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Improved Interior Acoustic Environment for Ultra-compact EVs (Fundamental Consideration of 1/*f* Fluctuation Including Music for Evaluation of Ride Comfort)

by

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Abstract

Since 2012, one- or two-seater ultra-compact electric vehicles, which have become easy-to-use mobility solutions for everyone, have been researched and actively developed. Even though it is extremely important to provide the ride comfort according to various situations and space preference of the passenger to advance the high-value-adds of automobiles, interior noise has not been researched sufficiently. In the study of the improvement of interior comfort, a technique to make the noise less noticeable is by using the music output of a second sound source. We conducted numerical experiments and calculated the fluctuation coefficient to select highly relaxing music. Moreover, we considered the quantitative evaluation of the comfort in the interior by using the human biological information as the initial stage of the comfort in the inside space of a car for various passengers. Furthermore, we studied music by real-time analysis to consider the relationship between the variation in the fluctuation coefficient, range of frequency, and time course.

Keywords: Ultra-compact electric vehicle, Giant magnetostrictive actuator, Masking, Brainwave, 1/*f* fluctuation

1. Introduction

Since 2012, one- or two-seater ultra-compact electric vehicles (EVs) with an electric motor as the engine, which have become easy-to-use mobility solutions for everyone, have been researched and actively developed[1)]. Ultra-compact EVs can easily make turns owing to their compactness, and they are environment-friendly. In addition, it is extremely important to provide ride comfort according to various situations and the space preference of a passenger to advance the high-value-adds of automobiles. Therefore, various studies on the ride comfort and interior environment of ultra-compact EVs have been performed recently [2,3)]. Particularly, interior noise, which includes road and wind noise from the outside, has a significant impact on the comfort of an occupant in an interior space. Recently, interior noise reduction by active noise control (ANC) has been widely employed in the automobile industry. Another research field, achieving comfortable interior space by a masking technique using background music (BGM) for the existing noise in a space, has been progressing [4)]. However, research on the determination of the ride comfort of ultra-compact EVs is mainly by questionnaires and organoleptic evaluation. In these studies, sufficient scientific and engineering research on human sensitivity has not been done.

We propose an ANC system whereby a giant magnetostrictive actuator is installed on the rooftop of an ultra-compact EV to actively reduce the interface vibration noise, i.e., road noise, transmission to its interior (see Fig. 1).

Furthermore, we consider a masking system to make the noise present in the cabin not noticeable by using the favorite

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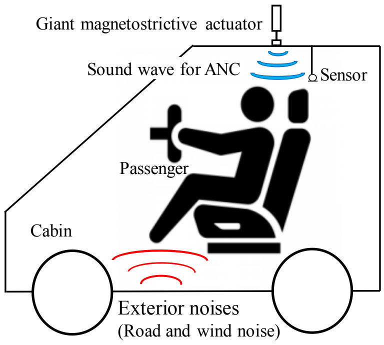


Fig. 1 Proposed ANC system by using a giant magnetostrictive actuator.

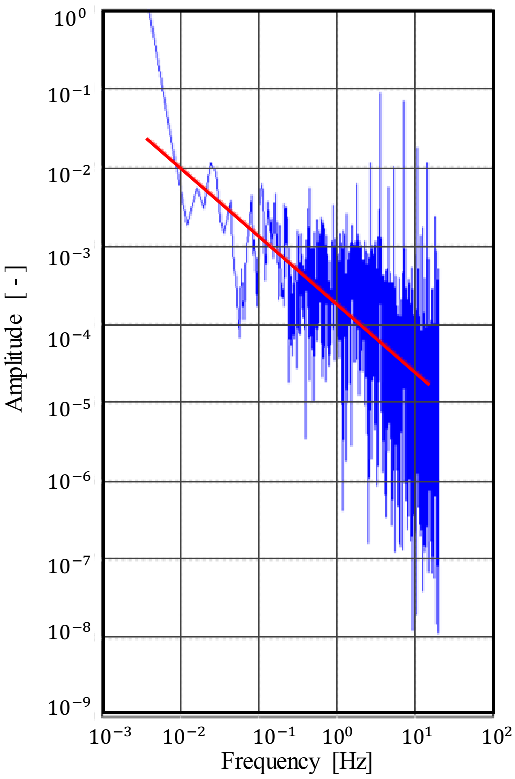


Fig. 2 Sample of music fluctuation obtained by numerical analysis.

music of the passenger [5,6]. These studies are not only aimed at "noise reduction" but also at "pleasant sound" to create a comfortable space for several passengers.

In this study, we focused on the 1/*f* fluctuation, which is expected to have a significant relaxation effect, and fundamentally studied masking the interior noise of an ultra-compact EV by using the favorite music of the passenger [7,8]. In the experiment, we numerically analyzed and calculated the fluctuation coefficient to select highly relaxing music. Moreover, we conducted a quantitative evaluation of the comfort of the interior by using the human biological information as the initial stage of the comfort in the inside space of a car for various passengers. Furthermore, we performed a real-time analysis of the music to consider the relationship between the variation in the fluctuation coefficient, range of frequency, and time course.

2. Analysis of the 1/*f* fluctuation of the music

2.1 *Feature of a 1/f fluctuation*

A 1/*f* fluctuation has a distinct mathematical feature: the power spectral density is proportional to the inverse of the Fourier frequency, *f* [9]. If the fluctuation is compared to a natural phenomenon, then it can the sunbeam shining through the branches of trees and shaking fire of a candle[10]. Regarding sound, the average of a regular sound and random sound can provide a relaxation effect. In general, various classic and modern music include a 1/*f* fluctuation.

2.2 *Numerical fluctuation analysis of the music*

Regarding the masking method, in which the interior noise in a cabin is made less noticeable using other sounds such as music, we selected music that would make the passengers feel more comfortable. We conducted spectral analysis for the selected music as WAV audio file, from start to end, to analyze the 1/*f* fluctuation. The spectrum had the discrete Fourier transform shown in the following equation:

$$F(k\Delta f) = \frac{N}{T_0}\sum_{n=0}^{N-1} f(n\Delta t)e^{-j\frac{2\pi}{N}kn} \tag{1}$$

In the above equation, T_0 is the music running time [s], Δt is the sampling time [s], N is the number of data, f is the sampled music data, Δf is the frequency resolution, and F is the spectral intensity of each frequency. In this experiment, for all cases, the sampling frequency of the music is 44.1 kHz and music length are 3 min.

Figure 2 shows a sample result of the spectral analysis including the 1/*f* fluctuation frequency between 0.05 Hz and 0.5 Hz, as obtained by the above equation. The figure shows spectrum of music date intensity on the vertical axis and frequency on the horizontal axis. The fluctuation coefficient was obtained by the calculation of the spectral slope from 0.05 Hz to 0.5 Hz. It shows that the music whose coefficient is approximately -1 contains a 1/*f* fluctuation. In this study, we analyzed each of the 1527 music that were used for masking and defined 340 music whose fluctuation coefficient was in the range from -1 to -2 as music containing a 1/*f* fluctuation.

2.3 *Experiment of the relaxation effect by the music including a 1/f fluctuation*

Fig. 3 Heart rate meter.

Fig. 4 Electroencephalograph.

Fig. 5 Measurement of the brainwave of a subject when he listens to music.

We conducted an experiment of the relaxation effect on a subject by using 340 selected music, which were analyzed by the method described in the previous sub-section. In the study on the relaxation effect, the relaxation state was quantitatively evaluated by using brainwaves, which are one of the biological information.[11)] In many studies of the relaxation effect, the α wave, which is one of the brainwaves, appeared during the feeling of relaxation. A high α wave appearance rate corresponds to high relaxation[12-14)]. In this study, we used the wave appearance rate as the evaluation index, which is defined as the ratio of a wave to all the appearing brainwaves in the composition ratio in each frequency band within the measurement time.

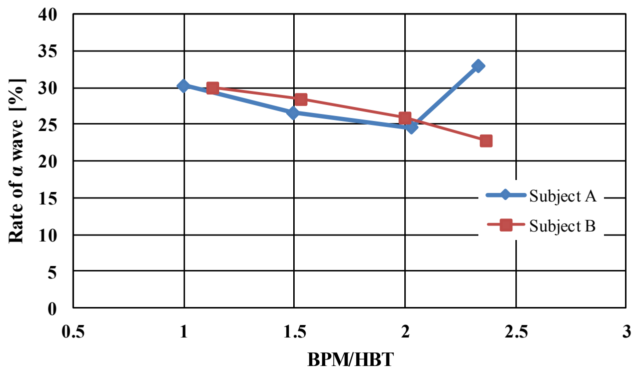


Fig. 6 Experiment result of the rate of two subjects for each music that they listened.

In this experiment, initially, the heart rate at rest of a seated subject was measured (see Fig. 3). We selected three out of the prepared 1527 songs from 60 bpm to 238 bpm, such that the bpm of the songs was approximately 1, 1.5, and 2 × the heart rate of the subject, and selected one music including a 1/*f* fluctuation among the selected 340 music. The brainwave of the subject was measured for each music by using Electroencephalograph (see Fig. 4). Moreover, music was outputted by a headphone for 3 min as shown Fig. 5. This experiment was approved by the Ethics Committee of Tokai University's "Research targeted humans."

2.4 *Experiment result*

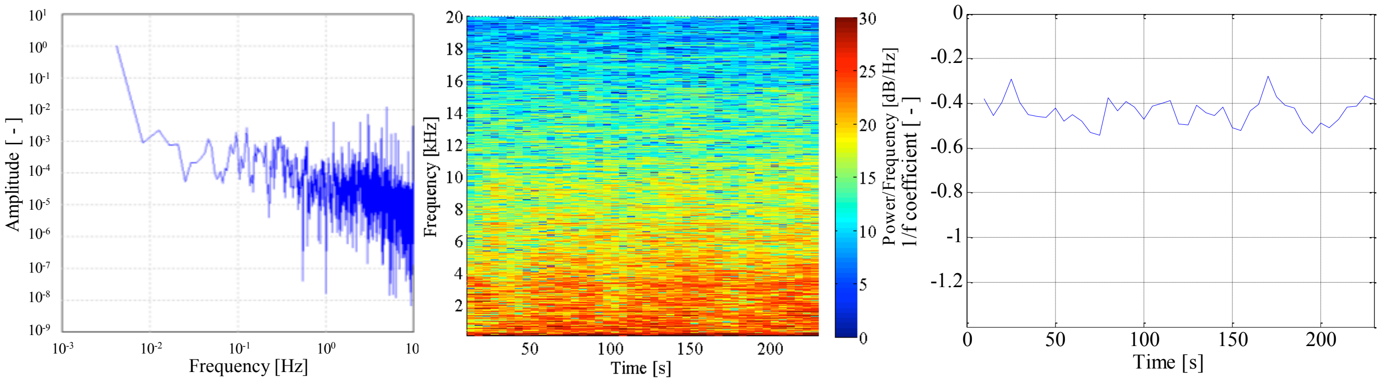
Figure 6 shows the experiment result of two subjects. The *α* wave appearance rate of both the subjects decreases up to three music. However, the *α* wave appearance rate of subject A increases when subject A listens to the fourth music including a 1/*f* fluctuation. In comparison, the α wave appearance rate of subject B decreases when it listens to the fourth music including a 1/*f* fluctuation.

From this experiment result, we proved that if a passenger listens to a music including a 1/*f* fluctuation, then he/she cannot relax even if he/she listen to whole of music including 1/*f* fluctuation. The cause of this result is that we consider that the subject did not listen to the music completely but only the part of the music containing a 1/*f* fluctuation. Therefore, subject B did not appear to exhibit a relaxing effect.

3. Real-time analysis of the 1/*f* fluctuation

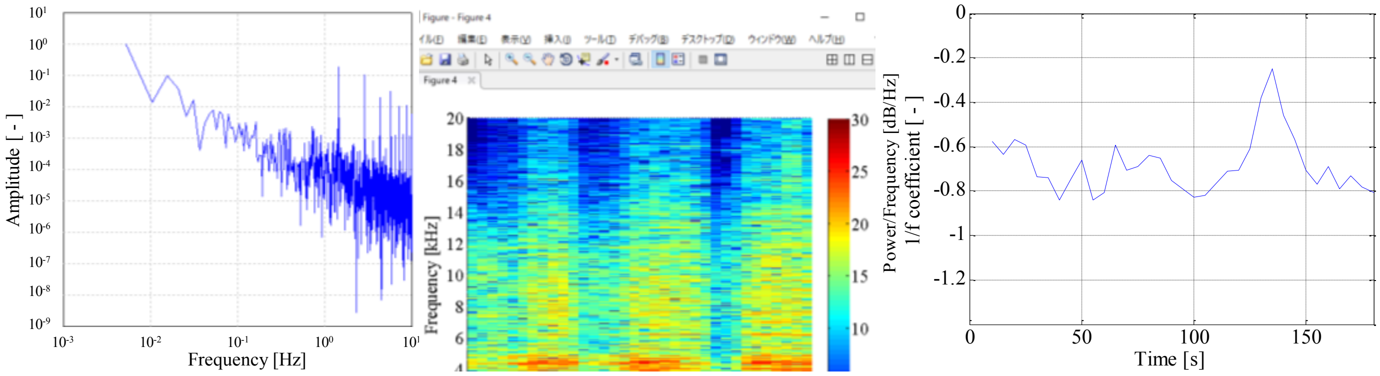
3.1 *Real-time analysis method of the music including a 1/f fluctuation*

In the previous section, we described both the analysis of the 1/*f* fluctuation occurring in the music and experiments conducted for comfort evaluation by using music including a 1/*f* fluctuation.



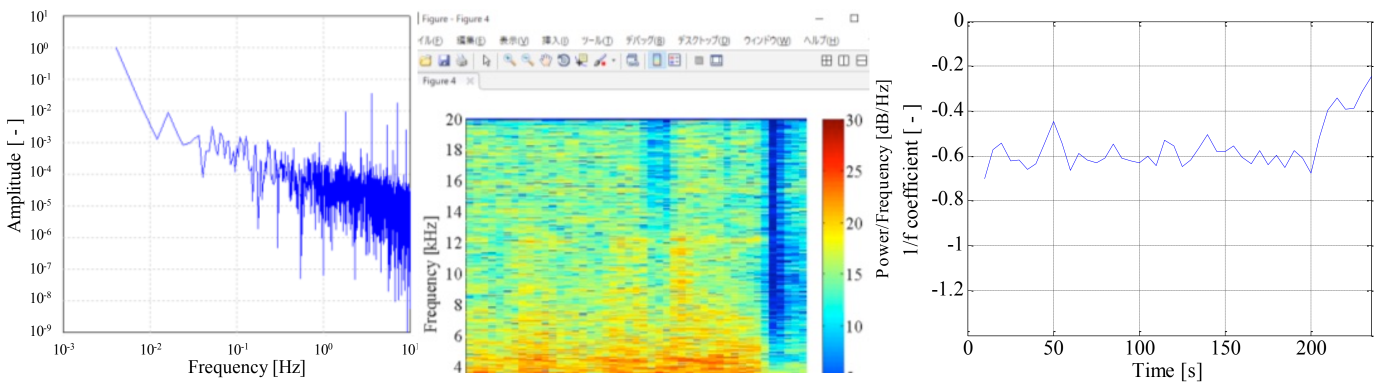
(a) Spectrum (b) Spectrogram (c) Time history of the fluctuation coefficient

Fig. 7 Fluctuation coefficient -1.1438 (Music A).



(a) Spectrum (b) Spectrogram (c) Time history of the fluctuation coefficient

Fig. 8 Fluctuation coefficient -1.1495 (Music B).



(a) Spectrum (b) Spectrogram (c) Time history of the fluctuation coefficient

Fig. 9 Fluctuation coefficient -1.1429 (Music C).

However, we did not prove in which part of the complete music the $1/f$ fluctuation occurred. Therefore, we divided the music and analyzed in which part the $1/f$ fluctuation occurred. In the experiment, we conducted short-time Fourier transform for 20 s of music data to obtain the fluctuation coefficient including 0.05 Hz with the $1/f$ fluctuation. From the evaluation of the transitional $1/f$ fluctuation of the music, the fluctuation coefficient was obtained from 0.05 Hz to 0.5 Hz every 5 s with data overlapping for 15 s. The music used for the analysis was three music selected from the 339 music whose analysis was discussed in the previous section. The three selected music were analyzed using a spectrum, spectrogram, and time course from 0.05 to 0.5 Hz, which is the frequency band of the fluctuation for each case[13].

3.2 *Analysis result*

The analysis results are shown in Figs. 7–9. Each result shows: (a), (b) spectrogram, and (c) time course from 0.05 to 0.5, which is the frequency band of the fluctuation. According to Fig, 7, in whole of music, the fluctuation occurs around -0.5, without any major change in the spectrogram. Based on Fig. 8, the fluctuation occurs between -0.8 and 1.0 for the whole of music B even though there are major changes in the spectrogram. In Fig. 9, the result of the spectrogram shows a weak sound above 20 throughout. The fluctuation in the whole of music C occurs around -0.5.

From this analysis result, we prove that the 1/*f* fluctuation changes according to various factors such as the playing time and frequency band included in the music, even when the 1/*f* fluctuation is included throughout the music.

4. Conclusion

In this study, we conducted a multilateral analysis of music focused on 1/*f* fluctuations, which had a tremendous relaxation effect, and fundamentally studied masking the interior noise of ultra-compact EVs by the favorite music of a passenger. In this experiment, we selected masking music based on the analysis result of each spectrum, without limiting to the music frequency band for the whole music. We proved that if a passenger listens to music including a 1/*f* fluctuation, then he/she cannot continuously relax. This was according to the quantitatively evaluated result obtained by measuring the brainwaves, which are one of the human biological information.

Therefore, we conducted real-time analysis of the music. From these results, we also proved that the 1/*f* fluctuation changed according to various factors such as playing time, rhythm, and frequency band included in the music even though the 1/*f* fluctuation occurred throughout the music.

In future research, we will conduct an experiment on 1/*f* fluctuations from other aspects such as tempo and rhythm in the music because the rhythm of a living body has 1/*f* fluctuations.

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References

1) The Ministry of Land, Infrastructure, Transport and Tourism, The Guideline Towards Ultra-Compact Mobility 2012 ,http :// www .mlit. go. Jp / common / 000212867 . pdf.
2) A. Endo, K. Ikeda, R. Minowa, H. Kato, and T. Narita, Evaluation of Ride Comfort and Vertical Vibration of Ultra-Compact Mobility Vehicles Using Brain Blood Flow, Proceedings of the School of Engineering of Tokai University, Series E, Vol.43, pp.17-23 (2018).
3) K. Ikeda, A. Endo, R. Minowa, T. Narita, H. Kato, Ride Comfort Control System Considering Physiological and Psychological Characteristics: Effect of Masking on Vertical Vibration on Passengers, Actuators, Vol.7, no.3, 42 (2018).
4) A. Horii, C. Yamamura, T. Katsumata, and A. Uchiyama, Physiological Response to Unpleasant Sound, J. Intl: Soc. Life Info. Sci, Vol.22, No.2, pp.536–544 (in Japanese) (2004).
5) T. Kato, R. Suzuki, R. Miyao, H. Kato, and T. Narita, A Fundamental Consideration of Active Noise Control System by Small Actuator for Ultra-Compact EV, Actuators, Vol.7, 49(2018).
6) K. Ishizuka, T. Kato, H. Kato, T. Narita, A. Kojima and H. Moriyama, Active Noise Control for Ultra-Compact Vehicle Using Giant Magnetostrictive Actuator (Comfort Evaluation of the Vehicle Interior Noise by EEG), Transactions of the JSME of Japan, Vol.25, No.2, pp.88–93 (in Japanese) (2017).
7) K. Nakajima, S. Hashimoto, and Y. Tahara, A Study on Physiopsychological Effects of Fluctuating Sound Environments, Journal of Archit. Plann Environment Engineering., AIJ, No.480, pp.77-85 (in Japanese) (1996).
8) S. Miyashita, T. Sunaga, Y. Saito, and C. Kato, A Study of 1/*f* Fluctuation, Proceedings of the School of Media center of Hosei University, Vol.21, pp.85-90 (in Japanese) (2008).
9) T. Musya, 1/*f* Fluctuations and Pleasant Sensation, The Journal of Acoustical Society of Japan, Vol.50, No.6, pp.485–488 (in Japanese) (1994).
10) S. Doi, T. Otsuka and H. Takahashi, Experimental Investigation on Lighting Control with 1/f- Fluctuation, The transactions of the Institute of Electrical Engineers of Japan. C, Vol.117, No.4, pp.409-415 (1997).
11) K. Kitagawa, M. Okazaki, and M. Koga, Changes in Physiological Responses during Addition and Music Stimulation with Eyes Open (Frequency analysis of EEG) Japanese Journal of Nursing Research, Vol. 28, No.1, pp.115–120 (in Japanese) (2005).
12) Y. Chinen, K. Ikami, and E. Kioka, The Image Formed and Feeling Produced by Clothing Colors (From the Relation to the Comfortable Factor Observed in Electroencephalography) Japanese Journal of The Japan Society of Home Economics, Vol.55, No.11, pp.845–851, (in Japanese) (2004).
13) H. Fukuhara, The Relationship Between the Brain Response and Wind Band Noise Added to Musical Sound, Noise Control, Vol.13, No.4, pp.224–228 (in Japanese) (1989).
14) Y. Tahara and S. Inoue: Evaluation and Control of Sound

Environment Based on Fluctuation Characteristics, Noise Control, Vol. 30, No. 3, pp.249–257 (in Japanese) (2006)