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HEARING PROTECTORS

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ABSTRACT

This paper addresses the important practical issues of hearing protectors attenuation that are used in industry to protect workers from high levels of noise. Comments on the difficulties in the measurement attenuation of hearing protectors are discussed. A new work on the numerical modelling of the outer ear-canal is presented that considers the eardrum acoustic impedance and examines finite element (FEM) and infinite FEM for the quantification of the noise attenuation of the protector. In addition, the numerical model considers the geometry of the outer ear, outer ear-canal and the eardrum acoustic characteristics. The model can serve as a quick and low cost tool for the optimisation of a protector design and the investigation of the effect of different parameters such as protector insertion, effect of leakage, materials, and others on the protector noise attenuation.

INTRODUCTION

Despite the great progress in noise control technology, there are many noise situations, where engineering noise reduction is not economical or technically feasible. Also, in many practical situations, it may be many years before noisy machines and processes can be modified or replaced. Therefore, in these cases, or during a period in which noise control actions are being undertaken, personal hearing protectors should be used as an interim solution.

The use of personal hearing protectors is an ideal solution in many situations where a worker is exposed to high noise levels for short periods of time, particularly if verbal communication is not essential. For example, such as cutting the of wood with a noisy circular saw. In this case, the machine itself can be enclosed in a special room where the operator can go and carry out the cutting task. Normally, the room will have an access door which is closed during the cutting operation. On entering the room, the operator will put on the hearing protectors before switching on the saw. After completing the cutting operation and switching off the saw, the protectors will be stored away inside the room ready for the next use. During the cutting period, which may last for minutes, there is no need to communicate verbally with any other person, and, normally, the operator can withstand a few moments of discomfort from the protector. Therefore, the use of hearing protectors in this and similar cases is an ideal solution in order to prevent any permanent damage to hearing which may occur over long exposure to high levels of noise.

Hearing protection devices may be divided broadly into four basic types: (1) earmuffs which cover the outer ear and act as an acoustic barrier sealing it against the head, (2) earplugs which can be inserted into the outer ear canal, thereby blocking the propagation of airborne sound to the middle ear and (3) canal caps (semi-aural) which are, basically, earplugs connected by flexible headband. Canal caps generally seal the ear canal at its opening and they are used extensively in the food industries. (4) Other types of special protectors are available, e.g., helmets with circumaural cups or muffs (sometimes with communication systems), active noise, frequency/amplitude-sensitivity and uniform attenuation devices [Casali and Berger, 1966].

There are many varieties of hearing protection devices available on the market and several factors have to be considered in addition to the level of noise attenuation they provide. Selection the most suitable type for each situation includes factors such as comfort, cost, durability, chemical stability, safety, wearer acceptability and hygiene. No particular brand is the obvious best choice for all cases.

All HPD (Hearing Protection Devices) reduce the airborne noise at the ear drum. The sound energy can also be transmitted through the skull by the bone conduction. This energy is attenuated by about 40 to 58 dB and, normally, is not a consideration in potential hearing loss problems. The use of conventional HPD reduce the ability for speech communication and the detection of warning sounds. This may create hazards for the users and, therefore, the recent generation of electronic HPD attempts to solve this problem [Casali and Berger, 1996].

This paper presents a short review on the problem of quantifying the noise attenuation of hearing protectors and the various analytical model used such as, for example, the one dimensional simple model of the outer ear canal. In this model the ratio of SPL at the ear drum to the outer SPL is considering using the acoustic impedance of the ear drum and is compared with more complex model of the pinna and real dimension ear canal using numerical methods such as Infinite/ Finite Element Method.

HEARING PROTECTOR ATTENUATION MEASUREMENTS

Several national and international standards are available for the laboratory determination of hearing protector noise attenuation [Franks J.R. et al. 1994], mainly the ANSI [S3.19/74, S12.9/84 & 97] standard used in the USA and ISO[4869-2/92] & EN used in Europe [see BS EN references].

The actual test method is called Real-Ear-Attenuation-at-Threshold (REAT), and the techniques for measuring REAT are specified in ANSI S 3.19-1974, "Measurement of Real - Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs". ANSI S 3.19 requires that auditory thresholds be obtained from a panel of 10 normal hearing listeners sitting in a diffuse random-incidence sound field. The test signals are pulsed one-third-octave bands of noise which have centre frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. Thresholds are determined with the listeners' ears open and with their ears occluded by the hearing protector under test. The difference between the open-ear threshold and the occluded-ear threshold at each frequency is the REAT for that frequency. Each listener is tested three times with their ears open and three times with their ears occluded. The REATs for all 10 listeners is arithmetically summed and the mean attenuation is calculated for each test frequency. Since there are three REATs at each test frequency for 10 listeners, the average is calculated by dividing the grand total by 30 to get the grand mean. The standard deviation is also calculated for each test frequency using the number 29 (n-1 from the formula for the standard deviation of a sample, where n is the number of samples) as the denominator, as if 30 separate subjects had provided one REAT each per test frequency.

The current American National Standards Institute's method for determining REATs for hearing protectors is ANSI S12.6-1984, "Measurement of the Real-Ear Attenuation of Hearing Protectors". This standard, which replaced ANSI S3.19, requires an experimenter-supervised fit in which the listener fits the hearing protector while listening to a fitting noise and while gaining insight from the experimenter on optimum fitting techniques. The experimenter does not physically touch the protector or the listener after the final fitting.

The European community also relies upon the REAT for determining hearing protector attenuation [ISO 4869, 1992]. However, there are differences in methods. The number of subjects required is 16 rather than 10 and each subject is tested only once with ears open and once with ears occluded to produce one REAT at each test frequency. In addition, ISO - 4869 relies upon a subject-fit in which the listeners fit the hearing protectors using a fitting noise to adjust the protectors for best perceived attenuation, but without feedback from the experimenter. Because of the lack of coaching by the experimenter, the reported REATs are usually lower than when they are tested by ANSI standards.

RATING SYSTEM

The mean attenuation and standard deviations as reported by hearing protector suppliers were used to calculate all ratings of protector performance according to the various methods [Franks J.R. et al. 1994].

The NRR is a single-number rating method attempts to describe a hearing protector on the basis of how much the overall noise level is reduced by the protector. The NRR is described in 40 CFR Part 211 EPA Product Noise Labelling Law, Subpart B Hearing Protective Devices, and was adapted by the EPA from Method 2 in the first NIOSH Compendium [Kroes et al., 1975]. The formula for calculating the NRR is

$$NRR = 107.9(dBC) - 3 - 10lg\left[\sum_{f=125}^{8k} 10^{0.1(L_{af} - APV_{f98})}\right] \qquad (1)$$

Where:

L_{af} is the A-weighted octave band level at centre frequency f of a pink noise spectrum with 100 dB at each frequency band and an overall level of 107.9 dBC;

APV_{f98} is the mean attenuation value minus 2 standard deviations at centre frequency f (two standard deviations accounts for 98% of the variance in a normal distribution).

The NRR assumes a background of pink noise with octave-band levels of 100 dB. The corrections for the C-weighting scale are then subtracted to compute unprotected C-weighted octave-band levels at the ear. These octave-band levels are logarithmically summed to obtain the overall sound level in dBC at the unprotected ear; this value is the first term of the equation and is always 107.9 dBC. The corrections for the A-weighting scale are then subtracted from the pink-noise octave-band levels to compute the A-weighted octave-band levels at the ear. The average attenuation minus twice the standard deviations are subtracted from the A-weighted octave-band levels to compute the protected A-weighted octave-band level at the ear. The adjustment of 2 standard deviations provides, theoretically, an NRR that 98% of the subjects will meet or exceed, provided that the wearers use the hearing protection device the way laboratory subjects did and that the subjects were a reasonable sample of the user population anatomically. The protected A-weighted octave-band levels at the ear is then logarithmically summed to calculate the overall protected A level. The NRR is computed by subtracting 3 dB from the difference between the unprotected C-weighted (107,9 dBC) and the protected A-weighted levels at the ear. The 3 dB factor is a correction for spectral uncertainty to account for whether the pink noise used in the computation really matches the noise in which the hearing protection devices is worn.

The NRR is intended to be used for calculating the exposure under the hearing protector by subtracting it from the C-weighted environmental noise exposure level. Thus, if a protector has an NRR of 17 dB and it is used in an environmental noise level of 95 dBC, the noise level entering the ear could be expected to be 78 dBA or lower in 98% of the cases. An alternative use of the NRR is with dBA measurements, the NRR can be applied if 7 dB is subtracted from its value. Thus for the same protector above, if it is used at an environmental noise level of 90 dBA, then the noise level entering the ear is 90 - (17-7) = 80 dBA.

In Europe, new rating systems have been adopted which may have as wide a use their as the NRR has in the United States. The systems are the Single-Number Rating (SNR), the High-Middle-Low (HML) rating, and the Assumed Protection Value (APV). These methods are based on REATs measured according to ISO 4869-1 (as discussed previously) for one-third octave bands in octave steps from 63 to 8000 Hz (when data for 63 Hz are not present, the summation occurs from 125 to 8000 Hz).

All of these methods provide the user with the option of selecting a protection performance value which is an indication of the percentage of test subjects who achieved the specified level of noise reduction. The protection performance is computed by subtracting a multiple of the standard deviation from the mean attenuation values. The most commonly utilised protection performance value in Europe is 80% which is computed by using a multiplier of 0.84 with the standard deviation values. However, in this document, a protection performance value of 98% (computed by multiplying 2.0 times the standard deviation) is utilised for all SNR, HML, and APV calculations in order to make them more directly comparable to the NRR values. It should be stressed, though, that these methods allow the user to select a protection performance level other than 98%, and that the ratings can be recalculated from the data provided.

The SNR is calculated much like the NRR, except that the values used may vary with the selected protection performance value and that there is no 3 dB spectral correction factor. The SNR differs from the NRR further in that the base spectrum for calculations is made-up of octave-band noise levels which sum to 100 dBC, rather than pink noise octave-band noise levels of 100 dB which sum to 107.9 dBC. The SNR considers attenuation only at the octave centre frequencies and does not include the third-octave centre frequencies of 3150 and 6300 Hz. The octave band levels are also adjusted by the A-weighting correction factors and summed to a value of 98.5 dBA. The mean attenuation value for each octave-band, minus the standard deviation for that octave band, multiplied by a protection-performance value, is subtracted from the A-weighted corrected octave-band levels in order to calculate the APV for each band. The sum of the APVs is subtracted from 100 dBC to calculate the SNR. The SNR may be subtracted from the environmental noise level in dBC to predict the effective A-weighted sound pressure level under the hearing protector. Thus, if a hearing protector had an SNR of 16 dB and was used in a noise level of 95 dBC, the effective A-weighted sound pressure level under the hearing protector would be assumed to be 79 dBA.

The HML method is a different rating system altogether in that it provides three numbers to describe hearing protector attenuation. The choice of number to be used in a given instance depends upon the noise from which protection is sought. The HML method has a number which describes the low-frequency attenuation (L value), the mid-frequency attenuation (M values), and the high-frequency attenuation (H value) of a protector. These numbers are calculated by taking into account typical industrial noise spectra. In the early 1970s, NIOSH collected noise spectra from a variety of industrial locations and developed the NIOSH 100 noises [Johnson and Nixon, 1974]. The noise-spectra array was reduced to 8 spectra for calculation of the HML based on the difference between the calculated dBC and dBA level for each noise.

As with the NRR and SNR values, the mean attenuation and the standard deviations for calculation of the H, M and L values are provided by the manufacturer. To use the values, the environmental noise level in dBA is subtracted from the environmental noise level in dBC to see which rating is appropriate . If the difference between the dBC and dBA levels is equal to or greater than 2 dB, the mean of the M and L values is used according to the equation:

$$M - \frac{(M - L)}{8}.(dBC - dBA - 2dB) \qquad (2)$$

If the difference is between 2 dB and - 2 dB, the mean of the M and H values is used according to the equation.

$$M - \frac{(H - M)}{4}.(dBC - dBA - 2dB) \qquad (3)$$

The HML method allows the selection of a hearing protector so that it can be effective at the frequency range where it is needed most.

The Assumed Protection Values (APV) are calculated for each test frequency by subtracting a coefficient multiplied by the standard deviation from the averaged attenuation. The coefficient varies depending upon the protection performance desired. For a protection performance of 80% the coefficient is 0.84, for 84% the coefficient is 1.0 and for 98% the coefficient is 2.0. The APVs are used in the calculation of the SNR and HML, and they may also be used frequency-by-frequency for a direct calculation of octave -band noise reduction. In a typical application, one would examine the noise spectrum to find the frequency regions with the most energy and then find a hearing protector with adequate APVs for those frequency bands so that the resultant overall dBA level at the ear would be safe.

The long-method calculation of hearing protector noise reduction is probably the most accurate method for rating. During the laboratory test to calculate the user's exposure level, and remembering that the protector user is wearing the device in the same manner as the listener (not necessarily true), then the most detailed and accurate method is to use the noise floor level in frequency bands together with laboratory test data. The following shows a numerical example of how to carry-out this calculation for the especial case of noise spectrum given in line 2 (see table 1).

1- Centre Frequency Octave band (Hz)	125	250	500	1 k	2 k	4 k	8 k	Total dBA
2- A-weighting SPL	83.9	93.4	101.8	106.0	102.2	97.0	88.9	109.0
3- Average attenuation	14	19	31	36	37	48*	40**	
4- Standard deviation x 2	10	12	12	14	14	14*	16**	
5- Estimated noise after protection = (step2 - step3 + step4)	79.9	86.4	82.8	84.0	79.2	63.0	64.9	90.3

Table 1: Long Method for Protection Calculation

* Arithmetic average of 3150 and 4000 Hz

** Arithmetic average of 6300 and 8000 Hz

The estimated protection for 98% of the users exposed to the environment levels of step 2, assuming that they wear the protector in the same manner as the listener during the laboratory test, is : **109.0 - 90.3 = 18.7 dBA**

THE PROBLEMS OF QUANTIFYING THE HEARING PROTECTORS NOISE ATTENUATION

REAT is the most commonly world wide procedure for the measurement of HPD attenuation in human subjects. The measured results represent, accurately, the attenuation obtained for a specific test subject (listeners), under specific conditions for fitting and wearing during a laboratory test [Royster et al., 1996]. The subject wearing and fitting of the HPD is very critical parameter to the measurement of sound attenuation especially for ear plug type HPD. Different standards permit various levels of interfering of subject by the measurement supervisor. The highest attenuation results can be obtained in laboratory conditions using trained subjects and supervised fitting. The results obtained from a round robin test on conventional set of HPD, that were tested by eight USA laboratories, showed very large discrepancies in both the mean values and the standard deviation and resulting in large differences in "Noise Reduction Ratio - NRR" (see figure 1). This is mainly due to fitting, selection and training of the subjects. Therefore, the HPD performance ranking is not possible using available data from different laboratories. Even if one laboratory is considered for a comparison of results then accuracy and repeatability have to be carefully considered over the period collecting data. That is why any changes of NRR of less than 3 dB should not be considered having any practical importance [Berger, e al, 1986].

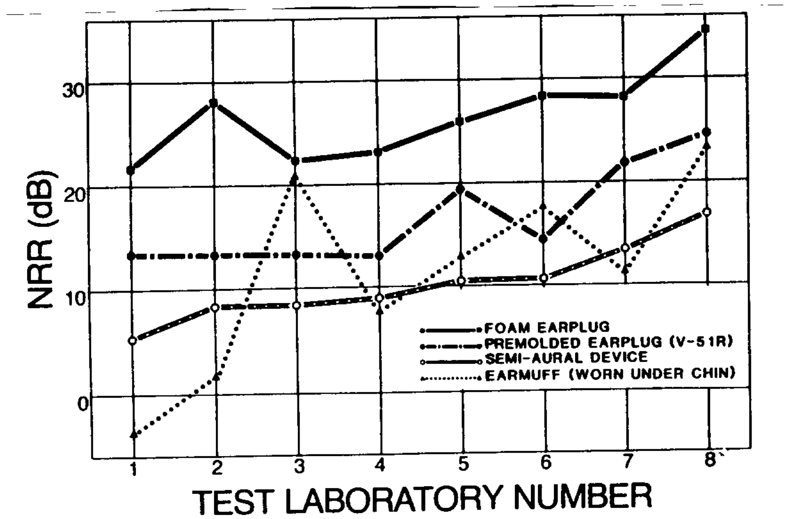


Figure 1: NRRs from eight USA laboratories [Berger et al, 1986]

It is evident that the data obtained for REAT laboratory tests misses frequency bands, since it considered test signals in the 1/3 octave bands at centre frequencies of 1/1 octave bands.
Attenuation measurements that are obtained in laboratory conditions normally involve trained subjects with correctly sized HPD that are fitted for maximum attenuation and where the subject is tested in a motionless state during a short period of about 10 minutes. All these conditions are very different from real world (field) users conditions, where workers is usually untrained with poorly fitted HPD that are, perhaps, fitted for comfort and not for maximum attenuation. Also, the effect physical forces, exerted by the worker moving about during several hours of the working day, can dislodge the protector. Therefore, new standards are being elaborated (such as ANSI S12. 1997) with naive subjects and with no training and fitting. Figure 2 shows an overview of field and manufacturers values for the NRR. In this figure, labelling values are between 25% to 40% of laboratory measured values for earplugs and about 60% for earmuffs. Laboratories and field evaluation of the same HPDs have shown that derating is not prudent because no single reduction value is accurate for all HPD [Berger, 1983 and Casali et al., 1991].

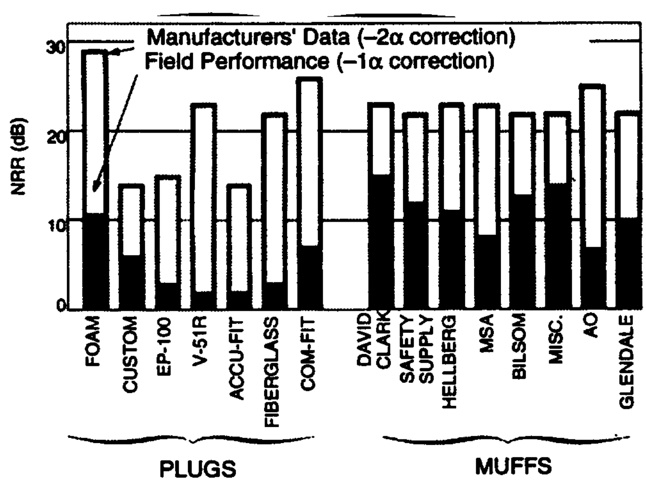


Figure 2: Comparison of NRRs published in USA of Labelled values to real-word “field” values from 22 separate studies [Berger, 1983]

Therefore, it is evident that laboratory standardised procedures overestimate the attenuation achieved in the real world. Laboratory standardised methods have been modified world wide in order to try to approximate the laboratory measured values to the real world values. This means that a large number of test subjects, using sophisticated test environment and more accurate digital measurement instrumentation are necessary. A complete test for a single model hearing protector requires each one of 10 qualified subjects (qualified in audiometric facilities prior to the test) to be tested three times. These conditions result in a long duration and expensive tests and, usually, take more that 25 hours at a cost of US$ 1500, approximately, for each type. Since we are dealing with large population of data, statistical analysis needs to be used. Measurements on large population with high confidence limits impose limitations on time and cost.

Alternative methods should be explored to quantify the hearing protectors attenuation with higher confidence limits. Also, it is necessary to use a low cost and quick methods that are simple for the manufacturers to use to investigate the effect of the protector parameters (e.g., geometrical variation of the human pinna, ear canal, HPD type and size, the effect of wearing and fitting conditions, the effect of design parameters such as materials, tolerances, geometrical form, etc.). Numerical modelling methods, such as Finite Element Method FEM and Boundary Element method BEM can be used to give accurate, quick, low cost and higher frequency resolution results. Also numerical methods can be used to model the effect of the pinna on the external sound field and the effect of ear canal geometry on the sound propagation along the varying ear canal geometry, with the effect of varying boundary conditions. Also numerical modelling can simulate real-world situation by allowing, for example, leakage of a poor fitting. Also can simulate double protection of ear muff and ear plug used simultaneously.

It must be noted that the system elements that we are trying to study have small dimensions. For example, the ear canal diameter which varies between a very small 7 mm value up to 12 mm, approximately. The ear canal length can vary between about 27 to 37 mm and the pinna size is about 70 x 50 mm, approximately, and has a complex geometrical shape. The numerical method is very suitable for such dimensions requires at least 6 elements for a wave length. For 20kHz frequency range, the element size has to be smaller than 2.8 mm which. Therefore, a very good accuracy and confidence on the numerical results can be obtained within the capacity of computer memory and speed.

The human hearing system can be modelled as a three dimensional coupled mechanical-acoustic system. The excitation is the external sound field. Boundary conditions can be imposed at the surface of the pinna, at the surfaces of the outer ear canal, by the acoustic impedance at the eardrum, and at both sides of the hearing protectors. The presence of human head, shoulder and body may modify the sound field . The external acoustic excitation field is modified by the pinna geometry due to the resonance of the pinna cavity. Limited accurate information is available on the quantitative characteristics of the sound field distribution around the head, the pinna, and in the outer ear.

ISO and ANSI REAT measurements are carried out only for continuos sound field and there is a lack of testing method for impulsive sound field.

One-dimensional models for a straight and curved outer ear canal have been considered. The simplest model is a straight uniform tub with the drum acoustic impedance at the closed end [Shaw 1976 , Kuhn 1979 and Ciskowski,1988 and others]. Most of these publications relate the Sound Presser Level SPL at the ear drum to the SPL at the ear entrance.

Johansen (1975) show ear canal geometry represented by a straight line axis with the area distribution of the outer ear canal. Stinson (1989) measure the physical dimensions the external ear canal in 14 subjects, 1000 points, approximately, each, and represented the results in the form of curved axis and perpendicular area slices 1 mm apart. Rabbitt (1991) used as asymptotic theory to calculate the cross-section pressure distribution, natural acoustic modes with some restrictions on the curvature and discontinuity of the ear canal.

The effect of small dimension details of the pinna and ear canal are in the high frequency range. The simple analytical model of straight uniform tube is valid up to 4kHz, approximately, but, above this frequency, there is effect from pinna cavity dimensions on resonance and on the SPL at the ear entrance. Above 10kHz, approximately, detail dimensional effects have to be considered for accurate estimate of the SPL.

The effects of the middle ear on the acoustic performance of the external ear, and of the external ear on the performance on the middle ear, can be determined by the input impedance of the middle ear and the output impedance of the external ear (both are connected in serial). The ratio of the two impedances influences the sound pressure level at the eardrum. At frequencies below 1kHz, the SPL at the eardrum by external sound field is relatively independent of the input impedance of the middle ear. Above 1 kHz the two impedances are nearly equal and the SPL at the eardrum will be influenced by them. Therefore, the middle ear effects can also be modelled numerically. An inner ear model seems more complex due to lack of information of the nerves and brain reaction to external noise field [Rosowski,1988].

NUMERICAL MODELLING FOR HPD NOISE ATTENUATION

A reliable model for the frequency range up to 20kHz needs to considered the geometry of the pinna and the outer ear canal with the eardrum characteristics. Also the characteristics of the hearing protector, such as ear plug or earmuff. Little published literature exists describing the application of numerical methods (FEM and BEM) to completely model the human ear. Some work by Ciskowski (1988), Mourad (1990) and Xie, Ke-jun (1990), who modelled the outer ear canal with the boundary element method, considered a elastic and viscoelastc plugs. The plug type hearing protector are usually made from foam which should be modelled as porous materials.
Limited Preliminary results are presented in the next section for the modelling of the ear canal and outer part of the pinna by FEM.

Pinna, Outer Ear Canal and Eardrum

Pinna and outer ear canal have a very complex geometry. Stinson (1989) presented a study of 14 human ear canals, by moulding silicone rubber and measuring 1000 co-ordinate points over the surface of each mould. The measurements are presented as individual ear canal area functions with the area of cross-sectional slices normal to a curved central axis following the bends of the canal. Very large intersubject differences were found, but several overall trends were evident in the area functions which lead to improved predictions of the sound pressure distribution field inside and outside the human ear at frequencies greater than about 4 kHz.

The eardrum impedance presented to the ear canal strongly affects the free-field response of the ear in the vicinity of resonance and is crucial when the ear is driven by an earphone inserted into the canal. Table 2 present updated estimates of average values based on data from over than 20 studies [Shaw,1997].

Parameter	100	200	300	500	700	1k	2k	3k	5k	7k	10k
Real [g/cm4. s]	490	430	390	350	320	320	390	420	400	400	400
Img.[g/cm4.s]x100	-28	-14	-9.5	-5.5	-3.6	-1.7	-0.8	-0.3	2	4.1	5.1

Table 2: Estimated average values for the eardrum resistance (Real) and reactance (Img.) For normal human ear [Shaw-1997].

Sound pressure distributions and resonance frequencies for the first five normal modes of the pinna with the ear canal closed at the entrance are studied by Shaw (1980) and are shown in figure 4. His data paved the way for the construction of physical models with relatively simple geometry that approximately the same mode frequencies, pressure distributions, directionality and excitation as the average human ear.

A real human ear was moulded using silicon materials. This mould was sliced each 2 mm apart to get a typically human ear mesh (see figure 3).

Figure 3: (a) Human ear; (b) silicon mould and (c) Silicon sliced mould

A 2-D finite element model of part of the open pinna and the outer era canal is created using real ear dimensions from figure 3. The first 14 resonance frequencies was calculated by the FEM. The values obtained are shown in table3.

Mode	Frequency kHz
1	2.592
2	3.954
3	5.358
4	7.375
5	9.228
6	10.865
7	11.986
8	13.165
9	14.507
10	14.615
11	16.009
12	17.302
13	18.663
14	19.389

Table 3: resonance frequencies of the modes shown in figure 4

Figure 5 shows some of the these 14 modes. It is interested to note that, if an efficient hearing protector has to be used, it is to be placed near the maximum particle velocity region (as in placing absorption materials near a wall). The pressure distribution shown in figure 5 can give valuable information for the understanding of the acoustic behaviour of the outer ear.

These finite element calculated values (see table 3) can be compared with Shaw (1980) values shown in figure 4. It is clear that numerical values gives in table 3 are more accurate than that presented by Shaw, where Shaw detect only 5 modes below 14.4KHz.

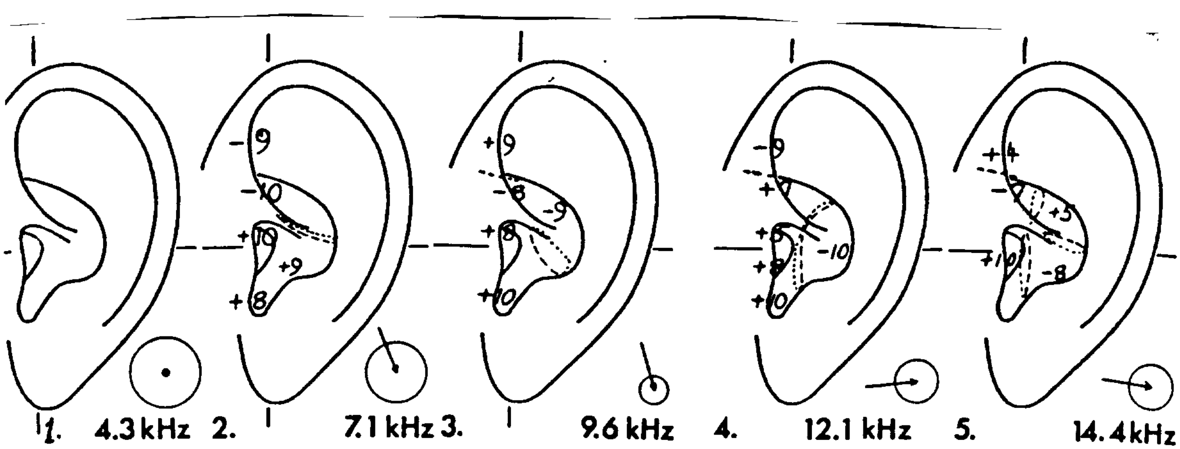


Figure 4: Average transverse pressure distributions and resonance frequencies of five normal modes in human ear with the ear canal closed at the entrance showing the nodal surfaces (broken lines) and relative pressure (numerals). Circles indicate relative degrees of excitation and arrows show directions of maximum response at grazing incidence [Shaw, 1980].

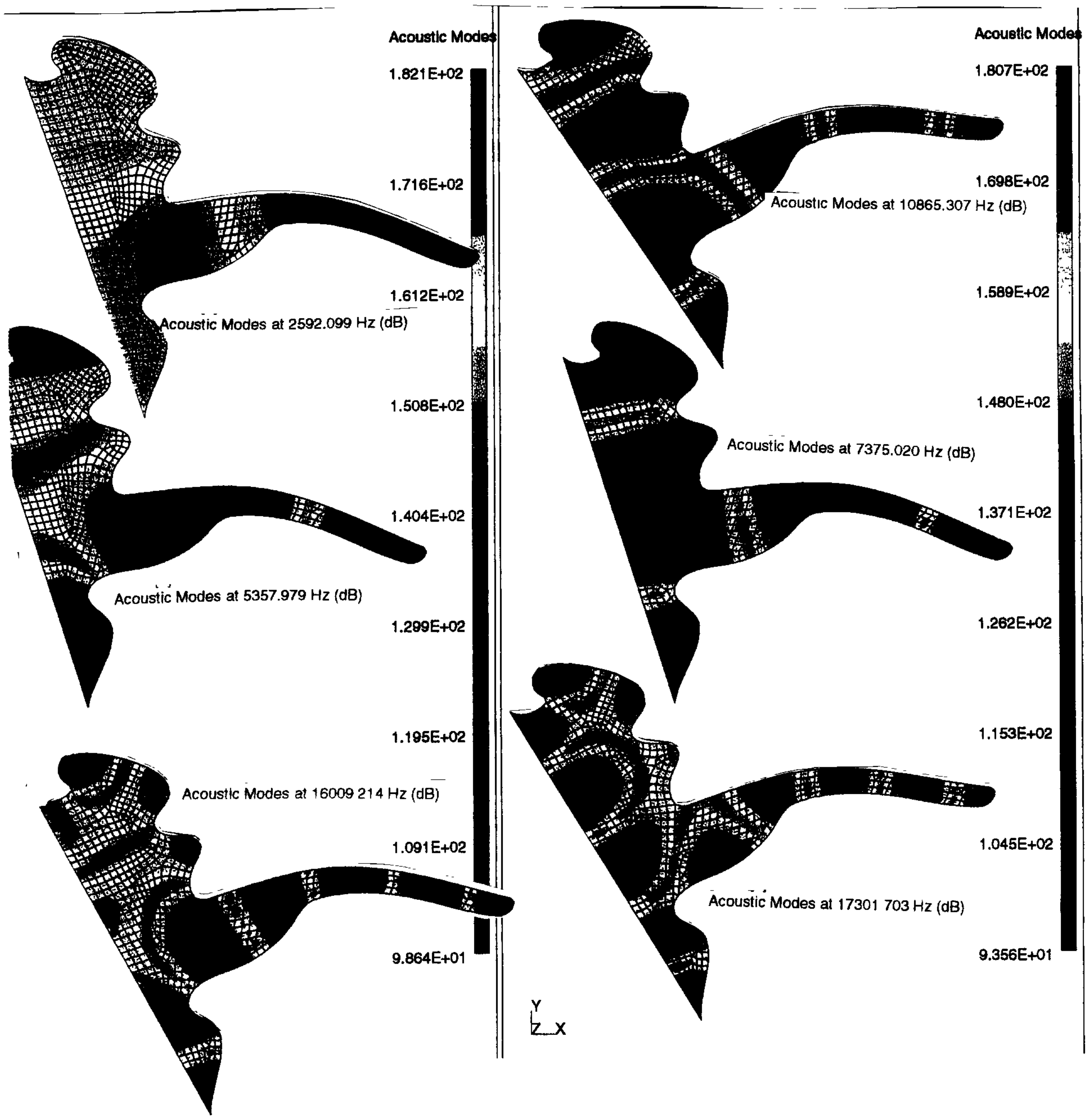


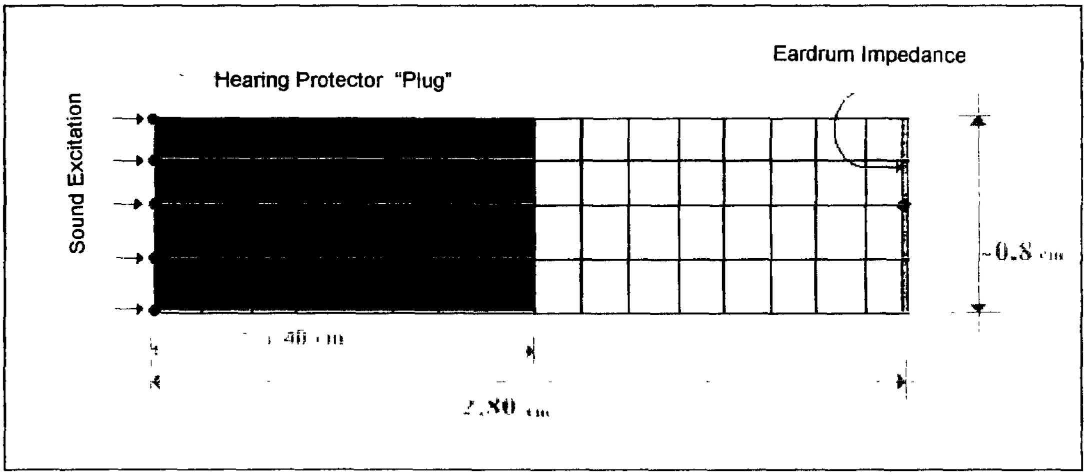
Figure 5: Acoustic resonance frequencies and mode shape of the pinna

Earplug model

Porous foam ear plug can be model numerically considering its materials as locally reacting with only one longitudinal wave propagation, in this case, the porous material's were assumed to have either zero (limp) or infinite (rigid) stiffness. Other more representative model by Biot (1956) considering three waves propagation in the porous materials (two longitudinal and one transverse). All FEM calculation in this paper are carried out using the commercial software SYSNOISE, where locally reacting absorption elements are used.

One-dimensional straight tube model

In this section results of the FEM model are presented, for one dimensional straight tube representing the outer ear (see figure 6). Consider a straight hard walls tube excited by incident sound wave at the open end and has the acoustic impedance of the eardrum at the other end (see table 2).



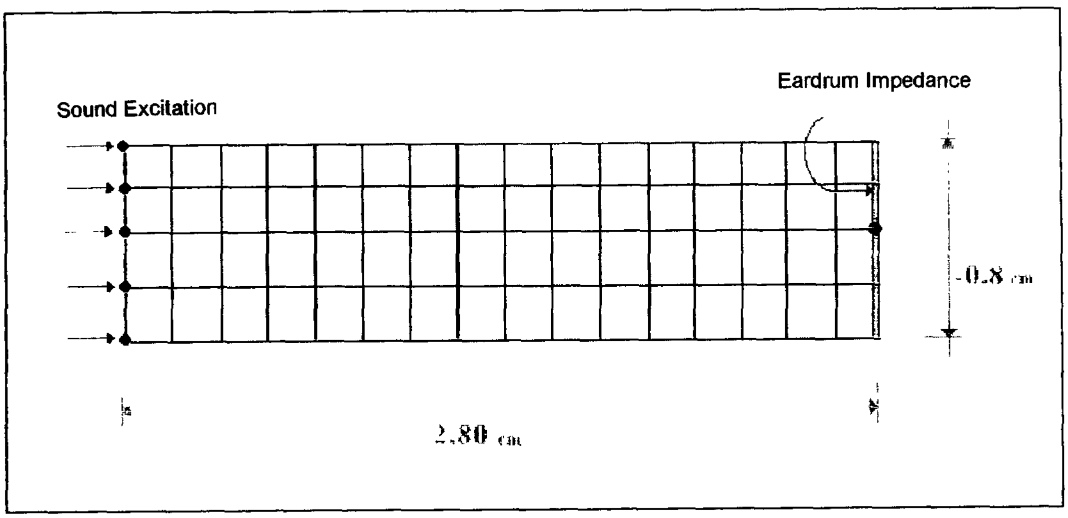


Figure 6: One dimensional simple model for the outer ear (without and with ear plug)

Figure 7 shows the comparison of the SPL response at the ear drum, with and without the ear plug, calculated by FEM. The foam earplug characteristics used has the following characteristics:
Sound velocity = 100 [m/s];
Flow resistance = 25000 [kg/m2.s]
Material Density = 15 [kg/m3]
Structure factor = 7.9
Porousity = 0.9

This figure 7 shows two peak values, which are the two natural frequencies for the unplugged tube associated with the first two longitudinal modes for an open-closed tube (3KHz and 9KHz approximately). As expected, the noise attenuation increases with frequency (the difference between the two curves). Note the peak at 400 Hz for the plugged case, which is due to rigid body vibration of the plug on the cavity stiffness. The second frequency at about 1.8 KHz is due wave propagating in the plug length which match one quarter wave length, f=100/(4x0.014) = 1.785 KHz. The other peaks are multiple of that frequency.

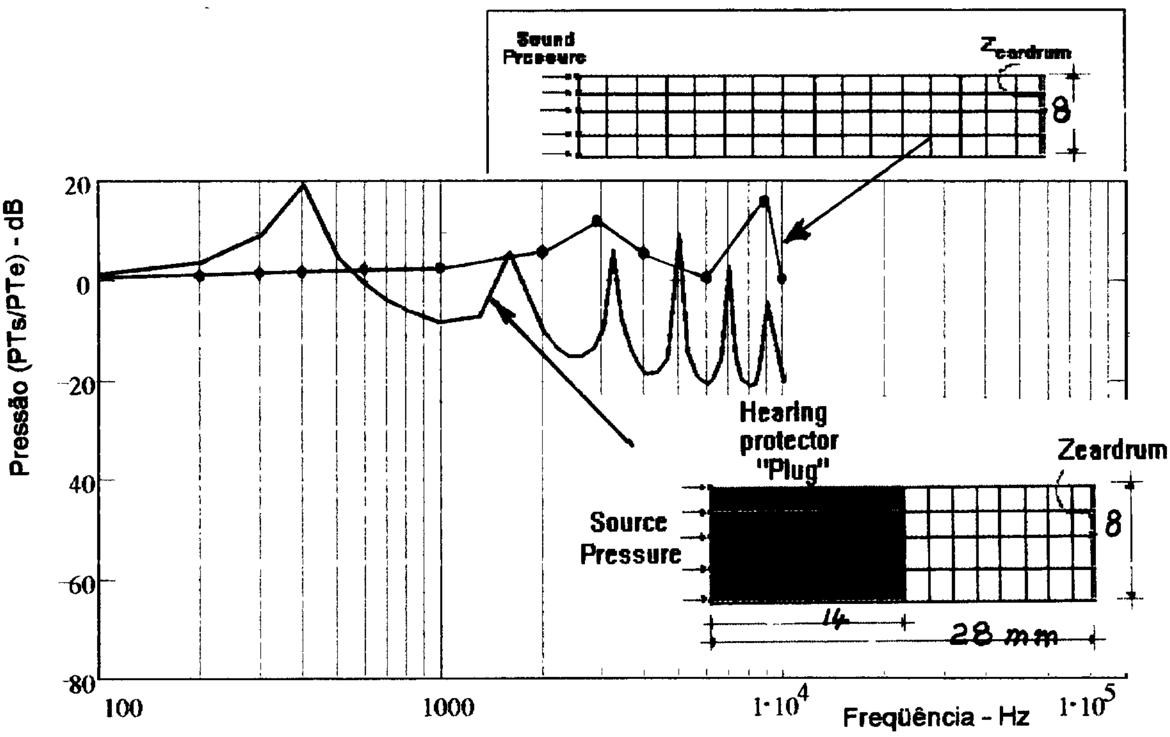


Figure 7: Eardrum SPL response for one-dimensional model with and without an ear plug

2-D Model for the Outer Ear

Figure 8 shows the results obtained by FEM for a 2-D model of the pinna with and without the foam ear plug . This figure show a simmilar behaviour as the tube model (figure 7), with the peaks slightly shifted and different amplitudes.

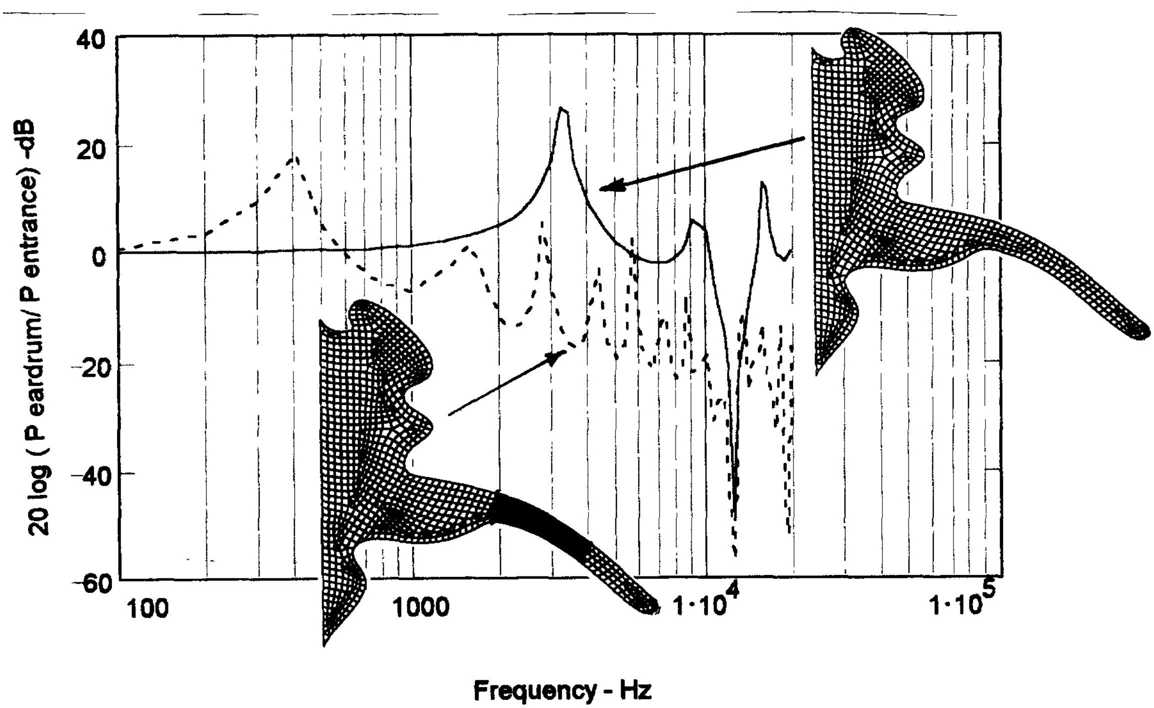


Figure 8: Eardrum SPL response for 2-D model for real ear with and without an ear plug

Figures 9 and 10 show the sound pressure levels distribution for the model of; outer ear canal, pinna, head and shoulders, with and without the ear plug at 5 KHz. Since the head and shoulders are about 20 cm dimensions, therefore there effect is expected to alter the sound field above about 900 Hz. For the unplugged case, the SPL =103 dB and for the plugged case, SPL = 82 dBA (all relative values), therefore the insertion loss is 21 dB.

CONCLUSIONS

The problem of quantification of the noise attenuation of hearing protectors is discussed. The conventional subjective test involves a large number of subjects, costly instrumentation, physical installations and long duration testing. Numerical modelling using finite element method (FEM) and boundary element method (BEM) may be considered a quick and low cost tool for the optimisation of the hearing protector devices and can cast light on the acoustic behaviour of the outer ear and ear canal.

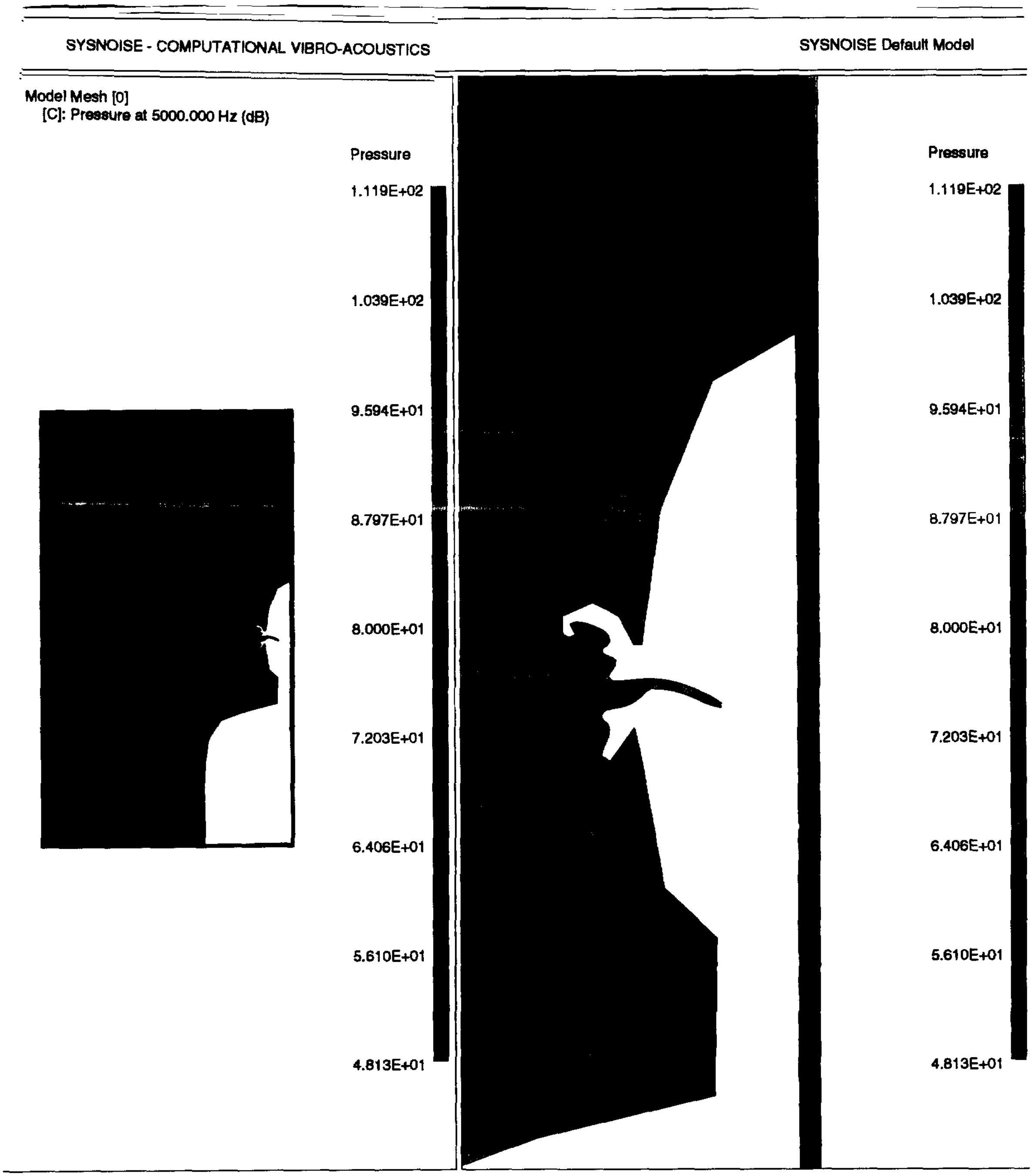


Figure 9: The eardrum SPL response for 2-D model for real ear canal, head and shoulders for unplugged ear at 5KHz for plugged ear at 5KHz.

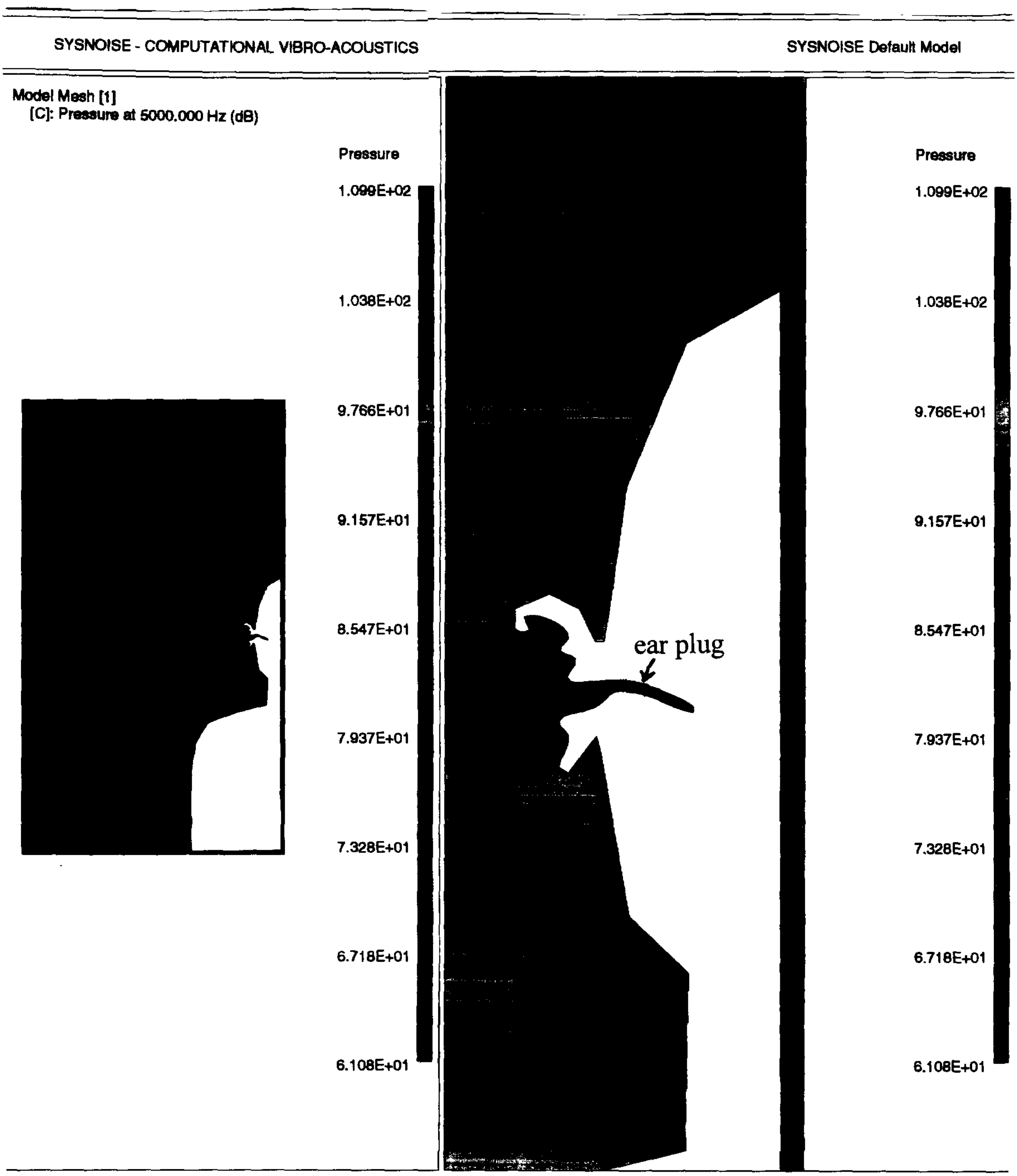


Figure 10: The eardrum SPL response for 2-D model for real ear canal, head and shoulders for plugged ear at 5KHz.

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