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OBJECTIVE EVALUATION OF INTERIOR NOISE IN RUNNING VEHICLES

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1. INTRODUCTION

Interior noise of vehicles is a mixture of various types of noises coming from engine, intake / exhaust, transmission, road and tire interaction, wind gust, etc. The majority of aforementioned noises are varying with the change of engine and vehicle speeds, and the power spectrum of interior noise varying with time can be best observed in wide open throttle or coast mode. This time-varying interior noise characteristics can be analyzed by using transient signal analysis methods, like spectrogram, Wigner-Ville or wavelet transform methods [1, 2]. Spectrogram or Wigner-Ville methods require lots of time and memory in computation. They are useful only for analyzing the interior noise with very short duration or frequency range of interest is very narrow [3]. However, the wavelet transform needs much less time and memory in calculation, and can afford 1/3-octave band spectra, which is useful in calculating objective figures for subjective impression such as loudness, noisiness, sharpness, or roughness. In this paper, a method for detecting problem ranges of engine speeds and/or frequency bands for effective noise control will be presented in the view point of subjective feeling by using the wavelet transform results in the 1/3-octave band format.

2. SIGNAL ANALYSIS USING WAVELET TRANSFORM

Conventional 1/3-octave band analysis with analog or digital band pass filter needs the memory size of the data length multiplied by the number of analyzing bands. Too large memory size is required in analyzing the characteristic of transient interior noise in a common personal computer, for example by using the short-time Fourier transform (STFT), because the data length of interior noise for vehicle running mode such as the wide open throttle (WOT) condition is about 10^5~10^6. On the other hand, by using the orthogonal wavelet transform such as the harmonic wavelet transform, the number of transformed data length is almost the same as the data length in time domain. However, since the grids are unevenly distributed on the time-scale map in orthogonal wavelet transforms including harmonic or Daubechies' wavelet transform, it is known that a representation pattern of noise components on the map can be significantly altered from the original signal or even be broken down into pieces when the signal has a shift along the time axis [4]. Other disadvantageous features of harmonic wavelets are the decay rate in proportion to 1/t in time domain and the edge effect in calculating IFFT of subbanded spectral data [3]. In this study, edges of each subband spectrum is tapered to improve localization in time domain and edge effect. In addition, in order to amend the distortion due to signal shift along the time axis, the interpolation technique using the zero-padding is used for yielding the same number of spectral lines within each subband. Fig. 1 shows the foregoing procedure briefly. Fig. 2 is the time-scale map by using this modified harmonic wavelet transform of interior noise in WOT mode.

Using the time-scale map, psychoacoustic evaluation parameters such as A-weighted sound pressure level, loudness, sharpness, roughness, etc. can be obtained. Schiffbänker [5] mentioned that most important phychoacoustic parameter is the loudness of which the contribution ratio to subjective perception amounts to 80~85%, while the ratio of periodicity, sharpness and roughness are below 10 %. In this context, the loudness is only considered in the subjective evaluation of interior car noise based on Schiffbänker's findings as a first step towards subjective quality evaluation. Fig. 3 shows the specific loudness contour and loudness by Zwicker's method [6]. Time domain masking is not yet considered in this paper, and it will be included in further study. In Fig. 3, engine speed corresponding to the largest loudness level can be found near 4848 rpm, and the firing frequency of 160 Hz of 4 cylinder engine is the major cause.

3. HARMONIC COMPONENT ANALYSIS BY SPECTROGRAM

Vehicle interior noise for various running modes is composed of harmonic and non-harmonic components and the former is related to the engine speed. Although 1/3-octave band analysis is useful for evaluating psychoacoustic parameters, it is not suitable for analyzing the auditory effects of harmonic components. In this study, a vehicle with 4 cylinder, 4 cycle engine is considered and the concerning operating range of engine speed is 2000~5000 rpm. In this case, major harmonic contributors to subjective perception are limited to within 1 kHz and 10th harmonics of firing frequency, which can be considered as enough for quality analysis. Although the original data was sampled by 32 kHz, the spectrogram can be obtained by resampling the original sampled data with 2 kHz. Fig. 4 shows a rpm-frequency based spectrogram of interior noise and the characteristic of each harmonic component can be observed very easily. Fig. 4 is the result of averaged spectrogram of multiple experimental data under the same test condition. In Fig. 4, it is noted that the amplitudes of 2.5, 3 and 3.5th harmonics are large comparable to the 2nd, 4th and 6th harmonics. However, the theory of hearing perception [7] says that large stimuli in low frequency range mask small stimuli in higher frequencies and, therefore, all the spectral components are not influential to the noise quality considering this viewpoint. By using the hearing model of ISO/IEC [7], modified spectrogram effective in actual perception can be drawn and is shown in Fig. 5. One can find in Fig. 5 that the 2nd harmonic component largely contributes to the total loudness at the maximum loudness condition and the 2nd, 4th, 5th and 6th harmonics are masking other harmonic components.

4. CONCLUSION

Wavelet transform is used in investigating the noise quality of vehicle interior noise in transient running modes. The wavelet transform represented by 1/3-octave band format is proved as useful for estimating psychoacoustic parameters. Time-scale map of interior noise is obtained from 1/3-octave band analysis based on the modified harmonic wavelet transform, and loudness and specific loudness at each time step are shown. Spectrogram obtained from resampled data and hearing model considering masking effect can give detailed information on the major contributors of harmonic noise components in subjective perception.

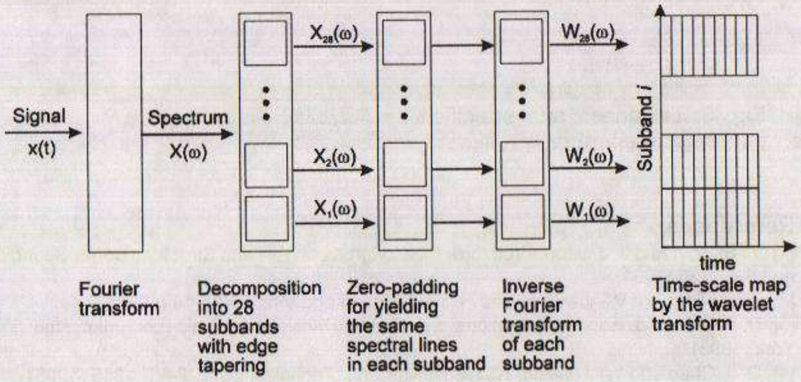

Fig. 1. 1/3-octave band analysis procedure using wavelet transform.

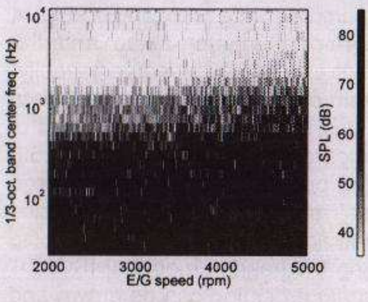

Fig. 2. Time-scale map as a result of wavelet transform.

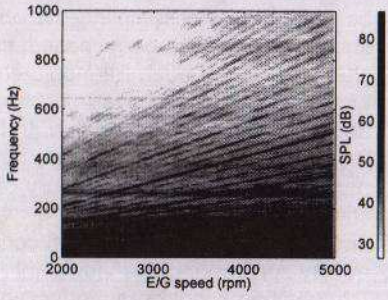

Fig. 4. Spectrogram of interior car noise below 1 kHz.

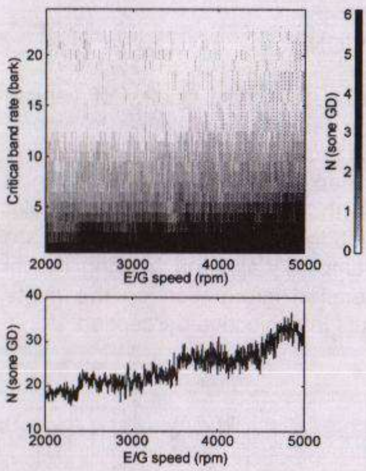

Fig. 3. Loudness and specific loudness of interior car noise.

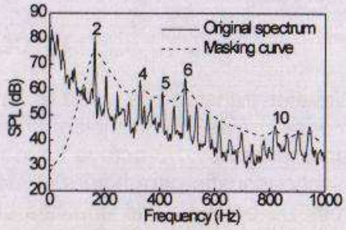

Fig. 5. Spectrum and masking curve of interior car noise at maximum loudness condition.

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