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Effects of pure tone frequency arrangement in inverter noise on perceived unpleasantness

Takuma Kaosri [1)] Masahiko Kondo [2)] Masao Yamaguchi [2)] Takeshi Toi [2)]

1) Chuo University, Graduate School of Science and Engineering
1-13-27 Kasuga, Bunkyo-ku, Tokyo, 112-8551, Japan (E-mail: takuma_kasori@camal.mech.chuo-u.ac.jp)
2) Chuo University, Faculty of Science and Engineering
1-13-27 Kasuga, Bunkyo-ku, Tokyo, 112-8551, Japan

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Compared to Internal Combustion Engine Vehicles (ICEVs), Electric Vehicles (EVs) lack engine noise and exhibit a higher degree of cabin quietness, which increases human sensitivity to powertrain-induced noise. Therefore, based on the steady-state masking theory of pure tones by broadband noise established by E. Zwicker et al., this study aims to establish an allowable threshold at which powertrain-induced noise is not perceived due to the background noise in vehicle cabin.

Noise generated by motors and reducers appears as rotational order components whose frequencies increase in proportion to rotational speed. In contrast, inverter noise consists of a fixed carrier frequency by sidebands that sweep toward the lower and higher frequency ranges depending on motor speed. Furthermore, humans exhibit an auditory characteristic known as the critical band, within which multiple pure tones are not perceived separately but rather as a single integrated sound. As the sidebands cross the critical band of the carrier frequency with changes in motor speed, sound perception varies with rpm. Therefore, it is essential to consider the critical band in this context.

In this study, we clarify the differences in masking effects when sidebands located inside and outside the critical band of the carrier frequency and identifies the minimum audible level of protrusion level (hereinafter referred to as Lp) at which inverter noise becomes perceptible in broadband noise. Furthermore, under conditions where protrusion level of inverter noise exceeds the becomes perceptible Lp, we investigate the optimal arrangement of pure tones to minimize discomfort.

The results showed that the masking effect on multiple pure tones varies depending on whether the sidebands are located inside or outside the critical band of the carrier frequency. In particular, when n pure tones exist within the same critical band, the Lp can be estimated by subtracting the total energy of the n pure tones from the Lp of a single carrier frequency. These results suggest that at low motor speeds, sidebands tend to remain within the critical band, thereby increasing the likelihood of perceiving EV noise. In contrast, when sidebands are located outside the critical band, the Lp can be estimated from the lower sideband, which is the lowest-frequency component among the constituent pure tones. This indicates that as motor speed increases and the interval between sidebands widens, the pure tone components become more perceptually detectable.

Under conditions where the protrusion level is sufficiently high to be perceived from background noise, it was confirmed that when multiple pure tones exist within the same critical band, the level of unpleasantness increases significantly if the sidebands are arranged at positions that maximized dissonance. Conversely, when sidebands are positioned such that dissonance is not maximized, the increase in pleasantness may be suppressed even if they remain within the critical band.

When multiple pure tones exist outside the critical band, it was suggested that the upper sideband contributes to increase unpleasantness across a wide range of age groups, despite being less perceptually detectable due to auditory characteristics. Therefore, providing appropriate masking for high-frequency components above 10 kHz is suggested to be effective in reducing overall unpleasantness.

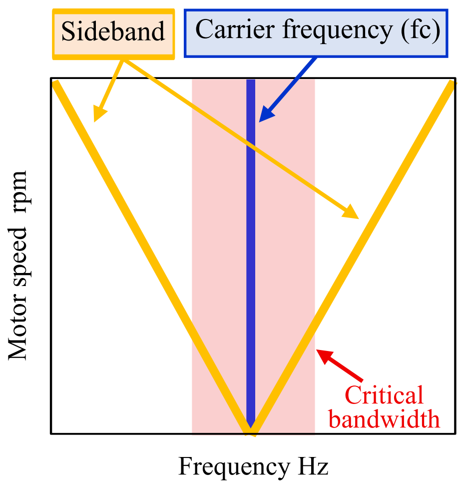

Fig. 1 Invertor noise generation status

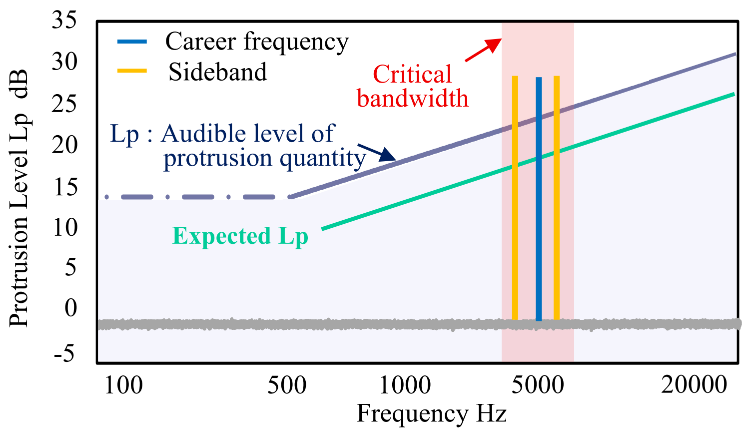

Fig. 2 Sample of evaluation sounds during low-speed driving