

Development of Active Control Engine Mount System for Reduction of Resonance Vibration at Engine Restart

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ABSTRACT

Active Control Engine Mounts are in mass production as a technology for the reduction of noise and vibration in complete vehicles associated with the use of V6 variable-cylinder engines. The research discussed in this paper developed a next-generation active control engine mount system that reduces vibration in complete vehicles occurring when the engine is restarted following idle stop or EV operation in a hybrid system. The fact that the timing of the powerplant resonance vibration that occurs at engine restart correlates strongly with the angle of rotation of the crankshaft was focused on, and a new control method was developed that predicts the timing and magnitude of resonance vibration and cancels it. In addition, the development of a system able to respond to high-amplitude engine resonance vibration has increased noise and vibration performance at engine restart following idle stop or EV operation in a hybrid system.

1. Introduction

Active Control Engine Mount (ACM) technologies actively operate the engine mounts using a pulse synchronized with engine speed as a reference signal in order to reduce the vibration transmitted to the body from the engine^{(1),(2)}. These ACM technologies are mainly employed in V6 variable-cylinder engines. Variable cylinder systems are technologies that reduce pumping loss and increase fuel efficiency by closing the valves in one bank of three cylinders during low-load operation, such as when the vehicle is traveling at a constant speed or decelerating. The amplitude of vibration increases in comparison to six-cylinder operation during three-cylinder operation due to the halving of the fundamental order frequency of the engine (from 3rd-order to 1.5th-order) as a result of the reduction in the number of firing cylinders and increased combustion pressure resulting from the increased work performed by each cylinder. ACM technologies realize the same level of noise and vibration (NV) performance during cylinder idling (three-cylinder operation) as during full-cylinder operation (six-cylinder operation), and thus contribute to the achievement of a balance between fuel efficiency and NV performance.

At present, the potential for introducing technologies such as idle-stop systems and hybrid systems to V6

variable-cylinder engines as a means of further increasing fuel efficiency is being investigated. Idle-stop systems control fuel consumption by shutting off the engine when the vehicle is stationary; hybrid systems perform the same function by shutting off the engine when the vehicle can be operated by the motor. These systems turn the engine off and restart it repeatedly during vehicle operation. Vibration occurs when the engine is restarted, and while it is of the same magnitude as the vibration that occurs when the driver intentionally starts the engine using an ignition switch or start button, it is more prone to be noticed because it suddenly occurs with no intention on the driver's part. In addition, a high frequency of stopping and restarting the engine while the vehicle is in operation makes the vibration even more noticeable, affecting the commercial appeal of the vehicle. Using a mass-production ACM system as a base, the research discussed in this paper advanced its functions to develop the first-ever ACM system that boosts NV performance at engine restart.

2. Development Goals

Goals for the development of a next-generation ACM system that would control the transmission of engine vibration to the vehicle at restart and realize NV

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performance targets were set as follows:

- (1) Study of the timing of vibration at engine restart, and development of a new ACM control method that operates the ACM at an amplitude that cancels the vibration; and
- (2) Development of an ACM system able to respond to high-amplitude resonance vibration at engine restart.

3. Configuration of ACM System

Figure 1 shows the ACM system fitted in a vehicle. The ACM are positioned at the front and rear of the V6 variable-cylinder engine, and an electronic control unit for control of the ACM (ACM-ECU) is positioned in the cabin. The data necessary for estimation of engine resonance vibration is received from an engine control unit (FI-ECU) positioned in the engine room. Figure 2 shows the communications configuration of the ACM system. The ACM-ECU receives an engine crank-angle signal, a top-dead-center signal, and engine information (information on the state of cylinder idling and information for judgment of the commencement of engine restart) from the FI-ECU, and operates the two ACM to reduce the transmission of engine vibration to the body.

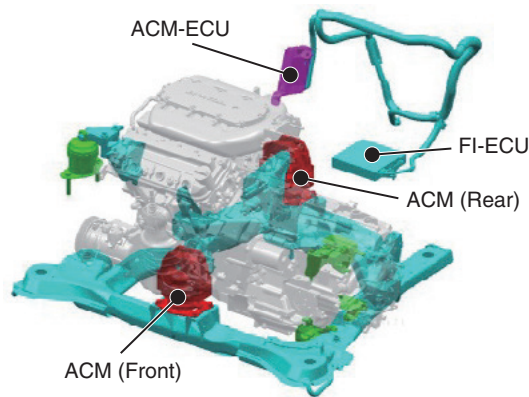


Fig. 1 ACM system layout

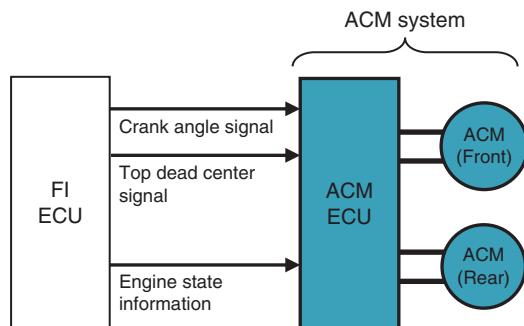


Fig. 2 ACM system communications configuration

Figure 3 shows the basic principle of reduction of vibration by the ACM. Vibration in the direction of rotation of the crank (roll), originating in torque fluctuations, is input to the front and rear engine mounts. In the case of conventional mounts, loads input from the engine are transmitted to the body via the mount rubber. By contrast, ACM systems reduce the transmission of vibration to the body by cancelling the engine vibration by means of the displacement of actuators positioned in the mounts.

Figure 4 shows the internal configuration of an ACM that cancels engine vibration. The ACM consists of a liquid-sealed mount and a linear solenoid. The impression of a current causes a plunger in the linear solenoid to oscillate vertically, vibrating an exciter plate that is connected to the plunger. This action causes the liquid pressure inside the liquid-sealed mount to fluctuate, displacing the rubber in the mount. The resulting vibration of the upper section of the mount, which is connected to the engine mount bracket, makes it possible to cancel engine vibration.

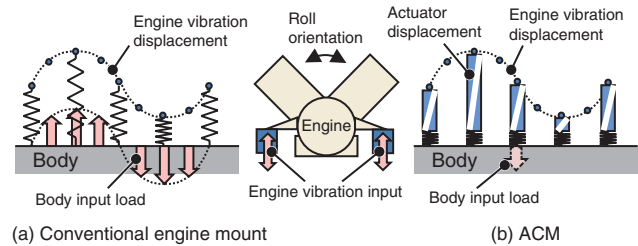


Fig. 3 Principle of vibration reduction

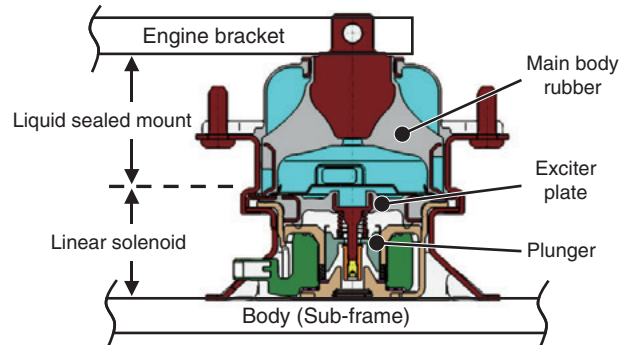


Fig. 4 Configuration of ACM

4. Reduction of Transmission of Resonance Vibration at Engine Restart to Body

4.1. Mechanism of Occurrence of Resonance Vibration at Engine Restart

As an example of the phenomenon of resonance vibration at engine restart, Fig. 5 shows vibration occurring when the engine is restarted following EV operation in a

hybrid system. This section will discuss the mechanism of occurrence of resonance vibration at engine restart.

When the engine is started, torque provided by the hybrid system motor rotates the engine crankshaft, and the pistons in the cylinders move up and down. At this time, the rotation of the crankshaft fluctuates, due mainly to in-cylinder pressure. The vibration resulting from this fluctuation is amplified as resonance vibration when engine speed increases and reaches the area of resonance, as determined by the spring characteristic of the engine mounts and the mass of the powerplant. This resonance vibration occurring at engine start is transmitted to the body via the engine mounts that support the powerplant. The difference between this phenomenon and the resonance vibration that occurs at engine restart in an idle-stop system is that the source of start-up torque is a starter motor rather than a hybrid system motor, and the starter motor torque does not reach the area of resonance of the powerplant, passing it due to the first firing of the engine. However, the basic principle of both types of resonance vibration is identical.

4.2. Development of ACM Control at Engine Restart

Resonance vibration at engine restart is a transient phenomenon, making the use of feedback control employing vibration data detected by sensors a challenge. In addition, the timing and magnitude of resonance vibration of the engine also change with the rapidity of the increase in engine speed when it passes the area of resonance of the powerplant. It was therefore necessary to develop a feed-forward control that would identify the timing and magnitude of resonance vibration in advance and control the ACM at the optimal timing and amplitude.

As indicated above, the vibration originating in fluctuation of the rotation of the crankshaft at engine restart is amplified and becomes resonance vibration when it reaches the area of resonance of the powerplant. This fluctuation in the rotation of the crankshaft is linked to the position of the pistons, in other words to the angle of crankshaft rotation, and the occurrence of resonance vibration at engine restart also has a correlation with the angle of rotation of the crankshaft. Figure 6 shows engine speed and resonance vibration at engine start-up in relation to the angle of rotation of the crankshaft. When the engine speed passes the area of resonance of the powerplant, the first resonance vibration occurs, with its point of origin at

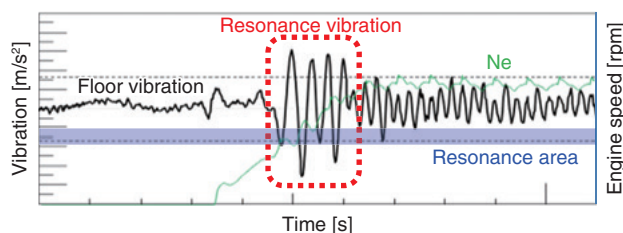


Fig. 5 Engine restart vibration (V6 engine hybrid vehicle)

the angle of rotation that represents top dead center. It is possible to estimate the timing of resonance vibration using the angle of rotation (crank angle) that becomes this point of origin.

To make it possible to estimate the magnitude of resonance vibration, it is necessary to stabilize that magnitude. Engine and motor control therefore attempts to prevent fluctuations in the magnitude of resonance vibration by controlling the speed of increase in engine speed at restart to a constant level.

Based on the above, using the crank angle and applying control to the speed of increase in engine speed at restart, a method of control was developed making it possible to estimate the timing (the crank angle at which vibration occurs) and magnitude of resonance vibration by means of the ACM-ECU.

Control of the ACM drive in response to transient high-amplitude resonance vibration will next be discussed. In order to respond to continuously occurring vibration in a variable-cylinder engine during full-cylinder and cylinder-idling operation, conventional ACM systems are able to rely on the continuous operation of the actuator to make it possible to change the amplitude of the ACM and cancel vibration. By contrast, in this case the actuator would not be in operation when resonance vibration occurred at engine restart, making it necessary to realize high-amplitude ACM operation by means of initial current control.

Figure 7 shows the control method employed in order to achieve the necessary amplitude of ACM vibration using initial current control. Vibration is generated in the ACM by repeated suction on the plunger in the ACM actuator due to the impression of a current in the coils and opening of the plunger due to the spring force of the exciter plate. At this time, the exciter plate position that represents the point of

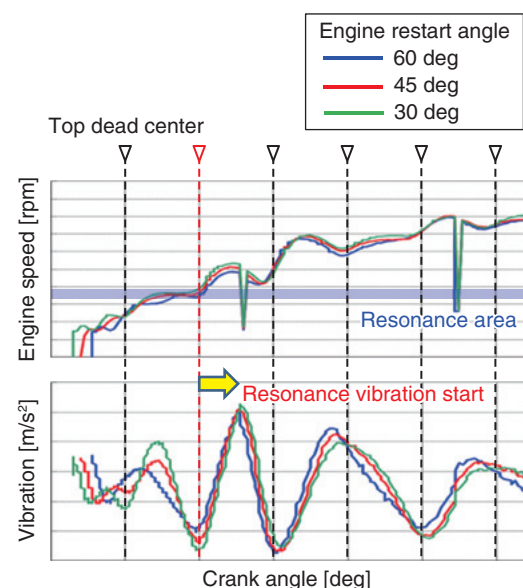


Fig. 6 Vibration at engine restart

balance between suction and opening of the plunger shifts further to the suction side the greater the magnitude of the vibration. The method adopted in order to cancel engine resonance vibration was therefore to impress a DC current in the coils and shift the position of the exciter plate to the suction side in advance, following which initial ACM current control is applied. Figure 8 shows the effects of this control method. The impression of an initial DC current makes it possible to drive the ACM to produce an amplitude of vibration that cancels resonance vibration at engine restart.

This method has made it possible to realize a feed-forward ACM control that accurately identifies the timing and magnitude of resonance vibration at engine start and drives the ACM to produce the necessary amplitude of vibration to cancel the resonance vibration.

4.3. Development of a High-amplitude ACM System

The maximum amplitude of vibration demanded from the ACM system in order to respond to resonance vibration at engine restart represented more than 1.5 times the force produced by a conventional ACM system. In addition, the greater amplitude of vibration also necessitated the realization of increased current responsiveness in the

actuators. In this development, it was therefore necessary to develop an ACM system that balanced high amplitude and high responsiveness.

To generate a high amplitude of vibration, it was necessary to increase the magnetomotive force that provides the source for ACM actuator thrust. Because magnetomotive force is the product of the number of coils in the actuator and the impressed current, this could be achieved by increasing the number of coils. However, if the number of coils was to be increased while retaining a conventional configuration, the exterior dimensions of the actuator would increase, thus increasing the size of the ACM, a factor that would affect their ease of vehicle fitting. In order to realize high amplitude without increasing the size of the ACM, a bobbinless configuration that did away with the bobbin that provided the support structure for the coils was adopted (Fig. 9). This helped to ensure coil winding space on the inner diameter of the coils, contributing to the prevention of an increase in the external dimensions of the ACM and making it possible to maintain the dimensions of a mass-production ACM while realizing high-amplitude operation.

The realization of the necessary increase in current responsiveness by increasing the number of coil windings will be discussed below. Current response, $I(t)$, is expressed by Eq. (1), and inductance, L , used in Eq. (1), is expressed by Eq. (2).

$$I(t) = \frac{V}{R} \left[1 - \exp\left(-\frac{R}{L} t\right) \right] \quad (1)$$

V : Voltage impressed in coil

R : Coil resistance

L : Inductance

$$L = \frac{\mu N^2 \pi r^2}{l} \quad (2)$$

μ : Magnetic permeability

N : Number of coil windings

r : Radius of coil

l : Length of coil

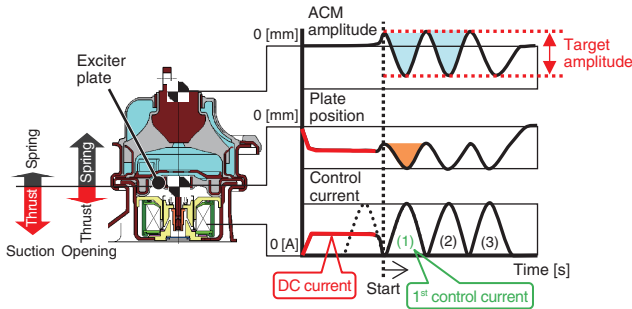


Fig. 7 ACM control method of using initial DC current

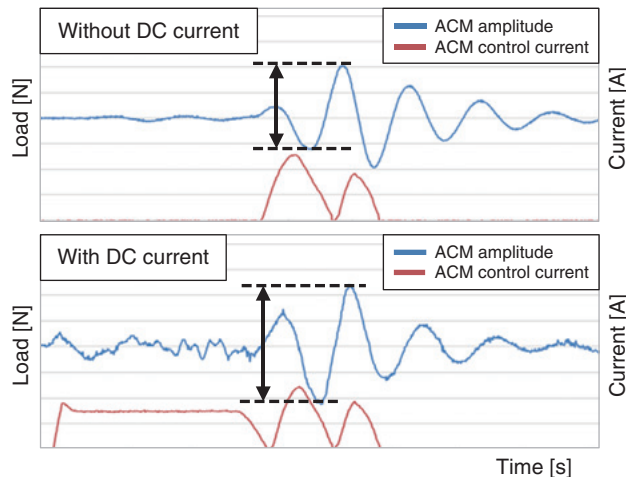


Fig. 8 Effect of developed ACM control method

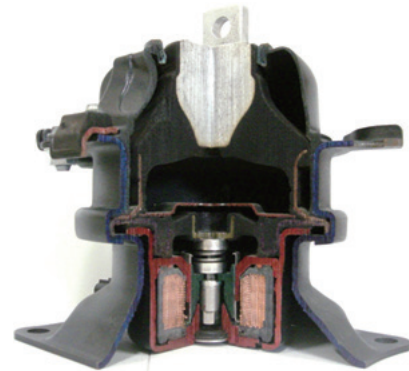


Fig. 9 Bobbinless ACM actuator

Equations (1) and (2) indicate that increasing the number of coil windings, N , in order to realize high amplitude will increase coil resistance, R , and inductance, L , resulting in a decline in current responsiveness. This research therefore employed a booster ACM ECU provided with a voltage booster circuit in order to increase current responsiveness by increasing the voltage impressed in the coil, term V in Eq. (1).

The use of a bobbinless actuator and a booster ACM ECU (Fig. 10) balanced high amplitude with high response, helping to enable the development of an ACM system able to respond to high-amplitude resonance vibration at engine start.



Fig. 10 Booster ACM ECU

5. Effect of System in Complete Vehicle

The effect of reduction in the transfer of resonance vibration to the body at engine restart realized by ACM control and the high-amplitude ACM system was verified. Figure 11 shows vibration measurement points in a complete vehicle. The load under the rear ACM (Point A in Fig. 11) and floor vibration under the driver's seat (Point B in Fig. 11) were selected for measurement, and the effect of the system on NV performance in a complete vehicle was studied.

Figure 12 shows the load under the rear ACM at engine restart with the ACM in operation and not in operation. The use of ACM control makes it possible to reduce the transmission of resonance vibration to the body at engine restart by 60% or more. Figure 13 shows vibration of the floor in the cabin at engine start. The target for NV performance in the complete vehicle is shown by the arrow. The use of ACM control reduced floor vibration, making it possible to realize the targets for NV performance.

The results discussed above verify the effect of application of ACM control at engine restart on NV performance in a complete vehicle.

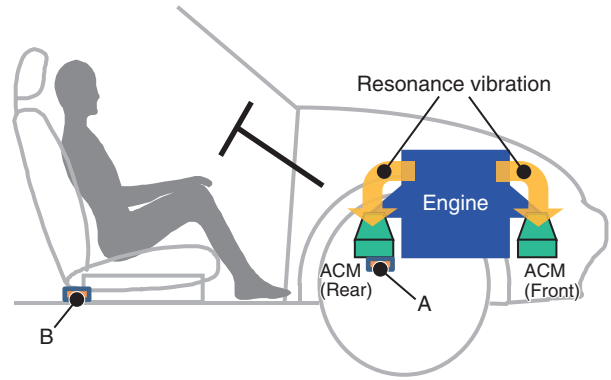


Fig. 11 Measurement points

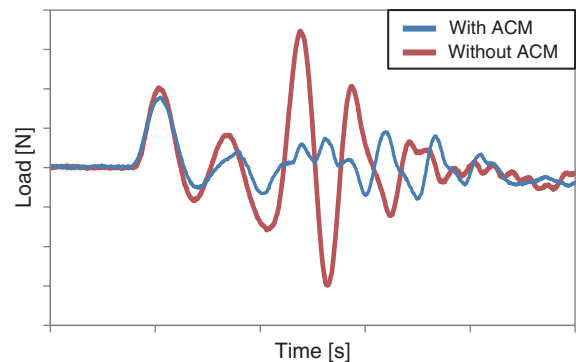


Fig. 12 Input load for rear ACM

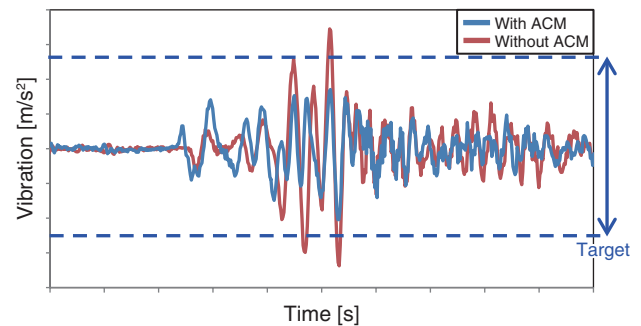


Fig. 13 Floor vibration

6. Conclusion

The development of a next-generation ACM to respond to the issue of resonance vibration produced at engine restart without the intention of the driver made it possible to realize NV performance targets in a complete vehicle.

- (1) A new ACM control method was developed that identifies the timing of resonance vibration at engine restart and impresses a DC current in advance, making it possible to realize the high-amplitude ACM drive

necessary to cancel the resonance vibration of the engine using initial current control, thus reducing the transmission of vibration to the body.

- (2) The use of a bobbinless actuator and a booster ACM ECU made it possible to develop an ACM system realizing high-amplitude vibration and high current responsiveness when resonance vibration occurs at engine restart.

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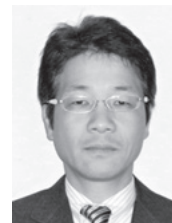
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