

Active Booming Noise Control for Hybrid Vehicles

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ABSTRACT

Pressure variation during engine combustion generates torque fluctuation that is delivered through the driveline. Torque fluctuation delivered to the tire shakes the vehicle body and causes the body components to vibrate, resulting in booming noise. HKMC (Hyundai Kia Motor Company)'s TMED (Transmission Mounted Electric Device) type generates booming noises due to increased weight from the addition of customized hybrid parts and the absence of a torque converter. Some of the improvements needed to overcome this weakness include reducing the torsion-damper stiffness, adding dynamic dampers, and moving the operation point of the engine from the optimized point. These modifications have some potential negative impacts such as increased cost and sacrificed fuel economy. Here, we introduce a method of reducing lock-up booming noise in an HEV at low engine speed. Generating a torque profile via the propulsion motor, which has the anti-phase profile of the driveline vibration, can therefore suppress driveline fluctuation. Engine vibration extracted from the HSG (Hybrid Starter Generator) is used for the desired input signal. The generated signal, based upon the rotation angle of the driving motor, is used as a reference input for the RLS adaptive filter. The filter updates its coefficients to minimize the phase difference between the reference signal and the desired input signal. Frequency response characteristics of the powertrain driveline components are used to generate the anti-phase vibration profile of the point causing booming. Effectiveness was verified with development vehicles under various driving conditions. The results show an 8dB(C) improvement in booming noise, and 9dB and 4dB improvements in floor panel vibration and steering wheel vibration, respectively.

CITATION: Kang, H., Chung, T., Lee, H., and Ihm, H., "Active Booming Noise Control for Hybrid Vehicles," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(1):2016, doi:10.4271/2016-01-1122.

INTRODUCTION

Sales of eco-friendly vehicles focused on hybrids are increasing such that automotive makers are aggressively seeking improved ecofriendly technologies. HKMC has developed its own hybrid system called TMED(Transmission Mounted Electric Device)[1]; the TMED is equipped in the Sonata, and Optima Hybrids, which are selling steadily in the market. The system shown in Figure 1 is comprised of a propulsion motor, HSG (Hybrid Starter Generator), 6 speed A/T, engine clutch, combustion engine and high-voltage main battery.

The primary feature of the system shown in Figure.1 is the inclusion of two motors: one for propulsion and one for generating energy. The engine power can be used for generation or for propulsion via engine clutch control.

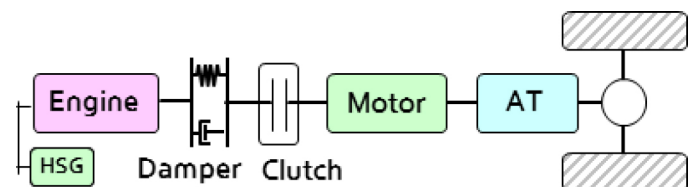


Figure 1. The power transmission structure of the TMED system

The TMED System has no torque converter, unlike the conventional internal combustion engine; and while this allows for minimal power loss, the driveline vibrations cannot be sufficiently attenuated, leading to poor NVH characteristics. Anti-Jerk technology is applied to reduce free vibration jerk in the drivetrain that occurs with the tipping of the pedal either in or out, gear shifting, and engine clutch jointing. [2,3] In addition, the booming noise generated by the excitation force from variations in engine combustion pressure causes the vehicle

body system to resonate at a particular engine speed. Lowering the torsion damper stiffness, adding dynamic dampers on the resonating body component and moving the engine operation point from the optimized point can reduce this booming noise, but the resulting increased cost and sacrificed fuel economy may degrade the vehicle's market value. While some additional advanced technologies such as active noise cancelling been developed, it needs components such as speakers, microphones, an amp and control devices.[4] Due to extra components which are relatively expensive limits its application only to the luxury vehicles.

In this paper, an active method is introduced to overcome the disadvantages of the passive methods mentioned previously. The active booming control method uses the frequency response characteristics of the powertrain driveline components to determine the anti-phase vibration of the booming and the point causing the vibration. Inserting the anti-phase torque of the booming causative torque reduces the noise very effectively, as verified using HKMC's 2016 Sonata Hybrid under various driving conditions.

MAIN SUBJECT

Booming noise can be divided in accordance with the rotational speed of the engine as follows: low-speed (under 1300 rpm), medium-speed (1800 to 2200 rpm) and high-speed booming noise (over 3000 rpm). Low-speed booming is a result of the resonance that occurs in body components such as the trunk lid and roof panel, and is caused by engine torque fluctuation transmitted through the driveline. We call this 'low-speed lock-up booming noise' in the TMED system because it only happens when the engine clutch has locked up.

Vibration Channel Analysis of TMED System

Booming noise, caused by driveline vibration from the excitation force generated at the ignition (power) stroke of the engine, has two pathways, as shown in Figure 2. One path is attenuated via the torsional damper and then travels through the motor, A/T, driveshaft, and tires, causing the vehicle to vibrate.

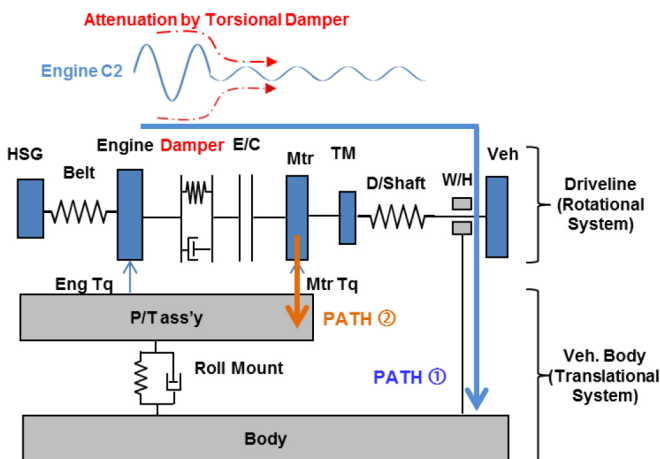


Figure 2. Delivery path of booming in the TMED System

In the case of a four-cylinder four-stroke engine, engine ignition occurs twice per one engine rotation, which means that the excitation force is two times faster than the engine speed (C2). When analyzing the frequency of low-speed lock up booming noise, the C2 component is the primary contributor, as seen in Figure 3.

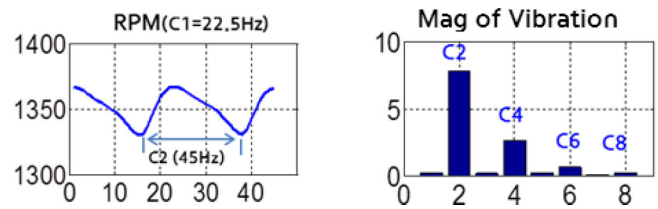


Figure 3. Frequency analysis result of booming noise in a 4-Stroke, 4-Cylinder Engine. The engine RPM (left) and the magnitude of the engine speed components via FFT (right)

The Active Booming Control

General Outline

The vibration caused by the engine excitation force is transmitted through the driveline including the propulsion motor. Therefore, if we identify the vibration phase, and include anti-phase vibration torque in the motor as shown in Figure 4, we can reduce the driveline vibration downstream of the motor. To this effect, we developed a combination of a phase estimation method based on frequency response and a feed-forward anti-phase torque control method.

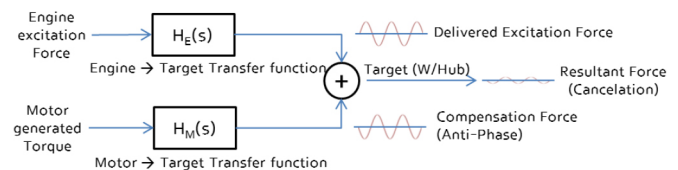


Figure 4. Main idea of anti-phase torque reduction in the driveline

Adaptive Filter [5]

The booming vibration phase is estimated using the adaptive filter, a base structure composed of a variable filter and updated algorithm, as shown in Figure 5.

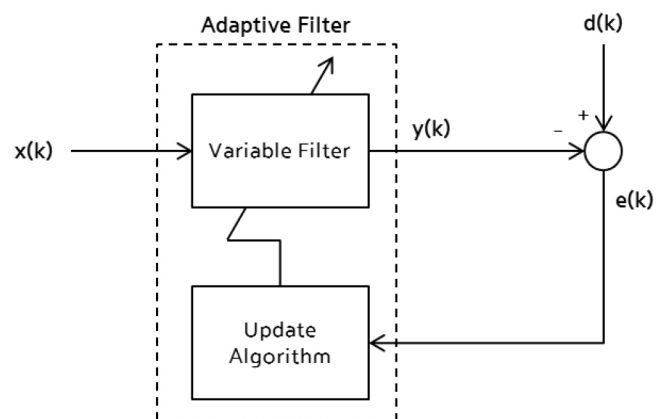


Figure 5. Outline of the adaptive Filter

Active Booming Control is based on a generic type of FIR (Finite Impulse Response) adaptive filter and can be realized in the direct form shown in [Figure 6](#).

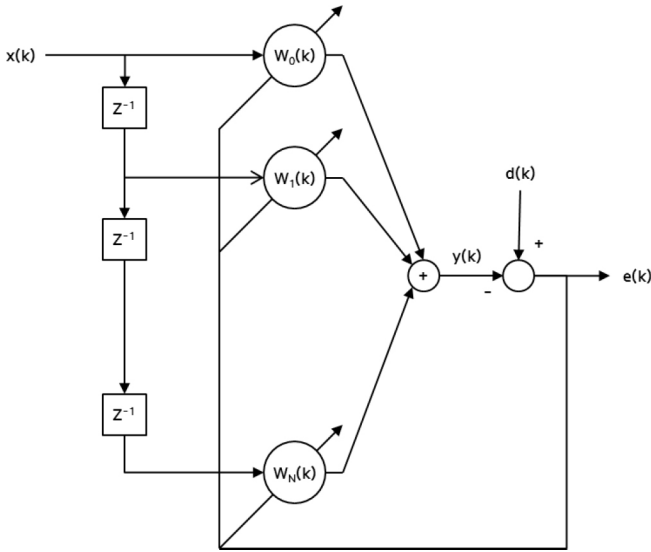


Figure 6. Adaptive FIR Filter

The input signal information vector at a given instant, k , is given by [\(1\)](#)

$$x(k) = [x(k) \quad x(k-1) \quad \cdots \quad x(k-N)]^T \quad (1)$$

N : Order of the filter

The coefficients, $w_j(k)$, for $j = 0, 1, \dots, N$ are adapted in order to minimize a given objective function. The objective function of an RLS adaptive filter utilized in the control algorithm is deterministic and is given by [\(2\)](#),

$$\begin{aligned} \xi^d(k) &= \sum_{i=0}^k \lambda^{k-i} \varepsilon^2(i) \\ &= \sum_{i=0}^k \lambda^{k-i} [d(i) - x^T w(k)]^2. \end{aligned} \quad (2)$$

Here, $w(k) = [w_0(k) \quad w_1(k) \quad \cdots \quad w_N(k)]^T$ is the adaptive-filter coefficient vector and $\varepsilon(i)$ is the a posteriori output error at instant i . The parameter λ is an exponential weighting factor that should be chosen in the range $0 \ll \lambda \leq 1$. This parameter is also called a “forgetting factor” since the information of the distant past has an increasingly negligible effect on the coefficient updating. As noted, each error consists of the difference between the desired signal, $d(k)$, and the filter output, using the most recent coefficients, $w(k)$. By differentiating $\xi^d(k)$ with respect to $w(k)$, we obtain the following [equation \(3\)](#):

$$\frac{\partial \xi^d(k)}{\partial w(k)} = -2 \sum_{i=0}^k \lambda^{k-i} x(i) [d(i) - x^T w(k)]. \quad (3)$$

By equating the result to zero, it is possible to determine the optimal vector, $w(k)$, that minimizes the least-squares error through the following relation shown in [equation \(4\)](#):

$$-\sum_{i=0}^k \lambda^{k-i} x(i) x^T(i) w(k) + \sum_{i=0}^k \lambda^{k-i} x(i) d(i) = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \quad (4)$$

The resulting expression for the optimal coefficient vector, $w(k)$, is given by [equation \(5\)](#),

$$\begin{aligned} w(k) &= \left[\sum_{i=0}^k \lambda^{k-i} x(i) x^T(i) \right]^{-1} \sum_{i=0}^k \lambda^{k-i} x(i) d(i) \\ &= R_D^{-1}(k) p_D(k), \end{aligned} \quad (5)$$

where $R_D(k)$ and $p_D(k)$ are the deterministic correlation matrix of the input signal and the deterministic cross-correlation vector between the input and desired signals, respectively. The inverse, $S_D(k)$, of the deterministic correlation matrix, $R_D(k)$, can then be calculated in the following [equation \(6\)](#),

$$\begin{aligned} S_D(k) &= R_D^{-1}(k) \\ &= \lambda^{k-i} \left[S_D(k-1) - \frac{S_D(k-1) x(k) x^T(k) S_D(k-1)}{\lambda + x^T(k) S_D(k-1) x(k)} \right]. \end{aligned} \quad (6)$$

By using the matrices above, the output signal, $y(k)$, priori error, $e(k)$, and filter coefficient, $w(k)$, can be expressed as [equation \(7\)](#) through [\(9\)](#), as shown below:

$$y(k) = w^T(k) x(k) \quad (7)$$

$$e(k) = d(k) - x^T(k) w(k-1) \quad (8)$$

$$w(k) = w(k-1) + e(k) S_D(k) x(k). \quad (9)$$

Estimation of Booming Vibration Phase

To minimize error, $e(k)$, the coefficients of the variable filter, $w(k)$, are updated via an updated algorithm using the objective function. Minimized error, $e(k)$, means that the output signal of the adaptive filters, $y(k)$, adequately tracks the desired signal, $d(k)$. Here, the desired signal, $d(k)$, is vibration speed with a C2 frequency caused by the engine excitation, which is transferred to the HSG. The output signal, $x(k)$, is a sine wave signal with a C2 frequency generated by the propulsion motor angle. The error signal, $e(k)$, is the difference between $d(k)$ and $y(k)$. The updating algorithm updates the variable filter coefficient, $w(k)$, to minimize error, $e(k)$, that makes the filter input, $x(k)$, phase modulated to the signal, $y(k)$, which tracks the