

Proposal of Parametric Road Feel Reproduction Based on Phase Coupling in Tire-Order Vibration Sidebands

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Steering vibration is a key source of road information for the driver. In steer-by-wire vehicles, which lack a mechanical steering linkage, road feel must be reproduced artificially, and a bench excitation method is required for efficient development. When a measured power spectrum is reproduced on a test bench by random-phase excitation, the phases occasionally align and reinforce one another, producing excessive vibration. Since vibration is defined by both amplitude and phase but the power spectrum specifies only the amplitude, the phase structure is not uniquely determined. Clarifying the phase structure among the components is therefore the key to accurate bench reproduction. In this study, by regarding tire-rotational vibration as a carrier and its sidebands, we found that the sideband components around the carrier possess a phase-coupling structure.

Steering vibration during constant-speed driving at 100 km/h was measured. The n -th tire-rotational component is referred to as the carrier frequency $f_c = n \cdot f_l$, where f_l is the first-order rotation frequency. This study focuses on the 2nd-order component (about 29 Hz at 100 km/h), which lies in the 15-50 Hz band regarded as important for road information. To examine the phase relation between the carrier and its sidebands, the instantaneous phase difference of the sidebands relative to the carrier was evaluated by STFT (1 Hz resolution). The phase differences of the sidebands ($f_c \pm 1$ Hz) concentrate near 180 deg, while the wings ($f_c \pm 2$ Hz) are uniform, indicating that the sidebands are phase-coupled to the carrier at 180 deg.

Tire-order vibration can be expressed as amplitude modulation (AM) of a single carrier. In pure AM, however, the sidebands lie at $f_c \pm f_m$, whose frequencies differ from the carrier, so their phase difference varies in time and the observed 180-deg phase coupling cannot be maintained. To preserve the coupling, the core components are placed at the same carrier frequency f_c with a 180-deg phase difference, and a phase modulation is introduced to reproduce the distribution width of the measured phase difference. The synthesized signal is given as follows:

$$x_{core}(t) = A_c \cos(2\pi f_c t) + A_{-1} \cos(2\pi f_c t + \pi + \delta_{-1}(t)) + A_{+1} \cos(2\pi f_c t + \pi + \delta_{+1}(t))$$

This equation adds two sidebands with a 180-deg phase difference (second and third terms) to the carrier (first term). The spectral dispersion caused by the phase modulation is compensated by an analytical Bessel-function correction so that the generated spectrum matches the measured one.

The proposed and conventional (random-phase) methods synthesize vibration from the same measured power spectrum, differing only in phase structure. The representative beat b_i is the median of the per one-second window envelope maxima, where i is the trial number ($i = 1$ to 500). For the measurement, the trimmed mean of the representative beats over five runs is used as the reference L , which represents the typical beat level of the actual vehicle. Since the total energy (RMS) is preserved, a large beat corresponds to a temporal concentration of the same energy and is perceived as excessive. To evaluate this upper-side deviation from L , the upper semi-deviation (USD) is adopted. As shown in Fig. 1, the conventional method scatters widely above L , whereas the proposed method concentrates near L . The upper semi-deviation (USD/ L) of the conventional method is about 1.8 times that of the proposed method, and the same tendency was confirmed for other orders.

By regarding tire-rotational vibration as a carrier and its sidebands, the sidebands were found to be phase-coupled to the carrier at 180 deg, and this coupling was formulated by introducing a phase modulation to the sidebands on the same carrier. Even when generated from the same power spectrum, the conventional method produces excessive vibration, whereas the proposed method keeps the beat near L . Thus, preserving the phase-coupling structure resolves the problem of excessive vibration arising from the same power spectrum and enables a highly reproducible bench test. This is considered to result from the suppression of the transient energy concentration caused by the random phase of the conventional method.

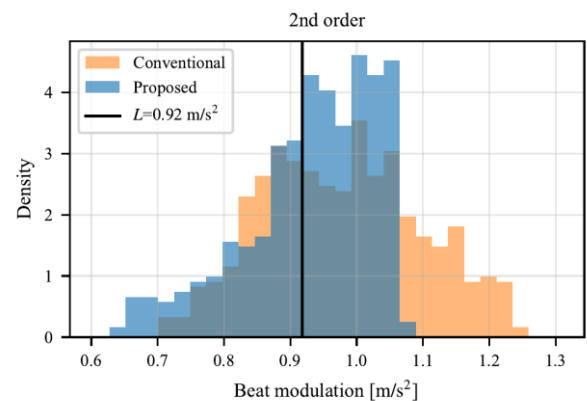


Fig. 1 Distribution of representative beat modulation generated by conventional and proposed methods (2nd order, $N = 500$ trials each); vertical line: measured reference L [m/s²].