SIMPLE ESTIMATION OF HIGH-FREQUENCY RADIATION FROM A MUFFLER SHELL

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1. INTRODUCTION

The exhaust noise is an important noise source in vehicles that not only contributes to the pass-by noise and the overall vehicle interior noise level but also determines the sound quality of the vehicle noise. Some amount of exhaust noise is transmitted into the ambient air through the shell of the muffler. This break-out noise through the outer jacket and the endplate has been studied by many researchers, e.g., Olson et al. (1977), Munjal (1998). In addition to such air-borne sound transmission, the outer wall of the muffler radiates structure-borne sound that is induced by the excitation of the exhaust gas flow and the vibration transmission from the connected exhaust pipes. The acoustic design of the exhaust muffler has mainly focused on reducing the discharge noise from the tailpipe. However, the noise that is transmitted through the muffler jacket and the endplate becomes important because the discharge noise is reduced by the muffler, which is due to its larger size in a recent, proper acoustic design. In many automotive companies, the design guidelines focus on the lowest resonance frequency and the stiffness of the shell, which is related to the noise radiation from the muffler shell.

In Figure 1, the exhaust-related noise spectra of a compact car are shown and these spectra were measured at a 45° angle and 0.5 m from the tailpipe's opening at the same height as the tailpipe when the engine speed was 3000 RPM. The acceleration of the engine block and the velocity of the muffler's surface were measured by using an accelerometer (PCB 353B16) and a laser vibrometer (Polytec OFV 3001, 303), respectively. The partial coherence function (PCF) technique (Wang and Crocker, 1983) was used to analyze the contribution of the muffler's surface to the overall exhaust noise. The noise radiates from the surface of the muffler can be classified as air-borne and structure-borne sound, as mentioned earlier. In Figure 1, the air-borne sound, like the discharge noise, was comprised of low frequency components and structure-borne sound, which was caused by the vibration of the muffler; the noise was concentrated in the 500~3000 Hz range. Here, the outer surface of the muffler was the most significant source of exhaust noise in the mid- and high-frequency ranges (630~3000 Hz). Consequently, the analysis of the exhaust noise should encompass a wide frequency range that includes very high frequencies. Unfortunately, it is not easy to find any unified method for dealing with such a wide frequency span. This problem persisted until recently because the muffler's design engineers could not find any appropriate computation tool to analyze the sound radiation from the shell, in particular at high frequencies.

To calculate the sound radiation from an arbitrary vibrating body, like a stamped muffler, the boundary element

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The direct boundary element method, which is based on the Kirchhoff-Helmholtz integral equation, has been popular for analyzing low frequencies in acoustic systems at the frequency range of $ka < 20$ (for example, Kim et al., 2007). This has been useful because the operating frequency of the power plant and its high-order harmonics are related to the low-frequency peaks. When using the BEM, the applicable high-frequency range is determined by the characteristic size of the elements. In spite of the fact that the number of elements should increase when calculating the acoustic response at high frequencies with precision, the available high frequency is limited due to the computer's capacity and the numerical errors. It is usually suggested that six linear elements or four quadratic elements are needed to handle the shortest wavelength of interest in the model (Marburg, 2002). By utilizing the acoustic BEM, one can predict the overall level or the energy envelope of the radiated sound from a vibrating arbitrary body. However, beyond the aforementioned high-frequency limit with a fixed number of boundary elements, the acoustic response cannot be calculated satisfactorily by using the conventional BEM. It should be recalled that the high frequency is very closely related to the subjective response of the human being. One can find many objective noise evaluation indices that are based on the 1/3-octave band spectrum, which includes a few kHz (Beranek and Ver, 1992). It should also be noted that the ISO standards related to the sound are usually described with 1/3-octave bands, which include high frequencies. Other techniques have been developed to deal with the high frequencies above: the Schroeder cutoff frequency (Schroeder, 1954), the statistical energy analysis (Lyon and Maidanik, 1962; Lyon and DeJong, 1975), the ray tracing method (Schroeder, 1969; Chae and Ih, 2001), and the beam tracing method (Jeong et al., 2009). However, a new technique has been clearly needed to deal with high-frequency sound radiation problems that incorporate small elements and short calculation times with acceptable precision.

To solve this problem, Seybert and Rengarajan (1987) first derived a simplified boundary integral equation that was based on the Sommerfeld radiation condition. It was certainly useful at high frequencies, but erroneous results were obtained in the low-frequency range due to the deficiency in dealing with bulk reacting features. Wu et al. (1993) adopted the interpolated Green function in the frequency domain and achieved a short computational time. However, this method had problems dealing with large models because it needed a large amount of memory. Guyader (1994) and Guyader and Loyau (1997) proposed a method that employed the frequency-averaged quadratic pressure. They considered a vibrating surface as the assemblage of monopole sources and neglected the dipole source distribution, from which errors were caused for nearly rigid surfaces. Mahe et al. (1993) introduced the radiation coefficient and the normalized impedance into the boundary integral equation. Unfortunately, these coefficients should have been determined from the user's experience. Fahline and Koopmann (1997) classified the boundary sources with dipoles, monopoles, and tripoles. The boundary integral could be evaluated with fewer elements than the conventional BEM. However, an additional modeling effort was needed. Kim and Ih (2002) modified the boundary integral equation into a quadratic form to enable the prediction of sound levels in the 1/3-octave band analysis. Monopole and dipole source terms in the conventional BEM were transformed into the auto- and cross-spectra of two vibrating sources, in which the cross-spectra were eventually neglected by assuming that the involved correlation coefficients were negligible. The over-determination for overcoming the nonuniqueness in the exterior radiation problems was unnecessary. All of the aforementioned studies were attempts to extend the applicable high-frequency range or to reduce the calculation time for a given boundary element model.

In this paper, by adopting the frequency band calculation method by Kim and Ih (2002), a high-frequency band analysis of the radiated sound from an arbitrarily shaped muffler shell was analyzed. To expand the applicable range to higher-frequency bands, the source terms in the Kirchhoff-Helmholtz integral equation were modeled with incoherent auto-spectra source elements and the phase term was removed. The method was actually applied to an arbitrarily shaped muffler with an approximate size of 0.5 m (L) × 0.3 m (W) × 0.08 m (H). The resulting trend in the frequency spectrum showed that the band analysis method, which was based on the modified BEM, can be used to approximately predict the exterior-radiated sound levels in the high-frequency bands.

2. SIMPLIFIED BOUNDARY ELEMENT METHOD

The acoustic pressure $p$ at a field point $r$ that is generated by the harmonic vibration of a surface with an area $S$, and a

![Figure 1. One-3rd octave levels of the classified sources.](image)