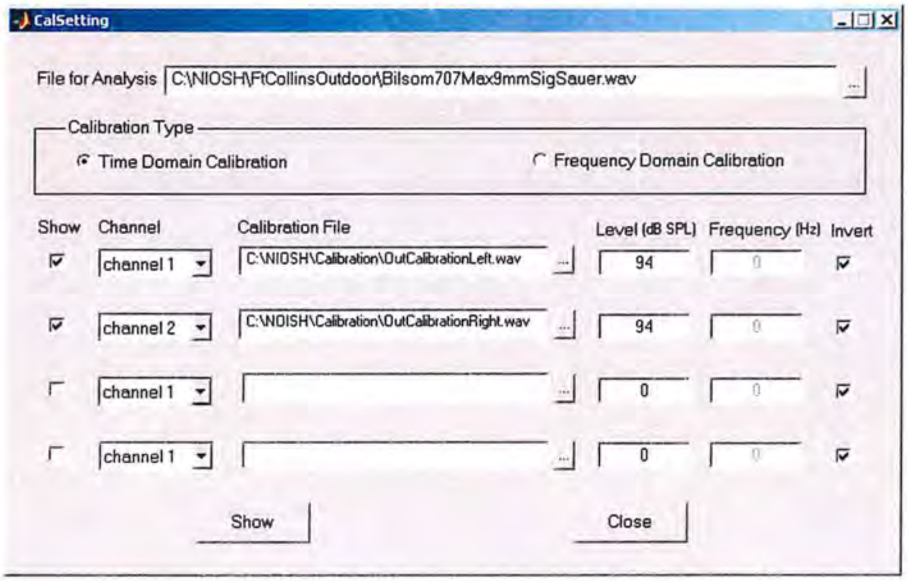
3. NEW MEASUREMENT SYSTEM

The NIOSH Impulse Noise Measurement System (NINMS) consists of a PCB Piezotronics Model 377A01 Prepolarized 1/4" microphone that can powered by PCB Piezotronics Model 480A25 power supply or, for portable applications, a PCB Model 485B36 ICP signal conditioner that can be powered from a computer's Universal Serial Bus (USB) port. The signal from the microphone is captured and digitized at 96 kHz and 24-bit resolution using

M-Audio Audiophile USB interface. The digitized signal is transferred and recorded to a portable hard drive or a portable computer. Analysis of the acquired impulse signals was conducted using custom software routines developed by the authors in MATLAB.

3.1 Graphical User Interface

The graphical interface of the NINMS program is shown in Figure 2. The user is able to select the waveform to be analyzed, the calibration files and levels associated with this waveform. Currently, NINMS is capable of reading a .wav and binary Matlab data files. Multi-channel files are supported by analyzing the file channel-by-channel.



File for Analysis: C:\NIOSH\FtCollinsOutdoor\Bilsom707Max9mmSigSauer.wav

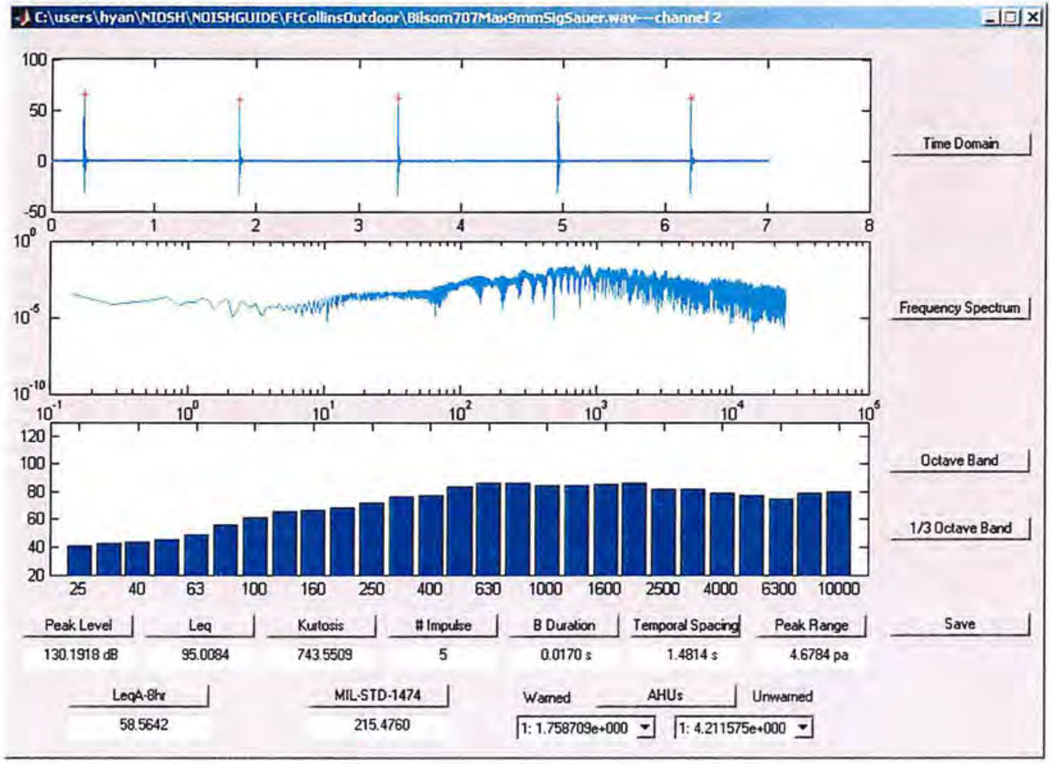
Calibration Type
● Time Domain Calibration
○ Frequency Domain Calibration

Show	Channel	Calibration File	Level (dB SPL)	Frequency (Hz)	Invert
☑	channel 1	C:\NIOSH\Calibration\OutCalibrationLeft.wav	94	0	☑
☑	channel 2	C:\NOISH\Calibration\OutCalibrationRight.wav	94	0	☑
☐	channel 1		0	0	☑
☐	channel 1		0	0	☑

Figure 2: Input screen of the NINMS graphical interface

3.2 Measurement and Analysis

NINMS is capable of displaying time domain waveform, frequency spectrum, and (1/1) and (1/3) octave-band spectra. Additionally, parameters such as peak pressure level, equivalent average level (Leq), kurtosis, B-duration, temporal spacing between impulses, and peak range are also calculated and displayed. An example display of NIMS is shown in Figure 3. Furthermore, the program utilizes an impulse detection routine to locate the impulsive events in the data stream.[19] Once the impulsive events have been identified, the program uses the three major damage risk criteria in use today (LeqA-8hr, MIL-STD 1474, and Price/Kalb Auditory Hazard Units) to determine the limits of exposure to a particular impulsive noise event. In addition to the graphical display, users can also save the results to an output file for further analysis.



C:\users\hyan\NIOSH\NOISHGUIDE\FtCollinsOutdoor\Bilsom707Max9mmSigSauer.wav---channel 2

Peak Level	Leq	Kurtosis	# Impulse	B Duration	Temporal Spacing	Peak Range
130.1918 dB	95.0084	743.5509	5	0.0170 s	1.4814 s	4.6784 pa

LeqA-8hr	MIL-STD-1474	Warned	AHUs	Unwarned
58.5642	215.4760	1: 1.758709e+000		1: 4.211575e+000

Figure 2: NINMS measurement and analysis graphical display

3.3 Damage Risk Criteria

The A-weighted acoustic energy ($L_{eq}A\text{-}8_{hr}$) criterion is based on work by Atherley and Martin, Dancer, and advocated by the French military.[20] It prescribes a limit of 85 dBA for an 8-hour, A-weighted, equivalent level. The attractiveness of the A-weighted energy is that it's simple and that it integrates both continuous and impulsive noise. It allows for the assessment of exposure to multiple impulse sources regardless of whether the event occurs in the free-field or a reverberant environment. Another major advantage of the $L_{eq}A\text{-}8_{hr}$ method is that it allows for measuring the effectiveness of hearing protection devices.

The second criterion is the U.S. Military standard, MIL-STD-1474D, and is based on the 1968 Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) criterion.[12] The criterion has been in use for 35 years, it is too simple and straightforward—one only needs to know the pressure time history of the impulse waveform close to the ear and the number of impulses. However, the CHABA criterion does not account for spectral or temporal content, nor does it account for combined exposure to continuous and impulse noise. In addition, this criterion does not provide the means to evaluate the effectiveness of hearing protection in use. MIL-STD-1474D calculates the allowable number of exposures per day based on the following equation:

$$N_1 = 10^X \text{ where } X = \frac{1}{5}\left[177 - L + 6.67 Log \frac{200}{T}\right],$$

$N_2 = 20N_1$, and

N_1 = allowable number of impulses/day (single protection),
N_2 = allowable number of impulses/day (double protection),
L= measured peak sound pressure level, in dB,
T = measured B-duration in milliseconds, if $B > 200$ msec, use $B = 200$ msec.
The standard does not require hearing protection for impulses with peak pressure levels under 140 dB (SPL).

The third damage risk criterion included in NINMS is the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model developed by Price and Kalb to estimate the risk of auditory damage from an impulsive noise captured as a pressure time-history waveform. The AHAAH model is a model of the auditory periphery that couples the acoustic signal with a nonlinear middle ear and a linear transmission line model of the cochlea. The nonlinear middle ear of the AHAAH model is unique because it attempts to model the behavior of the annular ligament supporting the stapes at the oval window. Typically the stapes is modeled as a harmonic oscillator. For extreme sound pressure levels, the stapes displacement would be unrealistic. Because the stapes displacement is limited, the nonlinearity provides asymptotic limits on the stapes displacement. A 4th order Runge-Kutta solution is used to model the acoustic transmission into the ear and to solve for the stapes displacement. Once the stapes motion is known, the linear cochlear transmission line model is solved with a WKB method to estimate the displacement and velocity of a 23-segment cochlea. The coarse solution of the cochlea corresponds to the distribution of critical bands for human hearing. The nonlinear response of the cochlea to low amplitude signals is saturated and dominated by the linear response of the basilar membrane for high-amplitude inputs. The AHAAH model estimates the basilar membrane velocity at zero displacement and integrates the stress over the duration of the input signal. The maximum response of the 23 bands yields the auditory hazard unit.

The AHAAH model permits three different locations for measurement of the acoustic signal to be inserted into the cochlear model: free-field, ear canal entrance and at the tympanic membrane. When the user analyzes the waveform, the pre- and post-impulse delays must be selected and the measurement point must be identified. For multiple impulses within a recording, the same parameters will be applied and the hazard for each impulse will be calculated for both the warned and unwarned conditions. A warned condition assumes that the stapedius muscle has been tensioned increasing the impedance of the ossicular chain and decreasing the amount of energy transmitted to the cochlea.

4. CURRENT STATE-OF-THE-ART IN INSTRUMENTATION

A new system for impulse noise measurements require the acquisition and storage of the original impulse waveform for post-processing of the parameters cited previously. The current state-of-the-art allows us to take advantage of advances in storage and compression schemes to design a portable system with the capability to record and retain the actual impulses. The application of lossless audio compression schemes such as MPEG-1, layer 3 or MPEG-4 are based on psychological principles and may prove feasible for capturing the essential impulse waveform time and frequency contents without substantial degradation.

Smart storage cards and removable media are also an option providing portability and added flexibility. Secondly, advances in microprocessor and digital signal processing technologies can be incorporated into the new system to allow for real-time calculation and measurement of impulse noise parameters, as well as implement modifications via software routines to adapt for changes in evolving damage risk criteria. These modifications can be performed using software algorithms that reside on computers that can be linked to the new system via infrared ports or by any of the new emerging wireless protocols, such as Bluetooth or 802.11.

5. CONCLUSION

The principal problem with current impulsive noise criteria is the lack of an empirical database to support exposure limits. The problem is compounded by the extremely broad variations of impulses that exist in industrial and military environments. A new system that is capable of accurately measuring continuous and impulse noise will serve to advance the collection of data on which a new and valid damage risk criterion can be established. This paper illustrates the current limitations of current noise instruments and introduces a new system for capturing or measuring impulse noise parameters that are correlated with risk of hearing loss. The new system is equipped with storage and archiving capabilities to retain the original impulse event. The new system provides the user with the capability to modify existing metrics and include new metric developments as more empirical data become available.

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