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Sound quality evaluation of the booming sensation for passenger cars

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ABSTRACT

Automotive booming noise due to powertrain occurs when pure or narrow band tones related to the firing frequency of engine and its harmonics excite the passenger cavity, which entails a prominent increase of sound intensity. The booming sensation has been considered as very important to the acoustic comfort of passengers. In this study, a sound quality index which can objectively evaluate the booming sensation was derived. Because of the tonal nature of powertrain booming noise, subjective pitch was employed to find only aurally relevant tonal components which influence booming sensation as well as loudness. Using the empirical data and the frequency difference limen for just-noticeable change of booming sensation obtained from the listening test, an existing pitch extraction algorithm could be modified. The modified pitch model was applied to the interior noises of accelerating passenger cars together with a loudness analysis for representing the objective features of booming feeling. Subjective tests using the magnitude estimation method were conducted to evaluate the degree of booming sensation. Finally, *booming strength* was proposed for quantifying the booming sensation, which was validated by subjective results. The correlation coefficient between the derived *booming strength* and the degree of booming sensation obtained by the subjective test was 0.926.

1. Introduction

Various vehicle noise sources and excitation mechanisms are related to various perceptual feelings and their attributes. Examples include cavity booming, driveline rumble, gear rattle, timing belt whine, intake hiss, exhaust roar, wind whistle, tire whiz, brake groan, door closing sound, etc. Annoyance of the car noise can be considered an overall feeling to a combined sound of these noises although the visual and vibrational inputs can additionally affect the sensation as well as the regional or racial preference. Among many noises which can be heard inside a car, the booming noise is usually considered as one of the very annoying acoustic features that influence the acoustic quality, thus the value, of the car. An international test results on the automotive sound quality [1] revealed that the peoples in the far-eastern Asian countries were more sensitive to booming noise than western peoples in general.

There are many origins of booming noise in a vehicle that cause the pressure rise problems when coupled with the passenger cavity resonance: engine and drive train excitation, excessive radiation from intake/exhaust systems, road excitation, wind fluctuation, etc. The road boom appears at certain speed of the vehicle when, usually, a part of body panels or cavity severely responds to the road excitation. The air buffeting appears at vehicle speeds at which the passenger cavity responds, in a feedback sense, to the flow fluctuation at the opening of a window or sunroof. The powertrain boom consists predominantly of pure or narrow band tones related to the fundamental firing frequency of the engine and its harmonics. The booming sound from intake or exhaust system also has similar characteristic with the powertrain boom. Consequently, a passenger in a vehicle is to be more often exposed to the booming phenomenon related with the engine rotation and firing than other causes of booming noise.

The purpose of this study is to suggest an improved sound quality (SQ) index that enables a precise and realistic evaluation of the degree of booming sensation mainly associated with the engine activities. To this end, first, previous works on analyzing the booming noise and evaluating the degree of booming sensation were investigated and the problems in using the previous methods were studied. Listening tests on the booming noises were conducted to find the extent of relation between loudness and booming sensation. Then, the pitch concept was employed to objectively and effectively represent the auditory perception due to the pure or very narrow band tones related to engine rotation and firing. Existing pitch extraction algorithm was modified to fit the empirical data by Zwicker and Fastl [2] and the frequency difference limen (DL) for just-noticeable change of booming sensation obtained from listening test. Finally, a SQ index, called the *booming strength* (abbreviated as BS hereafter), was derived for quantifying the

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booming sensation. Proposed BS was validated by the correlation between the subjective and objective results.

When the overall booming perception is being evaluated in an accelerating car, the time change rate of each major spectral component of interior sound contributes to the final overall impression as well as the aforementioned spectral composition of engine harmonics. Usually, for commercial cars, the former characteristic is counted as important only for several short engine speed ranges during low to high acceleration. This study was confined to the feeling due to the latter condition which is always felt, sometimes described as moaning, throughout all the periods of accelerating engine operations.

2. Review of the existing analysis techniques

2.1. Analysis methods for booming noise

The waterfall analyses such as short time Fourier transform (STFT) or wavelet transform have been used to see the spectral and temporal pattern of time-varying sounds. Specially, for characterizing the booming noise of an accelerating car, the order analysis, an abbreviated version of waterfall analysis, has been usually utilized. By order analysis, one can trace the change of sound level related to the fundamental frequency of engine firing and its harmonics, viz., for four-cylinder engines, C2, C4, C6, etc. as a function of engine revolution per minute (RPM) or vehicle speed. Here, C1 denotes the rotational frequency of crankshaft of an engine and the number after the character C signifies the harmonic order. Therefore, C2 means the second harmonic of crankshaft rotational frequency or the firing frequency of a four-cylinder engine.

Fig. 1a and b show the results of the STFT and order analysis on interior noise of a passenger car with a 4-cylinder engine in acceleration from 2000 to 6000 RPM, respectively. The noise was recorded by an artificial head fixed at the co-driver seat. One can find, along the variation of RPM, that the SPL of components related to rotational frequency of engine are prominent in comparison with other frequency components From these figures, two harmonic components of C2 and C4 for the car seem to be most important in the booming sensation as mentioned in a previous work [3] because they usually dominate the overall magnitude of interior noise. However, in some cases, sound level of one of higher harmonic components such as C6, C8, C10, etc., is more than or nearly equal to that of the C2 or C4 component. Such large values in high order harmonics usually come from the resonant radiation of intake or exhaust system. More important thing is not always easy to find any direct correlation between the results of an order analysis and the booming sensation, because A-weighted or flat-weighted SPL cannot sufficiently express the perceptual feeling [4].

Generally, SQ metrics such as loudness, sharpness, roughness, and fluctuation strength have been employed for the SQ analysis and among these SQ metrics, loudness is regarded as the most important metric. In Fig. 1c, the result of loudness analysis is displayed. It shows that loudness is dominant between 1 and 2 Bark (100–200 Hz in center frequencies of critical bands) corresponding to the C2 component within the range between 3000 and 4000 RPM. Additionally, in a rough manner, one can indicate that relatively strong booming would happen in this RPM range compared with other ranges. In spite of this result, however, one wonders about whether loudness analysis can describe the perceptual feeling associated with the sounds that are mainly dominated by pure

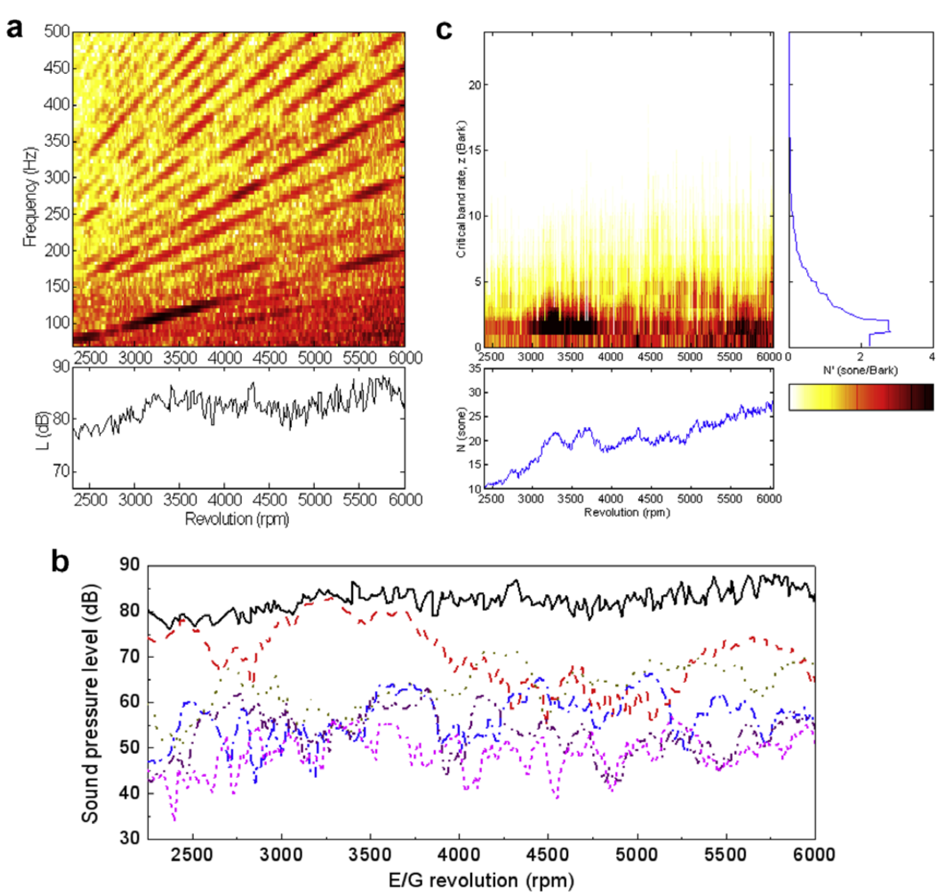

Fig. 1. Analysis of a car interior noise during acceleration: (a) STFT, (b) order analysis, (c) loudness analysis: at Fig. 1b, (—) overall; (- - -) 2nd order (C2); (···), 4th order (C4); (- · -) 6th order (C6); (- · ·-) 8th order (C8); (- - -) 10th order (C10).