AN APPROACH TO ESTIMATION OF UNDERWATER HEARING THRESHOLDS AND NOISE EXPOSURE LIMITS

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ABSTRACT: There are many difficulties to carry out hearing tests in water, for example, the necessity of preparing audiometric equipment for underwater measurement and diving equipment (SCUBA) for breathing of subjects, unavoidable background noise from surrounding and so on. As a result, there are very few studies on establishing the hearing thresholds and noise exposure limits in water even though they are fundamental and important characteristics of underwater hearing in man. One of the most efficient approaches to acquire these standard values is through transposition from air to water. We attempted to establish the relationship between the perceived loudness in water and in air by conducting hearing tests in a water tank. By applying this relationship to available data on hearing threshold and noise exposure limit in air, we have estimated the equivalent thresholds and exposure limits in water.

1. INTRODUCTION

Although both hearing thresholds and noise exposure limits in water are fundamental and important characteristics of hearing in man similar to the case in air, it seems that there is limited work done on acquiring these standard values. This is because of the difficulties to carry out hearing tests in water, for example, the necessity of preparing audiometric equipment for underwater measurement, diving equipment (SCUBA) for breathing of subjects and so on. Some investigators have examined the hearing thresholds in water [1-5] but there is a lot of scatter in their results. The main reason for the large scatter of existing experimental data may be attributed to the lack of appreciation of the significance of background noise and its masking effect on the threshold of hearing. Further, the influences of various factors have not been fully investigated, for example, differences in subjects, differences in experimental procedures, effects of water depth, influences of air trapped in the ear canal, effects of bubbles by breathing of divers and so on. So, the determination of underwater hearing thresholds need to be improved.

From the viewpoint of hearing protection for divers, it is necessary to determine the maximum sound pressure level that the divers can endure against noise exposure in water, that is, a damage-risk criterion for underwater noise exposure is required. Widely accepted damage-risk criterion for noise exposure in air already exists [6] but has not been found in water except for the recent work of Al-Masri et al [7,8]. In order to establish the criteria for noise exposure, it is necessary to carry out hearing tests of temporary threshold shift (TTS) [9-11]. In practice, however, many difficulties would be encountered in trying to realize the TTS measurements in water as mentioned above. One of the most efficient approaches to acquire these standard values is through transposition from air to water. Al-Masri and Martin estimated the value of underwater noise exposure limit from the value of hearing threshold in water by considering the "W-weighting scale" [7,8]. They assumed that the relationship between the 40-phon curve and the threshold curve is constant at each frequency both in air and in water. It is already mentioned that the threshold in water may be greatly influenced by the background noises or the experimental conditions. So, it is quite possible that underwater exposure limit will not be estimated accurately, if the exposure limit is derived from the hearing threshold as Al-Masri and Martin have done. Therefore, another approach for estimating the exposure limit in water becomes necessary.

The purpose of this study is to estimate the hearing thresholds and the noise exposure limits in water from the existing values in air using a different procedure from that of Al-Masri and Martin. We attempted to acquire the relationship between the perceived loudness in water and in air by conducting hearing tests in a water tank. Then, the hearing thresholds and the noise exposure limits in water are estimated respectively from the values in air by using this relationship.

2. HEARING TEST

In order to examine the relationship between the loudness in water and in air, two kinds of measurements for loudness levels were carried out by means of hearing tests in a water tank. One was to obtain, for a pure tone (175Hz, 1kHz, 5kHz), the sound pressure level in air that is perceived to be equal in loudness to a given sound pressure level in water. The other was to obtain the sound pressure level in air that is perceived to be equal in loudness as a constant sound pressure level of 142 dB (re 1μPa) in water for a range of frequencies. The water tank with dimensions 1m x 1m x 2m is shown in Figure 1. The spectrum level of the background noise in the water tank, determined by an FFT analyzer, is almost constant at 52 dB (re 1 $\mu Pa^2/Hz$) in the frequency range from 1 kHz to 5 kHz (Figure 5). We employed two male subjects with normal

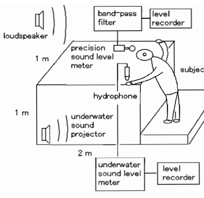

Figure 1 Experimental configuration of the water tank.

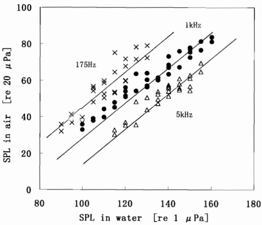

Figure 2 Equal-loudness relationship between SPL_A [dB re 20μPa] and SPL_W [dB re 1μPa] for a pure tone (X: 175Hz, ●: 1kHz △: 5kHz); Solid lines: equation(1).

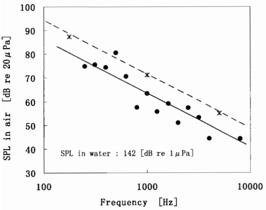

Figure 3 Equal-loudness relationship between SPL_A [dB re 20μPa] and a constant SPL_W of 142 [dB re 1μPa] for various frequencies *f*. Solid line: equation (2); * data from Figure 2.

hearing in air. The experimental procedure is as follows. Firstly, the subject submerged his head into water, making sure to remove air bubbles from the ear canals, and was exposed to a pure tone radiating from an underwater sound source in the water tank. Secondly, he raised his head above the water, clearing the air passage in the ear canals, and was exposed to the sound in air radiating from a loudspeaker. The sound pressure level in air was adjusted by the subject until the loudness in air was perceived to be equal to that heard in water. The above measurement was repeated five times per sound pressure level for various frequencies and the average value was used. All measurements were made for a pure tone and the sound pressure level and noise level were measured without using weighting filters. As the overall background noise in air around the water tank was about 50 dB (re 20μPa), we used a band-pass filter (RION SA-34) for measurements in air below 50 dB (re 20μPa). The sound pressure levels were obtained by reading the data sheet on level recorders (RION LR-4) calibrated, respectively, by an underwater sound level meter (OKI SW1020) for underwater and by a precision sound level meter (RION NA-20 at F-weighted characteristic) for air. The subject's head was suitably positioned in the water tank to minimise the influence of standing waves. Both the hydrophone in the water tank and the microphone in air were set up as close to the subject's ear as possible.

3. EXPERIMENTAL RESULTS

Results of the two kinds of measurements are indicated in Figures 2 and 3, respectively. From Figure 2, we can find a linear relationship between SPLA dB (re 20μPa) and SPLW dB (re 1μPa) as,

$$SPL_A = a\, SPL_W - C_1(f) \quad (1)$$

where a is the slope and $C_1(f)$ is a value depending on the frequency. Here, for convenience, we use a=1 for all three frequencies (175Hz, 1kHz, 5kHz), and by fitting the data points with lines of best fit, C_1 has been determined to be 53.0 dB at 175 Hz, 70.8 dB at 1kHz and 85.9 dB at 5kHz.

From Figure 3, we can also find a linear relationship between SPL_A [dB re 20μPa] and the logarithm of frequency *f* under a constant SPL_W of 142 dB re 1 μPa as,

$$SPL_A = -24.6 \log(f/1000) + C_2 \quad (2)$$

where C_2 is a value unrelated to the frequency but often varies with experimental conditions or subjects and has been determined to be 63.0 dB.

According to equations (1) and (2), a sound level of 142 dB re 1 μPa at 1 kHz in water corresponds to a sound level of 63-71 dB re 20 μPa in air. However, a sound level of 142 dB re 1 μPa in water has the same intensity as a sound level of 80 dB re 20 μPa in air. Therefore, it appears that a transmission loss of 9-17 dB has arisen from the internal ear and the exterior, probably because the coupling of the sound to the subject's head in air is different from that in water, resulting in different propagation paths through the head.

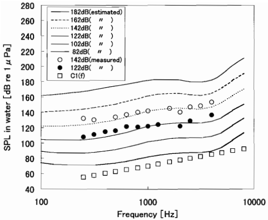

Figure 4 Comparisons of equal-loudness contours in water between experimental values [12,13] (○: 142dB and ●:122dB) and the estimations (six lines); □ : values $C_1(f)$ for each 1/3-octave centre frequency.

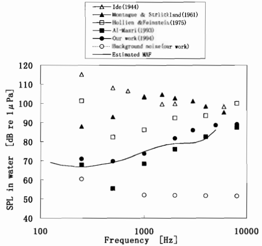

Figure 5 Comparison between underwater hearing thresholds measured in previous studies and estimations (solid line).

4. DISCUSSION

Practical expression between the loudness in water and in air

In order to estimate hearing thresholds and noise exposure limits in water from the values in air, we must derive a practical expression describing the relationship between the loudness in water and that in air. The expression can be derived from equations (1) and (2) as follows. Firstly, the sound pressure levels in air at three frequencies (175Hz, 1kHz, 5kHz) corresponding to the sound pressure level of 142 dB in water are obtained by means of equation (1). When these values (denoted by *) are plotted in Figure 3, we can fit a straight line to these data using equation (2). Thus, we can obtain the sound pressure level in air corresponding to the sound pressure level of 142 dB re 1 μPa in water for any frequency by using this line of best fit. By substituting these values for SPL_A in equation (1), where SPL_W is 142 dB re 1 μPa, we can determine each value of $C_1(f)$ in equation (1) for any frequency. The values of $C_1(f)$ obtained for each 1/3 octave band frequency are shown in Figure 4.

To verify the validity of this expression, we try to obtain the equal loudness contours in water from the values in air and compare them with the experimental results previously obtained in our study. The SPL_W is readily obtained from the practical expression by substituting the values of ISO R226-1961 [12] for SPL_A in $SPL_A = SPL_W - C_1(f)$. The contours thus obtained are described by six lines in Figure 4 together with our experimental values obtained by hearing tests in the pool [13,14]. The estimated results are in good agreement with the experimental values.

Estimate of underwater hearing thresholds

As mentioned before, the underwater hearing threshold has not been obtained accurately. Figure 5 shows the results of underwater hearing thresholds reported in the literature [1-8] and our previous work in the water tank [13,14]. It is found that there is a large scatter for the underwater hearing threshold value. In order to obtain the hearing threshold accurately, it is very important to consider the effect of background noise carefully. Our threshold values are more than 10 dB above the background noise. So, it is considered that our results could not have been affected by noise and are more reliable. It is advisable that tests of hearing threshold should be done in an anechoic chamber, which is difficult to realize in water. One alternative method is to estimate underwater hearing thresholds from values in air by using the practical expression obtained above. This method is simply based on the relationship between the perceived loudness in water and in air determined experimentally. By substituting the value of normal threshold of hearing in air [12] for SPL_A in $SPL_A = SPL_W - C_1(f)$, using the value of $C_1(f)$ at each frequency in Figure 4, the hearing thresholds in water can be readily obtained. The estimated threshold is described by the solid line in Figure 5. It is found that the estimated hearing thresholds in water show reasonable agreement with the ones obtained experimentally by us.

Estimate of noise exposure limits in water

Divers are sometimes directly exposed to vibrations and noises radiating from working equipment in water, e.g., water jet tools, rock drills, stud guns and so on. From the viewpoint of hearing protection for divers, it is necessary to determine the noise exposure limits in water. In air, damage-risk criteria for noise exposure has been recommended by the permission concentration committee of the Japanese Industry Sanitation Society in 1969 [6] and is widely adopted in our country for the purpose of hearing protection. On the other hand, a criterion for underwater noise exposure is difficult to find. Recently, Al-Masri and Martin estimated the value of underwater noise exposure limit from the value of hearing threshold in water by considering the "W-weighting scale"

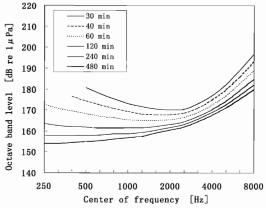

Figure 6 Estimated exposure limits for underwater noise.

[7,8]. But the value of hearing threshold is greatly influenced by the background noise or the experimental conditions. So, it is quite possible that the underwater exposure limit will not be estimated accurately. Therefore, the exposure limit in water must be verified from another viewpoint. In this study, we obtain the underwater noise exposure limits by transposition from air to water. By using the practical expression, $SPL_A = SPL_W - C_l(f)$ with the value of $C_l(f)$ in Figure 4, the noise exposure limit in water can be readily obtained from the values of exposure limit in air [6]. Figure 6 shows the estimated exposure limits for underwater noise. For example, the recommended maximum permissible noise exposure limit for an 8-hour day is 90 dB re 20μPa in air, whereas a maximum permissible octave band level for underwater noise exposure around 1 kHz for an 8-hour day is about 157 dB re 1μPa.

5. CONCLUSION

We examined carefully the relationship between loudness in water and in air by conducting hearing tests in a water tank and obtaining a practical expression describing the relationship of loudness between the two media. Then, the hearing thresholds and the noise exposure limits in water were estimated from the values in air by using this expression. It is very important to carry out the hearing tests in an anechoic chamber for thresholds and the measurement of temporary threshold shift (TTS) for exposure limits in water. However, there are many difficulties to realize this in practice. The present work provides additional data of underwater hearing threshold and exposure limit and develops the criteria for noise exposure. Our results may serve as a temporary standard for hearing threshold or as a guide to the evaluation of noise in water.

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