Harmonic Distortion Measurement for a Parametric Loudspeaker with Logarithmic Time Stretched Pulse
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Abstract: A parametric loudspeaker which utilizes the ultrasound can transmit the audible sound to a particular area. However, the sound reproduced by a parametric loudspeaker contains the harmonic distortions because the sound is demodulated by the nonlinearity in the air. Thus, measuring the harmonic distortions is required to evaluate the sound quality of a parametric loudspeaker. Measurement with a sine wave has used as the method to measure harmonic distortions. The harmonic distortion is measured by analyzing the integral multiplication frequency of a reproduced sine wave. Many measurements by using sine waves with each different frequency are required to measure the wideband harmonic distortions. Therefore, measuring the wideband harmonic distortions with sinusoidal wave method requires much more time. Recently, using Log-TSP (Logarithmic-Time-Str etched Pulse) signal was proposed to measure the wideband harmonic distortions in a short time for electrodynamic loudspeakers. Thus in this paper, we attempt to measure harmonic distortion of a parametric loudspeaker by using Log-TSP signal. We carried out an objective evaluation experiment in a soundproof room. The result by using Log-TSP signal was compared with that by using sinusoidal wave method. As a result, we confirmed the result with Log-TSP is equivalent to that with sinusoidal wave method.

Keywords: Parametric loudspeaker, Log-TSP, Harmonic distortion

1. Introduction
An electrodynamic loudspeaker can widely emit acoustic sound. Therefore, it is possible to transmit acoustic sound to many listeners at the same time. However, the widely emitted acoustic sound would be perceived as noise by the non-listeners. A parametric loudspeaker which utilizes the ultrasound can transmit acoustic sound to a particular area [1]. Parametric loudspeaker has already been utilized for announcement in museums and stations. Parametric loudspeaker emits an amplitude modulated (AM) wave which is generated by modulating the ultrasound with the audible sound. The AM wave which is emitted by a parametric loudspeaker is demodulated into the original audible sound by nonlinear interaction in the air. However, the sound quality of the parametric loudspeaker is inferior to that of an electrodynamic loudspeaker because the audible sound reproduced by a parametric loudspeaker contains the harmonic distortions as noise. The quantity of harmonic distortions depends on the modulation method for designing the AM wave. Thus, measuring the harmonic distortions is required to evaluate the sound quality of the parametric loudspeaker. Harmonic distortion measurement with a sine wave has been used as the conventional method to measure harmonic distortions. In this measurement method, the harmonic distortion is measured by analyzing the integral multiplication frequency of an input sine wave.
Therefore, this measurement method has difficulty in measuring the wideband harmonic distortions with high frequency resolution. Recently, a method with logarithmic time stretched pulse (Log-TSP) signal was proposed to measure the wideband harmonic distortions with high frequency resolution. It was confirmed that Log-TSP is effective for the measurement with electrodynamic loudspeaker. We considered that it needs to confirm the effectiveness of Log-TSP for parametric loudspeaker because the parametric loudspeaker emits the AM wave instead of the audible sound. Thus in this paper, we attempt to measure harmonic distortion of a parametric loudspeaker by using Log-TSP signal. We compared the result by using Log-TSP signal with that by using sine waves. We then confirmed that the harmonic distortion measurement with Log-TSP was effective for a parametric loudspeaker.

2. Conventional researches

2.1 Modulation methods in parametric loudspeaker

A parametric loudspeaker which utilizes the ultrasound as a carrier wave has a high directivity. A parametric loudspeaker emits an AM wave which is generated by modulating an ultrasound with an audible sound. The AM wave emitted by a parametric loudspeaker is demodulated into the original audible sound by nonlinear interaction in the air. An AM wave consists of the frequencies of the carrier and sidebands adjacent to the carrier. The difference tone between the carrier and each sideband is demodulated into the original audible sound by nonlinear interaction in the air. Double sideband (DSB) modulation method has been proposed as a modulation method which utilizes the double sidebands. However, DSB modulation method causes harmonic distortions by the difference tone between double sidebands. Single sideband (SSB) modulation method has been proposed as a modulation method to reduce harmonic distortions [2]. SSB modulation method can suppress the harmonic distortions between the double sidebands because SSB modulation method utilizes a single sideband. The quantity of harmonic distortions depends on the modulation method for designing the AM wave. Thus, measuring the harmonic distortions is required to evaluate the sound quality of a parametric loudspeaker with each modulation method.

2.2 Harmonic distortion measurement with a sine wave

Harmonic distortion measurement with a sine wave has been used as the conventional method to measure harmonic distortions [3]. In this method, a sine wave is used as an input signal. The input signal \( x(t) \) is indicated as follows:

\[
x(t) = A_0 \sin(2\pi f t),
\]

where \( A_0 \) is the amplitude of the input signal and \( f \) is the frequency of the input signal. The output signal \( y(t) \) is indicated as follows:

\[
y(t) = \sum_{n=1}^{\infty} A_n \sin(2\pi f n t + \phi_n),
\]

where \( n \) is harmonic number, \( A_n \) is the amplitude of each frequency component and \( \phi_n \) is each phase. In Eq. (2), \( A_1 \) is the same frequency component as input signal. Furthermore, \( A_n \sin(2\pi f n t + \phi_n), \ n = 2,3,4,\cdots, \infty \) is the \( n \)-th harmonic distortion. In harmonic distortion measurement with a sine wave, the harmonic distortion is measured by frequency analysis of \( y(t) \). Figure 1 shows the result measured with a sine wave of 1kHz. In Fig. 1, the harmonic distortions occur at 2 and 3 kHz which are the integral multiplication frequency of an input sine wave. Only the harmonic distortion of a single frequency can be measured with a sine wave. The wideband harmonic distortion
measurement is required because the quantity of harmonic distortions depend on the frequency. In this measurement method, many measurements by using sine waves with each different frequency are required to measure the wideband harmonic distortions. Therefore, measuring the wideband harmonic distortions with high frequency resolution is difficult in this measurement method.

3 Harmonic distortion measurement with Log-TSP

3.1 Definition of Log-TSP

Recently, a method with Log-TSP signal was proposed to measure the wideband harmonic distortions with high frequency resolution. The frequency characteristic of Log-TSP $H(k)$ and the inverse function $H^{-1}(k)$ is indicated as follows [4]:

$$H(k) = \begin{cases} 
1 & (k = 0) \\
\frac{\exp[-jak \log k]}{\sqrt{k}} & (0 < k \leq N / 2) \\
H^*(N-k), & (N / 2 < k < N)
\end{cases}$$  \hspace{1cm} (3)

$$H^{-1}(k) = \begin{cases} 
1 & (k = 0) \\
\sqrt{k} \exp[jak \log k] & (0 < k \leq N / 2) \\
H^{-1}*(N-k), & (N / 2 < k < N)
\end{cases}$$  \hspace{1cm} (4)

$$a = \frac{2m\pi}{(N / 2) \log(N / 2)},$$  \hspace{1cm} (5)

where $N$ is the parameter to decide a signal length of Log-TSP and $m$ is the parameter to decide a pulse width. The frequency of Log-TSP is logarithmically swept as time goes.

3.2 Harmonic distortion measurement with Log-TSP

The impulse response is measured by convoluting the measured Log-TSP with the inverse signal of
Log-TSP. The harmonic distortions appear as the independent responses apart from the main response in
the impulse response which is measured with Log-TSP [5]. Figure 3 shows the impulse response which
is measured with Log-TSP. The wideband harmonic distortion is measured by analyzing frequency
components of the harmonic distortions separated from the main response. Figure 4 shows the
frequency characteristic of the 2nd harmonic distortion which is measured with Log-TSP. In harmonic
distortion measurement with Log-TSP, the frequency characteristic of the wideband harmonic distortion
as shown in Fig. 4 is measured at a single measurement. It was confirmed that the measurement with
Log-TSP is effective for electrodynamic loudspeaker. However, the effectiveness of Log-TSP for a
parametric loudspeaker is not confirmed. Thus, in this paper, we attempt to measure the wideband
harmonic distortion of a parametric loudspeaker by using Log-TSP.

4 Evaluation experiment

We carried out an objective evaluation experiment to confirm the effectiveness of harmonic distortion
measurement with Log-TSP to a parametric loudspeaker. We compared the result with Log-TSP and
with sine waves.

4.1 Objective evaluation experiment

In objective evaluation experiment, the effectiveness of harmonic distortion measurement with Log-TSP
to a parametric loudspeaker is evaluated by comparing the result with Log-TSP and with sine waves. In
the measurement with sine waves, the frequency band between 500 and 5000 Hz is measured at 500 Hz
intervals. Then the frequency characteristic of the 2nd harmonic distortion on the frequency band
between 1000 and 10000 Hz is calculated at 1000 Hz intervals. Table 1 shows the experimental
conditions.

![Figure 3 – The impulse response measured with Log-TSP](image1)

![Figure 4 – The frequency characteristic of 2nd harmonic distortion measured with Log-TSP](image2)
4.2 Result of evaluation experiment

Figures 6 and 7 show the results using DSB modulation method. Figures 8 and 9 show the results using SSB modulation method. In Figs. 6 and 7, it is possible to confirm that the result with Log-TSP using DSB modulation method is equal to that with sine waves. Furthermore, in Fig. 8, it is possible to confirm that the result of the main response with Log-TSP using SSB modulation method is equal to that with sine waves. However, in Fig. 9, the difference between the result with Log-TSP and that with sine waves is observed. This difference is because of the effect of background noise by diminution of the sound pressure. This result suggests that harmonic distortion measurement with Log-TSP is effective for a parametric loudspeaker in low background noise. Thus in the future, we intend to measure the wideband harmonic distortion with high SNR.

<table>
<thead>
<tr>
<th>Table 1 – Experimental conditions</th>
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<tbody>
<tr>
<td>Background noise</td>
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<tr>
<td>Sampling</td>
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<tr>
<td>Parametric loudspeaker</td>
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<tr>
<td>Loudspeaker amplifier</td>
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<tr>
<td>Microphone</td>
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<td>A/D, D/A converter</td>
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<td>Sound source</td>
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5 Conclusions

A parametric loudspeaker which utilizes the ultrasound can transmit the audible sound to a particular area. However, the sound reproduced by a parametric loudspeaker contains the harmonic distortions which cause deterioration of the sound quality. Thus, measuring the harmonic distortions is required to evaluate the sound quality of a parametric loudspeaker. Harmonic distortion measurement with a sine wave has been used as the conventional method to measure harmonic distortions. However, it is difficult to measure the wideband harmonic distortion with a sine wave because only the harmonic distortion of a single frequency can be measured with a single measurement. Recently, a method with Log-TSP signal was proposed to measure the wideband harmonic distortions for electrodynamic loudspeakers. However, the effectiveness of harmonic distortion measurement with Log-TSP to a parametric loudspeaker had never been confirmed yet. Thus, in this paper, we proposed a method to measure the wideband harmonic distortion of a parametric loudspeaker. As a result, we confirmed the effectiveness of harmonic distortion measurement with Log-TSP to a parametric loudspeaker. In the future, we intend to measure the wideband harmonic distortions with high frequency resolution more exactly.

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References and links