Study on perception of complex low frequency tones

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This paper deals with the hearing of complex low frequency tones. Hearing thresholds of low frequency pure tone and complex tones were measured. The measurement frequencies are from 5Hz to 50 Hz. In the results, the hearing thresholds of complex tones are found to be lower than those of pure tones, whose frequencies are the same as the fundamentals. Hearing thresholds of complex tones are affected by the phase difference between fundamental and harmonic. This means that the hearing of a complex tone is influenced by a higher harmonic component though the component is not audible. The results are not in agreement with the audibility of complex tones in the middle frequency area. The complex low frequency tone is not heard separately as each component but is heard as one complex wave.

1. Introduction

Low frequency sound is generated by various sound sources such as automobiles, diesel engines, high speed trains, boilers, blowers, compressors, highway bridges, discharge of water from a dam, vibration screens etc. These low frequency sounds may sometimes be pure tones and sometimes complex tones. Pure tones have been used for the measurement of human auditory responses and for the measurement of psychological reactions to low frequency sound. It is possible to estimate the auditory response to a complex tone from the reaction to a pure tone in audible sound. In the case of low frequency sound, it is not always possible to apply the results of pure tones to complex tones as well as for audible sound.

In this study, auditory responses to low frequency complex tones with two frequency components were measured.

2. Measurement of hearing thresholds of pure tones and complex tones

Hearing thresholds of low frequency pure tone and complex tones were measured in a chamber about the size of a phone booth (850 x 850 x 1850mm). Four loudspeakers of 40cm diameter were installed in the booth. This booth is located in a sound measurement room and the background noise is adequately low.

The measurement frequencies of pure tone are 5Hz, 10Hz, 20Hz and 40Hz and the complex tones have the fundamentals of 5Hz, 10Hz, 20 Hz and higher harmonics. Complex tones whose component levels are equalised according to the level differences of individual hearing thresholds for pure tones for each subject were produced. The levels of the components were fixed during the measurement. The psychometric method is a method of limits.

The measurement includes three ascending series and descending series each time. The average is the hearing threshold level. The measurements are automatically controlled by computer. Nine students, whose hearing was within the normal range, participated in the experiment as subjects, Figure 1 shows the measuring set up.

The results of the hearing thresholds of complex tones whose fundamental frequencies are 5Hz and 10Hz, are shown in Figure 2. The figures show the averages and the standard deviations of 9 subjects. The hearing thresholds of complex tones are lower than those of pure tones, whose frequencies are the same as the fundamentals. As the number of components increases, the hearing threshold decreases. Figure 3 shows the hearing thresholds of complex tones and of pure tones for subject A. The figure shows that the hearing threshold of a complex tone is smaller that the threshold of the pure tone. The 5Hz and 10Hz complex tones are not separately heard in components. It is commonly said that human ears are able to analyse a sound wave into sinusoidal components like a Fourier Transform (1,2). This does not agree with this result. The same result was obtained in other complex tones. The result show that a complex tone is heard as one sound.

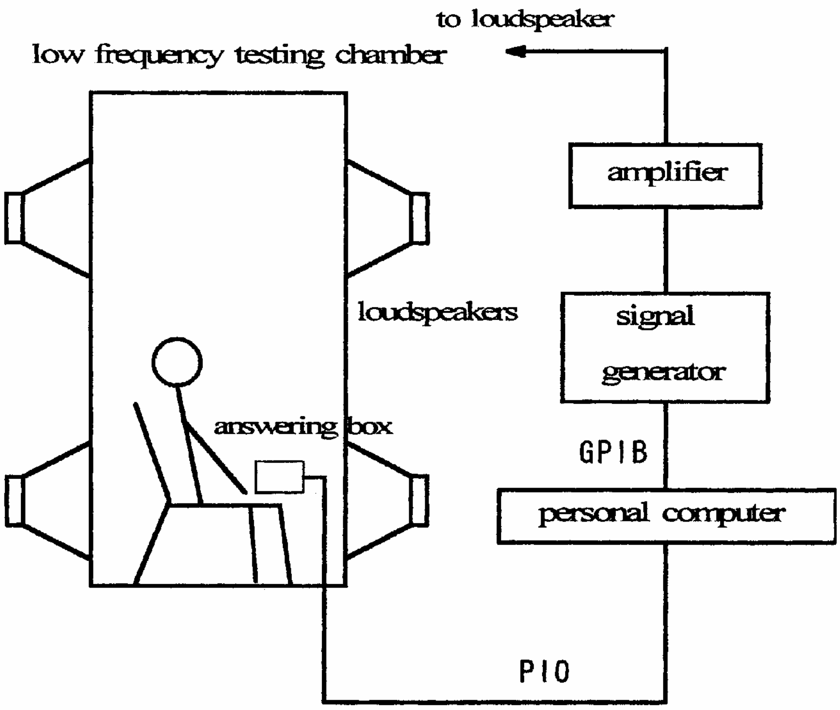


Figure 1. Measuring set up

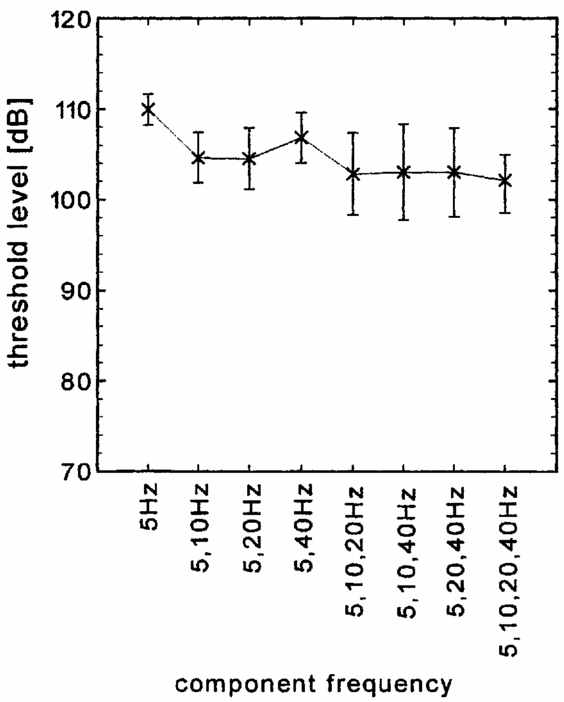


Figure 2. Hearing thresholds of complex tones (a)

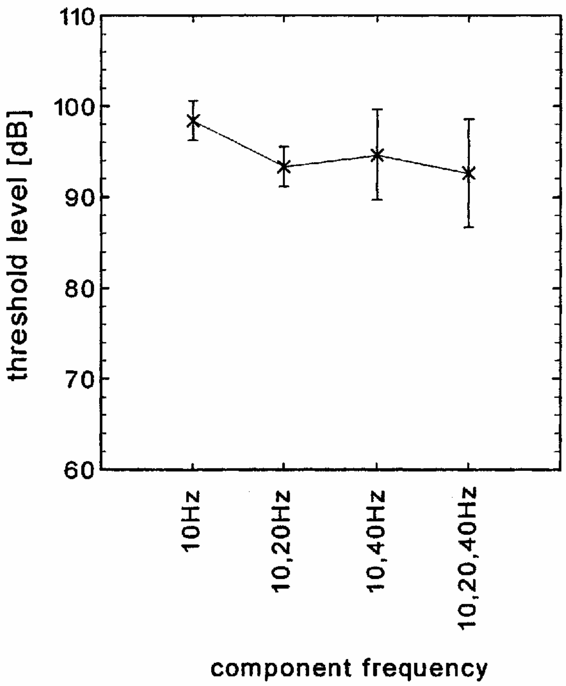


Figure 2. Hearing thresholds of complex tones (b)

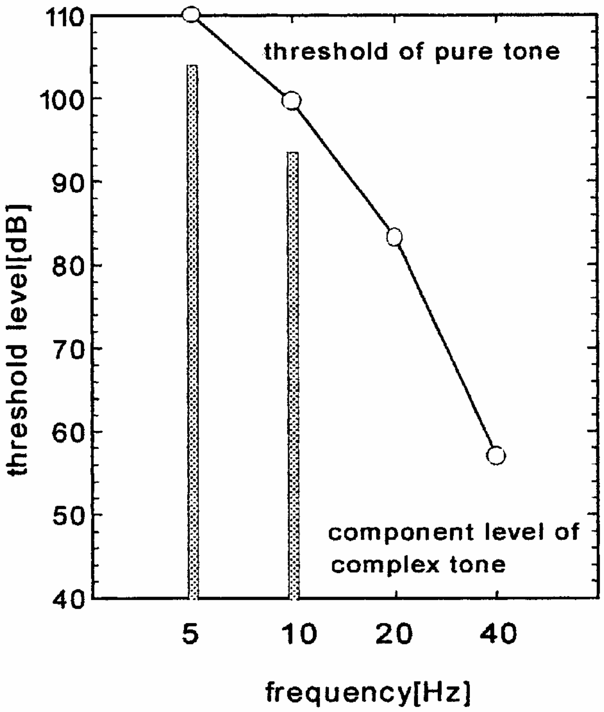


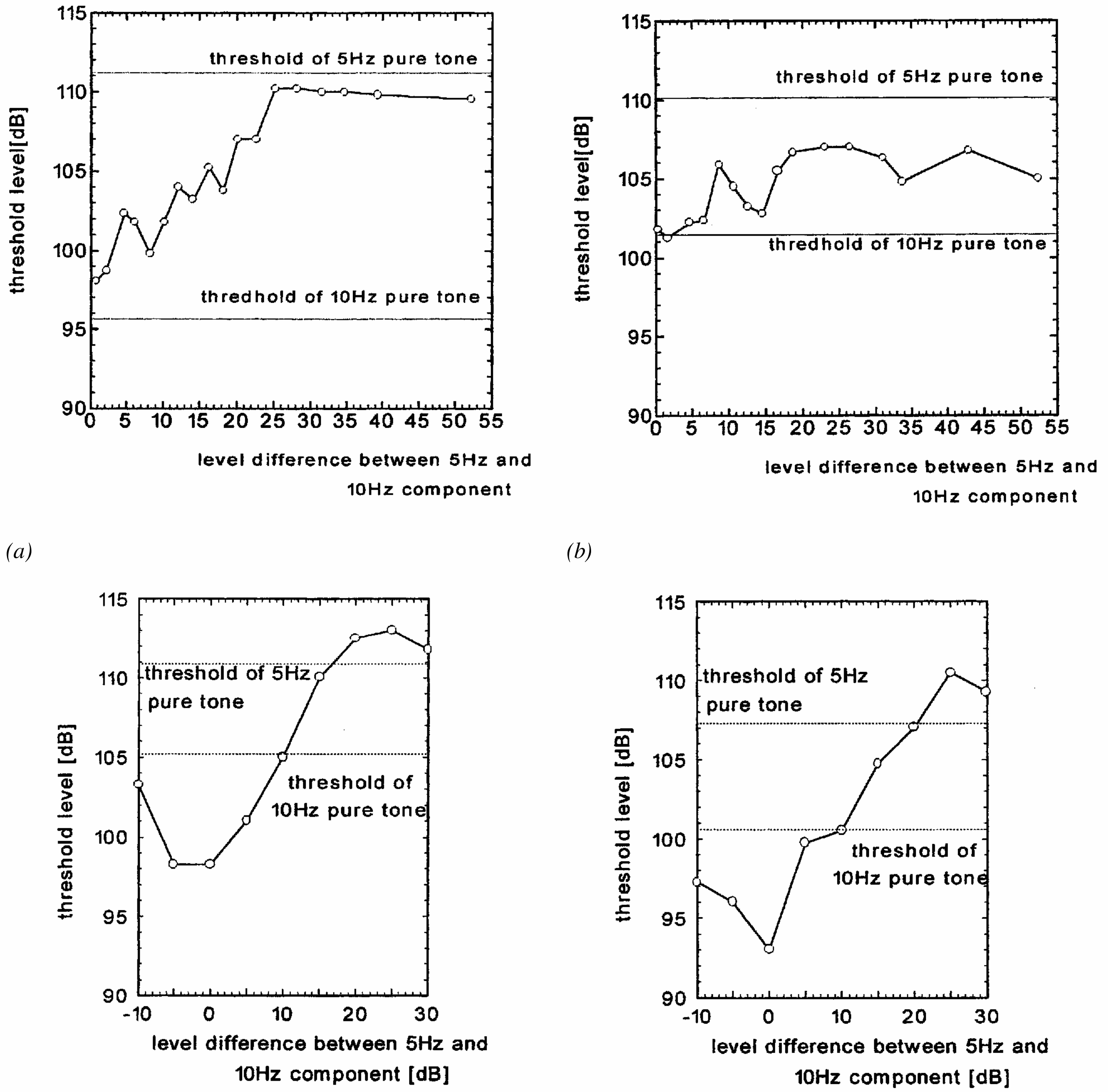
Figure 3. Hearing threshold of a complex tone with 5Hz and 10Hz components, and pure tones (subject A).

3. Hearing threshold of a complex tone with various harmonic component levels

It is confirmed in the previous section that a low frequency complex tone can be heard below the hearing threshold of a pure tone whose frequency is the same as the fundamental. The hearing threshold of a complex tone should be close to that of the pure tone if the higher harmonic level is small enough. Hearing thresholds of complex tones with various levels of harmonic were measured in order to check the relation between the component levels of complex tones. The complex tone, which contains the fundamental of 5Hz and the second harmonic of 10Hz, was used as a test sound source. The complex tone was produced by a computer. The phase difference between the fundamental and the second harmonic is always zero. The psychometric method is a method of limits. Seven subjects participated; three of them were new and four of them had participated in the previous experiment. Their hearing was within the normal range.

The results for four subjects are shown in Figure 4. The horizontal axis is the level difference, that is, (5Hz component level – 10 Hz component level). The negative value means that the component level of 5Hz is smaller than that of 10Hz.

The hearing threshold of subject A increases almost linearly with the level difference until the difference becomes about 25dB. The hearing threshold is close to that of the 5Hz pure tone at this point. The hearing threshold of subject C increases non linearly until the level difference becomes also about 25dB. The thresholds of the other subjects, not shown here, were similar except subject B. The hearing threshold of complex tones with the components of 5Hz and 10Hz is equal to the hearing threshold of a 5Hz pure tone when the 10Hz component level is smaller by 25dB that the 5Hz component level. The level difference between the hearing threshold of 5Hz pure tones and 10Hz pure tones is 5-10dB in this



(c)

(d)

Figure 4. Hearing threshold of complex tones with various component levels.

experiment. The hearing of a complex tone is influenced by the higher harmonic component though the component seems not to be audible.

When the level difference is small or has a negative value, the hearing threshold is close to the hearing threshold level of the 10Hz pure tone and the complex tone should be heard as a 10Hz tone. The hearing thresholds of complex tones of subject C and D are less than that of 10Hz pure tones when the level difference is small or negative. The level of 5Hz component is smaller by 10dB or more than the hearing threshold of the 5Hz pure tone. It seems that the 5Hz component is not heard by the subject. The hearing of complex tones is also influenced by the fundamental though the fundamental component is not audible.

When the component level at 10Hz is smaller than the hearing threshold of the 5Hz pure tone by 10dB-20dB, the hearing threshold of complex tone becomes the hearing threshold of 5Hz pure tone. The complex low frequency tone is not heard separately as each component but is heard as one complex wave.

4. Perception of the frequency of complex tones.

Complex tones whose component frequencies are 5Hz and 10Hz, and 5Hz and 20Hz were generated. The measurement procedure is as follows. The pure tone and the complex tone are alternately presented. Subjects say which tone is higher. If the complex tone is sensed to be higher, the frequency of pure tone is changed to be higher and presented again. The perception frequency, which is subjectively the same as the complex tone, is decided. The presented sound level is chosen to be easy for the subjects to hear.

Four new subjects participated. Their hearing thresholds were within the normal range. Figure 5 shows the perception frequencies of complex tones, whose component frequencies are 5Hz and 10Hz, and Figure 6 shows the perception frequencies of complex tones, whose component frequencies are 5Hz and 20Hz. They are the mean values of four subjects. The complex tone, of which the 10Hz component is bigger than the 5Hz component by about 10dB, is sensed as 10Hz. As the 10Hz component gradually becomes smaller than 10dB, the sensed frequency becomes lower. When the 10Hz component is 5dB bigger than the 5Hz components, the tone is sensed as 5Hz. The results for the complex tone, whose components are 5Hz and 20Hz are similar as shown in Figure 6. The complex tone in which level difference of the components is the same for each component is sensed as the fundamental frequency.

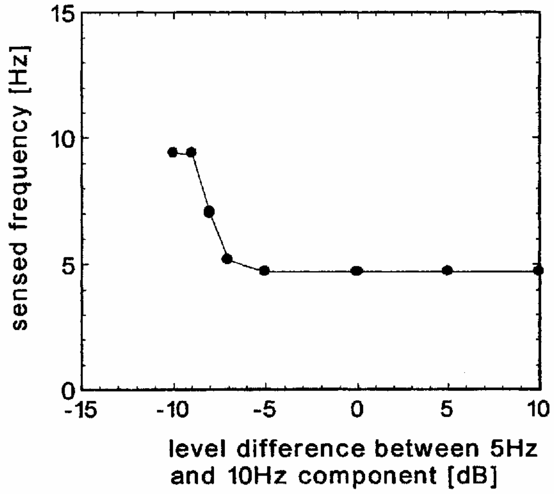


Figure 5. Sensed frequency of complex tone with 5Hz and 10Hz components

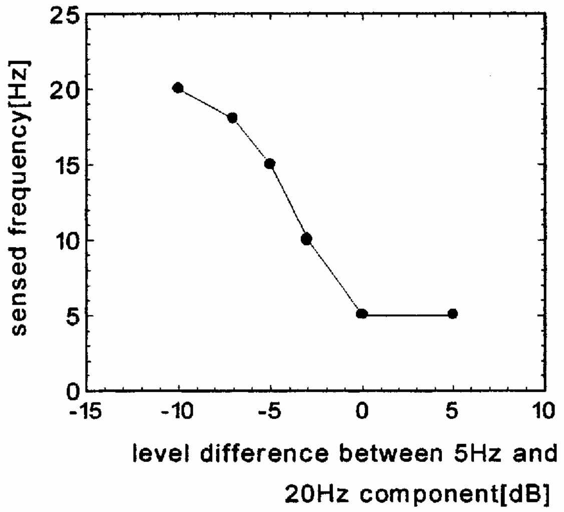


Figure 6. Sensed frequency of complex tone with 5Hz and 20Hz components

5. The effect of phase difference between fundamental and higher harmonic on the hearing threshold of complex tones.

The audibility of a complex tone is not affected by the phase difference between fundamental and harmonic in mid-frequency sounds. In the present experiment it seems that the hearing of low frequency sounds is affected by the wave form. The wave form depends on the phase difference between fundamental and harmonics.

5.1. Experimental Procedure

The thresholds of complex tones whose fundamental frequencies were 5Hz and 10Hz were measured. They have the second harmonics, 10Hz and 20Hz respectively. The wave form is given by the following equation.

$$a = a_1 \sin(2\pi f t) + a_2 \sin(4\pi f t - \phi) \quad (1)$$

where, f is frequency, ϕ is phase difference. a_1 and a_2 are amplitudes.

With the measurement of threshold, the phase difference ϕ is selected in 30 degree steps from 0 to 360 degrees. The relative magnitudes of a_1 and a_2 are chosen to be the same as the level differences between the individual thresholds of the fundamental and second harmonic. The level difference (ratio of a_1 and a_2) is kept constant during the experiment. The wave form is synthesised by the computer and the signal is fed into an amplifier. The volume of the amplifier is manually controlled by the operator. The psychometric method is the method of limits. The number of subjects is four. They are the same subjects who participated in the measurement of perception frequency.

5.2. Results

The hearing thresholds of complex tones with 5Hz and 10Hz and with 10Hz and 20Hz components versus phase difference between fundamental and second harmonic are shown in Figure 7 and in Figure 8. The threshold level fluctuates with the phase difference. The fluctuating range is almost 2-3dB except for subject C in Figure 7. The threshold levels of subjects C and D fluctuate periodically and are small, when phase differences are 0 and 180 degrees, and are big, when they are 90 and 270 degrees. The threshold of subject A and B changes irregularly.

5.3. Thresholds of complex tones and the phase differences.

The waveform pattern fluctuations with phase difference. Timbre and intensity of sound depend on the pattern of waveform. The perceived sound intensity is possibly affected by the waveform pattern or the peak level of the sound wave in the low frequency area. The relative peak values of equation (1) are calculated when the relative values of a_1 and a_2 are equal. Figure 9 shows an example of a

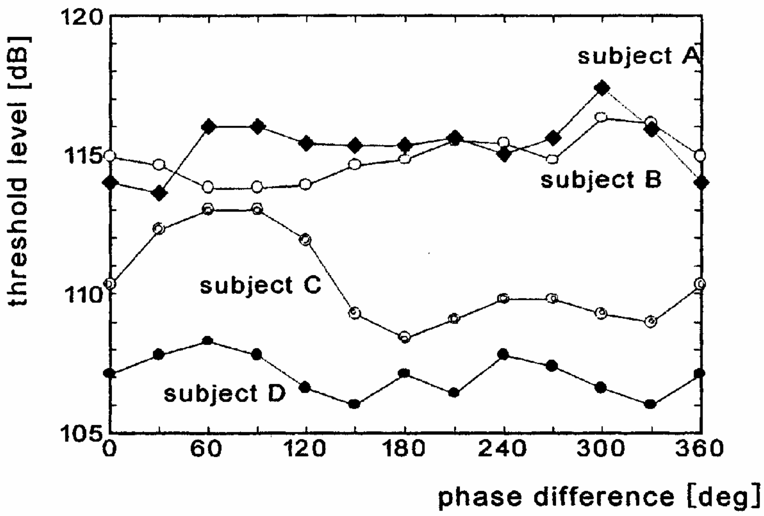


Figure 7. Hearing thresholds of complex tones versus phase differences between fundamental (5Hz) and second harmonic (10Hz)

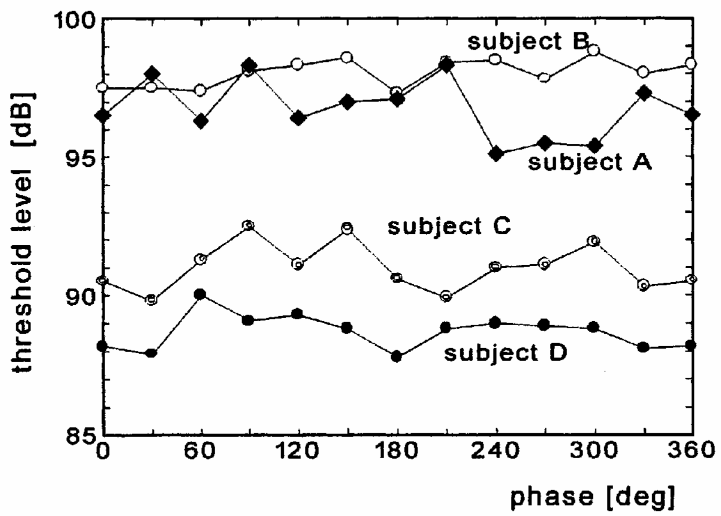


Figure 8. Hearing thresholds of complex tones versus phase differences between fundamental (10Hz) and second harmonic (20Hz)

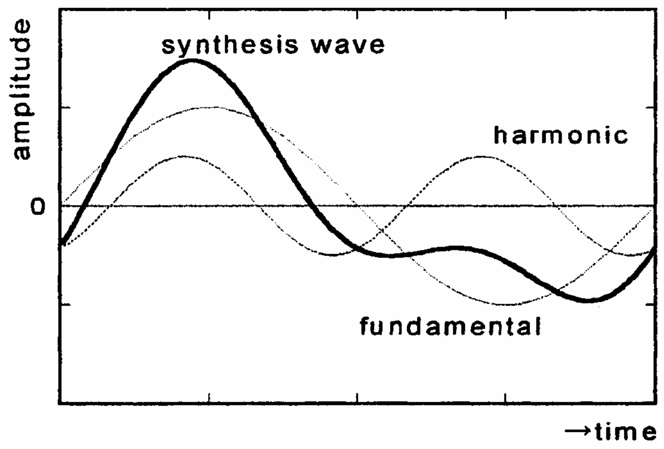


Figure 9. Example of synthesised wave of complex tone with fundamental and second harmonic.

synthesised waveform and Figure 10 shows the relative peak values versus the phase difference ϕ. The relative levels are smallest at 0 and 180 degrees and biggest at 90 and 270 degrees. The measured sound pressure level of a complex tone does not change even if the phase difference of the components changes. The hearing threshold of the complex tone with a high peak level is low, when the threshold is expressed in sound pressure level. Conversely, the hearing threshold of the complex tone with a low peak level is high to be big. Therefore, hearing threshold could be high when the phase differences are 0 and 180 degrees and could be low when the phase differences are 90 and 270 degrees. The hearing thresholds are low at 0 and 180 degree and are high at 90 and 270 degrees in the experimental results of subject C and subject D as shown in Figure 7 and in Figure 8. The experimental fluctuating pattern is contrary to the calculated results. The fluctuating period of phase difference is 180 degrees. Some agreement between experimental and calculated values was obtained. The fluctuating range is about 1dB by calculation but is 2-3dB by measurement. It is clear that the hearing threshold of a low frequency complex tone is affected by the amplitude of the synthesised waveform.

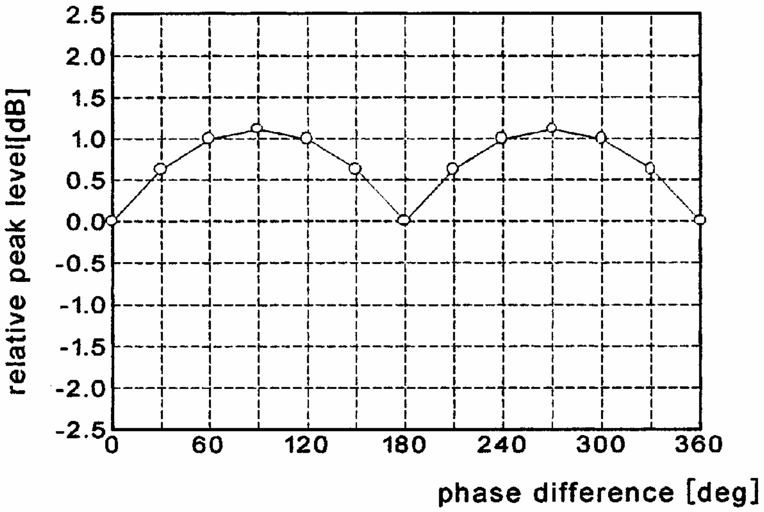


Figure 10. Relative peak level of synthesised wave between fundamental and second harmonic.

6. Conclusions

The hearing thresholds and the perception frequencies of complex frequency tones with higher harmonics in frequencies between 5Hz and 50Hz were measured. The following conclusions were obtained.

(1) Hearing thresholds of the complex tone with harmonics decrease compared to the hearing threshold of the pure tone, whose frequency is the same as the fundamental.
(2) As the number of harmonics increases, the hearing thresholds of complex tones decrease in many cases.
(3) A harmonic below the hearing threshold affects the hearing of a low frequency complex tone.
(4) The hearing threshold of a low frequency complex tone is affected by the phase difference between components.
(5) The perceived frequency of a complex low frequency tone with a second harmonic component is close to the fundamental frequency when the component level of second harmonic is small, and is close to the second harmonic frequency when the fundamental level is small.

References

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R. Plomp, "The Ear as a Frequency Analyzer", The Journal of the Acoustical Society of America, Vol. 36, No. 9, 1628-1636 (1964).

noise notes

Fish go deaf

Experiments on restrained fish has shown loud noise damages their hearing. Underwater noise was generated, and the main findings was that the sensory hair cells, were damaged – the investigators found holes where the hairs should have been, and the sensory hair cells did not grow back, contrary to expectations. Many fish species use sound to detect predators, find prey and mates. Yet another reason for mankind to be cautious in using devices that make intense sounds in environments inhabited by fish and marine mammals.