PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Evaluation of thermal runaway control based on frequency modulated carrier wave in parametric array loudspeaker

Kairi MORI[1]; Masato NAKAYAMA[2, 3]; Takanobu NISHIURA[4]

[1] Graduate School of Information Science and Engineering, Ritsumeikan University, Japan

[2] College of Design Technology, Osaka Sangyo University, Japan

[3] Research Organization of Science and Technology, Ritsumeian University, Japan

[4] College of Information Science and Engineering, Ritsumeikan University, Japan

ABSTRACT

A parametric array loudspeaker (PAL) can realize a sharper directivity by utilizing an ultrasound wave (carrier wave). The conventional PAL has a problem that ultrasonic transducers cause thermal runaway by strongly emitting an amplitude modulated (AM) wave through a long period of time. As a result, spectral peak noises are generated from the PAL including the ultrasonic transducer in which thermal runaway has occurred. Therefore, we have proposed a thermal runaway control method with a frequency modulated carrier wave. In the proposed method, we generate the AM wave with the frequency modulated carrier wave that the frequency of the carrier wave changes with time. By changing the frequency of the carrier wave with time, we can reduce the spectral peak noises and minimize the effects of thermal runaway in ultrasonic transducers. In the paper, to evaluate the effects of thermal runaway, we perform evaluation experiments for the power of the spectral peak noises with the conventional and the proposed methods. Specifically, we measured the time transition of the power of the spectral peak noises when emitting the frequency modulated carrier wave from the PAL for 20 minutes. Finally, we confirmed the effectiveness of the proposed method.

Keywords: Parametric array loudspeaker, Thermal runaway, Frequency modulated carrier wave

1. INTRODUCTION

Audible sounds such as music and voice are usually emitted by electrodynamic loudspeakers. An electrodynamic loudspeaker can transmit audible sound to a wide area because of its wider directivity. However, the audible sound emitted by electrodynamic loudspeakers can be a noise for non-target listeners [1]. Recently, to solve this problem, a parametric array loudspeaker (PAL) has attracted attention. The PAL can realize sharper directivity by utilizing an ultrasound wave and transmit the audible sound to a particular area [2,3,4]. Therefore, the PAL is expected to be used for announcements in museums, stations and so on. The PAL emits an intense amplitude modulated (AM) wave which is designed by modulating an ultrasound wave (carrier wave) with the audible sound [5]. The emitted intense AM wave is demodulated into the audible sound due to the nonlinear interaction in the air [6]. In the conventional modulation method, the frequency of the carrier wave is set at the resonance frequency of the ultrasonic transducer to intensely emit the AM wave. However, it tends to cause thermal runaway of the ultrasonic transducer because high load is applied to the ultrasonic transducer. Moreover, the vibration of the ultrasonic transducer constantly maximized because the frequency of the carrier wave coincides with the resonance frequency of the ultrasonic transducers, and it induces thermal runaway of the ultrasonic transducer. As a result, spectral peak noises are generated from a PAL including the ultrasonic transducer in which thermal runaway has occurred (crashed PAL). Especially, this is a severe problem in intensely emitting carrier wave using the audio-spot design based on separating emission with the carrier and sideband waves [7]. This is because it is necessary to emit intensely the carrier wave from the PAL compared with the conventional PAL, and the spectral peak noises are remarkably generated. Here, we focus on the fact that the power of the spectral peak

[1] is0284ie@ed.ritsumei.ac.jp
[2, 3] nakayama@ise.osaka-sandai.ac.jp
[4] nishiura@is.ritsumei.ac.jp

noises depends on the frequency of the carrier wave and the carrier wave of the pure tone induces thermal runaway of ultrasonic transducers. We have proposed the thermal runaway control method with the frequency modulated carrier wave for the PAL [8]. The proposed method designs the AM wave with the frequency modulated carrier wave that the frequency of the carrier wave changes with time. As the frequency of the carrier wave changes with time, the power of the spectral peak noises also changes. Consequently, the power of the spectral peak noises can be reduced. Experiment results show that the proposed method can achieve load reduction to the ultrasonic transducer.

2. PALAMETRIC ARRAY LOUDSPEAKER

2.1 Principle of Parametric Array Loudspeaker

The PAL can realize sharper directivity by utilizing the ultrasound wave. It emits the AM wave which is designed by modulating the amplitude of the ultrasound wave (carrier wave) with the audible sound. Audible sound source demodulates from the intense AM wave emitted from the PAL by the non-linear interaction in the process of propagation in the air.

The carrier wave $c(t)$ and the audible sound $s(t)$ are indicated as follows:

$$c(t) = A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t), \tag{1}$$

$$s(t) = A_{\mathrm{S}} \cos(2\pi f_{\mathrm{S}} t), \tag{2}$$

where t is a time index, A_{C} and A_{S} are the maximum amplitudes of the carrier wave and the audible sound, f_{C} and f_{S} are the frequencies of the carrier wave and the audible sound. The AM wave $v_{\mathrm{AM}}(t)$ is designed by modulating the carrier wave with the audible sound. From Eq. (1) and (2), the AM wave $v_{\mathrm{AM}}(t)$ is indicated as follows:

$$v_{\mathrm{AM}}(t) = \{1 + as(t)\}c(t), \tag{3}$$

$$a = \frac{A_{\mathrm{S}}}{A_{\mathrm{C}}}, \tag{4}$$

where a $(0 < a \leq 1)$ is an amplitude modulation index. Equation (3) can be transformed as follows by trigonometric functions.

$$\begin{aligned} v_{\mathrm{AM}}(t) &= \{1 + as(t)\}c(t) \\ &= \{1 + aA_{\mathrm{S}} \cos(2\pi f_{\mathrm{S}} t)\} A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t) \\ &= A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t) + aA_{\mathrm{C}} A_{\mathrm{S}} \cos(2\pi f_{\mathrm{C}} t) \cos(2\pi f_{\mathrm{S}} t) \\ &= A_{\mathrm{C}} \cos(2\pi f_{\mathrm{C}} t) + aA_{\mathrm{C}} A_{\mathrm{S}} \cos\{2\pi(f_{\mathrm{C}} + f_{\mathrm{S}})t\}/2 + aA_{\mathrm{C}} A_{\mathrm{S}} \cos\{2\pi(f_{\mathrm{C}} - f_{\mathrm{S}})t\}/2 \end{aligned} \tag{5}$$

From Eq. (5), it can be confirmed that the AM wave consists of the carrier wave (frequency: f_{C}), the lower sideband wave (frequency: $f_{\mathrm{C}} - f_{\mathrm{S}}$) and the higher sideband wave (frequency: $f_{\mathrm{C}} + f_{\mathrm{S}}$) [9]. The original audible sound demodulates as the difference tone between the carrier wave and sideband waves.

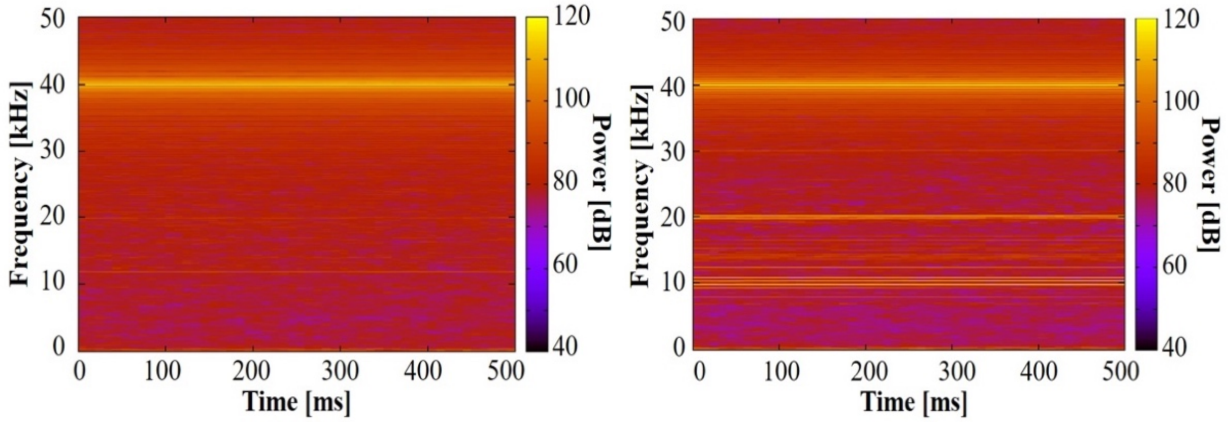
The demodulated sound $s'(t)$ are indicated as follows:

$$s'(t) = \mathrm{DM}[v_{\mathrm{AM}}(t)] \approx s(t), \tag{6}$$

where $\mathrm{DM}[\cdot]$ is expressed demodulation. The demodulated audible sound has a sharper directivity as with the ultrasound wave. Therefore, the PAL can transmit the original audible sound to a particular area.

2.2 Problem of Parametric array loudspeaker

The ultrasonic transducer of the PAL has a frequency response with steep peak at the resonance frequency. In the conventional modulation method, the frequency of the carrier wave is set at the resonance frequency of the ultrasonic transducer to intensely emit the AM wave. However, it tends to cause thermal runaway of ultrasonic transducers because high load is applied to the ultrasonic transducer for the extended period of time. As a result, the spectral peak noises are generated from the



(a) Normal PAL. (b) Crashed PAL.

Figure 1 – Spectrograms of the observed carrier wave.

crashed PAL. Figure 1 shows the spectrograms of the observed carrier wave of 40 kHz from a normal PAL and the crashed PAL. In Fig. 1, a horizontal axis shows time, a vertical axis shows frequency and a color bar represents the power of the frequency. From Fig. 1(b), we can confirm that the several spectral peaks of the noises appeared 4~20 kHz as compared with Fig. 1(a). In addition, the vibration of the ultrasonic transducer is constantly maximized because the frequency of the carrier wave coincides with the resonance frequency of the ultrasonic transducer. Thus the power of the spectral peak noises becomes maximum at this time. As indicated by the following equation, the spectral peak of the noises tends to appear around the frequency of the specified fraction of the integral number of the frequency of the carrier wave.

$$f_{\mathrm{n},l} = f_{\mathrm{C}}/l, \quad (l \geq 2 \wedge l \in \mathcal{Z}) \tag{7}$$

where $\mathcal{Z}$ is a set of whole integral numbers. Therefore, we have proposed the thermal runaway control method of the crashed PAL.

3. THERMAL RUNAWAY CONTROL METHOD WITH FREQUENCY MODULATED CARRIER WAVE IN PARAMETRIC ARRAY LOUDSPEAKER

3.1 Modulation Method Using Frequency Modulated Carrier Wave

We have proposed the thermal runaway control method of the crashed PAL. In the proposed method, we design the AM wave with the frequency modulated carrier wave which has been designed in such a way that the frequency of the carrier wave changes with time. Figure 2 shows the overview of the proposed method. In Fig. 2, $c(t)$ shows the carrier wave, and $c_{\mathrm{P}}(t)$ shows the frequency modulated carrier wave. In the 1st step, this method modulates the frequency of the carrier wave with modulation signal to design the frequency modulated carrier wave.

The frequency modulated carrier wave $c_{\mathrm{P}}(t)$ and the modulation signal $m(t)$ are indicated as follows:

$$\begin{aligned} c_{\mathrm{P}}(t) &= \mathrm{FM}[c(t)] \\ &= A_{\mathrm{C}} \cos\{2\pi f_{\mathrm{C}} t + k_{\mathrm{FM}} \cdot \int_0^t m(\tau) d\tau\}, \end{aligned} \tag{8}$$

$$m(t) = A_{\mathrm{M}} \cos(2\pi f_{\mathrm{M}} t), \tag{9}$$

$$k_{\mathrm{FM}} = (2\pi \cdot \Delta f)/f_{\mathrm{M}}, \tag{10}$$

where A_{M} is the maximum amplitude of the modulation signal, f_{M} is the frequency of the modulation signal, Δf is the frequency deviation, k_{FM} is the deviation constant, and FM[·] is a function that conducts frequency modulation [10]. Equation (8) can be transformed as follows by trigonometric functions.

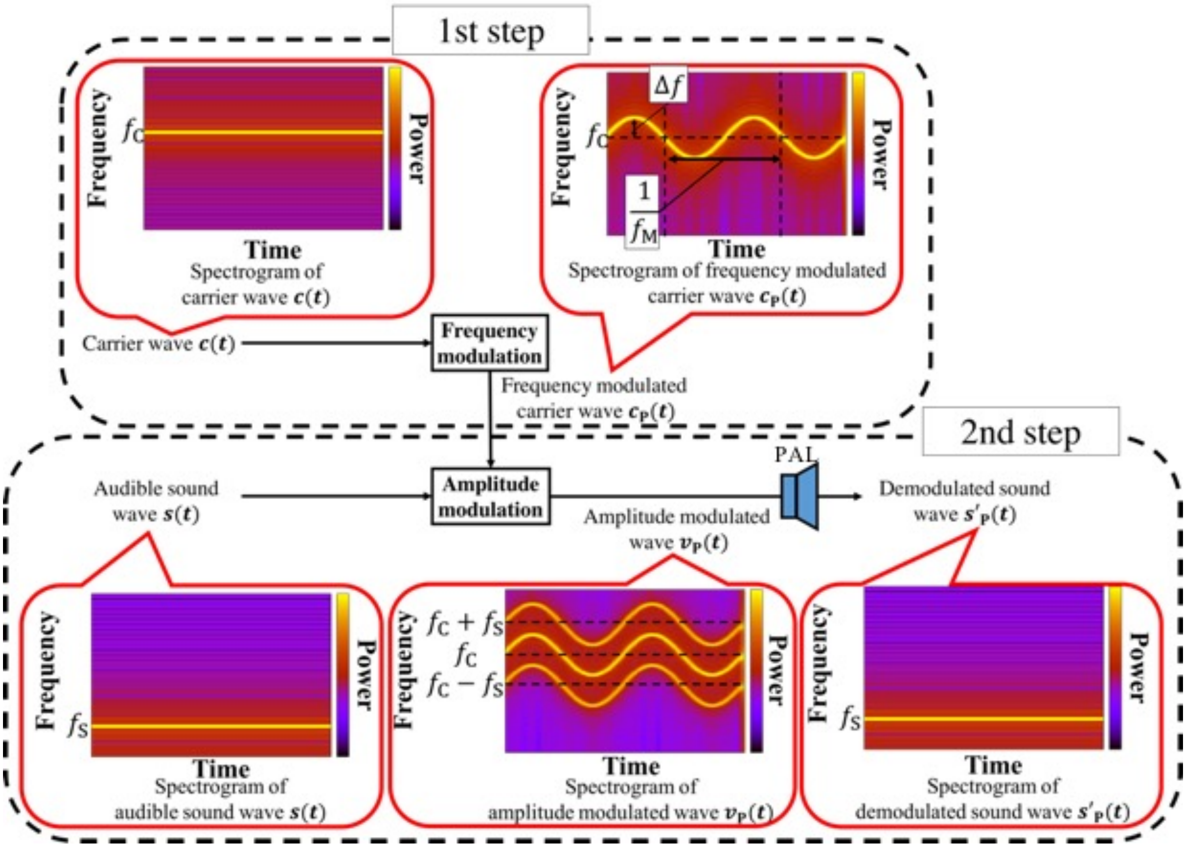


Figure 2 – Overview of the proposed method.

$$c_P(t) = A_C \cos\{2\pi f_C t + k_{FM} \cdot \int_0^t m(\tau) d\tau\}$$

$$= A_C \cos\{2\pi f_C t + k_{FM} \cdot \int_0^t A_M \cos(2\pi f_M \tau)\, d\tau\}$$

$$= A_C \cos\{2\pi f_C t + 2\pi \cdot \Delta f / f_M \cdot \int_0^t A_M \cos(2\pi f_M \tau)\, d\tau\}$$

$$= A_C \cos\{2\pi f_C t + \Delta f / f_M \cdot \sin(2\pi f_M t)\}. \quad (11)$$

In the 2nd step, this method modulates the amplitude of the frequency modulated carrier wave with the audible sound to design the AM wave.

The AM wave $v_P(t)$ is indicated as follows:

$$v_P(t) = \{1 + as(t)\} c_P(t). \quad (12)$$

In the proposed method, we design the AM wave with the frequency modulated carrier wave that the frequency of the carrier wave changes with time. Therefore, the frequencies of sideband waves also change with time. Accordingly, the difference tone between the carrier and the sideband waves, namely the demodulated sound, is demodulated in the same way as in the case for the conventional modulation method.

The demodulated sound $s'_P(t)$ are indicated as follows:

$$s'_P(t) = \mathrm{DM}[v_P(t)] \approx s(t). \quad (13)$$

3.2 Constraint Conditions of Modulation Parameters

As mentioned in the previous section, the ultrasonic transducer has the frequency response with steep peak at the resonance frequency. Therefore, the larger the difference between the frequency of the carrier wave and the resonance frequency of the ultrasonic transducer, the power of the demodulated sound is reduced. As a result, the power of the demodulated sound depends on both of the frequency deviation Δf and the frequency of the modulation signal f_{M}. The frequency deviation means the maximum amount of the frequency change against the frequency of the carrier wave. The frequency of the modulation signal indicates the change period of the frequency of the carrier wave. The smaller the difference between the frequency of the carrier wave and the resonance frequency of the ultrasonic transducer, the power of the spectral peak noises and that of the demodulated sound become larger. Thus, the larger the frequency deviation, the difference between the frequency of the carrier wave and the resonance frequency of the ultrasonic transducer becomes larger. Consequently, the power of the demodulated sound is reduced. In addition, the larger the frequency of the modulation signal, the shorter the modulation period for the frequency of the carrier wave. Consequently, the fluctuation period of the power of demodulated sound is shortened. As a result, the power of the demodulated sound becomes unsteady. In conclusion, the power of the demodulated sound needs to be maintained at the comparable level used the conventional modulation method. Therefore, the appropriate frequency deviation and the frequency of the modulation signal need to be established to reduce the spectral peak noises.

Figure 3 shows the frequency response of the PAL without modulation. In Fig. 3, a horizontal axis shows frequency, a vertical axis shows the power of the frequency. We thought that if the power reduction of the frequency of the carrier wave is less than 6 dB, it is no problem for human auditory characteristics. Thus, the frequency of the modulation signal f_{M} is defined as the following equation.

$$\Delta f < \Delta f_{\mathrm{max}}, \tag{14}$$

where Δf_{max} is the maximum amount of the frequency deviation. From Fig. 3, the maximum amount of the frequency deviation Δf_{max} is set to 1000 Hz. In addition, it is known that a demodulated sound is generated by frequency modulation in the PAL. Thus, it is necessary to set the frequency of the modulation signal f_{M} so that the demodulated sound generated by frequency modulation does not become a noise. Thus, the frequency of the modulation signal f_{M} is defined as the following equation.

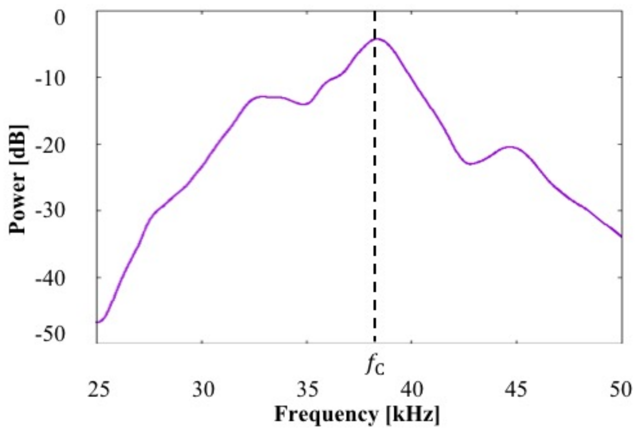


Figure 3 – Frequency response of the PAL without modulation.

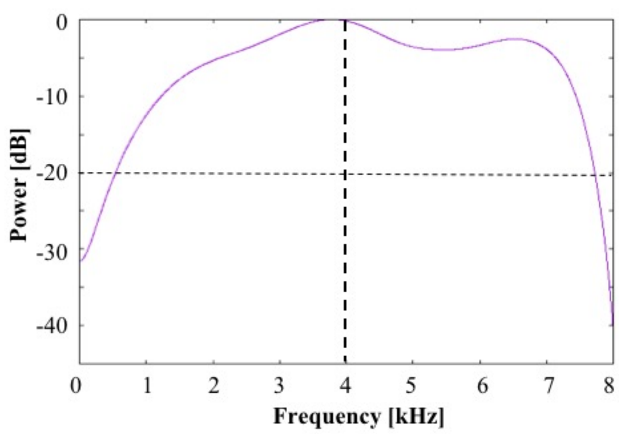


Figure 4 – Frequency response of the demodulated sound.

$$f_{\mathrm{M}} < f_{\mathrm{M}_{\max}}, \quad (15)$$

where $f_{\mathrm{M}_{\max}}$ is the maximum value of the frequency of the modulation signal. Figure 4 shows the frequency response of the demodulated sound. From Fig. 4, the PAL is difficult to represent the sound in lower-frequency band. Therefore, we set the frequency of the modulation signal f_{M} as the lower-frequency band that sound pressure is 20 dB lower than that of 4 kHz. From Fig. 4, the maximum value of the frequency of the modulation signal $f_{\mathrm{M}_{\max}}$ is set to 500 Hz.

4. EVATUATION EXPERIMENT

4.1 Evaluation Experiment for Spectral Peak Noise Reduction

We carried out the evaluation experiment to confirm the effectiveness of the proposed method. We measured the power of the spectral peak noises generated from the crashed PAL in the conventional and the proposed methods. Specifically, we measured the time transition of the power of the spectral peak noises when emitting the frequency modulated carrier wave for 20 minutes. In this experiment, the frequency of the carrier wave is set at the resonance frequency of the PAL calculated using time stretched pulse (TSP) method [11], and three crashed PALs are used in consideration of individual differences. Also, modulation parameters were determined from the preliminary experiment. Table 1 shows the experimental equipment, and Table 2 shows the experimental conditions.

The power of the spectral peak noises P is calculated by the following equation.

$$P = \left\{ 10 \log_{10} \left(\sum_{t=0}^{T-1} w(t)^2 \right) \right\} / T, \quad (16)$$

where t is a time index, T is a length of a signal, and $w(t)$ is the recorded signal.

4.2 Experimental Result for Spectral Peak Noise Reduction

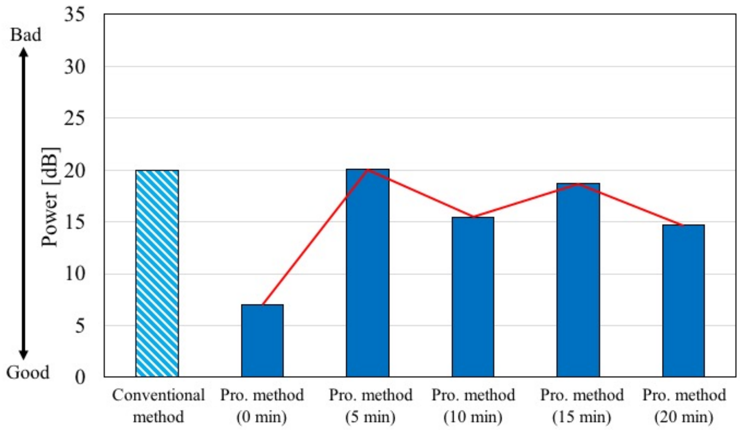
Figure 5 shows the experimental result for spectral peak noise reduction, and Table 3 shows the power of the spectral peak noises. In Fig. 5, a horizontal axis shows each carrier wave, a vertical

Table 1 – Experimental equipment.

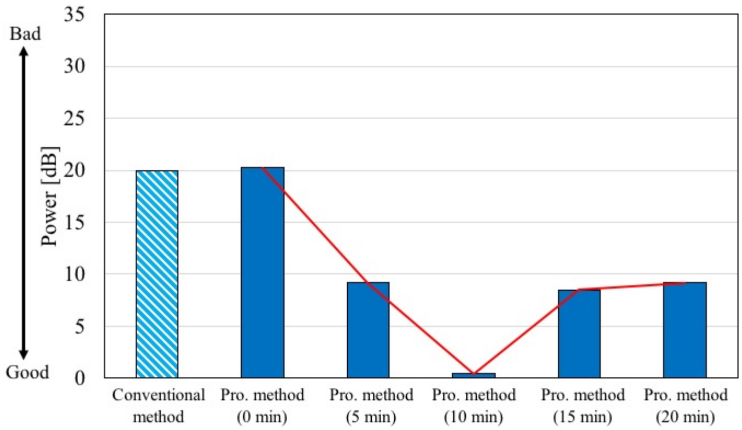
Parametric array loudspeaker	TRISTATE, TS-PARAMESP1
Microphone	SONY, ECM-88B
Microphone amplifier	HEG, MICA-800
A/D, D/A converter	RME, FIREFACE UFX
Power amplifier	YAMAHA, XM4180

Table 2 – Experimental conditions.

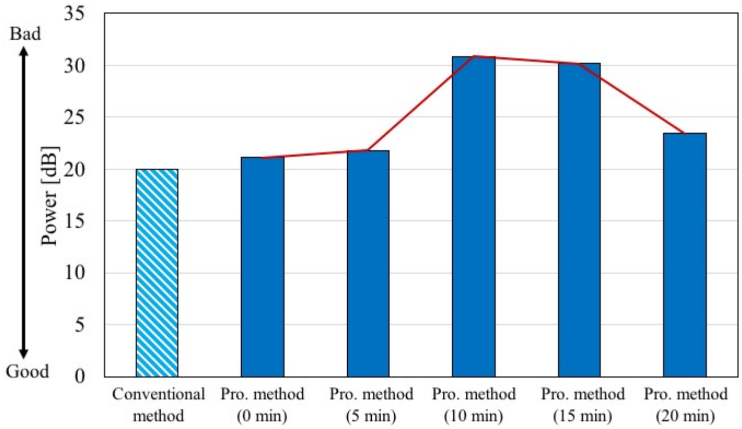
Ambient noise level	L_{A} = 38.7 dB
Reverberation time (T_{60})	650 ms
Sampling frequency	192 kHz
Quantization bit rate	32 bits
Distance between microphone and parametric array loudspeaker	0.3 m
Input voltage	12 V
Temperature / Humidity	19 ℃ / 46.8 %
Sound source	Carrier wave of pure tone (Conventional method), Frequency modulated carrier wave (Proposed method)
Frequency deviation Δf	20 Hz
Frequency of modulation signal f_{M}	70 Hz



(a) Crashed PAL(A).



(b) Crashed PAL(B).



(c) Crashed PAL(C).

Figure 5 – Experimental result for spectral peak noise reduction.

Table 3 – Power of the spectral peak noises.

	0 min	5 min	10 min	15 min	20 min	Average
Crashed PAL(A)	7.0 dB	20.1 dB	15.5 dB	18.7 dB	14.7 dB	**15.2** dB
Crashed PAL(B)	20.3 dB	9.2 dB	0.4 dB	8.5 dB	9.2 dB	**9.5** dB
Crashed PAL(C)	21.1 dB	21.8 dB	30.8 dB	30.2 dB	23.4 dB	**25.5** dB
Average	16.1 dB	17.0 dB	15.6 dB	19.1 dB	15.8 dB	16.7 dB

axis shows the power of the spectral peak noises. Figure 5 is normalized the power of the spectral peak noise in the conventional method to 20.0 dB. From Fig. 5 and Table 3, we confirmed that the spectral peak noise reduction performance had individual differences. In addition, we confirmed that the spectral peak noises were reduced by an average of 4.8 dB for crashed PAL(A), and 10.5 dB for crashed PAL(B). However, in crashed PAL(C), we confirmed that the spectral peak noise increased by 5.5 dB on average. The reason is considered to be that the optimum modulation parameters differ depending on the individual. Moreover, the spectral peak noise reduction performance changes with time. Thus, the optimal modulation parameters are expected to change with time. From the experimental result, we confirmed that the proposed method can reduce the spectral peak noises for the crashed PAL.

5. CONCLUSIONS

The PAL has a sharper directivity and can transmit an audible sound to only a particular area by utilizing the ultrasound wave. However, it tends to cause thermal runaway of the ultrasonic transducer because high load is applied to the ultrasonic transducer when the AM wave of the conventional modulation method is emitted for the extended period of time. In addition, spectral peak noises are generated from the crashed PAL. Therefore, we have proposed the thermal runaway control method with the frequency modulated carrier wave for the PAL. In this paper, we further evaluated the spectral peak noise reduction performance of the proposed method. Concretely, we measured the time transition of the power of the spectral peak noises when emitting the frequency modulated carrier wave for 20 minutes. From the result of the evaluation experiment, we confirm the effectiveness of the proposed method. In the future work, we intend to change modulation parameters adaptively to control thermal runaway of the crashed PAL.

ACKNOWLEDGEMENTS

This work was partly supported by JST COI, and JSPS KAKENHI Grant Number JP18K19829, JP18K11365 and JP19H04142.

REFERENCES

1. C. Shi and W. S. Gan, “Development of parametric loud-speaker: a novel directional sound generation technology,” *Proc IEEE Potentials*, vol. 29, no. 6, pp. 20-24, 2010.
2. P. J. Westervelt, “Parametric acoustic array,” *The Journal of Acoustical Society of America*, vol. 35, no. 4, pp.535-537, 1963.
3. K. Aoki, T. Kamakura, and Y. Kumamoto, “Parametric loudspeaker characteristics of acoustic field and suitable modulation of carrier ultrasound,” *Electronics and Communications in Japan*, vol. 74, no. 9, pp. 76-82, 1991.
4. M. Yoneyama, J. Fujimoto, Y. Kawamo, and S. Sasabe, “The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design,” *The Journal of Acoustical Society of America*, vol. 73, no. 5, pp. 1532-1536, 1983.
5. D. Olszewski and K. Linhard, “Optimum array configuration for parametric ultrasound loudspeakers using standard emitters,” *IEEE Ultrasonics Symposium*, pp. 657-660, 2006.
6. T. Kamakura, M. Yoneyama, and K. Ikegawa, “Developments of parametric loudspeaker for practical use,” *Proceedings of 10th International Symposium on Nonlinear Acoustics*, Kobe, Japan, pp. 147-150, 1984.
7. T. Matsui, D. Ikefuji, M. Nakayama, and T. Nishiura, “Multiple audio spots design based on separating emission of carrier and sideband waves,” in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Institute of Noise Control Engineering, pp. 2924-2928, 2014.
8. K. Mori, T. Fukumori, M. Nakayama, and T. Nishiura, “Spectral peak noise reduction with frequency modulated carrier wave for parametric loudspeaker,” in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Institute of Noise Control Engineering, pp. 2066-2076, 2018.
9. T. Kamakura, “Two model equations for describing nonlinear sound beams,” *Japanese journal of applied physics*, vol. 43, pp. 2808-2812, 2004.
10. H. Roder, “Amplitude, Phase and Frequency Modulation,” *Proceedings of Institute of Radio Engineers*, vol. 19, no. 12. pp. 2145-76, 1931.
11. N. Aoshima, “Computer-generated pulse signal applied for sound measurement,” *The Journal of Acoustical Society of America*, vol. 69, no. 5, pp. 1484-1488, 1981.