Methods for the determination of individual sound attenuation of ear plugs

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Introduction

The European directive 2003/10/EC on noise at the workplace defines exposure limit values that may not be exceeded at the ear of the worker. Thereby, also the attenuation of hearing protectors has to be taken into account. For the daily noise exposure the limit value is $L_{EX,8h}$=87 dB(A), whereas for impulsive noise it is L_{Cpeak}=140 dB(C). In the German regulation the values have been reduced to $L_{EX,8h}$=85 dB(A) and L_{Cpeak}=137 dB(C) respectively.

To get the resulting level at the ear a calculation can be performed: the sound pressure level at the workplace is reduced by the amount of attenuation provided by the hearing protector. Since the exposure limit values apply for every individual worker the employer is in principle obliged to check the compliance with these values (levels under the hearing protector) individually.

Sound attenuation of hearing protectors

Laboratory data from EC type examination

The method that is so far normally used for assessing the level under the hearing protector is based on the data from the EC type examination that can be found in the user information of the products. These values are determined by subjective tests: real-ear attenuation at threshold (REAT). For 16 test subjects the hearing level is measured with and without hearing protector for eight frequencies with narrow band noise. The difference of these two hearing levels for each frequency is the sound attenuation of the hearing protector. The results are averaged over the 16 subjects to get the mean value and the standard deviation. As a convention, for the selection of hearing protectors the so-called "assumed protection value" is used that is mean minus standard deviation. This value of sound attenuation is attained (or exceeded) by 84 % of the users. Nevertheless, the individual values of attenuation of one group member can significantly differ from the APV. Especially, for 16 % of the users the attenuation will be lower than the APV.

Real-world attenuation

A second problem that complicates checking compliance of hearing protectors in practice is the so-called real-world attenuation. Different international studies have shown that the sound attenuation that is reached outside of the laboratories often is significantly lower than the values from the type examination [1][2][3]. The amount of divergence depends on the type of hearing protector (muffs, plugs etc.) and is mainly caused by incorrectly usage or insertion the devices.

The largest deviations to the laboratory values are seen for ear plugs, especially the foam type that has to be rolled down tightly and inserted very carefully into the ear canal. But generally, for all plugs the insertion depth is crucial for the resulting sound attenuation. For the special case of custom moulded ear plugs that are manufactured for the ear canal of the individual user the correct fit is the decisive factor. Since, if the form of the plug is not correct, the user is not able to compensate this handicap with an accurate insertion.

But also for ear muffs different factors can reduce the sound attenuation, *e.g.* long hair, large earpieces of spectacles or damaged cushions.

Methods for checking the compliance with the exposure limit values

Sample mean values from type examination with or without derating

If the attenuation values from the laboratory measurements are used the noise exposure value is reduced by the sound attenuation of the hearing protector in use. The result can be compared to the noise exposure limit values. This method takes into account the variability between the test subjects by working with the APV (mean minus standard deviation).

It is possible to consider effects of the reduced real-world attenuation by derating, *i.e.* reduction of the sound attenuation (laboratory data) by a certain amount in order to get attenuation values that occur in field use. Different derating methods are in use around the world, *e.g.* subtracting a constant value from the laboratory attenuation (Germany [4]) or reducing the attenuation by a percentage (USA [5]).

But this approach cannot consider the individual situation, neither for the sound attenuation itself nor for the derating coefficients.

Sound attenuation measured individually

In order to overcome the difficulties mentioned above different methods have been developed to measure the correct fit and/or the sound attenuation of ear plugs for the individual user. These methods range from air leakage tests to acoustic systems (subjective or objective measurements). The different approaches will be described in more detail in the next chapter.

In principle it is possible to obtain reliable results for the sound attenuation, but the measurement method has to be calibrated with the current standard method, *i.e.* the laboratory data from type examination. Moreover the reproducibility of the test method has to be determined and considered especially for inexperienced test subjects. As known from REAT values, repeated measurements of *e.g.* a hearing threshold of one person can exhibit considerable variation.

Different methods for the determination of individual sound attenuation

Historically, fitting checks have been applied to custom moulded ear plugs for a long time. Thereby, normally some variant of the (non-acoustic) air leakage test has been used that gives no number for the sound attenuation but only the result "fitting is sufficient or not". In the last years, a variety of acoustical test methods has been developed, mostly also from manufacturers of custom moulded plugs, that provide values of attenuation and can (in some cases) also be used for other kinds of ear plugs.

The BGIA – Institute of Occupational Safety and Health has tested some of the systems. The following list is not necessarily comprehensive, but gives an overview of the different methods available on the market, offered by manufacturers of hearing protectors. Normally, the service of checking the fit is provided on request, but it is essential especially for custom moulded ear plugs in order to guarantee the required sound attenuation.

Air leakage test

This only non-acoustic method is only applicable to custom moulded ear plugs. Through a hole in the ear plug (*e.g.* after removal of the filter) a small static overpressure (some mbar) is generated in the ear canal. This pressure has to stay constant over a given period of time or at least decrease slowly. Small leakages are tolerable if the leakage caused by the filter to be used will be the dominating one. For very accurate results the pressure has to be monitored over quite a long time. Different designs of the measurement apparatus are available from simple mechanic types to electronic ones with automatic evaluation of the data. This method does not provide values for the sound attenuation of the hearing protector, but can be used as an indicator for good or bad fit of custom moulded plugs.

Measurement with MIRE technique (microphone in real ear)

Sound field generated by an (audiometric) headphone

In principle, the sound attenuation of an ear plug can be determined from the difference of the sound pressure levels in the ear canal with and without plug (insertion loss). Thereby the test sound can be generated by an audiometric headphone. Since the sound pressure level in the open ear canal cannot be measured directly a different measurement geometry with two microphones is used: the first one inserted in the plug from the outside (*e.g.* a tube microphone) and the second one outside of the ear (under the headphone that generates the test sounds). But this configuration provides a different quantity, the noise reduction. To get the sound attenuation of the hearing protector as experienced by the user the relationship between sound pressure level outside of the ear and in the open ear canal has to be accounted for – the so-called head-related transfer function (HRTF) that comprises the effect of ear and head on the sound field. It would be possible to perform this correction by including the mean value of the HRTF in the calculation [6]. Alternatively, as a preceding work to field measurements the MIRE method can be calibrated with REAT data from the same test subjects and the same products [7]. The necessary correction factors can be gained by matching the data from the two measurement techniques. The resulting MIRE data will exhibit an uncertainty because in both cases only group mean values with an uncertainty themselves (spreading, standard deviation) can be used for the correction procedure.

In principle, it is possible to test any plug that can be worn under a headphone, but probably the correction values discussed above need to be adjusted for every product. Moreover, the plugs have to be modified in order to incorporate the microphone for the measurement under the plug (*e.g.* a tube microphone).

Sound field generated by a loudspeaker

Similar to the method described in the last paragraph, the sound attenuation of a hearing protector can be determined in the sound field of a loudspeaker. Here again, corrections to the REAT values have to be incorporated. This method has the advantage that every kind of plug can be tested, also bulky types that would not fit under a headphone. But again, only specially modified plugs with an inserted microphone can be used.

Audiogram with and without ear plugs

Like in the laboratory tests, this method determines the hearing threshold of the test subjects with and without hearing protectors. The sound is generated by a headphone - with two essentially different possibilities: The test sounds can be narrow band noises (similar to the procedure in EN ISO 4869-1) or sine waves (used in audiometry). Since the sound field and (for sine waves) the test noises are different to the laboratory conditions the hearing thresholds can be expected to have other values. Thus, also the calculated sound attenuation could be different and has to be compared to REAT values. This method needs a quiet environment since it works at the hearing threshold. It can be used for all types or plugs that can be worn under a headphone.

Subjective loudness matching

In contrast to the laboratory test or the audiogram method described in the last paragraph this test procedure works at sound levels well above the hearing threshold with sounds produced by a headphone. The test subject has to balance the loudness between his two ears for three conditions: 1. both ears open, 2. only one open – the other with ear plug and 3. both ears with ear plugs. From these three measurements the sound attenuation of each ear plug can be calculated. This method works for all types of plugs that can be worn under a headphone and does not need an especially quiet environment.

Comments and discussion

The test methods described in the previous chapter can be used in the field for different purposes. First of all they are very helpful for the manufacturer of custom moulded ear plugs to identify the plugs that do not fit correctly to the user's ear. Moreover the test methods can be used for instruction and training of users of hearing protectors in order to visualize the effect of incorrect insertion of ear plugs. If the attenuation values have been calibrated with the results from the EC type examination (REAT) and the manufacturer has defined target values for the sound attenuation for a certain product it is possible to make also quantitative assessments, concerning the compliance of the hearing protection with the exposure limit values of the European noise directive.

For this evaluation of individual sound attenuation also the uncertainty of the result has to be considered. For the laboratory data (that is comprised of 16 single datasets) this is done by calculating the assumed protection value APV (mean value of sound attenuation minus standard deviation). This gives a safety margin of 84%, *i.e.* 84% of the users will get a sound attenuation of at least the APV.

For the individual test methods the uncertainty can be dominated by the correction values as described above for the MIRE technique. Otherwise, for subjective tests the ability of the test subjects to reproduce the results needs to be determined in order to be able to judge the reliability of the sound attenuation.

In summary, if the inevitable uncertainty of the results for the individual sound attenuation is taken into account the different test methods can make a valuable contribution to check and improve the sound attenuation of ear plugs in field use that is known to differ considerably from the laboratory data.

References

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