

Mechanism of Low Frequency Idling Vibration in Rear-Wheel Drive Hybrid Vehicle Equipped with THS II

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ABSTRACT

Although idling vibration is usually caused by 1st order of engine combustion force, other engine forces also occur at frequencies lower than the 1st order of combustion (called low frequency idling vibration in this paper). The drive-line of the Toyota Hybrid System II (THS II) has different torsional vibration characteristics compared to a conventional gasoline engine vehicle with an automatic transmission. Nonlinear characteristics caused by the state of backlash of pinions and splines influence changes in the torsional resonance frequency. The torsional resonance frequency of the drive-line can be controlled utilizing the hybrid system controls of the THS II.

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1. INTRODUCTION

A wide variety of hybrid vehicles (HVs) have been proposed and commercialized by automakers around the world. Generally, these HVs shut down the engine while the vehicle is stopped to improve fuel economy and lower emissions, resulting in an extremely quiet interior environment. However, HVs will engage the engine while stopped to charge the main battery or to warm-up the engine or catalytic converter. In these cases, idling vibration is generated by 1st order of engine combustion force. However, other engine forces occur at frequencies lower than the 1st order of combustion (called low frequency idling vibration in this paper). Low frequency idling vibration in vehicles installed with the Toyota Hybrid System II (THS II) [1] has a unique generation mechanism based on the characteristics of the drive-line and the engine speed during idling. This paper describes the mechanism of this low frequency idling vibration in a V6 rear-wheel drive (RWD) HV.

2. DEFINITION OF STEADY-STATE LOW-FREQUENCY IDLING VIBRATION

Idling vibration is generally described as a phenomenon caused by 1st order of engine combustion force. Low frequency idling vibration is the vibration that occurs at frequencies lower than the 1st order of combustion.

There are two types of low frequency idling vibration: steady-state vibration felt as a swaying motion and intermittent unsteady-state vibration felt as a rattling motion. The former is mainly caused by differences in combustion pressure between each cylinder in the engine [2] or imbalances in engine revolution. In contrast, the latter is

caused by unstable combustion pressure in each combustion cycle within the same cylinder [2][3][4]. This paper focuses on steady-state low frequency idling vibration (Table 1).

Table 1. Explanation of phenomenon.

V6 Engine	Idling Vibration	Low Frequency Idling Vibration
Engine Torque Fluctuation	1st Order of Engine Combustion (3rd Order of Revolution)	0.5th to 1st Order of Engine Revolution
Frequency (1,000 rpm)	50 Hz	8.3 to 16.7 Hz
Sensory Feeling	Shudder (Steady-State)	Sway (Steady-State) Rattle (Unsteady-State)

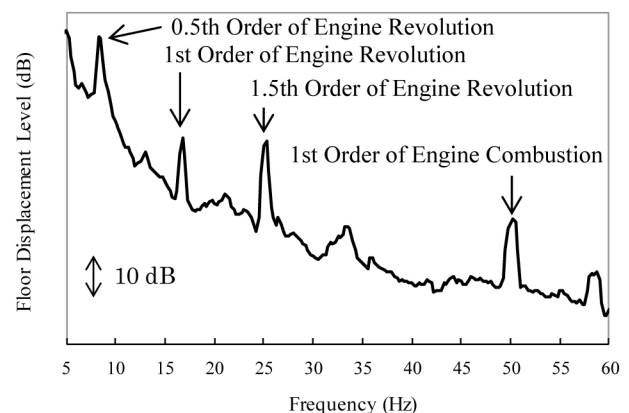


Figure 1. Floor vibration level of RWD HV under idling conditions.

Figure 1 shows the frequency analysis results for the floor vibration level at an engine speed of 1,000 rpm in a V6 rear-wheel drive (RWD) HV. The peak of idling vibration peak is at 16.7 Hz, which is the 1st order of

engine combustion (i.e., the 3rd order of engine revolution). However, there are multiple peaks at lower frequencies that are felt as a swaying motion. These peaks are examples of steady-state low frequency idling vibration. Vibration at the 0.5th and the 1.5th order of engine revolution are mainly caused by difference in combustion pressure between each cylinder. The 1st order of engine revolution is mainly caused by engine revolution imbalance. The level of vibration at 8.3 Hz, which corresponds to the 0.5th order of engine revolutions, is particularly large. The following sections focus on this frequency phenomenon.

3. FORCES GENERATING STEADY-STATE LOW-FREQUENCY IDLING VIBRATION

Of the forces generating steady-state low-frequency idling vibration, the primary cause of the 0.5th order of engine revolution is fluctuations in combustion pressure between each cylinder. The fluctuations are generally the result of differences in the air intake volume into each cylinder and differences in the quantity of fuel injected into each cylinder.

Figure 2 shows the measurement results of engine combustion pressure for each cylinder during idling in a V6 RWD HV. In this example, the combustion pressure increases cyclically in cylinder 5 and decreases cyclically in cylinders 3 and 4. This generates torque fluctuations in a cycle consisting of two engine revolutions, which acts as the 0.5th order of engine revolution force.

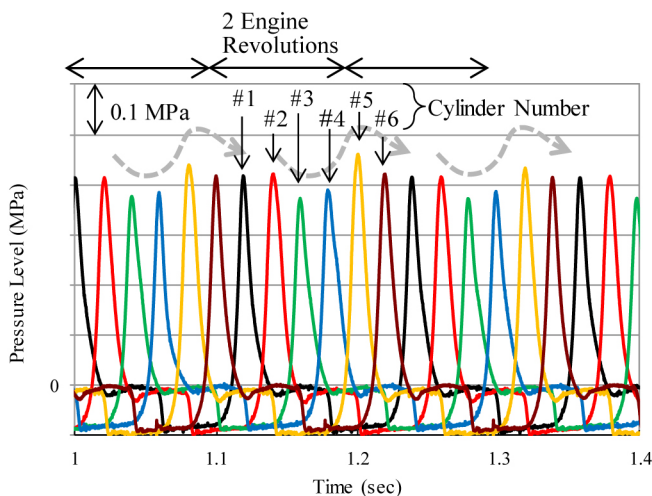


Figure 2. Internal cylinder pressure of engine.

4. VIBRATION TRANSFER PATHS

4.1. Effect of THS II Drive-Line on Vibration Amplitude

Steady-state low frequency idling vibration is the result of force generated by differences in combustion pressure between each cylinder. And the force is then transferred from the engine to the engine mounts and causes the floor to vibrate. This section focuses on the THS II drive-line as a transfer path specifically for HVs. Figure 3 compares the measurement results of crankshaft angular fluctuation in a V6 HV equipped with the THS II and a conventional

gasoline engine vehicle equipped with an automatic transmission (AT). Although the idling engine speed of the HV and conventional vehicle are different, the results were compared after changing the idling engine speed of the conventional vehicle to 1,000 rpm, the same as the HV. In both vehicles, the gear lever was placed in the P range and the air conditioning and all other accessory equipment were switched off.

The operating states of the HV include the application of high engine torque for charging the main battery (operation with load) and very low engine torque for warming up the engine or the catalytic converter (operation without load). However, to set an engine torque level similar to that of the conventional vehicle, both vehicles were operated without load. Under these conditions, the fuel injection quantity was adjusted to establish the same 0.5th order of engine revolution force. The other specifications of the test vehicles (i.e., the body and suspension) were the same. As shown in Table 2, the only difference between the two vehicles is the transmission.

Table 2. Test vehicle specifications.

		Hybrid Vehicle	Gasoline Engine Vehicle
Configuration	Engine	2GR-FXE	2GR-FSE
	Engine Mounts	Hydraulic Mounts	←
	Transmission	THS II	6-speed AT
	Suspension	Multi-Link	←
	Wheels	19-Inch	←
	Body	N-Platform	←
Operating Conditions	Engine Speed	1,000 rpm	←
	Shift Position	P	←
	Engine Torque	Low	←

Figure 3 shows that, at the 8.3 Hz peak for steady-state low frequency idling vibration, the HV was approximately 10 dB higher than the conventional vehicle.

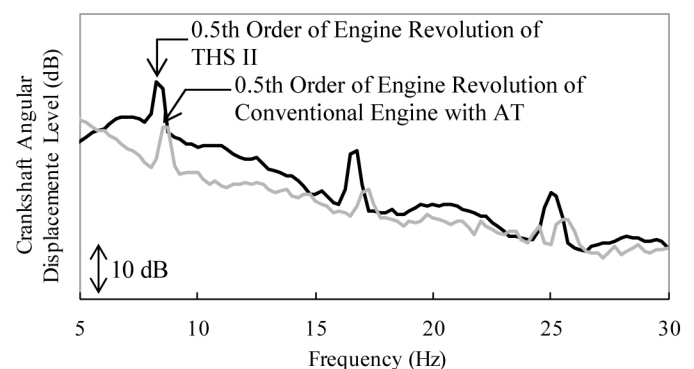


Figure 3. Comparison of crank angle vibration level.

Therefore, it was concluded that the THS II drive-line amplifies the 0.5th order of engine revolution component.

Figure 4 shows the inertia, stiffness, and damping elements of the THS II drive-line based on existing knowledge and the analysis results for torsional vibration [5]. For example, inertia reflects the