DIFFERENTIAL SENSITIVITY OF THE EAR FOR UNDERWATER PURE TONES

Kazuoki Kuramoto,[1] Shin'ya Kuwahara,[1] Kensei Oimatsu,[1] Shizuma Yamaguchi[2]
[1]Japan Coast Guard Academy, 5-1 Wakaba, Kure 737-8512
[2]Faculty of Engineering, Yamaguchi University, 2557 Tokiwadai, Ube 755-8611
JAPAN

ABSTRACT: As a part of the research for constructing an underwater transmission system to divers, differential sensitivity of the ear in water to sound intensity and frequency was examined by listening experiments in a water tank. Although the value of minimum audible field (MAF) in water was considerably different from that in air, it is found that the dependence of differential sensitivity at the same sensation level (SL) is almost the same both in water and in air. Resolution of the auditory sense (i.e. number of steps in distinguishable sound) was estimated in the underwater auditory area by using existing results in air.

1. INTRODUCTION

The ability to discriminate sound intensity and frequency is one of the fundamental auditory senses in man. It is reported that the differential sensitivity of the ear is very high in air [1,2,3] and that the number of sounds we can discriminate in the audible range is about 340,000 [4].

On the other hand, there are very few studies researching the differential sensitivity in water, except the study of the ability of localization [5], probably because there was little necessity until now. Recently, the necessity of ensuring the safety of divers occurs with the popularization of marine leisure and it is said that a direct transmission to divers using an audible acoustic signal is the most effective way in water [6-10]. When we consider the realization of this transmission system, the differential sensitivity of the ear becomes an important problem in relation to type and quantity of information.

In this study, we examine the differential sensitivity of the ear to sound intensity and frequency by listening experiments in a water tank and estimate the resolution of auditory sense (i.e. number of steps in distinguishable sound) in the underwater auditory area.

2. LISTENING EXPERIMENTS

The listening experiments were carried out in a water tank with dimensions 1m×1m×2m equipped in a silent experimental room. The spectrum level of the background noise in the tank was almost constant at 52dB [re 1μ Pa $/\sqrt{Hz}$] in the frequency range from 1kHz to 5 kHz. The subjects were two men with normal hearing in air. As shown in Fig.1, the subject immersed only the whole head in the water to minimize the effects of the background noise and listened to the underwater sound. Two hydrophones were set up as close to both the subject's ears as possible and the average was obtained from these. The value of sound pressure level (SPL) was obtained by reading the data sheet on a level recorder (LION LR-4) calibrated by an underwater sound level meter (OKI SW1020). The measured SPL was actually variable from place to place owing to the effects of standing waves in the water tank. So we regarded that the subject heard the sound of SPL just measured at that moment by the hydrophones.

As the present experiments deal with the differential sensitivity of auditory sense, what is called the threshold of difference or the difference limen (DL) determined as a smallest detectable change in the sound intensity or the frequency [5], we introduce the sensation level $SL = 10\log(I / I_0)$ with reference value of I_0 as a standard of sound intensity which corresponds to the value of minimum audible field (MAF). Here, the sound intensities of I and I_0 were inferred respectively from the SPLs actually measured by the underwater sound level meter on the assumption that there was a plane wave in the water tank. Furthermore, the value of I_0 was obtained in advance at every measurement of DL because it usually depends on the experimental conditions or subjects.

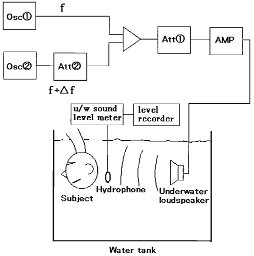

Fig. 1 Measurement of difference limen (DL) in the water tank

In order to obtain the value of DL to sound intensity, the listening experiment was carried out by a beat method [1]. A beat sound was synthesized from two pure tones, respectively, with slight different frequencies (f,$f + \Delta f$) and with different amplitudes (A, B). Therefore, the instantaneous pressure p of the beat is expressed as,

$$p = A\sin\omega t + B\sin(\omega+\Delta\omega)t$$
$$= \sqrt{A^2+B^2+2AB\cos\Delta\omega t}\cdot\sin(\omega t+\phi), \qquad \omega = 2\pi f. \tag{1}$$

The subject listened to the beat sound and compared the fluctuation of amplitude between the maximum ($A + B$) and the minimum ($A - B$). When the beat was perceived to vanish, the threshold was determined. As the sound intensity I is in proportion to the square of amplitude of the instantaneous pressure p, i.e. $I = p^2/\rho c$ where ρc is the acoustic impedance, the value of relative DL ($\Delta I_{th}/I$) was obtained as,

$$\frac{\Delta I}{I} = \frac{(A+B)^2-(A-B)^2}{(A-B)^2} = \frac{4AB}{(A-B)^2}. \tag{2}$$

The frequency of the beat Δf was made to be 3 Hz (referring to Riesz [1]) and the carrier frequencies f were 1 kHz, 2 kHz, 4 kHz and 6 kHz. The above measurement was repeated five times per every sensation level for every frequency and the average value was used as an experimental result.

A similar listening experiment was also carried out by a modulation method [2] to obtain the value of DL to frequency. A pure tone, in which the carrier frequency f was modulated by triangular wave with frequency f_p as shown in Fig.2, was radiated in the water tank. The subject listened to the modulated sound in water and checked whether it fluctuates or not. As the judgment becomes ambiguous in the vicinity of DL, the width of fluctuation of frequency change Δf was randomly presented and the relative DL ($\Delta f_{th}/f$) was statistically determined. The carrier frequency of the pure tone was made to be 1 kHz and the modulation frequency f_p was determined to 5 Hz experimentally afterward.

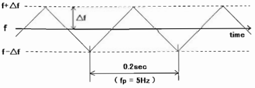

Fig. 2 Frequency change by the modulation method.

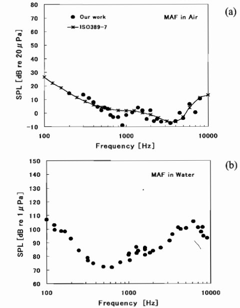

Fig. 3 Minimum audible field (MAF) measured (a) in the air at the anechoic room and (b) in water at the water tank.

3. RESULTS

Minimum Audible Field

Figure 3 shows the MAF for one subject measured (a) in air at anechoic room and (b) in water at the water tank. The MAF, which is also called the threshold value, is the absolute sensitivity of the ear determined as a minimal sound pressure in free space needed to excite a sensation of hearing [5]. The value of MAF in air obtained in the present work is in agreement with the ISO389-7 international standard [11]. Although the thresholds in water have been previously reported [7,10], the measurement frequency of them was limited above 500 Hz. The reporting of threshold in this paper is new data with respect to the fact that it was firstly measured in the wide audible frequency region. There are considerable differences in magnitude of SPL (44 – 64 dB) between air and water even though we take account of the factor of 26 dB (20log20) arising from the difference of the standard in SPL in each medium [9]. Furthermore, it is found that an essential difference occurs in the frequency dependences of MAF. This can be comprehended by a view that bone conduction is a main factor of the underwater hearing rather than air conduction, which is the usual mechanism in air.

Differential Sensitivity to Intensity

Figure 4 shows the relationship between the relative DL ($\Delta I_h/I$)) and the value of $SL = 10\log(I/I_0)$ at 4 kHz for two subjects. Above SL=30dB, $\Delta I_h/I$ shows a constant value in which Weber's law is established [4]. Near SL=0dB, namely, when the sound pressure level approaches the MAF, $\Delta I_h/I$ rapidly increases. The solid line in Fig.4 indicates the equation (3) proposed by Riesz [1] as,

$$\frac{\Delta I}{I} = S_\infty + (S_0 - S_\infty)\left(\frac{I_0}{I}\right)^\gamma \tag{3}$$

where S_∞,S_0 and γ are the parameters depending on the frequency. It is known that this equation represents the experimental results very well in air.

Although there is a scattering in experimental data, it can be said that our results in water (●) are in good agreement with the value in air (solid line). The differential sensitivity to sound intensity in water seems to be almost the same as in air at the same sensation level though the value of MAF is greatly different each other.

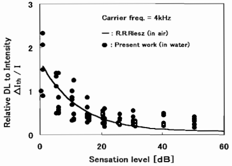

Fig. 4 Dependence of the relative DL to sound intensity $\Delta I_{th} / I$ for the sensation level SL = 10log(I / I_0).

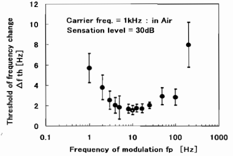

Fig. 5 Dependence of the threshold of difference Δf_{th} for the modulation frequency f_p.

Differential Sensitivity to Frequency

As an audible impression seems to change with increasing the modulation frequency f_p (for example, swing of frequency gradually changes into sideband wave sound and eventually muddy sound), the frequency f_p was determined experimentally as below. We examined the dependence of threshold of difference Δf_{th} for various modulation frequencies f_p at SL = 40dB in air. The carrier frequency was 1 kHz around which the tone was varied with frequency f_p. The value of Δf_{th} was determined statistically by randomly carrying out the frequency modulation for the various widths of fluctuations. Results thus obtained are indicated in Fig.5. It is found that the threshold of difference Δf_{th} minimizes when the modulation frequency f_p is 5–10 Hz, that is to say, the modulation frequency around this range is easiest to discriminate. Then, the modulation frequency f_p of 5 Hz was employed in the following experiments.

The experimental results of differential sensitivity to frequency obtained in this study are shown in Fig.6 denoted by (●) in water and by (○) in air. The horizontal axis is the sensation level SL=10log(I / I_o) and the vertical one is the relative DL (Δf_{th} /f). The indicated results in the figure were the mean value of two subjects. The experimental data in air, which have already been published in literature [2,3], were also described in the same figure. The ratio Δf_{th} / f has a constant value above 30dB, whereas it increases as the sensation level approaches 0dB.

Our results in air (○) are roughly close to the literature data in air (△: Shower & Biddulph or ◇: Harris) though we cannot compare these results directly from differences of the experimental methods. In water, the relative DL shows almost the same value and similar tendency as in air. Although the value of MAF itself varied with experimental situations, medium or subjects etc, the differential sensitivity to frequency at the same sensation level seems to be almost the same both in water and in air.

4. NUMBER OF DISTINGUISHABLE TONES

We can obtain the resolution of underwater auditory sense from the results of DL to the sound intensity and the frequency. Figure 7 shows the number of distinguishable tones in water in the frequency range from 31 Hz to 16kHz and in the sound pressure level above the MAF. A straight line in the figure is the formal curve of MAF in water derived from our experimental results shown in Fig.3(b). Here, the numbers of each cell were estimated from the results in air [4] assuming that the differential sensitivity of the ear in water is equal to that in air for the same sensation level. In each cell of 1/2 octave in width and 10dB in height, the upper left shows the distinguishable number of steps of sound intensity and the upper right shows the number of frequency steps. Then the bottom of the each cell shows the product of these two numbers, that is, the number of distinguishable tones. Let's use the case of f = 1 kHz and SL = 40dB as an example. From the present result of relative DL to intensity $\Delta I_{th}/I \cong 0.15$, the number of steps in distinguishable sound among the 10dB from 110dB to 120dB [re 1μ Pa] is 10/[10 log(1+0.15)] ≅ 16. On the other hand, from the result of relative DL to frequency Δf_{th} / f ≅ 0.004 the number of steps in distinguishable sound among the 1/2 octave band from 1 kHz to 1.41 kHz is 410/4 ≅ 100. Then, the total number of distinguishable tones in the cell with 1/2 octave band frequency range from 1 kHz to 1.41 kHz and with 10dB in SPL from 110dB to 120dB is about 16 × 100 = 1600, which is close to 17 × 90 = 1530 denoted by the shadowed portion in Fig.7. It seems that the sounds around 2 kHz of 170dB are more excellent for differential sensitivity in water and these sounds are more suitable for information transmission to the divers.

5. CONCLUSION

As a part of the research for constructing the underwater transmission system to divers, differential sensitivity of the ear to sound intensity and frequency was examined by listening experiments in the water tank. The value of MAF in water was considerably different from that in air. However, it is found that differential sensitivity to sound intensity and frequency at the same sensation level is almost the same both in water and in air. This implies that the discrimination of the sound intensity and frequency is a phenomenon mainly related to the internal ear both in water and in air. Furthermore, the resolution of auditory sense (i.e. number of steps in distinguishable sound) was estimated in the underwater auditory area from the results in air assuming that the differential sensitivity of the ear in water is equal to that in air for the same sensation level.

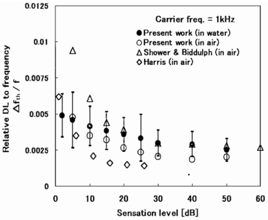

Fig. 6 Dependence of the relative DL to frequency $\Delta f/f$ for the sensation level SL=10log (I/I_0)

It is indispensable to carry out the listening experiments in water to investigate underwater hearing. In practice, however, many difficulties would be encountered for the reasons that audiometric equipment for underwater measurement is needed, diving equipment (SCUBA) for breathing of subjects is necessary, and the background noise from surroundings is unavoidable. Then, it is considered that an estimation by utilizing the experimental procedures or results in air like the present work is one of the effective methods in preparing underwater hearing data barely obtained until now.

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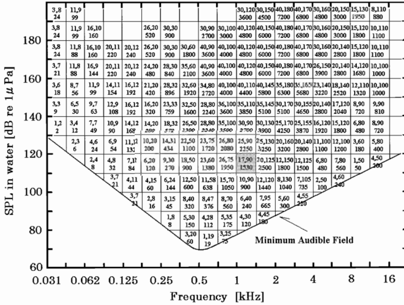

Fig. 7 The number of distinguishable tones in the underwater auditory area