Evaluation of effects on workers’ health due to exposure to different intensity SPLs arising from various work activities. Standardized procedures and integrative methods.

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Abstract

Risks arising from physical agents - such as noise pollution - are sometimes underrated or not treated in a suitable way. This happens especially when workplace wellbeing is considered. In Europe, security is ensured with the *Directive 2003/10/EC of the European Parliament and of the Council of February 6th, 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)*. It supplies the minimum health requirements to assure health-care and protection from loud sounds to those workers who are exposed to noise as a result of their work. Nevertheless, this standard is far away from guaranteeing a complete safeguard because of several shortcomings.

In this chapter, the working activities of workers who remain in noisy workplaces for prolonged periods are analyzed. These activities may produce serious risks for worker’s health with particular reference to the organ of hearing and its psychophysics functions. Therefore, parameters and acoustics quantities - which allow a better understanding of the physical phenomenon appointed within the Directive - are analyzed using data recorded with dosimeters and real time analyzers. Works carried out in environments characterized by different acoustic intensities are considered in this analysis. Depending on exposure time, each noisy environment can produces annoyance phenomena or permanent psychosomatic damage. In particular, the following activities are subject to investigation: office activities, work activities of public transportation drivers, university and research center’s laboratories (e.g. mechanics labs, engine testing room, material stress testing labs, etc.) and industrial activities.

Based on the sampled data, acoustics parameters used within the current Directive are evaluated to highlight that it underestimates the effective noise to which workers are subjected. The same data is used to prove that these parameters cannot guarantee a protection from noise as effective as in the Directive’s original aims. In practice, through several in-situ measurements the intensity of acoustic parameters is evaluated according to what is stated within the Directive. Then, the same data are analyzed using an integrative procedure – proposed by the authors – to evaluate the influence of impulsive components, which cannot be determined with the current standards. In addition, the influence of sound phenomena’s spectral composition and its influence on the interested portion of human cochlea are achieved.

1 - Introduction

Noise has become a prominent feature of the environment. Nowadays, people are constantly subjected to an increasing number of acoustic sources. Among them noise arising from: transportation, industrial activities, and work places. It has been demonstrated that noise interferes in complex task performance, modifies social behavior, and may cause several health problems (e. g.: annoyance, disturbance in sleep, interference with communication and other harmful effects) [1]. Noise can be defined as an invisible pollutant, completely different from other typologies of contaminant, and therefore unique in its characteristics. Indeed, the idea that noise pollution may have physical and health implications on people’s life is quite recent [2].

The risks arising from physical agents - such as noise pollution - are sometimes underrated or not always treated in a suitable way, particularly when workplace well being is considered. Indeed, it is absolutely unreasonable that workers may get injured while performing their jobs. For this reason, many regulations have been proposed to protect workers from risks arising from noise. In Europe, security is ensured with the *Directive 2003/10/EC of the European Parliament and of the Council of February 6th, 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)* [3]. It supplies the minimum health requirements to assure health-care and protection from loud sounds to those workers who are exposed to risks from noise as a result of their work. While the Directive addresses problems coming from noise exposition and suggests practical requirements for protecting workers, it is far away from guaranteeing a complete safeguard because of certain shortcomings [4].

Following the introductory, in which an overview of the hearing organ and the main acoustic descriptors is given, a critical analysis of noise produced by different work is carried out. Activities made in environments characterized by different acoustic intensities are considered. Depending on exposure time, each environment can produce effects on the human health that range from annoyance phenomena to permanent psychosomatic damage [5]. In particular, the following activities are hereby subject to investigation: office activities, work activities of public transportation drivers, university and research center's laboratories (e.g. mechanics labs, engine testing room, material stress testing labs, etc.) and industrial sector's activities. Through several in-situ measurements the intensity of acoustic descriptors is evaluated according to what is stated within the Directive. Then, to prove that chosen parameters cannot guarantee a full-protection from risk arising from noise, the same data will be analyzed using an integrative procedure to evaluate both the influence of impulsive components and sound spectral composition, which cannot be properly determined when currently used procedures are applied.

2 – Anatomy of the human hearing organ

Exposition to noise can create harmful effects on human depending on the characteristics of the acoustic phenomenon (sound pressure levels, frequency, impulsive components, tonal components, etc.), exposition time, and subjective sensitivity of the person [6].

Hurtful consequences are mainly due to loud sound exposition, even for short time periods. From a clinical and pathological point of view, they consist of irreversible or not-completely reversible alterations of ear's anatomic functionalities [7]. On the other hand, exposition to lower and not excessively prolonged sound pressure levels (SPLs) can cause disturbance effects that lead to temporal alteration of the physical and mental conditions of the exposed person [8]. In addition, extremely sensitive subjects may address a feeling of discomfort even if they are exposed to very low SPLs [9]. This pathology is referred to as annoyance and it represents the subjective response to noise. Since it is a personal reaction - usually of physiological origin - it cannot be found through clinical analyses [1].

Before analyzing noise effects on workers' hearing organs, it is necessary to understand the structure of the ear and the way it transmits the received acoustic signals to the brain. As shown in Figure 1, the ear can be divided in three parts: outer, middle, and inner ear.

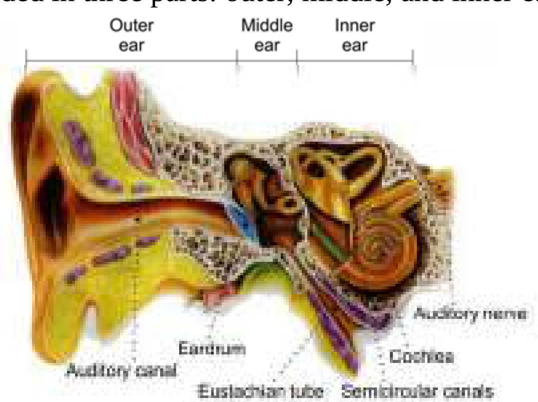


Fig. 1 – Section of the human hearing organ

2.1 – Outer ear

The outer ear is the most external part of the organ. It includes the pinna (or auricle) and the external acoustic meatus (or auditory canal) [10]. The auricle collects the acoustic waves, which hit the surface of the ear, and conveys them to the inner part. The acoustic meatus stretches for nearly 24 millimeters and is surrounded with bones and cartilages. It ends on the tympanic membrane (or eardrum), which divides the outer ear from the middle one.

2.2 – Middle ear

Tympanum is a cone-shaped membrane fixed on the temporal bone through a fibro-cartilaginous ring called tympanic annulus. The middle ear, also referred to as tympanic cavity, is an air-filled, irregular-shape cavity, dug in the temporal bone. It includes three bones (or ossicles): the hammer (or malleus), incus (or anvil), and stapes (or stirrup) [10]. The first one is a small-elongated bone – measuring lengths from 7 to 9 millimeters. It is made of a handle, connected to the eardrum, a neck, and a head, connected to the incus. The hammer transmits vibration of the membrane produced by sound waves. The incus is connected with the stapes through its lower branch. The three bones transmit the sound from the tympanic membrane to the ventricles of the ear [11]. In Figure 2 a representation of the ossicles is shown.

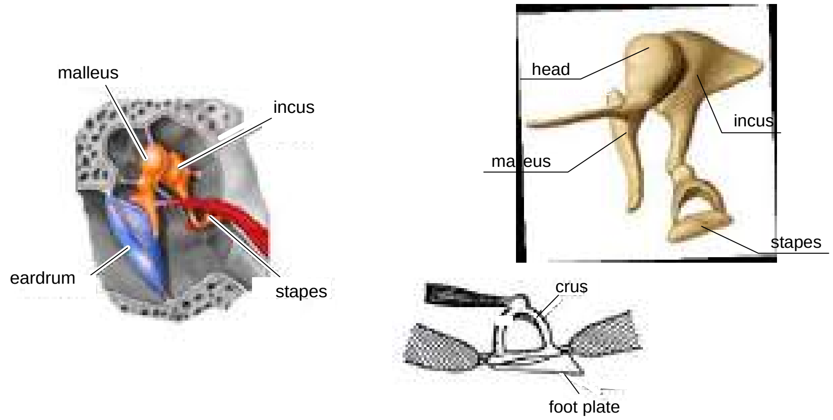


Fig. 2 – Representation of the three bones

Within the bony canal, there are two muscles: the stapedius muscle and the tensor tympani [10]. The middle ear also contains a canal called Eustachian tube. It connects the tympanic cavity to the nasopharynx, the uppermost part of the pharynx. This canal compensates for the force acting on the external part of the tympanic membrane due to atmospheric pressure. The air, which enters through the Eustachian tube, balances the high stresses placed on the membrane resultant from the atmospheric pressure [11]. The ending part of the stapes, called the base, rests on the oval window and separates the middle ear from the inner ear.

2.3 – Inner ear

The inner ear contains the sensory organ for balance and hearing. Here, it is possible to distinguish the vestibule, three semicircular canals, and the cochlea. The vestibule is the construct of the ear that communicates with the middle ear through the oval window. The semicircular canals are made of two parts: a bony labyrinth and a membranous labyrinth contained within the bony labyrinth, which reproduces its morphology. The bone canals are connected to the vestibule through three orifices. These are located perpendicular to one another and are arranged in the upper and rear of the vestibule. The cochlea starts from the base of the vestibule, as a tubular space, then makes 2.5 turns around its axis [10]. Figure 3 shows the main components of the inner ear.

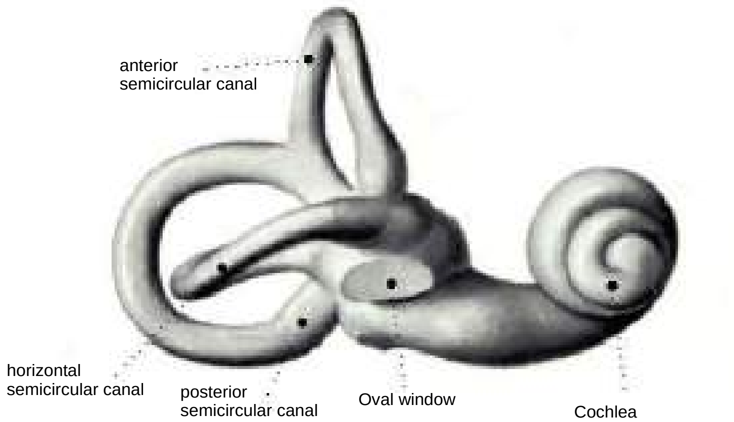


Fig. 3 - Components of the inner ear

The cochlea is the auditory portion of the inner ear and is the core of the auditory system [12]. This coiled tube is divided into two portions (scale) by means of an inner membranous partition: the scala vestibule and the scala tympani (see Figure 4.a). The two scales are filled with a fluid called perilymph and are separated everywhere along their length but the top, where a connection is made through a hole called helicotrema. The helicotrema allows fluid to move within the two ramps [10]. The lengthwise partition that divides most of the cochlea is itself a fluid-filled tube, called scala media or cochlear duct. It is bounded on three sides by the basilar membrane, the stria vascularis, and Reissner's membrane (see Figure 4.b) and it is filled with a fluid called endolymph.

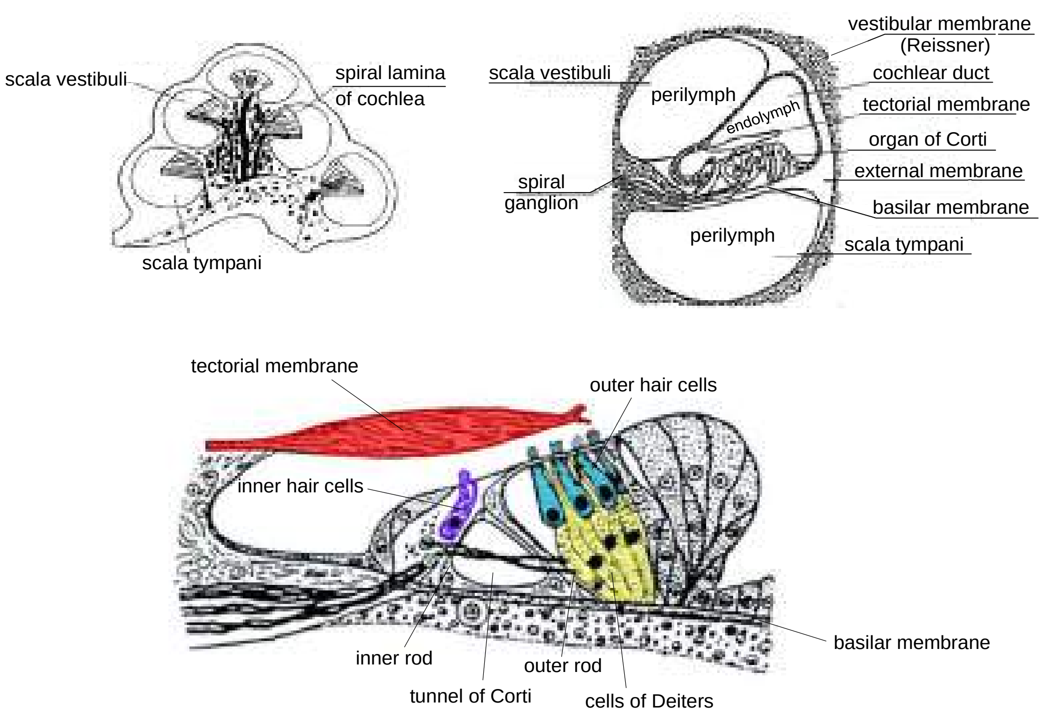


Fig. 4 – Sagittal section of the cochlea (a), of the cochlear canal (b), of the organ of Corti (c)

Sound vibration transmitted by the ossicular chain, becomes a change in the pressure of the fluid inside the cochlea. Because of this variation, the basilar membrane starts oscillating with different amplitudes depending on the intensity of the acoustic input. The basilar membrane is made of several elastic fibers, connected to two bony prominences. Fibers are short and dense at the beginning of the cochlea and become longer and thinned as they proceed toward the apex. At the same time, they modify their elasticity at an exponential rate. Different stiffness allows sounds of vary frequencies to excite different point of the membrane; areas close to the base are excited by high-frequency sounds, while areas close to the apex are excited by low-frequencies [13].

Resting on the basilar membrane and disposed along the entire cochlear duct, there is the Organ of Corti. As shown in Figure 4.c, it is made of several cells arranged in a pillar shape, which delimit the Tunnel of Corti. On both sides of that tunnel there are acoustic cells connected to cochlear nerve fibers (ganglion of Corti) [8]. There are two different types of cells: external and internal. The external cells are made of rigid hair and are connected to nerve endings called stereocilia. As shown in Figure 5, they are made of a bundle of tubes rigidly mounted at the top of the external cells and connected to the tectorial membrane, which transmits vibration from movements of the endolymph in the cochlear duct. The viscosity of the tectorial membrane has a fibro-gelatinous composition that allows it to adapt its shape to variations in the organ of Corti [14]. The internal cells, which, are connected to the basilar membrane have a sensing capacity which can transmit received signals to the cochlear nerve. Each module is made of a triplet of moveable hair cells and an internal cell. The physical structure of the system allows an amplification of high-frequency signals. Otherwise, this frequency range would be cut because of the reduced sensitivity of the motor cells.

Fig. 5 – Stereocilia

The mechanism underling the operation of the Organ of Corti is based on the electrical potential difference between the two scales because of the two different fluids running within them. The equivalent electrical circuit and electrical potentials are shown in Figure 6.

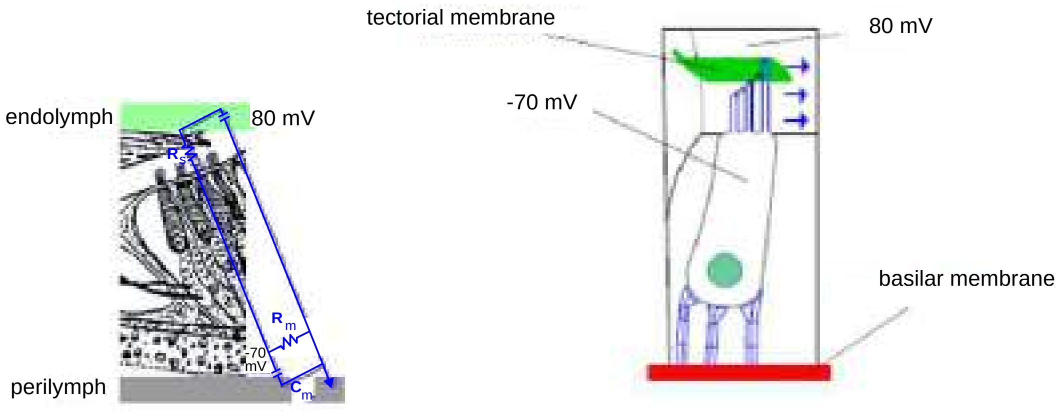


Fig. 6 – Equivalent electrical circuit and functioning of the Organ of Corti

Since hair cells are connected to the basilar membrane - which is the upper limit of the scala tympani filled with perilymph – they are subjected to an electrical potential of -70mV. On the extern, the same cells are connected with the tectorial membrane, which is the lower limit of the scala vestibule filled with endolymph. This has an electrical potential of +80mV. The sum of the total electrical potential is equal to 150mV with electrical currents up to $8*10^{-9}$ A [13]. Signal transmission happens because of stereocilia deflection that produces a decrease in the electrical resistance R_s. This decrease produces an electrical potential drop across the resistance of the membrane R_m and an increase in the electrical potential in the hair cell itself. The phenomenon depends on frequency of the sound because this parameter changes the electrical capacitance of the membrane C_m [14].

The functions of the Organ of Corti is extremely special, and has only recently been fully elucidated with particular reference to the mechanism of amplification of the received acoustic signal [15]. Amplification comes from the driving action of the outer hair cells, which - as already said- are organized in triplets that amplify the oscillations of the cochlea canal from the movements of the endolymph. Through actions of expansion or contraction, they leverage on the Organ of Corti to generate forces capable of neutralizing the viscous resistance of the cochlear membrane, which in turn allows the elastic oscillations to be transmitted to the basilar membrane.

2.4 - Sound transmission to the human ear

The transmission mechanism, through which hearing organ sends a sound to the brain centers, is extremely complex [16]. The pinna collects sound waves and directs them to the auditory canal. When sound reaches the tympanic membrane, it causes the vibration of the tympani. Through the membrane, waves are transmitted to the middle ear without changes in frequency or amplitude. Then, vibration reaches the ossicles and is transmitted to the oval window. This time, unlike what happens at the interface with the outer ear, acoustic waves are modified. During transmissions to the inner ear, the anatomic structure of the organ allows an amplification of the sound pressure acting on the oval window. This amplification is nearly 100 times the amplification acting on the tympanic membrane outer wall. In addition, the vibration amplitude of transmitted sound waves is significantly reduced [13]. Pressure amplification happens for mainly four reasons:

a) Three bones act as a lever with an amplification factor of nearly 3. The location of the fulcrum is closer to the oval window than to the tympanic membrane. This causes an increase in the transmitted force in comparison to those acting on the membrane itself.

b) The surface on which pressure is applied is smaller. The oval window is on average 30 times smaller than the tympanic membrane (2.5 mm^2 and 80 mm^2 respectively).

c) The braincase acts as a sounding board.

d) The resonant effect on the acoustic meatus.

This complex system of sound transmission constitutes a kind of mechanical transformer. It works as a hydraulic press and increases the portion of absorbed energy at the expense of that reflected. Basically, it allows without great losses, the transmission of energy of the incident sound. The function of the stapedius muscle and tensor tympani enables the adaptation of the operation of the ear to the type of incident disturbance [14]. For instance, consider a sound having low intensity. When the wave hits the tympanic membrane, tensor tympani causes a refinement of the membrane. Because of the section reduction, the membane will vibe with more energy allowing a better auditory sensation. On the other hand, if the sound hitting the membrane is a high-intensity and quickly raising signal, stapedius muscle protects the ear from possible damage by reducing excursions of the ossicles and reducing the energy moving from the tympanum to the oval window. This ear defensive mechanism intervenes with a characteristic muscle reflex time (nearly 1 second). Because the sound waves come to the oval window before the defensive mechanism can be activated, it is not effective against impulsive noises [13]. Sound waves, transmitted through the previously described mechanism, arrive filtered to the oval window. Here the energy is transmitted to the incompressible fluid, the perilymph, which is placed in the scala vestibule. Vibration propagates along the scala and through the helicotrema, reaches the scala tympanic. At its end - closed by a membrane called secondary tympanic - there is the round window which allows the perilymph to oscillate. Figure 7 shows a stretched-out section of the cochlea.

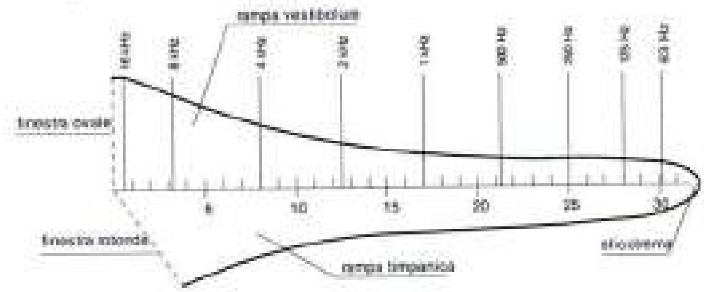


Fig. 7 – Stretched-out section of the cochlea

For each frequency, there is a portion of the membrane characterized by maximum vibration amplitude. High frequency vibrations excite the areas close to the oval window (beginning of the cochlear duct), while low frequency vibrations excite those close to the helicotrema. For humans, the lower frequency of the audible range is 20Hz. Because of the length of the cochlear canal (30 millimeters) [10], sound pressure, which propagates on the scala vestibule, reaches the helicotrema in a time equal to a period. Therefore, no pressure difference is generated between the two scales and the basilar membrane is not excited. The 20Hz limit is due to the fact that if the ear were sensitive to lower frequencies, it would be possible to detect muscle contractions and impact with the ground as well. The upper limit of the audible range is, instead, 20kHz [17]. If the frequency of the sound exceeds this value, the mechanical inertia of the three bones does not allow the transmission of the sound wave to the perilymph, preventing the hearing organ from perceiving the sound.

To conclude, it is important to point out that the dissymmetry of the vibrating system produces a non-linear response when a sound wave has high intensity impacts on the tympanic membrane. Because of this dissymmetry, when a pure tone hits the hearing organ, the ear will perceive the harmonics of the incident sound. These are called subjective harmonics and are easily generated with low pitch sounds. When two pure tones with enough high intensity reaches the tympanic membrane, several different sounds are perceived. The two fundamental frequencies are the partial sounds in harmonic relation with the two pure tones, and the linear combination of the two fundamental tones. The fundamental tones are called combination tones and because of them, the brain can reconstruct a complex sound even if it does not get all the information about the original sound. Based on what is stated in this paragraph, it is clear that cochlea is not only an acoustic signal transducer for the brain, but it also performs functions of signal processing, favoring its decoding. In addition, the cochlea eliminates the weak signals at frequencies close to those characterized by greater intensity in order to suppress the noises that may disturb the main signal. This happens because the cochlear amplification system is saturated by the signals of higher intensity. Furthermore, cochlea promotes perfect decoding of complex sounds, which are characterized by tones that quickly change their amplitude and frequency. It transforms the signal so that tones with different intensities can produce an effect on the acoustic nerve stimuli of almost equal intensity.

3 – Acoustic descriptors and characteristics of sound events

The human ear is clearly a uniquely sophisticated yet delicate organ. It can be compared to a sensing device able to detect change in acoustic pressure and vibration. This paragraph addresses the relevance between sounds and the above-described elements, introducing the main acoustic descriptors and how they can be used to evaluate possible risks arising from noise. In particular, phenomena of impulsive sounds and the change of sensitivity at the different frequencies is analyzed.

Usually, the acoustic descriptors used to characterize the acoustic phenomenon are the following [18]:

a) Effective A-frequency weighted SPLs (L_{AS}, L_{AF}, L_{AI} values determined using slow, fast, and impulse time constant respectively)

b) Maximum A-frequency weighted SPLs (L_{ASmax}, L_{AFmax}, L_{AImax} maximum values determined using slow, fast, and impulse time constant respectivel)

c) Equivalent continuous A-weighted sound pressure level $L_{A,\,eq}$-
This is the constant noise level that would result in the same total sound energy (or the same mean square pressure) produced over a given period T by the real fluctuating noise. Basically, it is the stationary SPL that in the considered time T, produces the same effect of the real sound, whose level changes in time. The equivalent continuous A-weighted SPL can be evaluated using the following equation:

$$L_{A,eq} = 10\log\left[\frac{1}{T}\int_0^T\left(\frac{p\,(t)}{p_0}\right)^2 dt\right] \quad (1)$$

where T is the measurement time, p (t) the instantaneous value of the sound pressure in Pascal, and p_0 is the reference value of pressure (20 μPa). From a graphical point of view, the equivalent continuous A-weighted sound pressure level is the constant SPL that in the considered time subtends an area equivalent to that subtended by the real curve representing the evolution of the real phenomenon as shown in Figure 8.

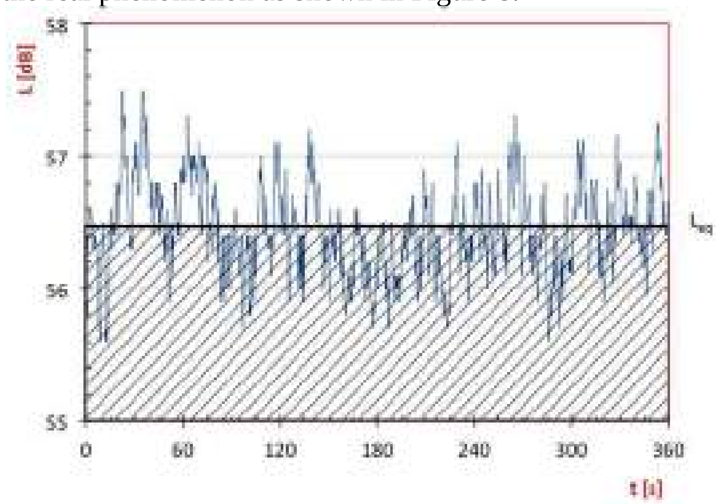


Fig. 8 - Graphical representation of the equivalent continuous SPL

Historically, because of limited computational and analysis capacities, the continuous equivalent SPL has been the only parameter used. The choice of $L_{A,\,eq}$ is also determined from a link connecting it to hearing loss. This is carried out during an evaluation of effects on individuals who are subjected to constant SPL for a sufficiently long time (e. g.: workplaces) [19]. The equivalent continuous level allows the sound to be characterized with only the value of the sound energy produced by all sources present, regardless of their characteristics (fluctuating or continuous sources, impulsive, etc.). By contrast, it does not enable the identification of the individual noisy events that have contributed to the overall value. Therefore, it is clear that the $L_{A,\,eq}$ is not suitable to completely describe all the sound characteristics, especially for those phenomena which are extremely dynamic, or when data usable for identifying corrective operations is required.

d) A-weighted sound exposure level L_{AE};
This is the SPL of a sound that is constant for 1 second, which has the same sound energy of the measured real event. Practically, it is the SPL of a phenomenon that in 1 second produces the same energy produced by the phenomenon being studied in the period $T = t_2 - t_1$. It can also be seen as an equivalently continuous SPL normalized to 1 second. L_{AE} can be evaluated using the following equation:

$$L_{AE} = 10 \log \left[\frac{1}{T_0} \int_{t_1}^{t_2} \left(\frac{p\,(t)}{p_0} \right)^2 dt \right] \tag{2}$$

where t_2-t_1 is the time in which the phenomenon is measured and T_0 the reference duration (1 second). The relation existing between $L_{A,\,eq}$ and L_{AE} is shown here:

$$L_{AE} = L_{A,eq} + 10 \log \left(\frac{T}{T_0} \right) \tag{3}$$

3.1 – Characterization of impulsive noise

Impulse noise is a category of noise which includes unwanted, almost instantaneous sharp sounds. Using the above-described parameters, it is possible to characterize the peculiarity of a sound. To detect if a sound can be classified as impulsive or not, the following parameters have to be measured and analyzed: L_{AFmax}, L_{ASmax}, L_{AImax}. According to current standards and legislative acts, a sound can be considered as impulsive when the following characteristics recur[20]:

- The difference between L_{AImax} and L_{ASmax} is bigger than 6 dB;
- The value of L_{AFmax} decays of at least 10 dB in less than 1 second;
- The event occurs at least 10 times during the day reference time and at least 2 times during the night reference time.

Figure 9 shows a practical example for the individuation of impulsive events. The graph represents the time histories of the phenomenon being studied, obtained using the L_{AFmax}, L_{ASmax}, L_{AImax} time constants.

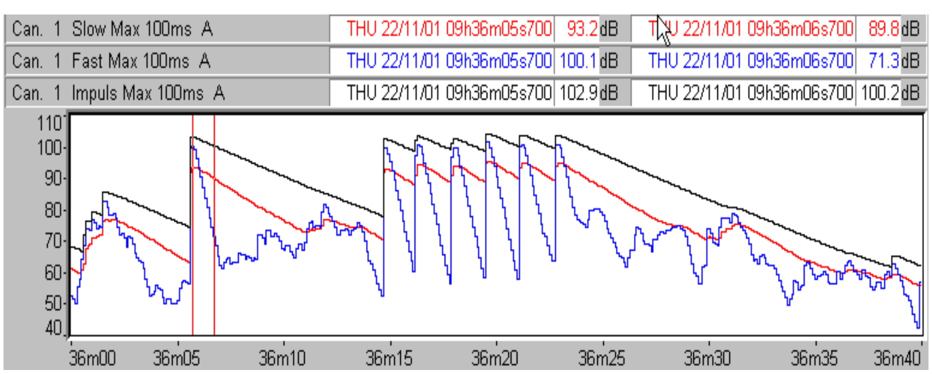


Fig. 9 – Time histories for the individuation of impulsive events

Between the two vertical red lines (which represent a time span of 1 second from 09:36:05.700 to 09:36:06.700) the trend of the three profiles is studied. The difference between L_{AImax} and L_{ASmax} is bigger that 6 dB(A) (L_{AImax} - L_{ASmax} = 9.7 dB(A)) and the value of L_{AFmax} falls to 29.8 dB(A). In the above shown example, in 40 seconds seven impulsive events can be observed.

Over a longer time span (e.g.: 8 hours), these events are too short in time to increase the overall energy of the studied phenomenon and its continuous equivalent sound pressure level. Nevertheless, they are potentially harmful. They are characterized by extremely high-energy content and can probably reach the vestibular window before any defense mechanisms can be activated [21]. As already explained, ear protection - in the case of high-intensity and quickly raising signals - is entrusted to the stapedius muscle, whose contractions reduce ossicles excursion. Basically, this action results in a reduction of the sound energy that propagates from the tympanic membrane to the oval window. The guaranteed protection is nearly 10 dB at 1000 Hz, because the excursion reduction of the ossicular chain results in a decrease of nearly 60 μPa [18]. This ear defensive mechanism intervenes with a characteristic muscle reflex time (nearly 1 second) [22]. For this reason, it is not effective against impulsive noises, because the sound waves come to the oval window before the defensive mechanism can be activated. Indeed, it is important to point out that impulsive events are characterized by a persistent propagation time of a few milliseconds. Impulsive events are absolutely faster than the time human ears need to respond with a defensive mechanism that is comparable with the time of a muscle reflex.

3.2 - Frequency weight curve

One of the main problems in the study of the psychoacoustic comes from the matching of the objectively measured acoustic parameters, with the subjective sensations they cause on the auditory system. The human’s auditory response is neither constant with the frequency nor with the level [23]. A compensation of the levels at the different frequencies is required to obtain a suitable approximation of the human sensation. Frequency weighted curves are used in order to do so. Starting from the equal-loudness curve on the normal equal-loudness contours proceeded from Fletcher and Manson we can first obtain these curves and then standardize them to the ISO 226:2003 [24,25]. An equal-loudness contour is a measure of SPL over the frequency spectrum, for which a listener perceives a constant loudness when presented with pure steady tones. The unit of measurement for loudness levels is the phon, and is obtained through the reference to equal-loudness contours. By definition, two pure tones of differing frequencies are said to have equal-loudness level (i.e.: the same levels in phon) if they are perceived as equally loud.

Usually, four different frequency-weighted curves are individuated. The A-frequency weighted curve is the inverse of the 40-phon equal-loudness contour. It is the most commonly used and approximates the behavior of the human ear in the low-frequencies range. The B-frequency weighted curve is the inverse of the 60-phon equal-loudness contour, but it is no longer used. The C-frequency weighted curve is the inverse of the 100-phon equal-loudness contour, while the D-frequency weighted curve is the inverse of the 40-noy curve. Basically, through the use of these curves, the energetic content of the acoustic signal is modified (decreased or increased) in as a function of its frequencies. As shown in Figure 10, when a signal is processed using the C-frequency weighted curve it is artificially lowered in low frequencies up to 160 Hz and from 1600 Hz on. As a result the total energy of the also signal decreases.

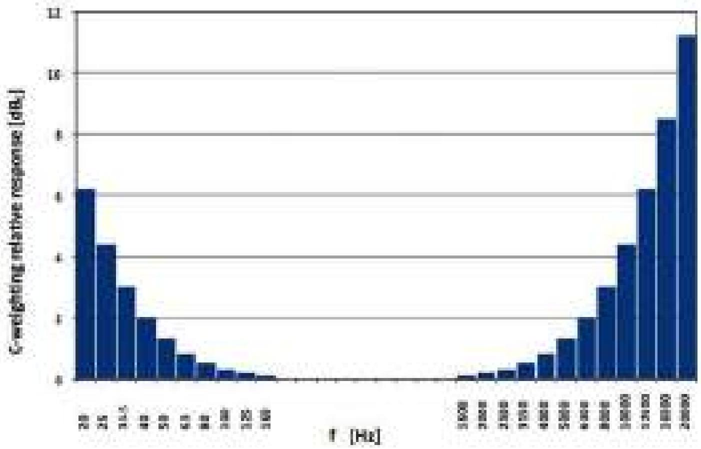


Fig. 10 - C-frequency weighted relative response

4 – Workers protection from noise and normative scenario

Workers protection from the risks arising from prolonged exposure to a noisy processes is one of the trickiest pollutant issues to solve. The problem is made even more complicated as the possible solutions of an event that produces potentially harmful contexts to the physical integrity of individuals cannot always be implemented. For instance, even use of headsets is often prohibited as they may induce unacceptable limitations for other aspects of the workers' security. The analysis of acoustic scenarios that may be found in different working activities is usually complex and the conclusions may not be free of errors because of the particular environmental conditions in which analysis is carried out.

In order to avoid conflicting analyses on the measured phenomena, several directives regarding workers' health-care and protection from noise have been issued. For instance, in the United States procedures for guaranteeing security of workers in the workplace are regulated by the OSHA (Occupational Safety & Health Administration) Standard "*1910 Occupational Safety and Health Standards, Subpart G*" in observance of the 1970 Law on safety and health in the workplace, (OSHA Act) [26].

On the other hand, in Europe, protection from noise in a work environment is upheld by *Directive 2003/10/EC of the European Parliament and of the Council of February 6th, 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)* [3]. The Directive supplies the minimum safety prescriptions to ensure health-care and protection from noise to those workers who are, or are likely to be exposed to risks from noise as a result of their work. The Directive also suggests priority to reducing risk at the source, to reduce the level of exposure to noise by incorporating preventive measures in the design of workstations and to select suitable personal protective equipment (PPE). Furthermore, it promotes provisions relating to work equipment and methods, thus contributing to the protection of the workers involved. All member states must conform their national directives according to what is stated in this European Directive.

The European standard uses the following parameters, calculated with a reference pressure of 20 µPa, for the protection of workers [3]:

a) Daily noise exposure level ($L_{EX,\,8h}$);

b) Weekly noise exposure level ($L_{WE,\,8h}$);

c) Peak sound pressure (p_{peak}).

The daily noise exposure level $L_{EX,\,8h}$ is the time-weighted average of noise exposure levels for a nominal eight-hour working day as defined by international standard ISO 1999: 1990 [27], point 3 paragraph 6 (and its modifications and updates [28]), covers all those noises present in a workplace, including impulsive noise. On the other hand, the weekly noise exposure level $L_{WE,\ 8h}$ is the time-weighted average of noise exposure levels for a nominal week of five eight-hour working days, as defined again by international standard ISO 1999:1990, point 3 paragraph 6 and its modification and updates [27], [28]. Both are used to determine workers' exposure to noise during their working activities and they offer an averaged absorbed dose during their working hours. Additionally, the peak sound pressure $p_{peak,\ C}$ represents the maximum value of the instantaneous C-frequency weighted noise pressure. In reference to the pressure of 20 µPa, the Directive establishes the peak sound pressure maximum admissible value (exposure limit value) at $p_{peak,\ C}$ = 200 Pa [140 dB (C)]. Moreover, it states that the maximum value for which the use of individual hearing protection devices is not obligatory (lower exposure action values) is $p_{peak,\ C}$ = 112 Pa [135 dB (C)], while the maximum value for which usage of individual hearing protection devices is obligatory (upper exposure action value) is $p_{peak,\ C}$ = 140 Pa [137 dB (C)] [3]. This means that in those working environments where $L_{EX,\ 8h}$ is below 80 dB (A) (daily noise exposure level limit) and the $p_{peak,\ C}$ levels are less than 135 dB (C), the employer can refuse to supply workers with headsets and other personal protective equipment.

Contrary to what is stated in the earlier laws, the Directive currently requires the determination of peak sound pressure levels to be carried out using only frequency-weighting scales. Furthermore, no record of any other physical-quantity temporal evolution such as impulsive events is required, even if those events may be relevant for detecting the effective solicitations on the ear.

In summary, the Directive 2003/10/EC provides that analyses only have to be carried out by sampling the maximum C-frequency weighted value of the instantaneous sound pressure level $p_{peak,\ C}$ and the A-frequency weighted equivalent level normalized to a standardized 8 hours working day $L_{EX,\ 8}$,or to a standardized 40 hours working week $L_{WE,\ 8h}$. In these equivalent levels, all the noises produced in the working places include the impulsive ones. It is clear that the Directive lacks complete worker protection. Indeed, one of the main assumptions of this procedure is that impulsive events simply contribute to the determination of an exposure value and further, that their evaluation converges in the calculation of the previously mentioned action values ($L_{EX,\ 8h}$, $L_{WE,\ 8h}$). They are not separately considered as dangerous effects on the acoustic phenomenon. According to the Directive, for environments in which noise exposure levels are below the threshold, a simple evaluation of the $p_{peak,\ C}$ value is sufficient. No importance is given to signal's time history, which is the sampled-signal temporal trend.

While cases in which peak sound pressure levels are high (but still lower than the exposure action value) and noise exposure levels are below the action levels may seem rare, they are extremely common situations in workplaces characterized by occasional loud impulsive sounds but a short temporal persistence. For instance: material stress testing laboratories, mechanical workshop activities, metal-plates pressing operations, furnaces' crucible cleaning after the production of ferrous materials, etc. Other limitations of the Directive are embodied in the choice of the C-frequency weighting curve, which corresponds to the inverse of 100-phon equal-loudness curve on the normal equal-loudness-level chart [25]. This curve artificially decreases the value of the SPLs at low and high frequencies. Therefore, it may lead to an erroneous evaluation of peak value and therefore to an inadequate protection of the workers.

As stated before, the Directive fixes the value of $p_{peak,\ C}$ = 112 Pa [135 dB (C)] as the maximum admissible value for which any individual hearing protection devices is not obligatory. It is possible to highlight how this setting is actually unreasonable. Indeed, analyses of the normalized audiogram [25] of the human ear show how the threshold of pain is less than 135 dB for all those frequencies in the audibility range (1 – 8 kHz). Moreover, for frequencies above 1 kHz this threshold is much lower than the value chosen as a reference in the norm. In addition, several medical diagnoses and studies have demonstrated that repeated exposures for middle-long periods to impulsive noise even significantly lower than 135 dB, can produce irreversible damage to the ear [29].

Negative implications embodied in this procedure of noise measurement, along with the assumption that impulsive events contribute solely to the determination of the entity of exposition only, are clearly an excessive simplification that may lead to shortcomings in workers protection. This is because the potentially harmful events are omitted in the analyses and the signal is artificially depowered. From the experience gained with the analyses carried out, it is evident that acoustic-characteristics of a work place are poorly represented when the descriptors indicated in the Directive (p_{peak}, $L_{EX, 8h}$, $L_{WE, 8h}$) are used. As a result, several situations of risk, which in time may cause irreversible damage to workers, are considered non-hazardous and therefore the procedures for protecting workers health are not implemented at all. Indeed, the main failures of the investigation pattern can be summarized as following:

a) Inability to identify, solely through the data for the peak sound pressure ppeak, the incidence of energy on the human ear and to determine risky situations.

b) Inability to identify, solely through the data for the noise exposure levels $L_{EX, 8h}$ and $L_{WE, 8h}$, the incidence of energy on the human ear.

c) Inadequacy of weighting scale used for determining actual exposure to the maximum peak sound pressure.

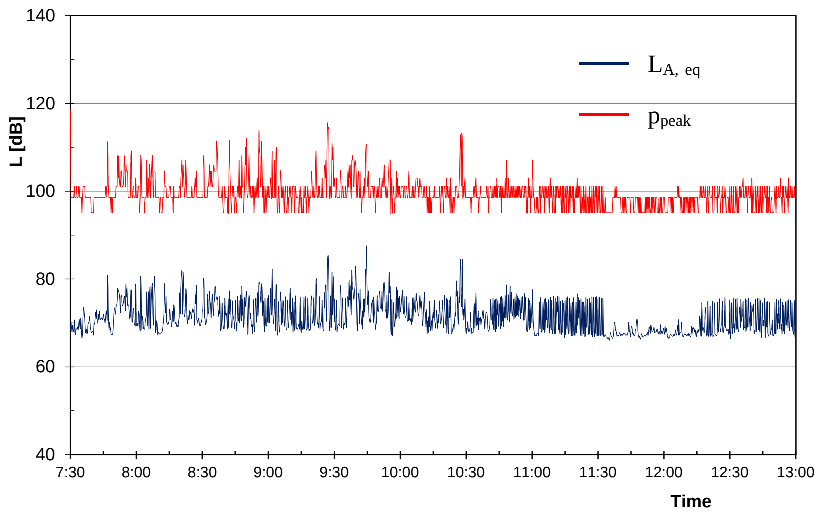
For these reasons, the authors have individuated an integration procedure mainly consisting of: the individuation of the time history describing the phenomenon being tested, the research of occurring impulsive events, the use of the un-weighted peak sound pressure levels and the study of the spectral composition of the analyzed sound with the possibility of using a Fast Fourier Transform (FFT) analysis.

5 - Critical analysis of parameters used in the Directive for hearing risk determination

The incompleteness of the pattern currently used has emerged during numerous noise analyses that the Laboratorio di TCA at Universitá della Calabria Italy has carried out during its research and consulting work. Measures carried out in the last fifteen years have developed a large database of surveys regarding several working activities in different fields of the industrial sector (testing laboratories, repair shops, joineries, metalworking industries, etc.) under commission to the University by health authorities and courts. These surveys were conducted in response to a demand for medical specialists and magistrates who wished to gain knowledge about sound field peculiarities during working activities. These surveys were used to determine the possible causes of pathological phenomena onset in workers and whether or not these problems could be connected to the tasks carried out during work.

Critical analysis of sampled data clearly shows that descriptors used in the *Directive 2003/10/EC* do not always highlight the criticalities of work situations. Through all the completed analyses, the researchers have acquired data according to what is stated in the European and Italian regulations regarding acoustics signal surveys [20], [30] and have analyzed them according to prescriptions provided by European Community legislation [3], [31]. In some analyzed scenarios, descriptors indicated in the European Directive are sufficient to fully represent the real situation of risk and can be used to identify protection procedures for workers. Nevertheless, situations in which they can be used are related to scenarios not characterized by harsh acoustic environments.

In the following figures, measures related to activities for which it is possible to use noise exposure levels for evaluating the risk are reported. Figure 11, shows the time histories of the equivalent continuous A-weighted sound pressure level $L_{A, eq}$, the un-weighted peak sound pressure level p_{peak}, and other main acoustic descriptors (A-weighted single event level L_{AE}, A-weighted daily noise exposure level on 5.5 hours $L_{AEX, 5.5}$, A-weighted daily noise exposure level normalized to 8 hours $L_{AEX, 8h}$ and percentile levels L_{max}, L_{10}, L_{30}, L_{50}, L_{70}, L_{90}, L_{min}) calculated from rough data for activities carried out in nearly a half-day of work (5.5 hours), by an operator of a cast iron production factory. The instrumentation used consisted of a dosimeter, which is a device used to detect an individual or object exposure to noise. During this study, the Larson Davis 705 model was used. This device measures in the dynamic range 70 – 140 dB. In addition, it offers the possibility of storing the equivalent continuous sound pressure level L_{eq}, the un-weighted peak sound pressure level p_{peak} the A-weighted single event level L_{AE} and the percentile levels L_n in three different frequency-weighted scales: A, C and un-weighted, according to the ANSI S1.4 1983 norm [21]. The device was placed with a microphone on the shoulder of the subject being tested to detect the effective SPLs acting on his ear. The signal was sampled using the previously mentioned European and Italian laws and then analyzed focusing attention on the temporal evolution of the phenomenon.



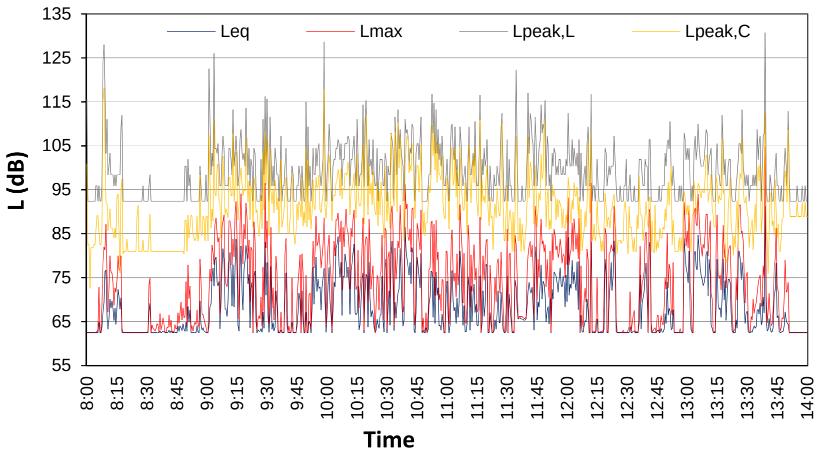
L_{AE}	112.0
$L_{AEX,\ 8h}$	71.5
$L_{AEX,\ 5.5h}$	73.1
L_{max}	107.2
L_{min}	65.4

L_{10}	75.7
L_{30}	71.1
L_{50}	69.2
L_{70}	68.0
L_{90}	67.1
P_{peak}	118.6

Fig. 11 – Time history measurements of the peak and equivalent continuous A-weighted sound pressure level for an industrial activity

It is possible to observe that carrying out an analysis with procedures from the Directive 2003/10/EC is correct and allows for the identification of hazardous conditions for workers. In particular, it is possible to notice that the dose adsorbed by the worker during the cleaning activity has an A-weighted daily noise exposure level of 5.5 hours $L_{AEX,\ 5.5h}$ of 73.1 dB(A), which scaled on the whole working day correspond to an A-weighted sound pressure level normalized to 8 hours, $L_{AEX,\ 8h}$ equal to 71.5 dB(A). Both values are far below the threshold of 80 dB(A) indicated in the Directive, therefore, the only parameter that could force the worker to use a suitable personal protective equipment (PPE) is the C-frequency weighted peak sound pressure value $p_{peak,\ C}$. In the considered example, the un-weighted peak sound pressure value p_{peak} is equal to 118.6 dB, which evaluated using the C-frequency weighted curve is far below the threshold of 135 dB(C) which is the lower exposure action values presented in the Directive.

Cleaning of a crucible is a quite noisy activity. If the Directive can ensure an effective protection in this situation, this could be legitimate thinking that can ensure the same protection even in situation less noisy. Nevertheless, the following example shows that the current legislation has several weaknesses, which render protection not as effective as its original aims. This can be highlighted analyzing the SPLs of Figure 12 and Figure 13, which show a dosimetric analysis relating to activities carried out in 6 hours by an operator in an open-to-the-public secretarial office.



L_{AE}	111.5
$L_{AEX,\ 8h}$	51.1
$L_{AEX,\ 6h}$	68.1
L_{max}	104.8
L_{min}	62.6

L_{10}	77.2
L_{30}	75.8
L_{50}	66.5
L_{70}	62.9
L_{90}	62.5
$P_{peak,C}$	118.2
$P_{peak,\ L}$	130.7

Fig. 12 – $L_{A,\ eq}$, L_{max}, $L_{peak,\ L}$, and $L_{peak,\ C}$ time histories for an office work

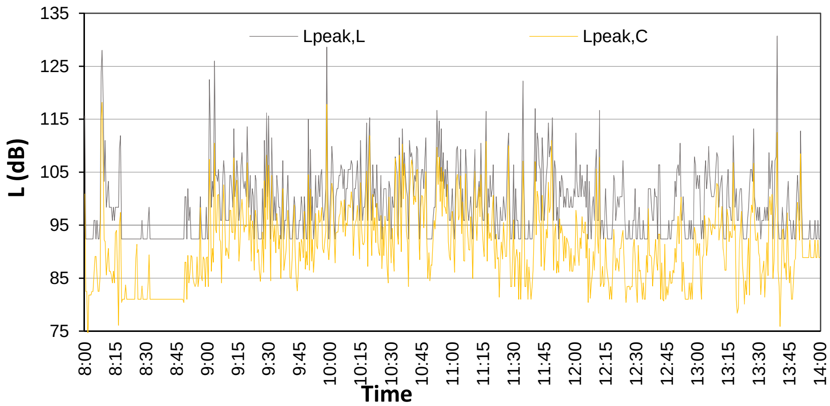


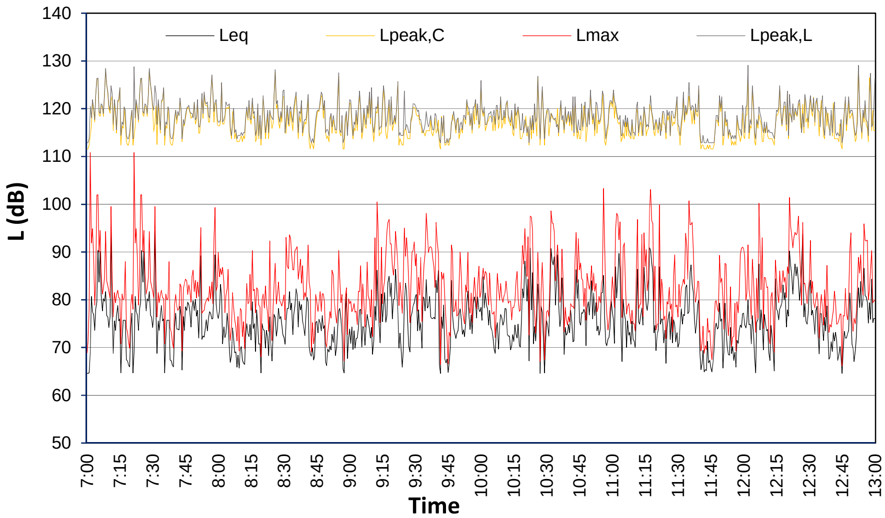
Fig. 13 – Comparison between $L_{peak,\ L}$ and $L_{peak,\ C}$ time history for an office work

This activity is clearly less noisy than that described in the previous example. It as can also be observed from the value of the A-weighted sound pressure level normalized to 8 hours, $L_{AEX,\ 8h}$ equal to 51.1 dB(A), nearly 20 dB(A) smaller than the $L_{AEX,\ 8h}$ which characterizes the industrial activity. The value of the daily noise exposure level is smaller than the limit presented in the Directive, as well as the value of the peak sound pressure [130.7 dB]. As stated before, the Directive fixes the value of $p_{peak,\ C}$ = 135 dB (C) as the maximum admissible value for which use of any individual hearing protection devices is not obligatory. Again, it is worth noting that the value of the acoustic peak presented in Figure 12 is still un-weighted, so when the C-frequency weighted curve is applied, maximum value will decrease and it will be lower. Nevertheless, it is possible to highlight how the setting stated in the Directive is actually unreasonable When data is analyzed using prescriptions presented in the Directive, the working place being studied is safe for workers' health. Form Figure 13 one can observe that this is not completely true because at least four events having intensity bigger than the threshold of pain occur.

Another interesting example that shows how the currently used regulation does not allow for the presence of risks to the organ of hearing, is the noise to which public urban transportation drivers are exposed. Several surveys were carried out during the working hours of public transportation drivers in the city of Cosenza, Italy. Three different buses were used for the analyses: an IRISBUS 203e 9.27/CNG, a BREDA MENARINI BUS M24, and an IVECO 49e. The First two are methane-fueled vehicles which are used on the "Circolare veloce" route. This line connects the Northern bound with Southern bound of the city with a low penetration (about 30% of the whole route) in the urban fabric. The IRISBUS 203e 9.27/CNG has a length of 9.00 meters, a width of

2.35 meters, and weighs 9000 kilograms. The BREDA MENARINI BUS M24 has a length of 12.10 meters, a width of 2.55 meters, and weighs 11200 kilograms. The third one, instead, is a small gasoline-fueled vehicle used to connect the historical part of the city with the valley area and has a length of 8.10 meters and a width of 2.00 meters.

Drivers were supplied with two Larson Davis 705 dosimeters; one set to detect the C-frequency weighted peak sound pressure value $p_{peak,\ C}$, the other set to measure the un-weighted peak sound pressure value p_{peak}.
Figure 14 shows the SPL time history recorded on the smallest bus, the IVECO 49e during the seven hours work shift of the driver, while Figure 15 shows the detail of the C-frequency weighted peak sound pressure level and the un- weighted peak sound pressure level.



L_{AE}	107.4
$L_{AEX,\ 8h}$	52.8
$L_{AEX,\ 6h}$	69.6
L_{max}	101.5
L_{min}	62.3

L_{10}	75.7
L_{30}	75.8
L_{50}	66.5
L_{70}	62.9
L_{90}	62.5
$P_{peak,\ C}$	118.6
$P_{peak,\ L}$	119.0

Fig. 14 - $L_{A,\ eq}$, L_{max}, $L_{peak,\ L}$, and $L_{peak,\ C}$ time histories for the driver of the IVECO 49e bus

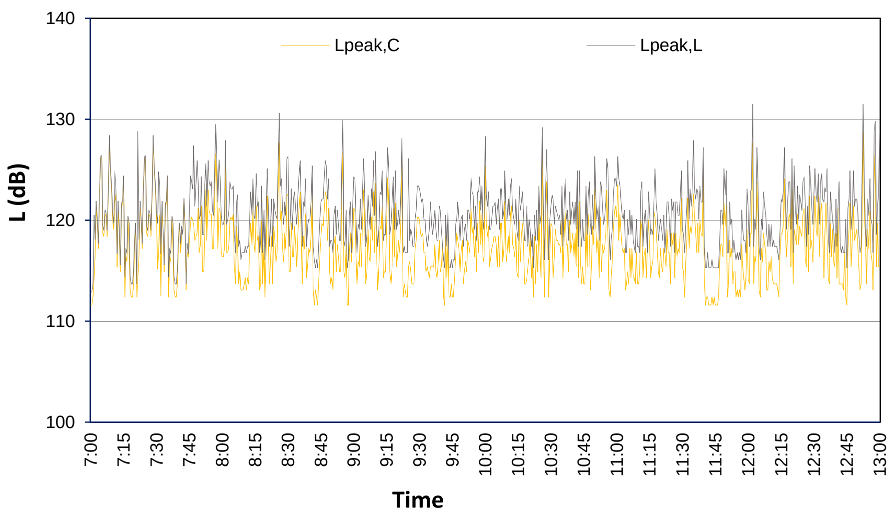
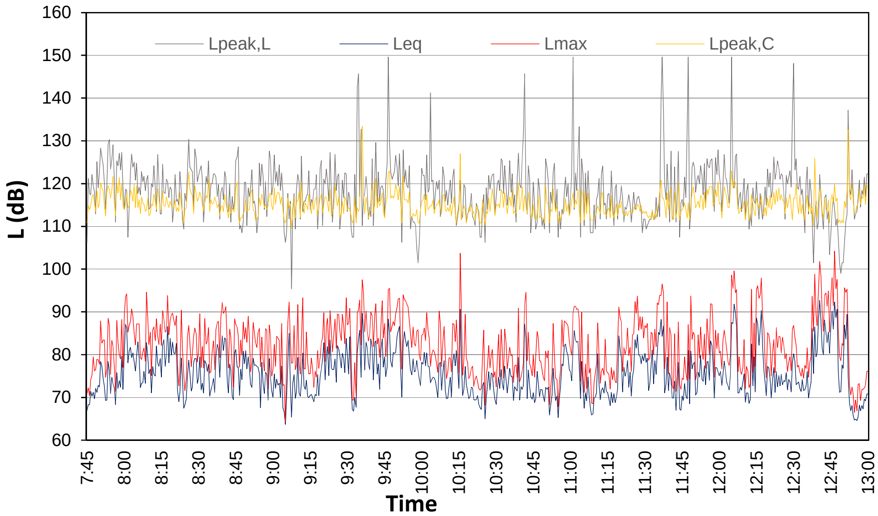


Fig. 15 - Comparison between $L_{peak,\ L}$ and $L_{peak,\ C}$ time history for the driver of the IVECO 49e bus

It is possible to observe that the daily exposure dose is smaller than the value prescribed in the Directive. Therefore, the only analysis that can be done is with regards to the value of the peak sound pressure. In this case, both the C-frequency weighted and the un-weighted values are almost the same below the threshold indicated in the legislation and below the threshold of pain. This happens because of the diesel engine that propels the vehicle. The diesel engine's acoustic emissions are mainly in the middle range of the audible range (200 – 1500 Hz), and therefore, are not influenced by the penalization of the C-frequency weight curve. Since the IVECO49e bus goes through urban streets not affected by high volumes of traffic and it moves at low speed, the use of Directive 2003/10/CE does not imply errors in the evaluation of the noise to which workers are subjected. The situation is different if data collected on the methane-fueled buses are analyzed. The following figures 16, through 19 shown the time histories measured on the IRISBUS 203e 9.27/CNG and BREDA MENARINI BUS M24 busses.



L_{AE}	120.6
$L_{AEX,\ 8h}$	51.1
$L_{AEX,\ 6.25h}$	77.8
L_{max}	104.2
L_{min}	64.3

L_{10}	87.6
L_{30}	84.7
L_{50}	76.9
L_{70}	73.3
L_{90}	70.7
$P_{peak,\ C}$	133.4
$P_{peak,\ L}$	149.6

Fig. 16 - $L_{A,\ eq}$, L_{max}, $L_{peak,\ L}$, and $L_{peak,\ C}$ time histories for the driver of the IRISBUS 203e 9.27/CNG bus

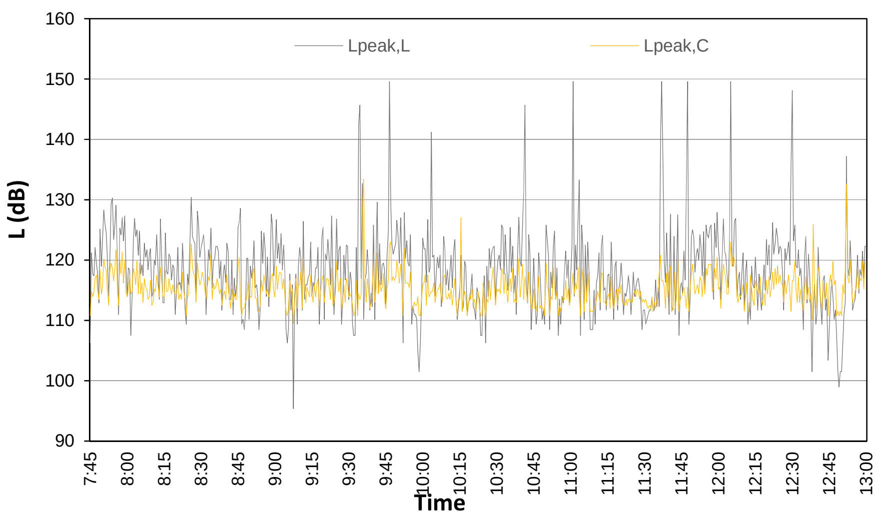
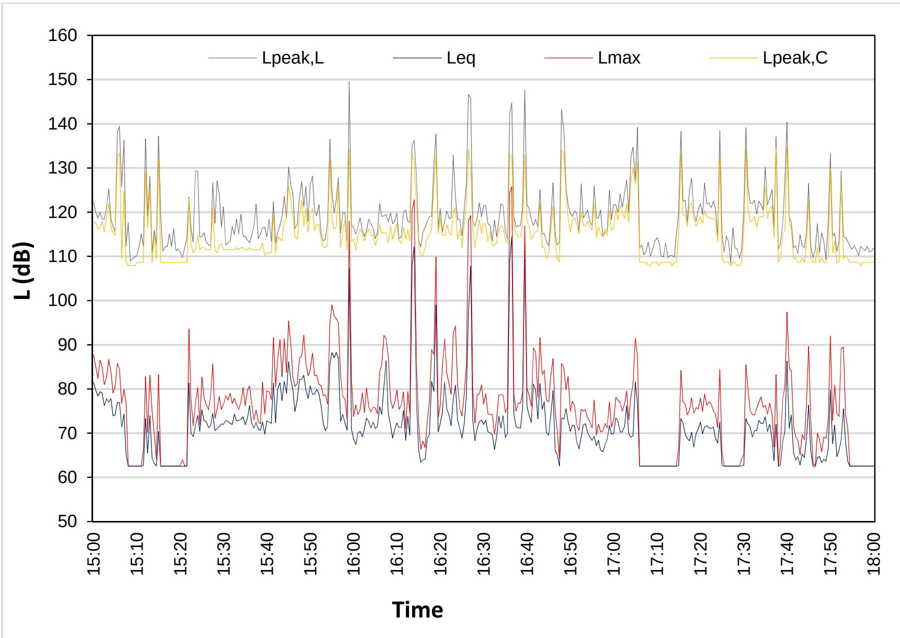


Fig. 17 - Comparison between $L_{peak,\ L}$ and $L_{peak,\ C}$ time history for the driver of the IRISBUS 203e 9.27/CNG bus



L_{AE}	113.1
$L_{AEX,\ 8h}$	27.3
$L_{AEX,\ 3h}$	72.7
L_{max}	125.8
L_{min}	62.6

L_{10}	79.9
L_{30}	78.1
L_{50}	72.7
L_{70}	70.1
L_{90}	66.5
$P_{peak,\ C}$	134.8
$P_{peak,\ L}$	149.6

Fig. 18 - $L_{A,\ eq}$, L_{max}, $L_{peak,\ L}$, and $L_{peak,\ C}$ histories for the driver of the BREDA MENARINI BUS M24 bus

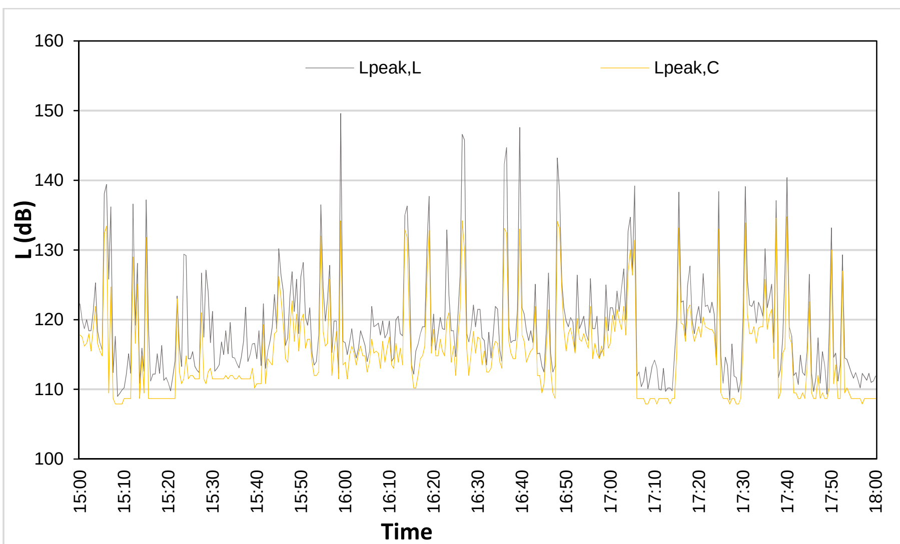


Fig. 19 - Comparison between $L_{peak,\ L}$ and $L_{peak,\ C}$ time history for the driver of the BREDA MENARINI BUS M24 bus

Through the analysis of data it is possible to observe how the equivalent continuous A-weighted sound pressure level is below the limit expressed in the Directive. It is equal to 77.8 dB(A) and 72.7 dB(A) respectively, and becomes even smaller when it is scaled and normalized to 8 hours. One more time, the most important observation can be done on the peak sound pressure. In the first considered example, the un-weighted peak sound pressure value p_{peak} is equal to 149.6 dB, which evaluated using the C-frequency weighted curve becomes $p_{peak,\ C}$ = 134.3 dB (C). One can observe that when the un-weighted conditions are considered, the maximum peak value is even higher than the upper exposure action value (value for which usage of individual hearing protection devices is obligatory). Nevertheless, when the C-frequency weighted curve is applied it becomes smaller than the lower exposure action values [135 dB (C)] presented in the legislation and therefore the use of individual hearing protection devices is not obligatory. In this case, since values for daily exposure and peak sound pressure are both smaller than the lower value of action, there is no obligation for the employer to provide workers with individual hearing protecting devices, even if they are exposed to sounds potentially harmful to the ear.

On the other hand, it is important to note that if the value of the parameter adopted in the previously used Directive 86/188/CEE [33] (which refers to the un-weighted value) was still stored, the worker would have to be supplied with PPEs. Indeed, one of the considerations the authors would suggest - at least concerning peak sound pressure value - is to refer to the limit reported in that Directive. The same consideration can be done observing data recorded on the BREDA MENARINI BUS M24 bus, where the same values are reached. It is important to note that a sound having intensity close to 150 dB may cause irreversible damages to the laceration of the tympanic membrane. In addition to these damages, the problem is made more complex by the presence of impulsive components, which are completely ignored in the Directive 2003/10/EC.

5.1 – Determination of the energy discharged on the ear using p_{peak}, $L_{EX,\,8h}$, $L_{WE,\,8h}$

The problem of the impulsive events can be highlighted when the following surveys are considered. Figure 20 shows in detail the temporal profiles of the un-weighted peak level and maximum impulse level, recorded with a sampling time of 60 milliseconds in a mechanical workshop.

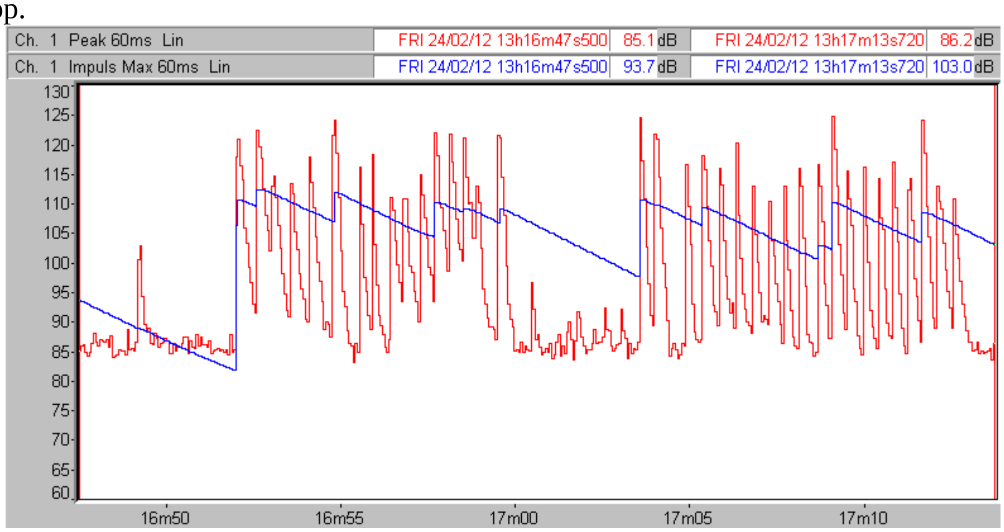


Fig. 20 – Detail of the linear peak and maximum impulsive level time histories recorded in a mechanical workshop

A comparative analysis shows that peak levels (in red) change faster than impulsive signal (in blue), which represents an input capable of stressing the ear. In addition, the presence of several components having high energy is completely ignored for risk determination purposes. Indeed, acquisition with the Impulse time constant remains inhibited for all the time in which the pulse signal decreases. This happens because the tool is not able to record other signals before it is completely discharged. Acquisition of the maximum value of p_{peak} can insure a protection only if attention or risk levels are reached, but it does not consider all the energy that is discharged on the tympanic membrane. Basically, stapedius defensive mechanism is not activated and damages may happen in the event of prolonged exposures.

When numerical data is considered, is it possible to note that if the threshold regarding the daily exposure dose $L_{EX,\,8h}$ is not reached (because when the 30 minutes signal is normalized to 8 hours, the equivalent level will become smaller), the only evaluation that can be done is about the value of the single peak sound pressure p_{peak}. In the example shown this value is equal to 125.6 dB, which is smaller than the value pointed out in the Directive. On the other hand, several energetic events having level bigger that 120 dB happen. The Directive does not consider them at all, even if they are potentially dangerous. Indeed, several studies have demonstrated how damages of impulsive noise on hearing loss are much more than that of continuous and stationary noise [32]. Because of stationary sounds, the ear can adopt constant and steady state protection mechanisms until it reduces the intensity of the pressure acting on ear's inner parts [13]. However, for variable and impulsive sounds the ear cannot apply the same protections. This is a clear example of a simple evaluation of the exposure limit values, which is not enough to ensure workers protection.

5.2 – Importance of impulsive events on the ear

Experimental data collected over a long period of time shows that analysis procedures contained in the Directive does not seem to be appropriate to protect the health of workers for all cases that may occur, especially when events that repeat over short time period are considered. Determination of the effects is unsatisfactory because these events do not have enough energy for reaching the threshold indicated in the Directive. However, they are potentially harmful since they can reach the vestibular window before defensive mechanism may be activated [21].

The stapedius muscle, which contraction reduces the oscillation of the ossicles and limits the acoustic energy transmitted through the tympanic membrane, guarantees principal protection from these events. Defensive mechanisms happen with the typical time characteristic of a muscle reflex. Therefore, it is not effective against sounds characterized by a persistence of a few milliseconds. Effects of impulsive events are extremely dangerous, bot for the particular conformation of the ear and the mechanism of stimuli transmission to the brain.

Impulsive events occur more frequently than thought. Sometimes they are characterized by low SPLs, but at the same time by a repetitiveness that is likely to go unnoticed. This is a significant source of danger due to the accumulation of energy on the tympanic membrane. The stress condition can be extremely serious because other factors may aggravate the situation. Very often the particular spectral energy distribution amplifies the problems. An example of this situation can be shown using the data collected on the buses for urban transport in the city of Cosenza.

Beyond the two dosimeters placed close to drivers' ear a Class 1 real time SPL Meter "Symphony" by 01dB with preamplifier and microphone from the same manufacturer was used. It recorded the SPLs in the cockpit indicating points from the Italian Directive for the measurement of environmental noise [20]. Figure 21 shows the A-frequency weighted SPL time history obtained using the Slow time constant and recorded during the journey from the city center to Northern terminus.

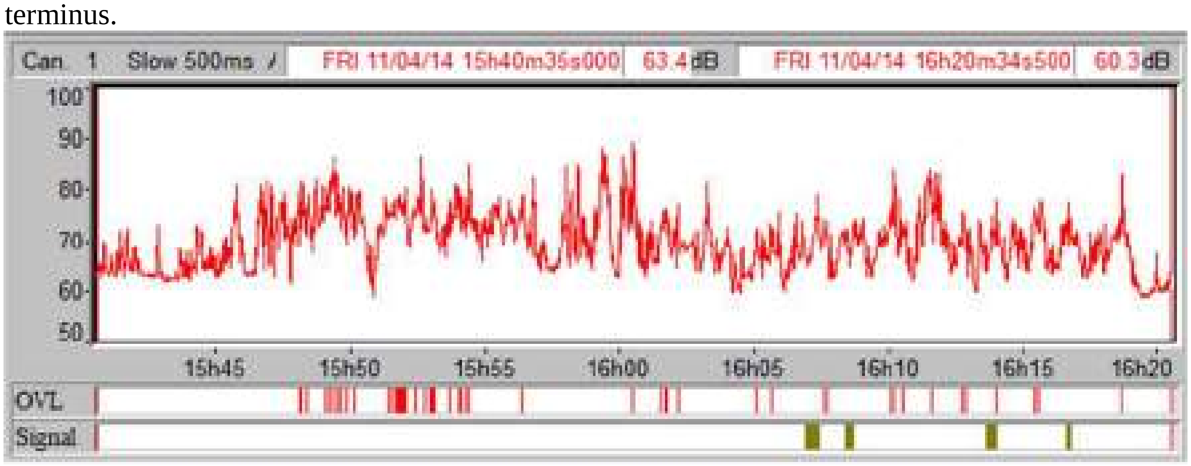


Fig. 21 – A-frequency weighted SPL time history recorded in the bus cockpit

Figure 22 shows the same journey, and for a time lag including within the previous, the SPL trend obtained using the time constant Slow (red line), Fast (blue) and Impulse (grey). It is clear the presence of several components having high energy. This characteristic is constant for the whole journey (not shown here for the sake of brevity) and it gives an idea of how important the energy overload on the driver's ear is.

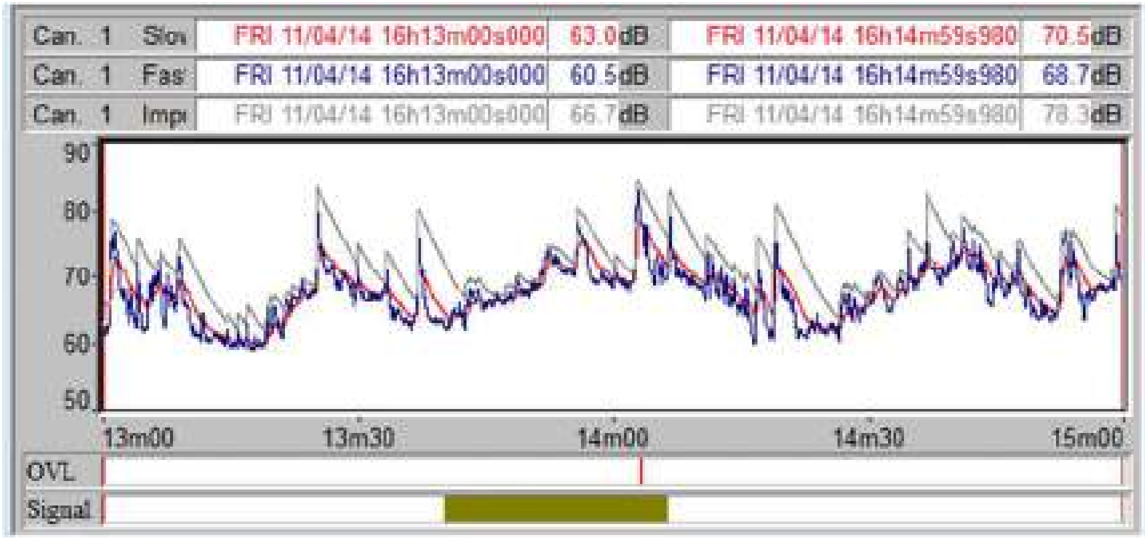


Fig. 22 – Detail of the A-frequency weighted SPL time history recorded in the bus cockpit with the S, F, I time constant

In addition, in order to prove that situation is made worst because of the frequencies of the sound, an analysis in frequency domain is carried out. This consists of a FFT analyses using normalized 1/3 of octave band. Results show that energy is mainly released at low frequencies and that the most energetic components are below 50 Hz. This situation makes noise exposure particularly critical. Following figures, 23 and 24 show the frequency domain results when two different weighting contours are applied to the signal.

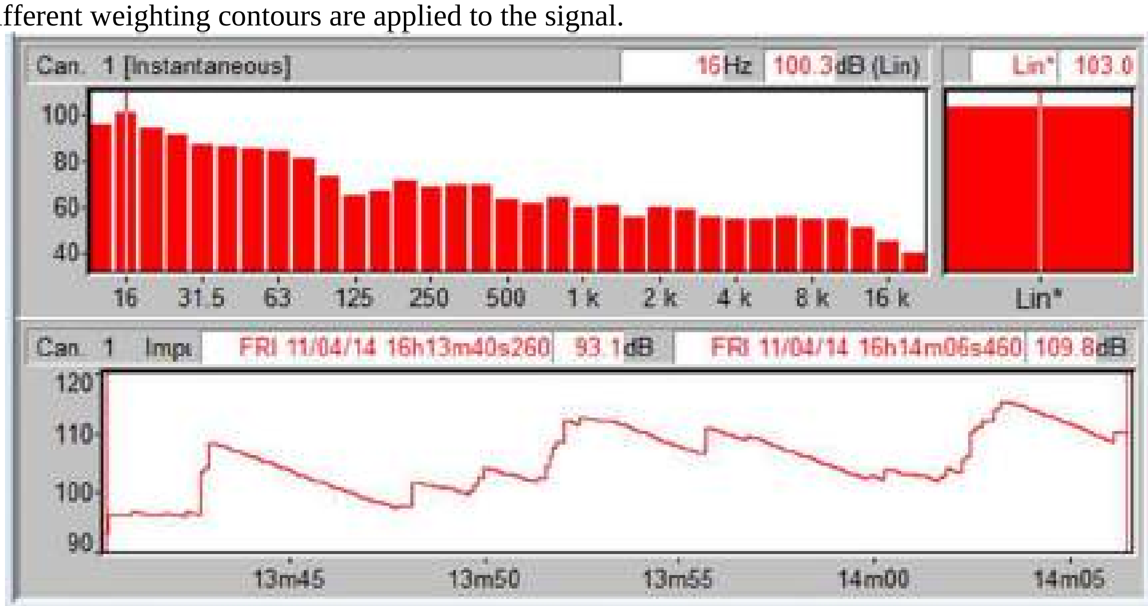


Fig. 23 – Un-weighted spectral composition (1/3 octave bands) for the signal recorded in the cockpit

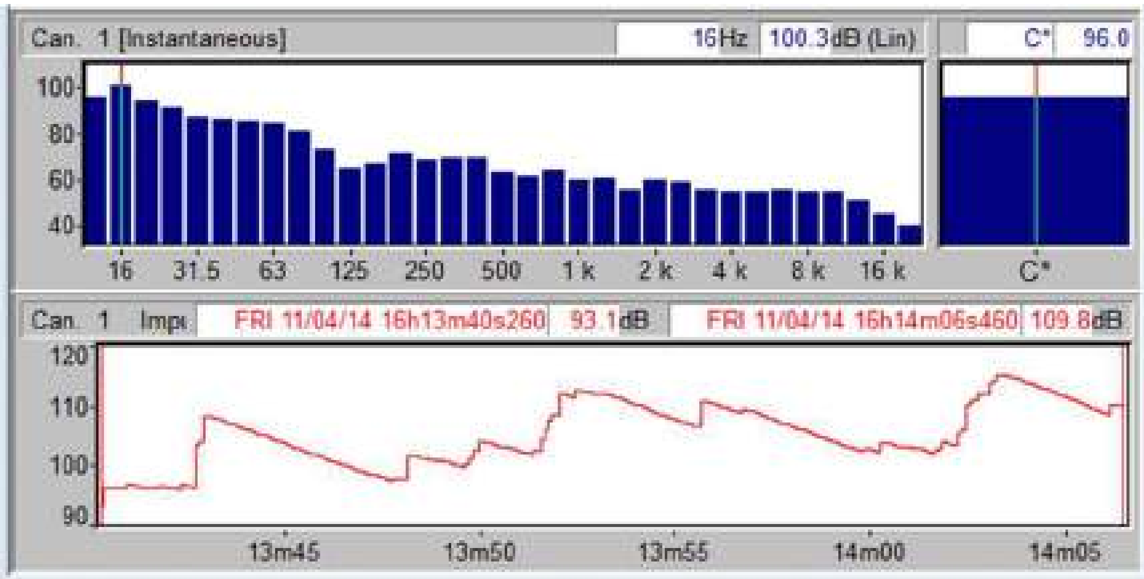


Fig. 24 - C-frequency weighted spectral composition (1/3 octave bands) for the signal recorded in the cockpit

When the C-frequency weighted curve is used, it is possible to observe how the energy of the signal is dangerously underestimated. The situation may get worse when more energetic exposure levels are considered. The situation is particularly significant because during the journey, the stresses having a high value of the measured energy are numerous. The phenomenon varies rapidly in time, reaching the conditions which according to the rule are recognized as impulsive events.

Fig. 25 – Impulsive event recorded at in the bus cockpit at 16.26.47.300

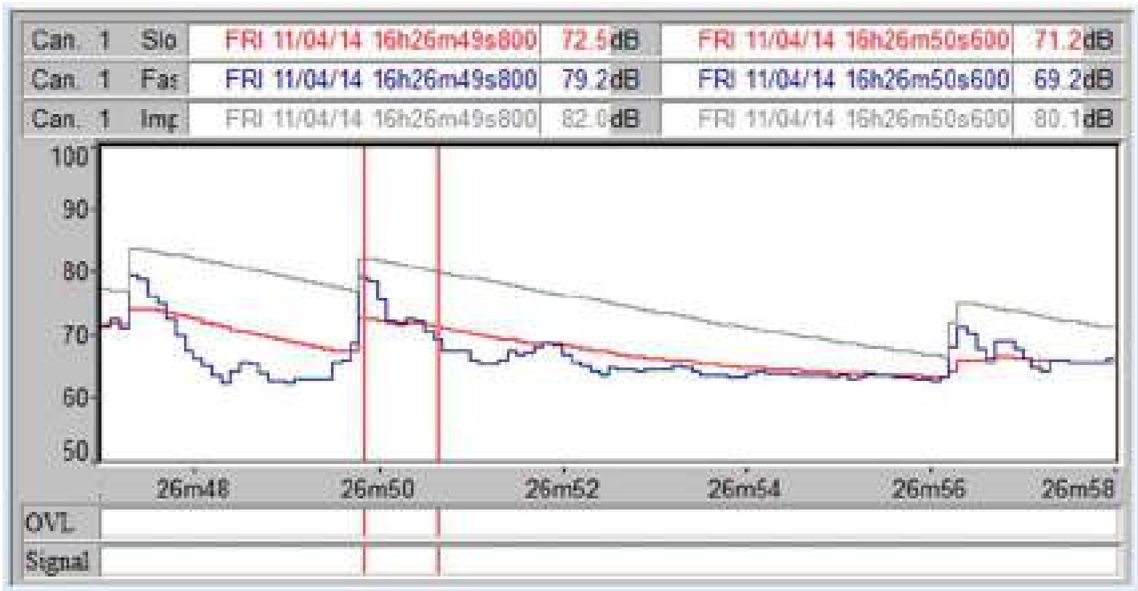


Fig. 26 – Impulsive event recorded at in the bus cockpit at 16.26.49.800

Fig. 27 – Impulsive event recorded at in the bus cockpit at 16.39.42.800

Examples also demonstrate how these situations occur almost continuously. The solution to the specific problem is not simple, because drivers of a bus cannot protect themselves by using headphones insulators, which means that the problem must be solved more generally, in terms of the design of the means of transport.

6 - Conclusions

Analyses regarding the minimum health and safety requirements for the exposure of workers to the risks arising from noise have been conducted in Europe since the early 1990s. Through years, several progresses have been achieved in the protection of workers. Nevertheless, the currently used legislation is not so effective as in its original aims. In this chapter, starting from the anatomic description of the characteristics of the hearing organ a description of the weaknesses embodied in the Directive 2003/10/EC of the European Parliament and of the Council of February 6th, 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) is carried out. The main acoustic descriptors are then presented along with the characteristic of the impulsive noise and the different frequency weighed contours.

As it has been observed in the first example provided, the Directive can individuate the most common critical situations, but in other instances it fails in guaranteeing effective protection of the most sensitive parts of the ear such as the tympanic membrane. Analyses show that to determine risks caused by exposure to noise sources during the performing of working activities, it is necessary to monitor the phenomena's dynamic of the phenomena through analyses of SPL time histories. Otherwise several situations of risk, which in time may cause irreversible damage to workers health, may go undetected. From the experience gained with the analyses carried out, it is evident that acoustic-characteristics of a work place are poorly represented when the descriptors indicated in the Directive (p_{peak}, $L_{EX, 8h}$, $L_{WE, 8h}$) are used. For instance, the use of the only peak sound pressure p_{peak} leads to non-identification of possible components with significantly high energetic content probably harmful to the human ear. This leads to one of the main lapses in the currently used legislation; no importance is given to the impulsive components. They are only considered in the evaluation of the overall exposure level (either $L_{EX, 8h}$ and $L_{WE, 8h}$). Because they are characterized by high pressure level, but short duration (a few milliseconds), they do not increase the continuous equivalent SPL of the signal. Therefore their contribution, is not considered at all and no protective measurements are taken.

The second weakness of the Directive is the choice of the C-frequency weighted curve for the evaluation of the peak pressure levels. It artificially decreases the energy value of the signal at the low and very high frequencies, where the protection mechanisms of the human ear are less effective. Weighing operations modify the energy content of the studied phenomenon and this, as shown in this chapter, can dangerously underestimate the effective stress to which the ear organ is subjected to in terms of pressure applied on the internal ear.

The analysis procedures here proposed consist of an integration of the existing norm. These implementations could permit technicians to highlight the presence of certain events and phenomena, which are extremely harmful to hearing and the health of the ear (e.g. impulsive, periodic high-energy events, etc.) that cannot be recognized when the Directive 2003/10/EC is used. Furthermore, the new proposed method suggests to no longer use the C-frequency weighted scale, which artificially decreases the potential danger of noise at low and high frequencies. It is clear that if an effective protection has to be achieved, the whole sound spectrum has to be considered. Conducing analyses using an un-weighted signal allows for a more conservative, and likely more protective action to ensure worker health care and protection from damage arising from prolonged exposure to noisy processes.

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