AHAAH – A Comprehensive Concept to Assess Auditory Hazard Risk

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Introduction

The European Noise Directive EN-71-1 “Safety of Toys - Part 1: Mechanical and Physical Properties- Amendment 2: Acoustics” [1], which has been prepared by CEN/TC 52 “Safety of Toys” follows two approaches to limit the risk for the hearing losses of children playing with toys designed to make noise. The first approach is to limit the possible daily noise dose, the second is to limit the short term impact.

The first approach tries to avoid the metabolic exhaustion of the ear. The A-weighted dose L_{ASE} is defined by

$$L_{ASE} = 10 \cdot \log(1/T \cdot \int p(t)_A^2 / p_o^2 \cdot dt$$

where $p_A(t)$ is the A-weighted sound pressure, $p_o = 20\mu Pa$ and T the expected daily time of exposure. The second approach limits the peak level of the C-weighted sound pressure to avoid direct hearing damages. This limit has been derived from the European Directive 2003/10/EU [2]. It cannot be excluded that toys, for instance those using percussion caps, might be fired close to the ear, the limit is set in EN 71-1 [1] for the C-weighted peak value to L_{CPeak} = 125 dB at a distance of 0,5 m, which translates to 145 dB for a close to the ear usage at 0,05 m, whereas at the workplace [2] the lower limit is at 135 dB at the position of the ear! The question is whether or not this limit can be considered to be safe for impulse sounds in particular for those from toys using percussion caps.

Impulse noise

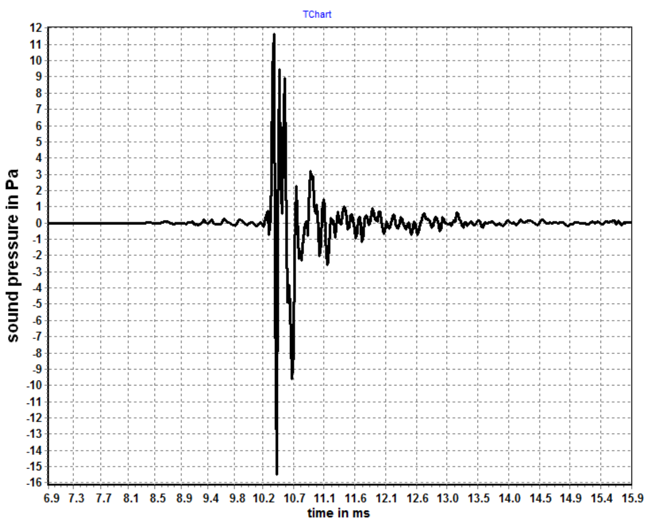

Figure 1: Time history of the Z-weighted sound pressure of a pistol firing a percussion cap measured at 0,5m distance by deBAKOM 2012 using EN71-1 [1], L_{CPeak} = 119 dB

Figure 1 depicts a typical impulse of a toy pistol using a percussion cap. The measurement has been performed at a distance of 0.5 m. The duration of the impulse sound can be characterized by the time t_{10} in which the sound level remains 10 dB below the peak value. Typically for percussion caps, see Figure 1, the t_{10} time is shorter than 0,3 ms.

In principle, the sound pressure alone does not provide the information about the mechanical momentum or impact applied to the outer ear by the impulse sound event. The mechanical momentum M is obtained via the time integral:

$$M(t) = F \cdot \int_0^t p(t') \cdot dt' \quad [\frac{Nm}{s}]$$

where F is the area of the earlobe and p(t) the sound pressure over time t. To estimate the maximum momentum the integration should be performed for t ~ t_{10}. This means that the impact on the auditory system is governed by the time integral of the sound and not just the maximum value.. A simple estimate for M is to multiply the maximum value by the time duration t_{10}. As a consequence, the effect on the auditory system is governed by the product of the peak pressure and impulse duration. However for blasts from percussion caps, these two parameters are correlated. According to the Weber model [3] which reliably describes muzzle blasts from firearms, the duration increases if the charge load is increased. And there is no significant difference between the structure of sounds from percussion caps and muzzle blasts.

The AHAAH-model

The mechanical momentum provides an estimate of the overall effect but cannot account for the transfer of such impulsive sounds to the inner ear. After passing the outer ear the sound reaches the eardrum and moves it. This movement is transferred via then middle ear to the stapes, which move the oval window, the entrance of the inner ear, causing the liquid movement in the cochlea, The movement leads to displacements of the hair cells in the cochlea and at the basilar membrane depending from the distance to the oval window. It is obvious, if these displacements exceeds certain values the inner ear may suffer harm at just those locations. As a consequence, the displacement at the oval window or the stapes and the resulting movements of the basilar membrane respectively is the basic indicator for the assessment of auditory hazard risks. The so-called AHHAH model developed by Price and others 1990 [5] is just doing this. The model is depicted in in Figure 2:

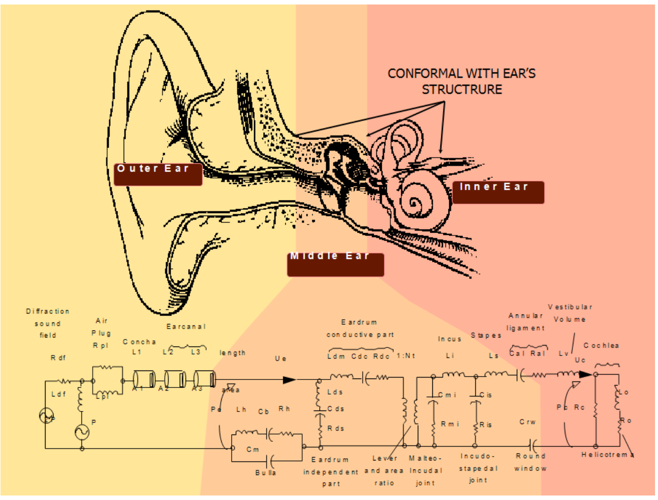

Figure 2: Sketch of the ear model by Price, [5]

Today, this model is widely used be the USA military and is proposed as an ANSI standard [ANSI WG S3.62] for predicting auditory risks. Detailed information including a sketch of the model is given at www.arl.army.mil where also links can be found to papers that discusses various applications of the model and reports on the validation. From this web site, there is also a program available that performs the AHAAH model for user specified pressure time histories. The following results presented in Figure 3 and Figure 4 are taken from the in-built examples processed by this program.

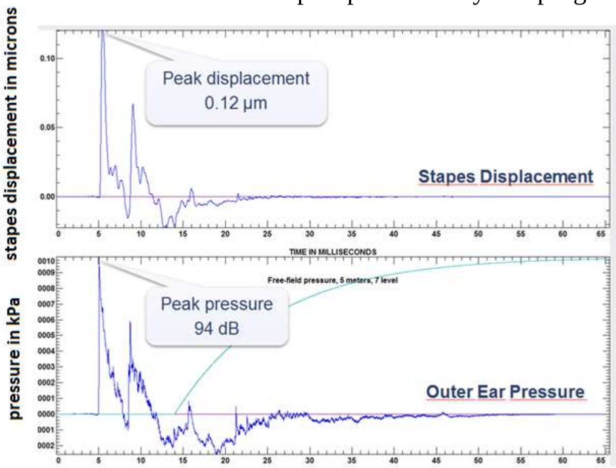

Figure 3: Time histories of the stapes displacement (upper part) and of the related outer ear sound pressure (lower part)

Figure 3 shows the time history of an impulse with a peak level 94 dB at the outer ear and the related stapes movement that is not exceeding 0,12 µm. Obviously, the time structure of the stapes response follows closely the causative outer ear pressure signal. This indicates as expected a linear transfer even for such pressures above 90 dB.

Figure 4 shows the findings for the same pressure signal numerically amplified to a peak level of 190 dB. The model yields an entire different behavior of the stapes. There is no linear transfer anymore. If the stapes react linearly, the displacement would peak at 7500 µm. The maximum value - as can be seen from Figure 4 - is only 19 µm or 52 dB less.

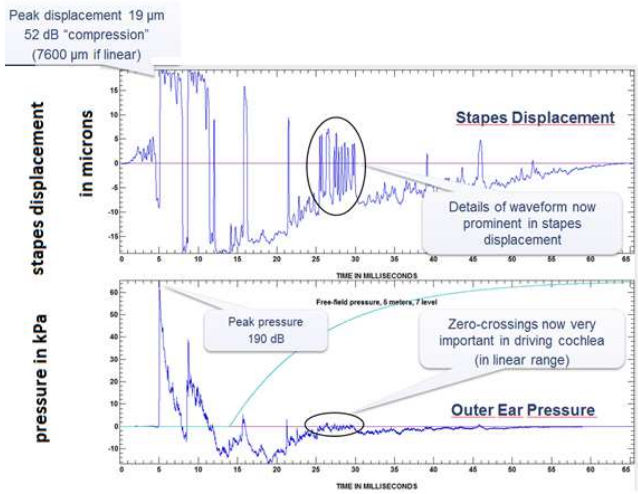

Figure 4: As Figure 3 but with a peak pressure of 90 dB

In addition, parts of the incoming waveform – indicated by an ellipse in Figure 4 - are enhanced and become prominent in the stapes displacement and will therefore determine the movement of the basilar membrane and could cause damages to the hair cells. The non-linear behavior is the result of a protection mechanism in the stapes decoupling the angular movement between the stapes if a certain angle is exceeded: The annular ligament limits the peak stapes displacement to about 10-20 µm.

This process has been experimentally studied using animals by Price et al. [5] and later on with volunteers. Based on the calculated movements of the stapes the AHAAH model provides so-called auditory risk units (ARU's) to be used to estimate the combined hearing threshold shift CTS (temporal or permanent) 30 minutes after exposure:

$$CTS = 26{,}6 \cdot \ln(ARU) - 140{,}1 \text{ dB}$$

For ARU = 200, CTS becomes zero, which means that no threshold shift will be observed with a probability of more than 0,95. For ARU = 500 a 25 dB threshold shift will be observed, which may be partly temporary or permanent. Since the late 1990ties the model is used by the US-military to evaluate and assess the effect of shooting noise on the human hearing system.

One important and published application, see links at www.arl.army.mil – outside the military use - were complains about hearing damages after air bag explosions in passenger cars in the US. The AHAAH-model was applied to modify the air bags (in particular the way the explosives are fired) in such a way that hearing damages are minimized.

Application

In the mean time, the AHAAH-model has been improved and modified (the latest version is from 2009) and is available at the Web site given above. This version imports measured sound pressures as function of time if given in a well-defined text file format. Therefore, the AHAAH model can directly be used to predict the auditory hazards from blast from percussion caps.

Figure 5: Typical toy pistol using percussion caps

Figure 5 shows a toy gun using percussion caps. From the construction of such a toy it is clear that the sound radiated will have a high directionality. Hence, the relevant test plan in EN-71-1 [1] for such toys prescribes measurements for 6 directions, at 0°, 90°, 180° and 270° in the plane of the barrel pointing at 0° and to measuring position above and beneath the toy. All positions are located at a distance of 50 cm. The highest L_{CPeak} value has to be less or equal 125 dB.

As an example, Figure 1 shows the pressure time history out of the measurements at the 6 directions which produces 0,22 ARU and a L_{Cpeak} of 119 dB.

By linearly amplifying the amplitude of the pressure signal the increase in the ARU's can be studied using the AHAAH-model. The results are depicted in Figure 6.

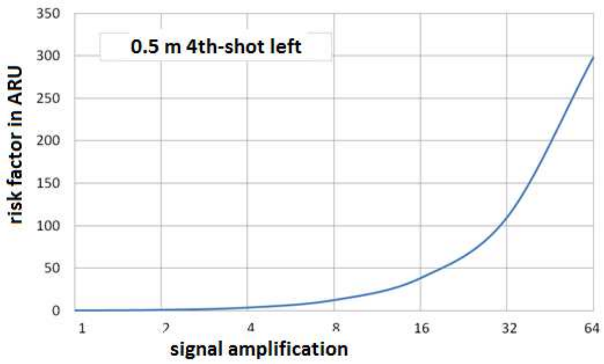

Figure 6: Auditory hazard risk factor as a function of amplification

In order to obtain a risk factor CTS of zero or more (200 ARU) an amplification of 45 is needed or a level increase of 33,1 dB.

Due to the non-linear acoustic regime very close to the blast sources, the level decrease close to the source differs from the geometric law given by 1/r², where r is the distance. Thus, for a close to the ear positions at 0,05 m, measurements show on the average an increase of the C-weighted peak level of 18 dB instead of 20 dB.

Nevertheless, assuming a factor ten (20 dB increase) for the shot with the highest risk will translate in approximately 20 ARU at 0,05 m according to Figure 6. There still remains an additional increase by a factor of 4 before 200 ARU are exceeded and the risk factor CTS becomes nonzero.

It is a well-known effect as described in ISO 17201-2 [7] that an increase in the amplitude can only be achieved by increasing the explosive mass. This will lower the frequency content of the time history of the sound pressure. To incorporate this effect, the sample frequency was assumed to vary between 50.000 Hz down to 50000 Hz, which means a variance of the frequency amplification factor between 0,1 and 1. The results are depicted in Figure 7.

For the lowest dark blue line 7 in Figure 7, no amplitude increase is assumed and one can see that without increasing the amplitude of the signal the ARU value increases from about 12 to 50 by lowering the frequency and drops below 10 at a frequency of 0,47 times 50.000 = 23.500 Hz.

The diagrams show that an increase of the amplitude by a factor of 4 (green line 5) +12 dB will increase the risk relative from 12 to 150 ARU's. By lowering the frequency, which will necessarily occur with increasing the load [7], the risk becomes non zero for 200 ARU's and drops relative to 100 ARU's if the frequency reduction factor 0,4 is reached.

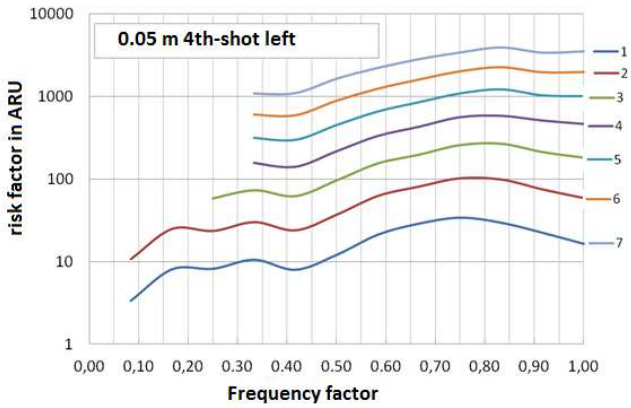

Figure 7: Relationship between frequency reduction factor (due to an increased explosion mass) and ARU risk factor

Figure 7 shows that such a shift of the frequency dependent auditory curve is comparable to a shift to lower frequencies of the impulse sound, which means according to Figure 7 an overall shift to smaller risk factors. Therefore, the results depicted in Figure 7 can be generalized in the sense that shifts in the auditory threshold for children to higher frequencies do not increase the risk. The auditory threshold curve of smaller children is more sensitive to higher frequencies compared to a 18 years old adult, due the change of the geometry produced by a shorter ear channel of the children, which shifts the optimal impedance to higher frequencies.

Evaluation of reported PTS due to a toy pistol in literature

There is a publication by Fleischer et al. [6] titled "Strategies of the Hearing System against Noise – an Auditory Damage". It shows on page 95 the sound pressure time history of impulse produced by a toy pistol for a distance of 0,025 m together with sound pressure time history of a tank gun fired at 25 m distance. Fleischer states for the toy gun a peak level of 179 dB at 0,025 m distance, a position which he assumed has been used by a boy who showed a considerable permanent threshold shift (PTS).

The given 179 dB peak value translates to a level of L_{CPeak} = 153 dB at least at a distance of 0,5 m. In 1999, deBAKOM has measured levels that were about 6 dB less, which means that the above given value for 0,5 m is realistic.

The measurements in 1999 showed an impulse duration of less than 0,2 ms or a relationship between the L_{CPeak} value and its sound exposure level $L_{eq,1s}$ of about 40 dB. If this is taken this into account one obtains for the emitted sound energy level L_E

$$L_E = 153 \text{ dB} – 6 \text{ dB} + 11 \text{ dB} – 40 \text{ dB} = 118 \text{ dB}$$

decibels relative to 10^{-12} J, The -6 dB stand for the increase in distance from 0,5 m to 1 m. The 11 dB represent 10 lg(4π) the surface of a sphere with a radius of 1 m and the -40 dB consider the average duration of the impulse in relation to the peak level of 0,1 ms. This means that the emitted energy for this shot was in the order of

$$E = 0.65 \text{ J}$$

The sound emission energy of measured products in 2012 is

$$L_E = 125 – 6 + 11 – 40 = 90 \text{ dB}$$

or

$$E = 0.001 \text{ J},$$

which is about a factor of 650 less, indicating the impact of the revision of the EN71-1 introduced in 2003 on the manufactured toy pistols and guns using percussion caps.

The risk factor received by a shot as measured by Fleischer is in the order of = 50.000 ARU. That is 250 times higher as the proposed safety limit of 200 ARU according to the CTS-formula. 50.000 ARU lead to threshold shifts after 30 minutes of 148 dB, which will result with a very high probability in permanent TS.

Other applications

The length of the impulse of a toy gun using a percussion cap is now in the order of 0,3 ms whereas the signals of tone producing toys last up to 1 s.

The limit of 200 ARU for a tone emitting instrument are reached (Table 1):

Frequency	Peak Pressure	L_{CPeak} at 0,05 m	L_{CPeak} at 0,5 m
kHz	Pa	dB	dB
2	160	138	118
4	60	130	110
8	18	119	99

Table 1: Sound pressure and peak levels of a one second tonal impulse producing 200 ARU at 0,05 m distance and the resulting peak level at a distance of 0,5 m.

This application and its evaluation using OAE-measurement will be published by Pazen and Walger at the DAGA 2013 conference.

Conclusion

The limiting value for toy guns using percussion caps set at L_{CPeak} = 125 dB at 0,5 m distance is scientifically well based as can be seen from the AHAAH-hearing model, even if the distance is 0,05 m to the ear . The very short duration in the order of 0,3 ms ensures that no temporary threshold shifts will be observed, which are to be expected if the impulse last much longer with the same peak level. The latter can occur for typical impulsive noises in work places. The very short duration of the percussion cap impulses allows a control of the auditory risk by solely looking at the peak level of the impulse, preferably not the C-weighted but the Z-weighted level.

The situation may be completely different for other toys producing more stationary sounds of short duration with tonal components in the higher frequency region.

Acknowledgement

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