

Effects of carrier frequency modulation control on the unpleasantness of inverter noise

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

KEY WORDS: Vibration, noise, and ride comfort, Whine[powertrain], Sound quality evaluation, Background noise [B3]

Inverter noise in electrified vehicles consists of multiple pure-tone components generated by the carrier frequency and its sidebands due to PWM control. These tonal components often cause auditory discomfort to passengers, motivating the development of evaluation methods based on the psychoacoustic masking effect of broadband noise. Recently, carrier frequency hopping (Random PWM) has been introduced to disperse tonal components over a wider frequency range and thereby enhance the masking effect. This study investigates the influence of carrier frequency hopping parameters, namely hopping width and holding time, on the perceived annoyance of inverter noise.

Evaluation sounds were generated by superimposing inverter noise on broadband background noise at a level of $L_p + 5$ dB, where L_p denotes the perceptible protrusion level of the pure-tone components. Subjective listening tests were conducted with seven participants in their twenties using an absolute rating scale through headphones. The initial evaluation considered two holding times (0.2 s and 2.0 s), two hopping widths (± 50 Hz and ± 1000 Hz), and two sideband conditions (Inside and outside the carrier frequency critical band).

Although carrier frequency hopping generally reduced annoyance, its effect strongly depended on the combination of hopping width and holding time. In particular, the combination of a short holding time and a large hopping width produced a distinct switching sensation that strongly attracted auditory attention and increased annoyance. In addition, a long holding time combined with a large hopping width resulted in clearly perceptible frequency fluctuations, which were also evaluated as unpleasant.

To investigate whether reducing the holding time to a sufficiently short duration could suppress the switching sensation, additional evaluations were conducted with holding times of 0.1 s, 0.01 s, and 0.001 s. When the sidebands were located outside the critical band, shorter holding times reduced annoyance, suggesting that rapid hopping weakened tonal perception and promoted perceptual blending with the background noise. In contrast, when the sidebands were located within the critical band, narrower hopping widths and longer holding times were more effective, whereas rapid hopping increased annoyance because the beat pattern was interrupted before a complete beat cycle was perceived.

Finally, multiple regression analysis was performed to quantify the contributions of the hopping parameters to annoyance. Larger hopping widths, shorter holding times, and sideband placement within the critical band were identified as significant factors increasing annoyance. Moreover, a significant interaction between holding time and hopping width indicated that large hopping widths became more unpleasant as holding time increased because frequency fluctuations became more perceptible. These results suggest that hopping parameters should be adapted to the acoustic characteristics associated with motor operating conditions.

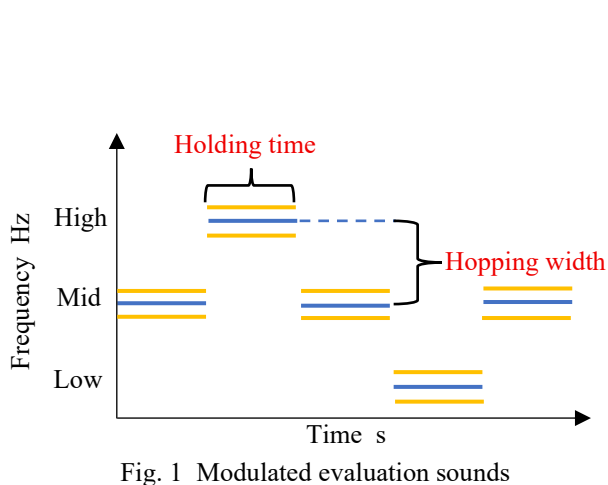


Fig. 1 Modulated evaluation sounds

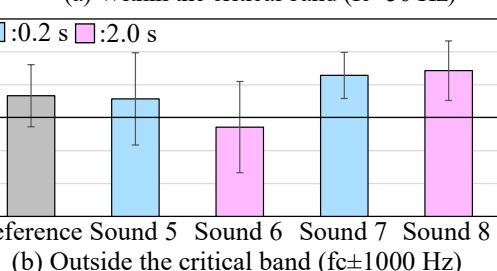
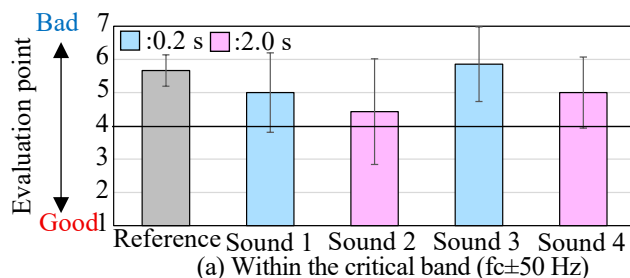


Fig. 2 Evaluation results