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Technical Paper

Attenuation of airborne noise by wet and dry neoprene diving hoods

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Abstract

The insertion losses of five neoprene diving hoods of varying thicknesses (2 mm–9 mm) were measured in one-third octave bands using a Kemar manikin in a diffuse broadband noise field. The insertion losses were measured in air for both dry and wet hoods. The insertion loss was calculated as the sound level in each frequency band measured with the hood, minus the corresponding sound level measured without the hood. The insertion losses were similar for both ears of the manikin. Both wet and dry hoods neither attenuated nor amplified sound below 250 Hz. Between 315 Hz–1250 Hz, the insertion loss of each hood was negative, displaying a broad resonance with a gain of 6–8 dB. In this frequency range the hood acts as a mass-spring system, resonating like a drum skin when stretched over the ears. Above 1000 Hz, the insertion loss increased with frequency (10 dB per octave), reaching a maximum of 5000 Hz–6000 Hz. Wetting each hood did not significantly affect the insertion loss; the 'drum-skin' resonance frequency was marginally lower with a wet hood, and insertion losses may be marginally greater between 1000 Hz–10 000 Hz. The resonance frequency decreased with increasing thicknesses of hood, and the insertion loss at frequencies above the resonance increased with hood thickness.

Keywords: noise, neoprene diving hood, thickness, noise attenuation, insertion loss

1. Introduction

When undertaking activities in or under open water, individuals often wear some form of body covering to keep them warm, such as a drysuit or wetsuit. These activities may be work related (for example, repair and maintenance, sea rescue), or for recreation or sport, such as surfing, swimming and diving. The drysuit or wetsuit usually covers the whole body with openings for feet, hands and head; separate items (gloves and boots) might be worn on the hands and feet. To keep feet warm, socks may also be worn with the boots. A head covering in the form of a hood may be used to keep the head warm. All these items are usually made from neoprene, a stretchy synthetic material composed of closed-cell foam set between layers of either nylon or Lycra®. Wetsuits and supplementary gear are available in varying thicknesses depending on the type of activity and environment in which the activity is intended.

Different types of headgear can be used by divers, ranging from complete full-face helmets with self-contained underwater breathing apparatus (SCUBA) to neoprene hoods. The type of headgear used depends on the activity being carried out. Although the primary purpose of a hood is to provide thermal protection, it is thought by some divers who operate noisy machinery under water that hoods provide some protection from noise while under water, and may also provide some reduction of the noise under dry conditions when their heads are out of the water. However, diving hoods are not designed, and should not be relied upon, to provide hearing protection against noise in air, although they can provide protection against noise when under water. The use of a neoprene hood as hearing protection arose as some wearers were increasing 'protection' around the ears of the hoods by 'doubling' the material thickness of the hood. The exposure of divers to high levels of noise is a recognised risk included in the Health and Safety Executive (HSE) Approved Code of Practice and Guidance, *Commercial diving projects offshore: Diving at work regulations 1997* (Health and Safety Executive, 2014).

The effect of diving hoods on hearing thresholds under water has been reported elsewhere, mostly based on experiments with one thickness of hood. A diving hood of 5 mm thickness was used in experiments conducted by Montague and Strickland (1961), and by Hollien and Feinstein (1975). Smith (1969) conducted a series of experiments on hearing thresholds using a neoprene hood of 10 mm

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thickness. However, these experiments were not designed to determine the effect of diving hood thickness on sound attenuation when used under water, since only one thickness of diving hood was used in each of these studies.

A particular problem of noise exposure was observed within the military sector. Divers wearing neoprene hoods were sometimes required to be under water for short periods before surfacing to operate noisy tools or equipment. In other cases, divers would wade or swim through water without immersing their heads before operating these tools. Thus, depending on the circumstances, divers operated the tools while wearing either 'wet' or 'dry' neoprene hoods. However, wearing hearing protection such as earplugs is not practical within this military environment. Some divers 'double-up' the thickness of the hood at the area near the ears with the aim that this would increase their protection from exposure to noise. Therefore, a study was undertaken to investigate the reduction of airborne noise provided by wet or dry neoprene diving hoods when worn out of water.

The aims of the present study were: (i) to determine the reduction in airborne noise (i.e. the insertion loss) provided by neoprene diving hoods of varying thickness; and (ii) to determine the difference in the insertion loss between dry and wet diving hoods. The insertion loss of a hood is the noise reduction of the hood, i.e. the sound level measured at the ear (in decibels) without the hood, minus the sound level (in decibels) at the ear with the hood. The related term 'sound attenuation' is usually reserved for the noise reduction measured on a panel of human listeners using the 'real-ear at threshold' method. For the purposes of the present study, the wet diving hood condition is taken as a wet hood out of water and without water in the external ear canal to reflect what happens in practice.

The insertion loss can be measured in each one-third octave band separately. These one-third octave band insertion losses can be used to calculate a noise spectrum and level at the ear by subtracting the insertion loss in each one-third octave band from the ambient external noise in that band. The effective overall A-weighted noise level at the ear can then be calculated by A-weighting the levels in each band and summing the values.

2. Equipment and procedure

2.1. The neoprene hoods tested

Five commercial neoprene diving hoods of varying thicknesses were used in the present study. These were as follows:

- 2 mm thickness (Sport Series Model H30 by Waterproof)
- 3 mm thickness (Typhoon Raptor)
- 5 mm thickness (Typhoon Raptor)
- 7 mm thickness (Typhoon Raptor)
- 9 mm thickness (Santi basic diving hood), with 7 mm thickness in face area

All hoods were size 'L', or 'Large', which was selected as a good fit for the Kemar manikin used in the present study. These hoods are shown in Fig 1.

2.2. Noise source and measurement

The tests were carried out in the small reverberation chamber of the Institute of Sound and Vibration Research at the University of Southampton.

Fig 2 is a schematic diagram of the equipment used in the present study. A ten-second long sound file with two non-coherent channels of white noise was generated on a laptop computer. The sound file was replayed on a continuous 'loop' from the computer to two Yamaha TX4n two-channel power amplifiers. One of the amplifiers was used to drive two Community R2-52Z full range loudspeakers, while the other was used to drive two Turbosound B18 sub-woofers. The full-range loudspeakers were placed on top of the sub-woofers and directed into two corners of the reverberant chamber to optimise the diffuse field in the room.

Previous tests in this room with the same amplifier and loudspeaker set-up have shown that the sound field meets the requirements of ANSI/ASA S12.42-2010 clause 8.2.1 for uniformity in all

Fig 1: Diving hoods of different thickness used in the present study. From left to right: 2 mm, 3 mm, 5 mm, 7 mm, 9 mm thickness

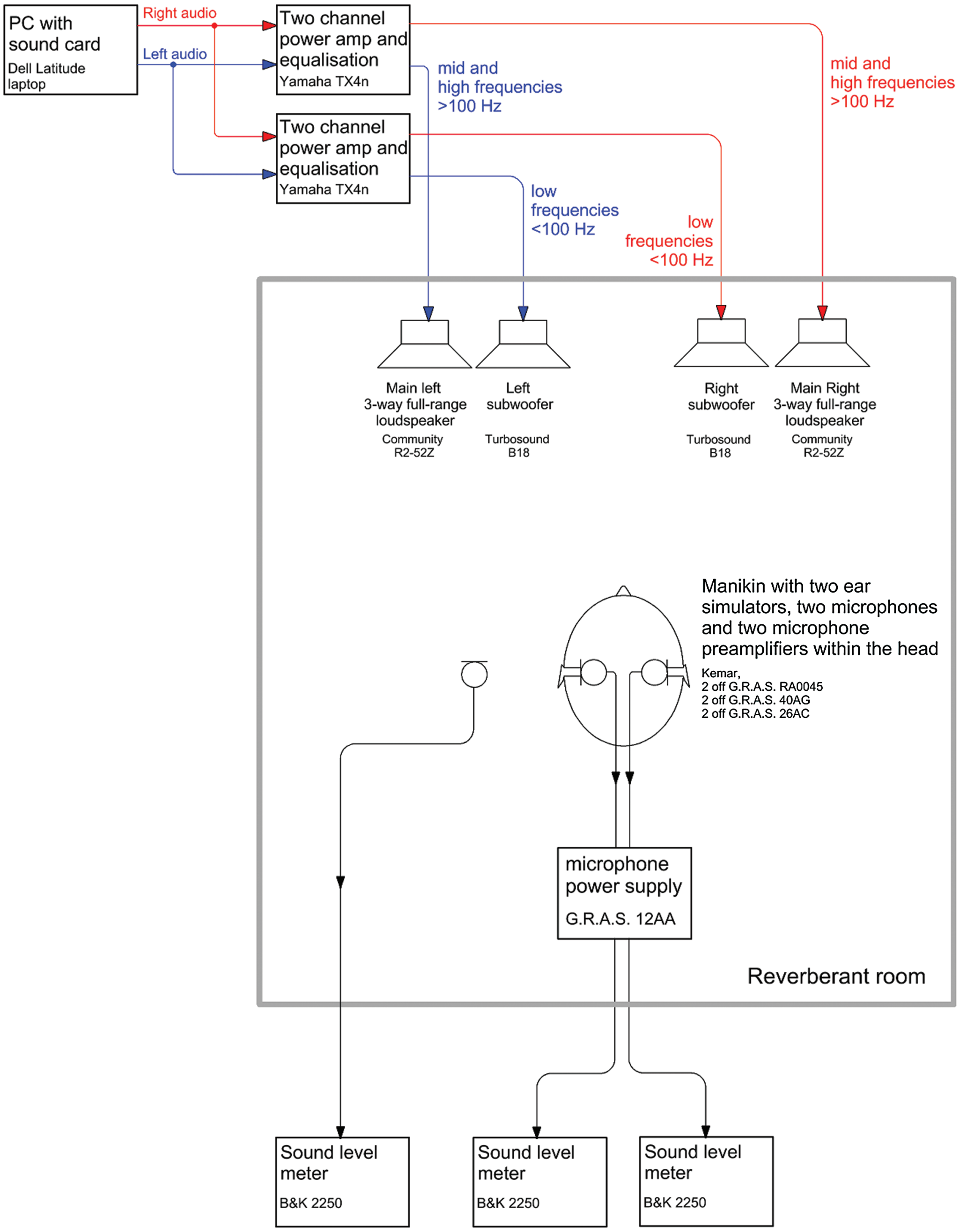

Fig 2: Block diagram of the equipment used

frequency bands up to 10 kHz, and clause 8.2.2 for directionality in frequency bands up to and including 8 kHz (ANSI/ASA, 2010).

Fig 3 shows the sound field in the room. The spectra were measured during the tests using a Brüel & Kjær (B&K) type 2250 sound level meter. The sound level meter microphone and preamplifier were positioned 30 cm from the side of the manikin's head. Each spectrum was averaged over a period of 30 seconds. Fig 3 shows the mean band levels and the mean ± one standard deviation of the 100 spectra. Fig 3 also shows the A- and C-weighted levels averaged over the 30 second periods; these are L_{Aeq} and L_{Ceq}, respectively. The overall level, L_{Aeq}, selected for the tests was nominally 75 dB(A).

Fig 3: One-third octave band spectra measured in the room averaged for one hundred individual measurements. Mean band levels ± one standard deviation

The spectrum in the room was stable and repeatable in the 50 Hz band and above. The band level at 20 000 Hz, though stable, was relatively low, as the outputs from the full-range loudspeakers rolled off above 16 000 Hz. Below 50 Hz the test spectrum was less repeatable, and was influenced by the room dimensions, averaging time, background noise from outside, and reduced output of the sub-woofers below 50 Hz. The optimal range for measuring the insertion loss for the neoprene hoods was therefore 50 Hz–16 000 Hz.

A Kemar manikin was used to measure the insertion losses of the neoprene hoods. The manikin is a head and torso simulator incorporating two G.R.A.S. type RA0045 ear simulators, with one in each ear. Each ear simulator contains a G.R.A.S. type 40AG 'half-inch' pressure microphone at the eardrum position. The 'eardrum' microphones were each connected to a sound level meter (Brüel & Kjær type 2250) via a microphone preamplifier (G.R.A.S. type 26AC) and a microphone power module (G.R.A.S. type 12AA). Therefore, three sound level meters were used during the tests: one to measure the noise field in the room with a microphone at 30 cm from the manikin's head, and one each to measure the sound levels at the manikin's left and right eardrum microphones.

Each of the sound level meters was programmed to measure the one-third octave band spectrum, and the overall average A- and C-weighted level (the L_{Aeq} and L_{Ceq}) over the 30 second duration of each test. The human ear does not respond equally at all frequencies; therefore, the A-weighting is applied to the audible frequency range to represent the reduction in sensitivity to the low frequencies. Long-term damage to hearing from moderate to loud noise is well correlated to noise exposure in dB(A); consequently, damage risk criteria for long-term hearing damage are usually expressed in dB(A). The difference between the L_{Aeq} and L_{Ceq} values provides an indication of the effect of the two frequency weightings and the frequency content of the noise. The mechanism of instant damage to the ear for extremely loud noise is different, and is related to peak C-weighted levels (Health and Safety Executive, 2005).

The calibration of each 'eardrum' microphone, ear simulator and the associated sound level meter was checked using a B&K type 4220 pistonphone. The calibration of the external microphone, positioned 30 cm from the head, and its associated sound level meter was checked using a B&K type 4231 sound level calibrator. All calibrations were stable and checked before and after the tests.

2.3. Procedure

The equipment used in the present study is appropriate for measurements with 'dry ears', but is not designed for measurements with water in the ear canal, as this would destroy the microphones used. All measurements in the present study with wet or dry hoods can be classified as 'dry ear'. The insertion loss of each neoprene hood was measured first with the hood dry, then with the hood wet. The noise field was switched on approximately 30 seconds before the first test to allow the loudspeakers to stabilise. The procedure was then as follows:

2.3.1. Tests with dry hoods

With the manikin bare-headed, the spectrum and overall levels at the manikin's two eardrum microphones were averaged over a 30 second period. The spectrum and level at the external microphone were averaged simultaneously. A dry diving hood was then fitted on the manikin and the measurements repeated. This procedure was repeated, alternating the measurements with and without the diving hood, until five tests with and five tests without the hood had been completed. Once all the measurements were completed for one hood, each of the other hoods was tested in turn.

The 2 mm thick hood was tested first, then the 3 mm, 5 mm, 7 mm and 9 mm thick hoods, in that order. When fitting the hoods on the manikin, care was taken to ensure that the flexible ears were not folded over during the sound measurements.

2.3.2. Tests with wet hoods

The tests with the wet hoods followed the same procedure and were in the same order as the tests with the dry hoods, starting with the 2 mm thick hood and ending with the 9 mm thick hood. Immediately before the first 'wet' test of each hood, the hood was immersed in a bowl of water at approximately room temperature (17 °C), and shaken and agitated for approximately 30 seconds to absorb water. The hood was then lifted from the water, and surface water was allowed to run off into the bowl. Then the hood was placed on the manikin as before. The hood was only immersed before the first 'wet' test, and not re-immersed before the second, third, fourth and fifth tests; each hood was therefore at its wettest during the first test and slightly drier during subsequent tests. The Kemar manikin's head and pinnae became slightly damp during the tests, though no water entered the ear canals.

2.4. Analysis of recordings

During the tests, the sound levels and spectra at the manikin's 'eardrum' microphones, and the sound levels and spectra in the test chamber, were stored in the sound level meters. After the tests, the data were downloaded to a computer using B&K utility software (part number BZ-5503). The means and

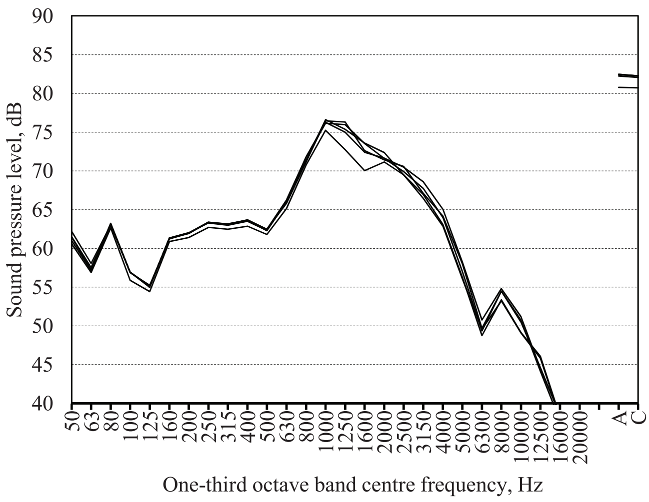

Fig 4: One-third octave band spectra measured at the left ear for each of the five measurements with the 2 mm wet hood

95 % confidence intervals were calculated for the insertion losses of each hood in each frequency band, as described in Section 3.2.

3. Results

3.1. Variation in repeat measures

Fig 4 shows the sound pressure levels averaged over each of the five repeat runs at the left ear of the Kemar manikin with a wet neoprene hood of 2 mm thickness. This shows that the variation between the repeat measures was low, indicating high confidence in the measured data. The hood was wetted prior to the first run; the hood would have slightly dried with successive runs. There is no consistent trend in the sound pressure levels between the five runs, indicating that the slight drying effect over the 20–25 minute duration of the tests had no measurable effect on the sound pressure levels. Because the measurements with the hood were alternated with the measurements without the hood, the hood was put on the manikin anew before each measurement. Fig 4 shows the 'fit-refit' variation.

3.2. Individual insertion losses

The insertion loss of a hood is the sound level at the ear in decibels without the hood, minus the sound level in decibels at the ear with the hood. The insertion loss of each hood was calculated in one-third octave bands. The insertion losses of a hood depend on whether it is wet or dry, and therefore separate calculations were carried out for the hoods when wet and when dry.

Insertion losses were also calculated for the A- and C-weighted levels, but these only apply for the broadband noise spectrum used in these tests. For other ambient noise spectra, the effective overall A- and C-weighted levels at the ear will need to be calculated from the one-third octave band levels of the ambient noise spectrum outside the hood and the one-third octave band insertion losses, as described previously.

The insertion losses for each dry and wet hood were calculated as follows. The mean value and standard deviation in each one-third octave band were calculated from the five measurements of the sound levels at the left eardrum microphone of the manikin *without* a hood, and the mean value and standard deviation were similarly calculated from the five measurements of the sound levels at the left eardrum of the manikin *with* a hood. The insertion loss in each band was then obtained by subtracting the mean band level with the hood from the mean band level without the hood. This procedure was then repeated using the measured levels at the manikin's right eardrum.

To estimate the variability of the insertion losses in each band in each ear, the 95 % confidence intervals of the band insertion losses were calculated. The variance in the insertion loss in each frequency band was the pooled variance of the five measurements without hoods and the five measurements with hoods. As the same number of measurements were made with and without hoods, the pooled variance was the average of the variance with and without the hood. The 95 % confidence limit was then the square root of the pooled variance (the standard error of the difference) multiplied by the value of Student's t, where $t = 2.306$ ($\alpha = 0.05$, two-tailed distribution, 8 degrees of freedom). The 95 % confidence intervals are shown in Fig 5.

3.3. Insertion losses for 2 mm neoprene hood

Before presenting the results for all the wet and dry hoods, it is useful to review the results for one of the hoods in detail, as the same or similar features can be seen for all the hoods.

The mean insertion loss values for the 2 mm thick hood are shown in Fig 5 for the four possible combinations of left and right ears with wet and dry conditions. The mean values are based on the five repeat measurements. Also illustrated in Fig 5 are the mean ± 95 % confidence limits for each one-third octave frequency band. Fig 5 shows that the hood had little if any effect on noise levels at frequencies below around 250 Hz, but amplified the noise (giving a negative insertion loss) at and around 1000 Hz, at approximately 600 Hz–1800 Hz. There was an increase in insertion loss from around 1000 Hz–6300 Hz at a rate of approximately 10 dB–13 dB/octave. Furthermore, there was a slight reduction in insertion loss at around 10 000 Hz compared to the higher and lower bands. Superimposed on this

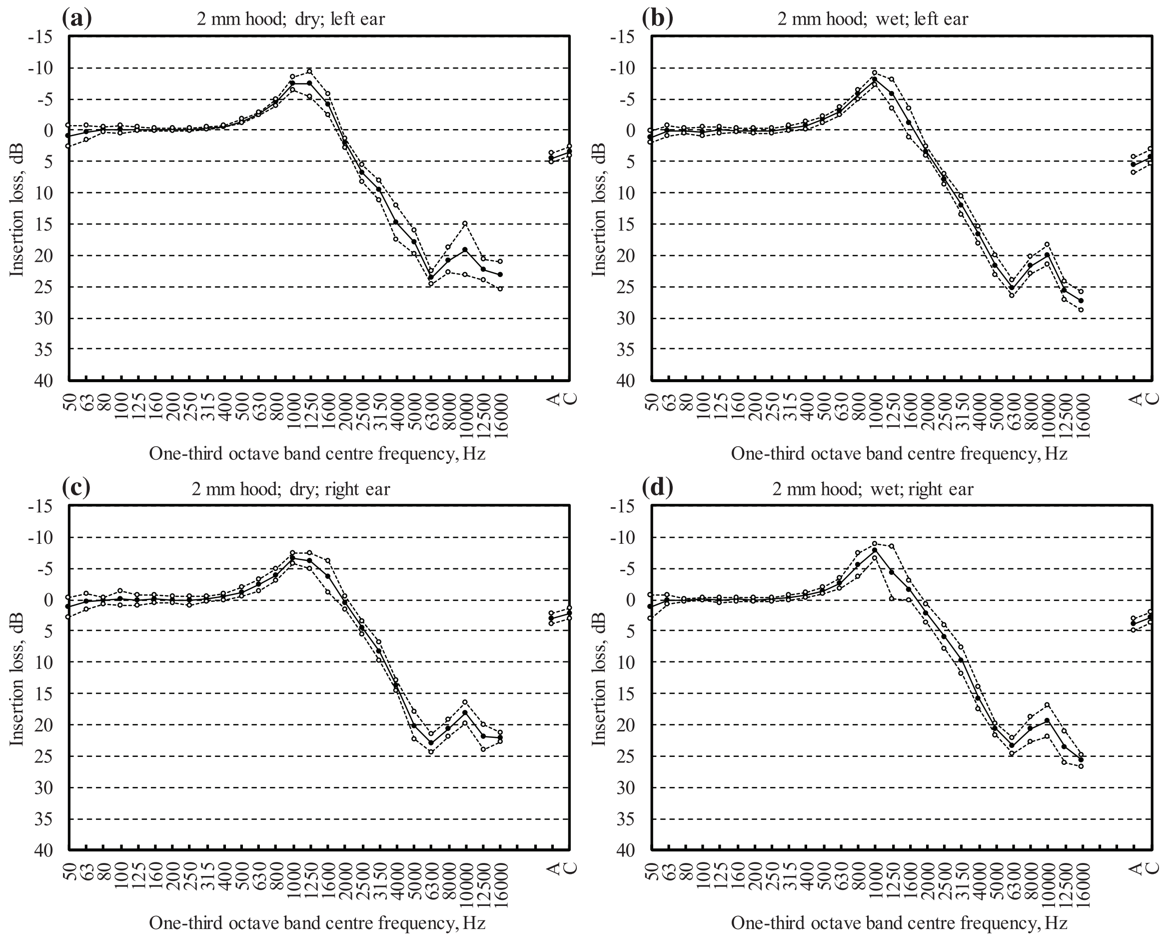

Fig 5: Insertion losses for the 2 mm thickness neoprene hood with left and right ears and with wet and dry conditions (mean ± 95 % confidence limits). (Note that the insertion losses are plotted with values increasing down the graphs)

general trend of insertion losses at different frequencies, there were small differences between left and right ears and between dry and wet conditions. Measurements at the right ear show a slight reduction in insertion loss at around 1000 Hz compared with the left ear. The main difference between wet (Figs 5b and 5d) and dry (Figs 5a and 5c) conditions of the hood is a slight decrease in the frequency at which the minimum insertion loss occurred from 1250 Hz–1000 Hz for the wet hood compared with the dry hood, possibly related to an increase in the mass of the hood when wet.

3.4. Comparison of measurements on the left and right ears

Fig 6 shows the mean difference in insertion loss between left and right ears as measured on the manikin for each dry and wet hood separately. Fig 6 also shows that the values of difference in insertion loss measured on the left and right ears of the manikin were similar, and almost identical at most frequencies (from approximately 63 Hz–1600 Hz). There was a tendency, however, for the insertion loss at the right ear to be marginally less than the insertion loss at the left ear in the frequency range from approximately 2000 Hz–4000 Hz ($p < 0.05$, Student's *t* test). Although statistically significant at the 5 % level, this difference is small and not noticeable in practice. The reason for the difference was not explored but may be related to the Kemar manikin being not perfectly symmetrical. Differences in insertion loss were similar for both dry (Fig 6a) and wet (Fig 6b) conditions.

Since the differences in insertion losses between the left and the right ears were minimal, the insertion losses were averaged over the two ears.

3.5. Comparison of insertion losses of the hoods when wet and dry

Fig 7 shows the insertion losses of each hood when dry, compared to the insertion losses of the same hood when wet. Also shown in Fig 7 are the 95 % confidence intervals for the insertion losses. Wetting the hood had little effect on the measured insertion loss. The resonance frequency (at around 1000 Hz) may be marginally lower when the hood is wet, and the insertion losses may be marginally greater between 1000 Hz–10 000 Hz. Although the effects are visually apparent in Figs 7 and 8, these are not particularly noticeable in practice. A reduction

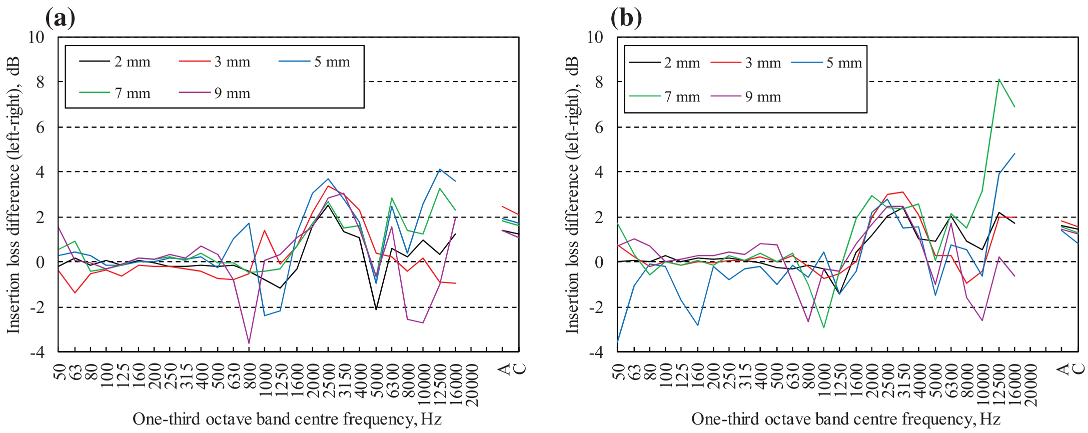

Fig 6: Difference in insertion loss between left and right ears with a) dry conditions, and b) wet conditions of the different thickness of neoprene hoods

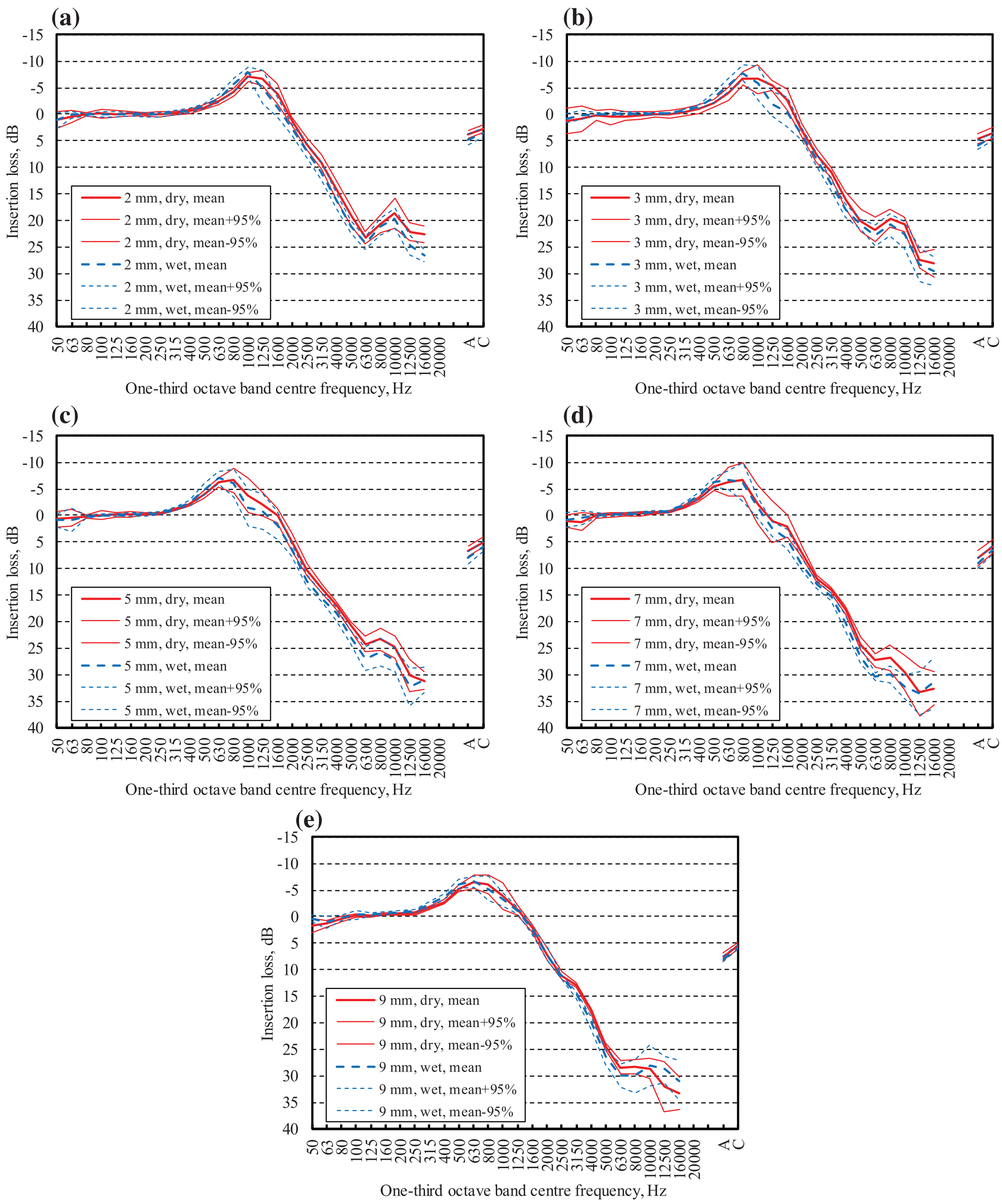

Fig 7: Insertion losses for dry and wet conditions for different thickness of neoprene hoods (mean and 95 % confidence intervals)

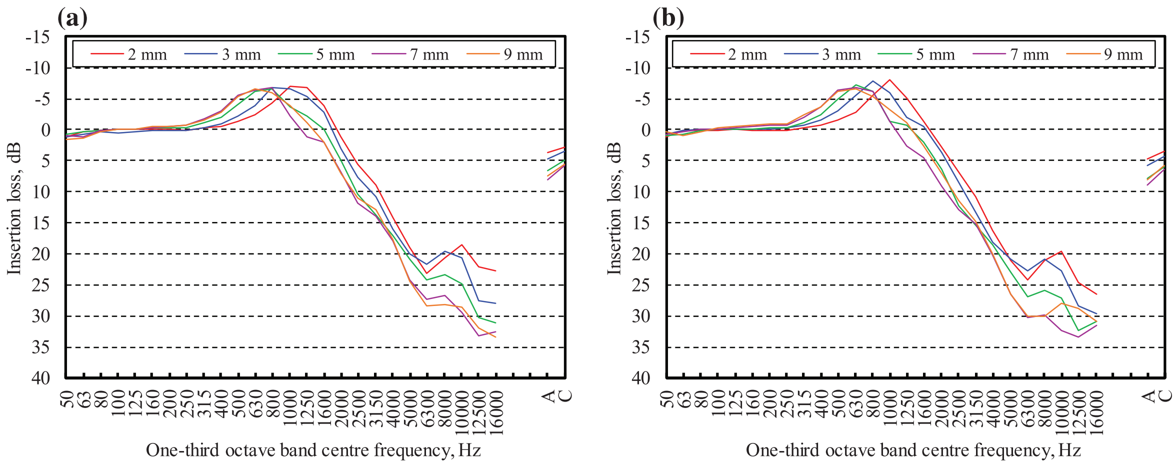

Fig 8: Effect of thickness of neoprene hood on the insertion losses under a) dry conditions, and b) wet conditions

in resonance frequency and an increase in insertion loss would, however, be consistent with the mass of the hood being slightly greater when wet than when dry. It is noted that the increase in mass would have been minimal since the neoprene hoods were composed of closed-cell foam. The data in Fig 7 show that the differences in insertion loss between wet and dry hoods were slightly greater than the differences in insertion loss between left and right ears (see Fig 5).

3.6. Effect of the thickness of a hood

Fig 8 shows the mean insertion loss of each hood when dry and wet. The trend is for the peak frequency (resonance) at around 1000 Hz to decrease with increasing thickness of hood. Furthermore, the insertion loss at frequencies above the resonance appears to increase with hood thickness. The effect is more noticeable with thinner hoods of 2 mm–7 mm in thickness, compared with that between hoods of 7 mm–9 mm thickness.

4. Discussion

The noise reduction can be measured using a Real Ear at Threshold (REAT) method (International Organization for Standardization, 2018) in which the hearing thresholds of several human listeners are measured with and without a hood, and the noise reduction is known as the ‘sound attenuation’. Alternatively, the noise reduction can be determined from objective measurements of sound levels with and without a hood as the ‘insertion loss’.

The insertion loss of a diving hood can be measured in different ways: (i) on several real (human) heads using miniature microphones placed at the ear, or (ii) on a manikin (a head and torso simulator). Measurements on manikins make no allowance for different fits on real heads, so they are likely to produce lower variation than measurements on groups of real people. The Kemar manikin used for these measurements has the dimensions and acoustic properties of a median human adult, so the measured insertion losses should be representative of a median adult (see e.g., Berger, 1992).

Figs 5 to 8 show that the neoprene hoods all have similar effects on the insertion loss. Below approximately 250 Hz they neither reduce nor amplify sound. Between 315 Hz–1600 Hz, the insertion loss is negative, showing a maximum amplification of around 6 dB–8 dB. In this frequency range, the hood acts as a mass-spring system, with the neoprene providing the mass and the spring effect from the tension in the stretched hood. In effect, a hood stretched over the ears acts like a drum skin resonating in this frequency band. Above 1000 Hz, the insertion loss of each hood increases with frequency at around 12 dB per octave, reaching a maximum at around 5000 Hz–6000 Hz. When assessing the effect of thickness of hood on the insertion loss, the trend is for the ‘drum-skin’ resonance to decrease in frequency with increasing thickness of hood, and for the insertion loss at frequencies above the resonance to increase with the hood thickness. Both effects would have been expected, as the thicker hoods will have greater mass, thus resulting in a decrease in resonance frequency.

Some tasks require an operator to wear a neoprene diving hood while under water and then, with their head out of the water, to operate tools that would expose them to noise. These operators would be wearing a wet hood and would be expected to have a ‘wet’ ear, that is, there would be ‘water in the auditory canal and in contact with the tympanic membrane’ (Anthony et al., 2010). In contrast, a ‘dry’ ear would have air or another gas, but not water, within the ear canal. Anthony et al. (2010) report that ‘as hearing is more sensitive in air than in water …, it is assumed that a given noise level is more damaging to the “dry” ear than the “wet” ear’.

The present study arose from tasks carried out by military divers. In some cases the divers would be under water for a brief period before leaving the water to operate noise-producing tools. These divers would not be under water for long enough to get a 'wet' ear. In other cases, they would wade through water before operating the tools, and their heads would not be immersed in water at all. Therefore, the divers would be operating their tools with a 'dry' ear while wearing a neoprene hood. The study reported in the present investigation would be categorised as a 'dry ear' study, and a Kemar manikin is therefore ideal as the ears are not immersed in water.

A comprehensive review on the human effects of noise under water, covering research up to 1989, was presented by Kirkland et al. (1989). The review, comprising three studies, indicated that thicker flexible hoods might provide greater sound reduction under water than thinner hoods, although the data were inconclusive. Another literature review, by Cudahy and Parvin (2001), reported that the thickness of a flexible diving hood only had a small effect on the reduction of noise. The sound attenuation properties of a 3 mm neoprene wetsuit hood when worn under water have been reported elsewhere (Fothergill et al., 2004): the reduction offered by the neoprene hood depends on the frequencies present in the noise. Anthony et al. (2010) state that a foam neoprene hood is likely to offer a reduction of 5 dB–15 dB, depending on the thickness of the neoprene and the frequency of the noise when assessed under water. Anthony et al. (2010) reported that the sound attenuation provided by the hood decreases as the thickness of the hood decreases with depth of the dive, caused by the compressible nature of the hood. They showed that the diving hoods reduced noise by 5 dB–15 dB, depending on the thickness of the diving hood.

These previous studies were conducted under water, whereas the present study was conducted out of water. Although a direct comparison between the previous data and the present study cannot be presented because of experimental differences, a broadly similar reduction in noise is noted. The reduction offered by a diving hood when assessed under water would depend on many factors, including depth of water and whether the auditory canal was 'dry' or 'wet'. Depth of water would have an effect since the mechanical impedance on either side of the diving hood would be different, depending on whether there was gas or water in the auditory canal.

The measurements of the insertion loss described in the present study can be used to calculate noise levels at the ears of personnel wearing these hoods in air, but not under water, provided the spectrum and level of the ambient noise is known or can be estimated. In the pink noise field (equal energy in all octaves of frequency) used in these tests, the reduction in the A-weighted sound levels by the hoods was between 4 dB–9 dB. In most cases, a neoprene hood will provide little reduction in airborne noise and should not be relied upon to protect hearing. The data presented in the present study are consistent with the finding that noise insertion losses increase as the thickness of neoprene increases. Although the hood will be compressed more at depth (resulting in a smaller hood thickness), the principle remains.

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