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Adsorption in activated carbon and its effects on the low frequency performance of hearing defenders

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Activated carbon displays interesting behaviours at low frequencies due to its large internal surface area and complex network of pores of various sizes and shapes. The material can produce larger than expected absorption and change the compliance of acoustic enclosures. This paper investigates the performance of hearing defenders that utilise activated carbon as the lining material of the cup. Compared to a standard foam liner, the introduction of activated carbon increases the insertion loss by up to 10dB at frequencies between 31.5 and 250Hz. Part of this energy loss could be due to the substantial change in local density as air molecules adsorb onto, and desorb from, the activated carbon during sound propagation. There is a change in entropy and energy loss from the sound wave during the adsorption / desorption process due to the existence of a hysteresis loop. This additional absorption enhances performance. The other part of the energy loss could be due to the existence of a slip flow in the carbon micropores, where the continuum hypothesis is no longer valid.

1 Introduction

“If a man come on them unwittingly and lend ear to their Siren-voices, he will never again behold wife and little ones rising to greet him with bright faces when he comes home from sea... Wherefore sail right past them: and to achieve this successfully you must work bees-wax till it is plastic and therewith stop the ears of your companions so that they do not hear a sound.”

*Homer, The Odyssey, Book XII
(Translated by T. E. Lawrence)*

It took more than three thousand years to produce hearing protectors that rivalled the performance of the beeswax described in Homer’s Odyssey and which proved invaluable to Odysseus on his long journey back to Ithaca following the fall of Troy. These are the circumaural hearing protectors, which have seen ‘rapid advancement in their performance in the decade following World War 2’ [1], but reached a plateau some forty years ago. Recently, considerable interest has been placed on the performance of attenuation in hearing protectors, mainly driven by legislation to reduce occupational noise exposure. Such interest extends down to frequencies at and below the usual limit of 125Hz (current standards [2] only require testing between 125Hz and 8kHz, with the option to test at 63Hz.) British Standard BS-EN352-1:2002 states the following minimum requirements for third-octave band attenuation data [3]:

Freq. in Hz	125	250	500	1k	2k	4k	8k
($M_f - s_f$) in dB	5	8	10	12	12	12	12

Table 1. Minimum attenuation requirements. M_f are the mean attenuation data and s_f are the standard deviations as measured in accordance with EN 13819-2:2002.

Most manufacturers produce protective devices with a range of attenuations to suit exposures to various levels, it having been established that ‘over-protection’ can result in user rejection of a device due to communication difficulties. The most highly attenuating products remain constrained in their performance at low frequencies by such factors as flesh compliance and particularly on the volume of air underneath the cups. Studies suggest that prolonged exposure to high amplitude low frequency noise can be

very harmful [eg 4] and work continues to quantify and objectively measure the extent of damage caused by such exposure [5]. Several methods have been investigated for improving low frequency performance. Most adventurously, different gases have been used to fill the cup volume and transducers have been used in ‘active control’ configurations to increase the apparent volume of the cavity. More prosaically, it is common practice to attach cups to an adjustable headband to minimise fit problems and ‘leaks’ which detract from low-frequency performance; gel cushions and shaped cushions have been used to likewise minimise leaks; and the porous cup liners typically used to control the h.f. diffuse field under the cup may also be optimised for small increases in l.f. attenuation, [1].

The current paper describes the use of activated carbon, a microporous granular material, as the inner liner of a circum-aural hearing protector. The results obtained show attenuation figures increased by up to 10dB below 200Hz. This significant enhancement results from the very large internal surface area presented by the microporous carbon granules, and the physical processes that accompany wave propagation through them. At low frequencies, where the time between consecutive compression and rarefaction cycles is significant, air molecules penetrating the activated carbon sample will be attracted by strong interstitial forces in the carbon micropores, and will start to bond to the pore walls. This process is called adsorption, and comprises a weak physical bond between air molecules and the carbon atoms through Van der Waals’ forces.

In the rarefaction cycle, adsorbed molecules leave the pore walls and are released back into the surrounding medium – in our case, air. This is known as desorption. This physisorption process forms a hysteresis loop, inducing a change in the system entropy and leading to energy loss by heat transfer. Additionally, it has been proposed that the increased attenuation may be due to a slip-flow condition present in the carbon micropores, where the continuum hypothesis is no longer valid [6].

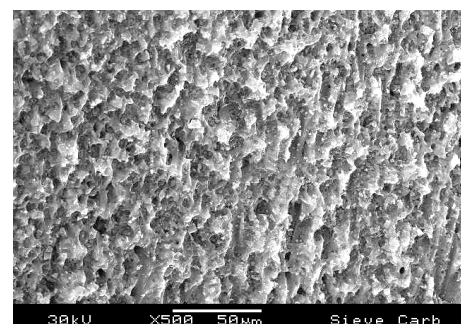


Figure 1. SEM Image of an activated carbon granule at 500 times magnification showing the large number of pores.

The results presented in this paper compare two kinds of porous liners; unconsolidated granular activated carbon and open-cell foam. Two hearing protectors with different cup volumes are considered in this comparison. They are commercially available, and it might be reasonable to expect their performance regarding leakage, and the choice of enclosed volume, cushion stiffness and cup mass, to be reasonably optimal. Therefore we can be confident that the performance changes implied by the use of carbon liners are representative of those that might be achievable in any production hearing protector. The results show the frequency response for insertion loss of both porous liners, as well as the improved performance due to the activated carbon lining as related to an apparent increase in cup volume, when treating the impedance of the enclosed air as a lumped acoustic compliance. Observations from results, conclusions and suggestions for further work are also presented.

2 Preparation of the samples and test setup

2.1 The samples

For the purpose of the tests in question, two commercially available circumaural hearing protectors were chosen, having respective cup volumes of 175ml (A) and 200ml (B). The porous liners consisted of one open-cell foam liner supplied with the hearing protectors, having a density $\rho_f=70\text{kg/m}^3$ and flow resistivity $\sigma_f=12475$ MKSRayls, as well as a 100ml sample of unconsolidated granular activated carbon sieved between 0.3 and 0.42mm with $\sigma_c=65724$ MKSRayls, placed in an ‘acoustically transparent’ fabric with $\sigma=10$ MKSRayls. It was not possible to measure the pore size distribution for this particular sample - typical pore diameters range from 50nm to 1000nm [7].

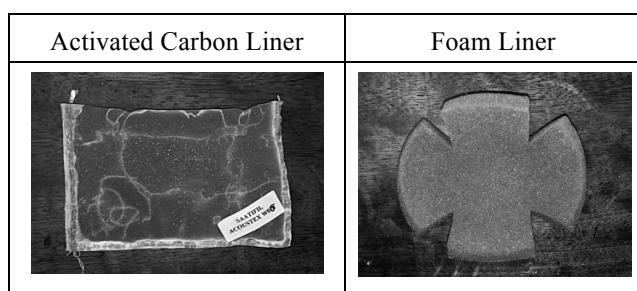


Figure 2. Activated Carbon liner in acoustically transparent fabric and foam liner.

2.2 Measurement procedure

The measurements were performed with reference to BS EN 13819-2 [2] using an ATF measurement rig in anechoic conditions, shown in Figure 3. The room has been shown to produce reliable free-field conditions down to 104Hz, but it is possible and quite usual to measure below that specified frequency, with care in the interpretation of results. The

standard requires the insertion loss of each cup to be measured at specified one-third octave band centre frequencies between 125Hz and 8kHz, with the mean and standard deviations reported at the above third-octave frequencies. The standard procedure was modified to include an optional pseudo-random pink noise test signal with a much broader frequency bandwidth than that required by the standard. The noise signal was radiated using a tetrahedral loudspeaker array, generating a random incidence (‘diffuse’) sound field in the frequency range of interest. The results were recorded as narrow-band spectra between 20Hz and 20kHz, in order to preserve as much detail as possible. Five measurements were performed on each of the hearing protectors with the foam and carbon liners respectively, in order to investigate measurement (and particularly ‘fit’) repeatability. The mean values for frequency response were calculated then compared to the averaged reference unoccluded measurement and the insertion loss was calculated. Furthermore, a subjective ‘REAT’ test was performed on four trained subjects according to BS EN 24869-1 [8] in order to validate the measured results.

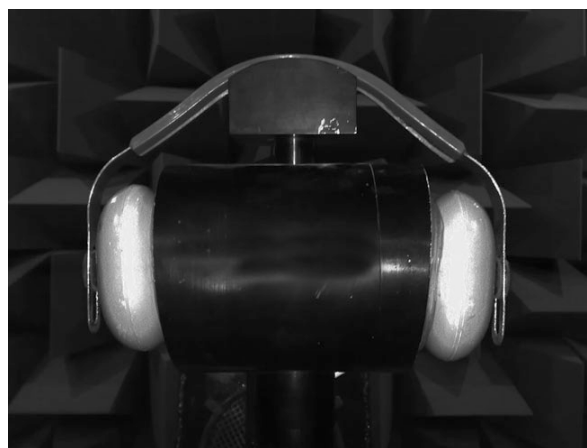


Figure 3. Acoustic Test Fixture.

3 Results

The narrow-band frequency response of both cup sizes between 20Hz and 20kHz will be presented to illustrate the performance of the activated carbon liner as compared to the foam liner. The third-octave standard deviation results for sample A are listed in the table below for the left cup.

Freq., Hz	125	250	500	1k	2k	4k	8k
s_f foam, dB	1.6	1.9	1.6	1.0	1.4	1.2	0.5
s_f carbon, dB	1.7	1.8	1.5	1.2	1.1	1.5	0.4

Table 2. Standard deviation values for the left cup of hearing protector A (175ml).

The following set of figures show the left and right cup insertion loss for each of the samples with the two liners, as well as the difference between them so as to highlight the improvement in performance. Figures 4 to 7 relate to the hearing protector with 175ml cup volume and figures 8 to 11 to that with 200ml cup volume.

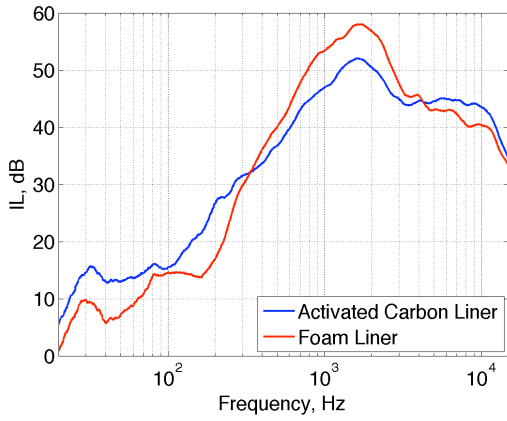


Figure 4. 175ml cup insertion loss – left

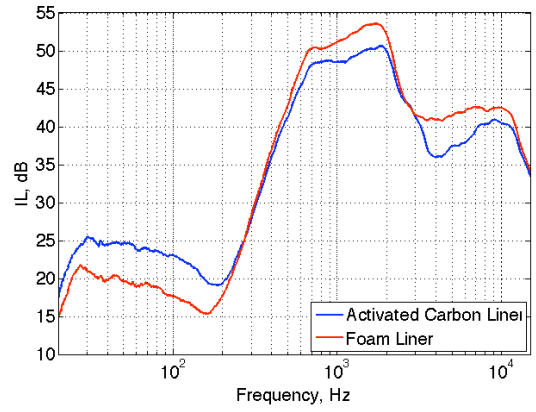


Figure 8. 200ml cup insertion loss – left

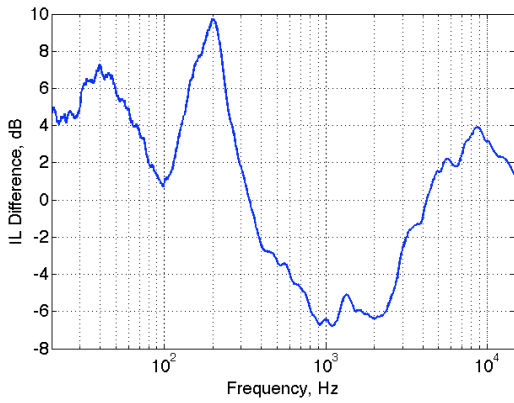


Figure 5. 175ml cup - insertion loss difference – left

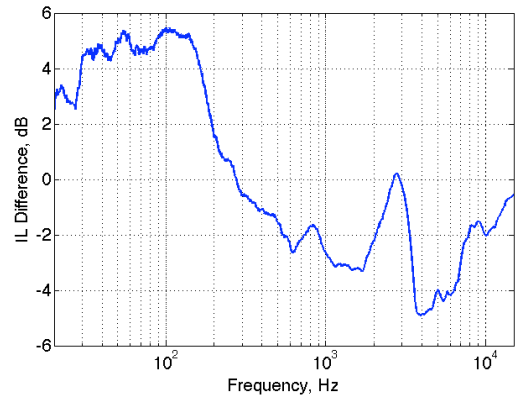


Figure 9. 200ml cup - insertion loss difference – left

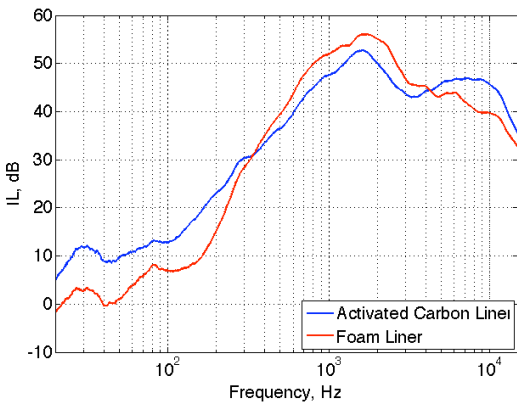


Figure 6. 175ml cup insertion loss – right

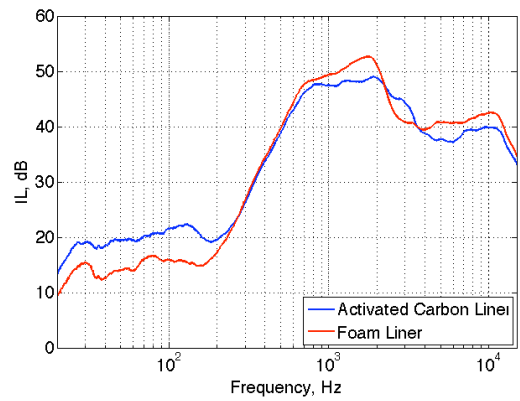


Figure 10. 200ml cup insertion loss – right

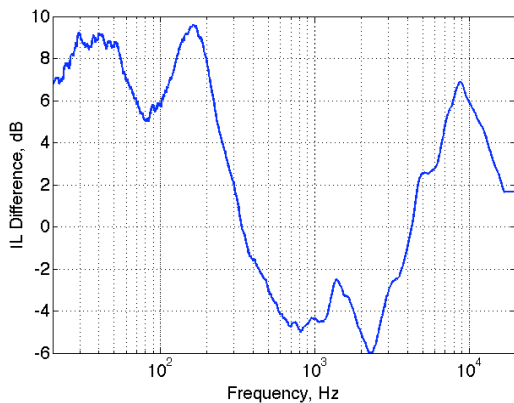


Figure 7. 175ml cup insertion loss difference – right

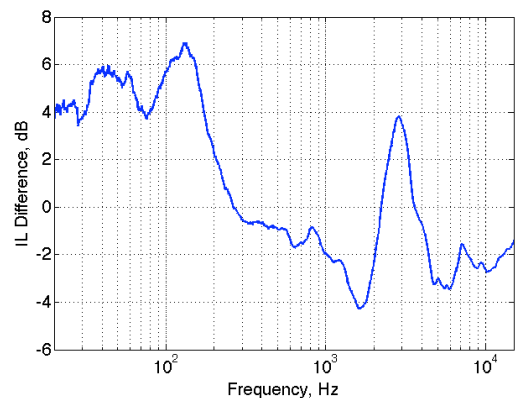


Figure 11. 200ml cup - insertion loss difference – right

In order to examine the results shown above, the behavior of an ideal airtight circumaural hearing protector is shown in the figure below.

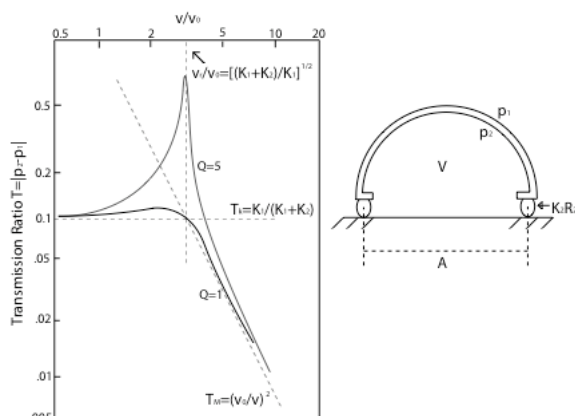


Figure 12. Theoretical attenuation curves for ideal circumaural hearing protector [1].

In the above figure, v_r refers to the cup resonant frequency, K_2 and R_2 denote the cushion spring constant and resistance, K_1 represents the stiffness of the enclosed air, V is the internal cup volume, A is the cushion area and p_1 and p_2 are the acoustic pressures outside and inside the cup, respectively. Above the whole-body lumped resonant frequency of the system, the performance is dominated by the mass line T_m with an increase in attenuation achieved by increasing the cup mass or reducing the cushion area. However, it has been shown [1] that in practice, a threefold increase in cup mass leads to surprisingly little increase in attenuation. This is due to flanking paths, where sound is transmitted to the inside of the cup via leaks or bone conduction (or equivalently, structure-borne conduction through an acoustic test fixture). This partially explains why in Figures 4,6,8 and 10, the mass-controlled attenuation does not always follow the anticipated 12dB/octave slope. Additionally, distributed resonant modes of cup and headband can complicate the measured attenuation behaviour.

Below resonance, the attenuation curve follows the stiffness line T_k and it becomes clear that in order to achieve an improvement in attenuation in this region, one must look into increasing the cup volume or using a stiffer cushion. In the latter case, stiff materials can result in leakage and user discomfort, with the result that gel cushions are sometimes employed. However, flesh compliance places a practical limit on how much of a performance improvement is possible following this approach.

The performance improvements demonstrated here using carbon liners are therefore encouraging, in offering a new approach to a difficult problem. The results from both hearing protectors show a significant improvement in insertion loss below 300Hz when the activated carbon liner is used. It can be seen from figures 5 and 7 that for 'sample A' this improvement reaches 10dB at 200Hz in the left cup. In the right cup, the insertion loss difference reaches 9dB between 30 and 50Hz and 9.5dB at 170Hz. In 'sample B', the improvement in performance is slightly smaller and is restricted to low frequencies, but it can be seen from figures 9 and 11 that this increased attenuation is more uniform across the range, where roughly 5dB of extra attenuation is

achieved between 30Hz and 150Hz. For some applications it could be argued that the loss in performance at high frequency (where the carbon liner inhibits the build-up of the in-cup diffuse field less effectively than the foam liner) might be acceptable, since attenuation performance is more constant as a function of frequency – possibly an advantage for speech communication in a less severe noise environment.

At low frequencies, the increased attenuation difference in 'sample A' is partly due to a smaller cup volume (and hence a larger proportion covered with the activated carbon liner), and partly due to the fact that 'sample A' has a lower spring constant K_2 hence has a poorer low frequency performance as compared to 'sample B'. The performance gain due to the activated carbon is therefore more apparent.

In order to validate the above results, a 'REAT' subjective test was performed on four trained subjects using one-third octave band pseudo-random pink noise signals. The results are shown in figure 13.

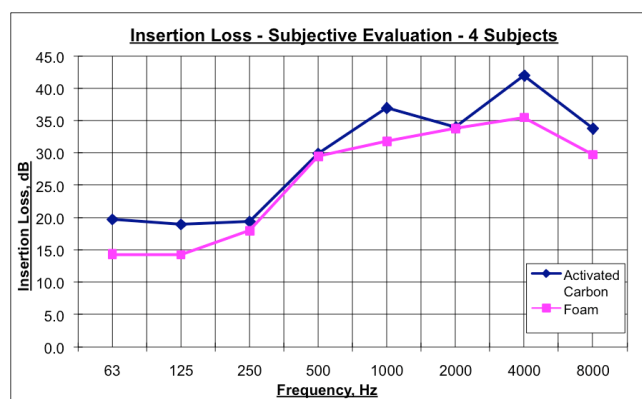


Figure 13. Subjective test results for insertion loss in sample B.

This result suggests that the perceived attenuation using an activated carbon liner is improved across the whole frequency range, as compared with results using a foam liner. The results below 250Hz confirm the measured results seen in figure 9, with a perceived insertion loss difference of 5dB between 63Hz and 125Hz dropping to around 1dB at 250Hz.

4 Conclusion

This paper presented results for insertion loss from two hearing protectors of different sizes, and has shown a significant improvement in low-frequency attenuation performance when using activated carbon as the porous liner in the cup. Between 5dB and 10dB of extra attenuation was achieved below the lumped resonance of the cup acting on the flesh / cushion compliance. It is believed that the added energy loss at low frequencies is due to the change in the system entropy as air molecules adsorb onto and desorb from the many pores of the activated carbon sample [9]. Work is ongoing to provide an acoustic model for this physical process [10]. This process is only effective at low frequencies, and at higher frequencies the foam liner is more effective in controlling the build-up of an in-cup reverberant field. Therefore most measurements show a

superior performance for foam liners in this band. In the case of the activated carbon liner, a reduced performance at high frequencies may be desirable for some applications, where lower performance can be tolerated in order to achieve improved speech communication. Although the subjective test results confirm the measured data at low frequencies, the small listening panel perceived a better performance from the hearing protector with the activated carbon lining over the whole frequency range. Testing with more subjects is required to validate these results.

Practically, there are several significant obstacles to overcome if the commercial application of activated carbon liners for hearing protectors is to be realized. The most prominent of these is the hydrophilic property of microporous materials, which hinder their performance over time as pores become clogged with adsorbed water. The market expects that a porous material for the liners of hearing protectors should resist the daily wear and tear in the workplace, and that the humid environment under the cup due to user perspiration should not unduly affect attenuation performance. Further tests are required in order to ensure the proper prolonged use of activated carbon as a porous liner.

Acknowledgments

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