

Development of Active Control Engine Mount

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ABSTRACT

An active control engine mount system has been developed to control noise and vibration in a completed vehicle employing a 3-liter V6 cylinder-on-demand engine. The research described in this paper focused on the fact that engine vibrations caused by fluctuations in torque can be estimated from fluctuations in crank revolution, and developed a new fixed feed forward control algorithm which does not employ sensors such as a load cell or an accelerometer. A higher responsive low-heat linear solenoid actuator has been developed for use in the system, and its unique coupling structure with an excitation plate inside the hydraulic engine mount makes it extremely reliable. The results show that noise and vibration performance during three-cylinder drive is equivalent to that obtained at full-cylinder drive.

1. Introduction

Active Control Engine Mount (ACM) technology is to control engine mounts actively by taking pulses synchronized with engine rpm as reference signals. Active Control Engine Mounts have been studied since the 1980s⁽¹⁾. Various adaptive feedforward control methods have been investigated, such as one to monitor and cancel the input load of engine vibrations using a load sensor, and one to monitor directly and cancel the evaluation points of noise and vibrations (NV) of the car body using microphone or accelerometer. In the late 90s, two types of ACMs were developed and practically used. One is a method to operate the vacuum actuator by using mapping control⁽²⁾. Another one is to operate the electromagnetic actuator by using adaptive control⁽³⁾. The functions of the former are limited to the idling range, so that the system is extremely simple. The latter method controls a wider range up to 130 Hz, however it employs an electromagnetic actuator with a permanent magnet or an exclusive load sensor, and this results in higher

system costs and heavier weight. The target of this research is an engine equipped with the cylinder-on-demand system. From the point of view of cost reduction, this study focuses on ACM that ensures reliability and adequate vibration isolation over the rpm range in three-cylinder drive, and the control method that does not require exclusive sensors.

The cylinder-on-demand system reduces pumping loss and improves mileage by keeping the valves of the three cylinders on one bank closed when the load during operation is light, such as, when the engine is running at constant speed or decelerating. However, the vibration amplitude in three-cylinder operation increases due to the halved basic order caused by less cylinders in operation and the higher combustion pressure due to the increase in the workload per cylinder. Therefore, the isolation capacity of conventional engine mounts is insufficient, and the deterioration of NV performance in the completed vehicle is one of the biggest concerns. The aim of the ACM development is to minimize the costs and to achieve NV performance that does not make a driver feel like a vehicle is under three-cylinder operation.

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2. Overview

2.1. Vibrations of the V6 Cylinder-On-Demand Engine

Generally, engine vibration is classified into two categories. One is generated due to the inertia force caused by the motion of components, and another one is generated due to engine combustion. The vibration under three-cylinder operation of the 60-degree V6 cylinder-on-demand engine is mainly due to the 1.5th order of the engine rpm. However, vibration caused by engine combustion becomes the main contributor since the inertia force that accompanies the motion of the piston-crank is balanced regardless of the number of cylinders in operation. Thus, if the combustion pressure or the fluctuation in crank rotation that occurs due to the combustion pressure is determined, the engine vibration is estimated and applied in ACM control.

2.2. System Overview

Figure 1 shows the system configuration. The V6 power plant is mounted on ACMs at the front and rear parts of the sub-frame, under the transmission, and on both sides of the side frame. The most efficient ACM locations are at the front and rear since the engine rotational vibrations due to combustion occur in vertical direction at these locations, and the vibration highly contributes to NV phenomena in a completed vehicle. The ACM control unit (Electronic Control Unit, ECU) is located in the cabin, and is connected to the engine ECU. The harness for driving the ACM is connected to the two ACMs in the engine room.

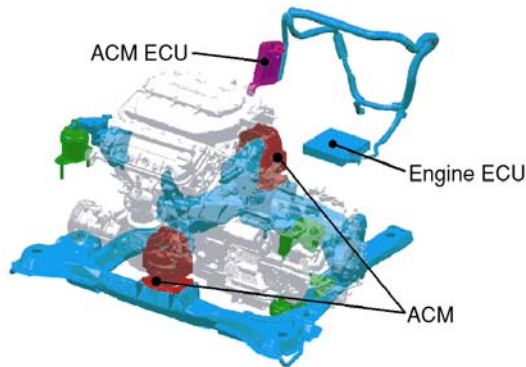


Fig. 1 ACM system configuration

Figure 2 shows the block diagram. The ACM ECU receives the crank and the cylinder pulse signals for the existing engine control from the engine ECU. The deviations in the crank rotation caused by engine combustion are detected from the crank pulse, while the cylinder pulse is applied as the phase reference for control. Thus, this system

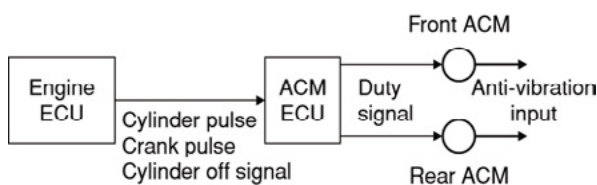


Fig. 2 Block diagram of ACM system

estimates the magnitude and phase of the engine vibrations, determines the duty signal for operating the ACM and vibrates the excitation plate inside of the ACM using the actuator.

3. Control System

3.1. Engine Excitation Force and Crank Rotation Torque

Figure 3 shows a general piston-crank model. Because of the angle of connecting rod β , the force F due to combustion is separated into the force F_s , which pushes the cylinder walls, and the force F_c , which pushes the connecting rod.

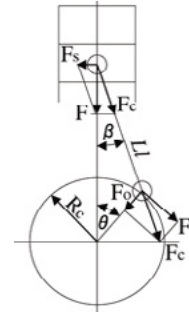


Fig. 3 Piston-crank model

The force that pushes the cylinder walls, F_s , and turns the crank, T_q during combustion are expressed as below.

$$\begin{aligned} F_s &= F \tan \beta \\ F_c &= \frac{F}{\cos \beta} \end{aligned} \quad (1)$$

$$\begin{aligned} T_q &= F_c R_c \sin(\theta + \beta) \\ &= F R_c \sin(\theta + \beta) / \cos \beta \\ &= F R_c \left(\sin \theta + \frac{1}{2 \lambda_c} \sin 2\theta \right) \\ \lambda_c &= L_l / R_c \end{aligned} \quad (2)$$

As calculating the effect of phase θ of the crank with the equation above, F_s and T_q are considered to have an almost proportional relationship at the ignition timing ($\theta = 0 \sim 20^\circ$) in the three-cylinder operating condition. Therefore, the magnitude of the engine vibrations is estimated by detecting the fluctuations in the crank rotation from the crank pulse and calculating the P-P value. The phase is also calculated by comparing the timing at the maximum P-P value and the cylinder pulse (TDC reference pulse).

3.2. Control Algorithm

Figure 4 shows the details of the control algorithm. This system determines the current waveform that drives the actuator based on the estimated engine vibration values mentioned in 3.1. The vibration calculation part calculates

the P-P value of the crank rotation, compares the peak timing and the TDC timing, and calculates the phase. Next, the duty control part inputs a waveform to the front and rear ACM to cancel the engine vibration in every cycle. Concretely, the aggregates of duty signals are outputted in the drive cycle. The phase is obtained from the reference pulse of each TDC.

Compared to the method to control the replacement of fixed maps as an engine is in operation, this one is superior because it is capable to follow up even if operating conditions such as engine rpm and load fluctuate or deteriorate.

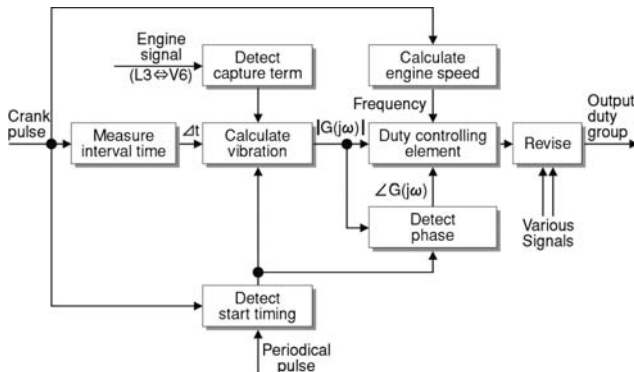


Fig. 4 Detailed block diagram of ACM

4. Actuator

The characteristics required for the ACM actuator are high response / force, small size, low weight, minimum heat buildup in coil, reliability, and low cost. Various types of electromagnetic actuators are compared based on these requirements. As a result, a linear solenoid system with well-balanced performance in those requirements was adopted and developed exclusively.

4.1. Characteristics of the Electromagnetic Circuit

For the shape of the air gap that generates force, a tapered configuration is used (Fig. 6) to stabilize the force–lift characteristics. For the electromagnetic circuit, a configuration

$$d\phi / dU = Pg \quad (3)$$

is established to minimize the iron loss and the coil copper loss. Concretely, as shown in Fig. 5, α_1 and α_2 are set so as to be approximated at point P, the intersection of the iron core magnetization curve and a line from constant electromagnetic energy U1 (impressed current*the number of coil winding) at $\theta = \tan^{-1}Pg$ (Pg is air gap permeance).

4.2. Magnetic Flux Density Distribution

Figure 6 shows the calculation results of the magnetic flux density distribution in the electromagnetic circuit that consists of the coil, core, and armature. The equation (3) holds well since the magnetic flux density in the circuit does not use the area that exceeds the permissible value (flux saturation area) but the area close to the permissible value.

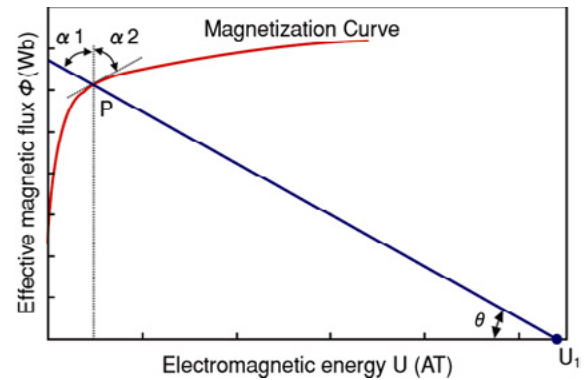


Fig. 5 Magnetic circuit characteristic of linear solenoid

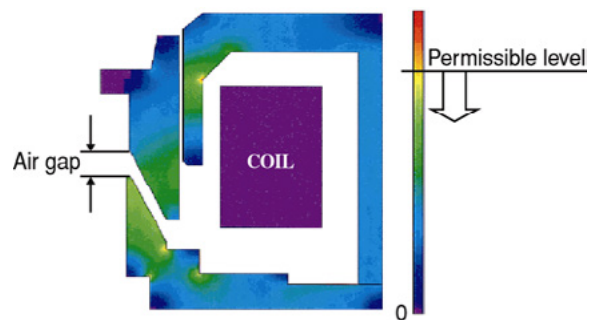


Fig. 6 Magnetic flux density of magnetic circuit

4.3. Heat Build-up Characteristics

An engine mount is generally exposed to high temperatures like radiant heat from the exhaust system. If the electromagnetic actuator is employed in the ACM drive, special attention must be paid to the heat build-up characteristics to ensure reliability. The applied linear solenoid actuator in this study has superior energy conversion efficiency. Furthermore, this actuator includes a driving circuit capable to impress the current waveform, in which unnecessary current components that generate heat internally have been removed. Thus, a very low heat buildup that does not affect the reliability is achieved. As seen in Fig. 7, even in continuous conductive operations, the rise in temperature of the coil surface is below 30 °C, and the rise in temperature

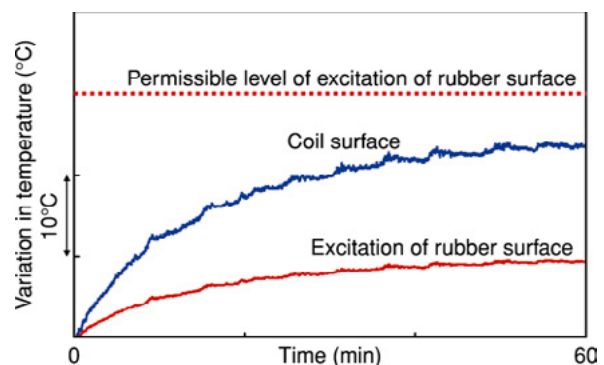


Fig. 7 Temperature characteristics

of the rubber surface (See Fig. 9) of the excitation plate closest to the actuator is about 10 °C. These values are sufficiently lower than the permissible temperatures.

4.4. ACM Control Unit

In order to drive an actuator that has high response and force, an ACM ECU is developed which includes a function to amplify high electric current in variable frequency and a driving circuit durable to the generated heat during these fluctuations. Also a diagnosis function is provided that includes a monitoring function for the actuator control unit Fig. 8.

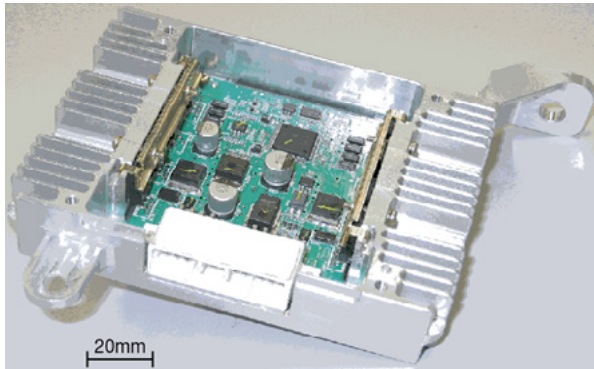


Fig. 8 ECM ECU

5. Structure of ACM

5.1. Structure Overview

Figure 9 shows a cutaway view of the ACM. The structure of the upper part of the ACM is similar to the conventional hydraulic engine mount. A linear solenoid type actuator is fitted in the lower part. The main feature of the hydraulic engine mount is the air-release diaphragm, located above the mounting rubber. Accordingly, overall height of the mount is shortened. This helped in achieving the compactness of the actuator mentioned earlier and overall height similar to that of the conventional hydraulic engine mount. Furthermore, as the rubber body that holds load is enveloped in mount liquid, hardening of rubber due to ozone

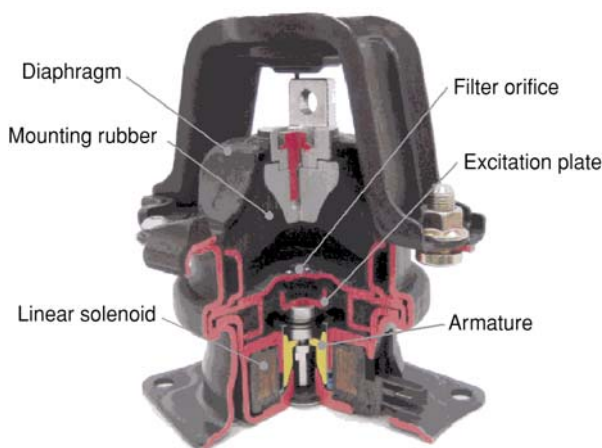


Fig. 9 Cutaway view of ACM

aging and heat aging is reduced. This contributes to the stabilization of aging deterioration performance in the active control system. The actuator is coupled to the excitation plate on the mount side, and it is constructed to convert the actuator driving force to liquid pressure. Generally, the engine mount is equipped to the part which is exposed to water. Therefore, the direct coupler structure with double-molded coils is adopted to ensure reliability of the electrical circuit.

5.2. Coupling of Actuator and Excitation Plate

The coupling structure of the linear solenoid and the liquid hydraulic engine mount has two features as mentioned below to work both functions properly.

- (1) Use of a mechanism for adjusting the armature (mover) setting position.
- (2) Use of a mechanism that enables to couple the armature and shaft of the excitation plate, allowing coaxial misalignment and deflection.

Accordingly, the linear solenoid and hydraulic engine mount are coupled with the precise control of conventional construction, and a balance between the force stabilization and bearing reliability is established.

6. Characteristics of ACM

6.1. Determination of Hydraulic Engine Mount Characteristics

Characteristics required for the hydraulic engine mount in an ACM are mentioned below:

- (1) It ensures damping force equivalent to a hydraulic engine mount having equivalent static spring constant.
- (2) The ratio of mount generating amplitude / actuator force is high.
- (3) It lowers the dynamic spring constant in the driving frequency range.
- (4) It satisfies the durability requirements of the actuator drive.

Appropriate selection of the excitation plate specification is particularly important to optimize a balance of the four characteristics above. In this study, the specification of the excitation plate is selected based on tests on several types of samples and parameter studies on rubber hardness and the outer diameter of the excitation plate using a dynamics calculation model of the hydraulic engine mount and the characteristics of the dynamic spring constant is determined.

6.2. Reduction of Harmonics

The generation of harmonics becomes an issue in the base order of driving in ACM development. Harmonics is generated due to free vibrations of the excitation plate when electric current is cut-off by the duty drive. Thus, countermeasures are provided for the excitation plate and current control respectively. Figure 9 shows one of the measures that utilizes a filter orifice above the excitation plate. The filter orifice function includes assisting generative force characteristics by controlling the dynamic spring constant in addition to free vibration control of the excitation plate. Figure 10 shows the dynamic spring characteristics. Since the characteristics are stabilized in the control zone, the bottom frequency of the filter orifice is set up at 90 Hz. As a result, the reduction of harmonics generative force during actuator drive is possible as shown in Fig. 11.

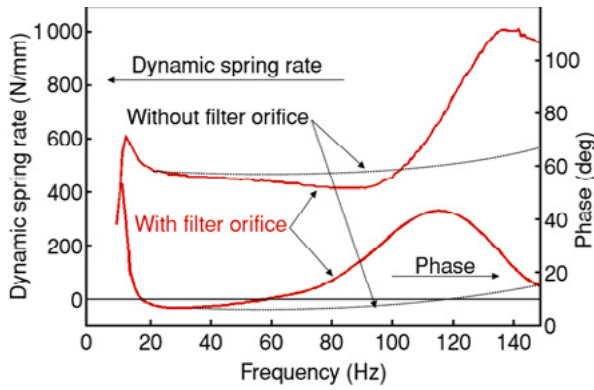


Fig. 10 Passive characteristics of ACM

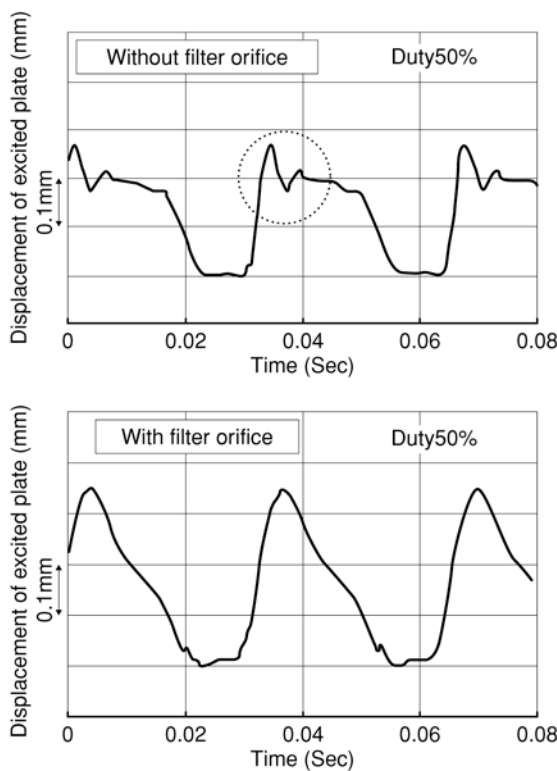


Fig. 11 Effect of filter orifice

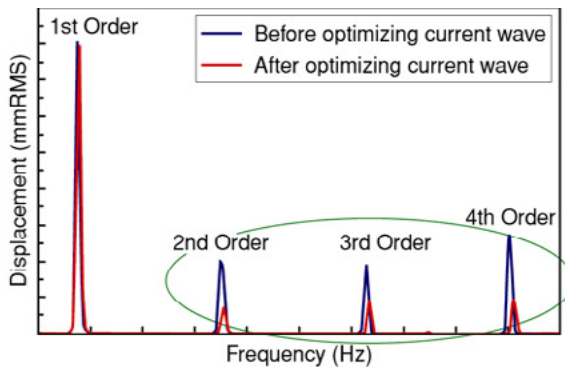


Fig. 12 Effect of harmonics of optimizing current wave

Another measure for control of harmonics is to improve the drive current. By gradually cutting off the electric current generated by the duty drive, the improvement in amplitude of the harmonics is confirmed (as shown in Fig. 12) in wide frequency ranges for components greater than the second order components of the drive.

7. Achievements

7.1. Generating Displacement of ACM Unit

Figure 13 shows the unit displacement generation. As shown in the figure, the current system achieves a better displacement performance in the entire range compared to the engine displacement in the three-cylinder drive condition.

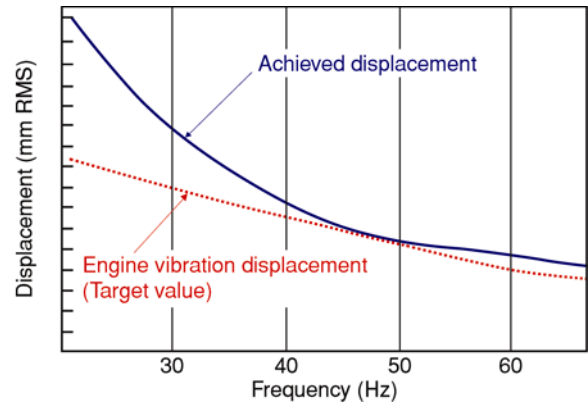


Fig. 13 Characteristics of ACM

7.2. Completed Vehicle Noise and Vibration Performance

This ACM system is applied to a vehicle equipped with V6 cylinder-on-demand engine, and the noise and vibration level in the three-cylinder drive is checked. As shown in Fig. 14, the result shows that the ACM load transfer is reduced by approximately 10 dB in the entire operating range compared to the no controlled condition. And the booming noise in the cabin and steering vibrations, shown in Figs. 15 and 16, are drastically reduced as well. Moreover, further booming noise reduction is achieved by applying active noise control with the ACM system together, and noise and vibration performance is realized equivalent to that experienced during full-cylinder operation, even in three cylinders operation.

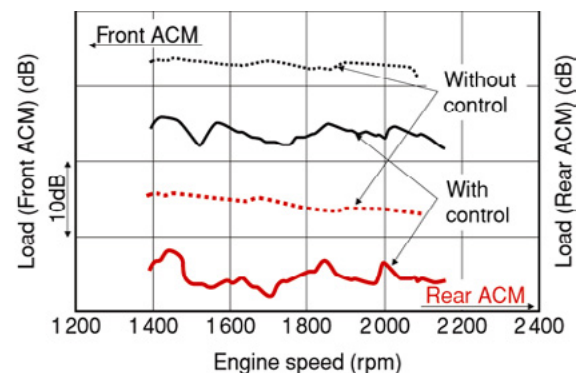


Fig. 14 Reduction of transfer load at three-cylinder drive

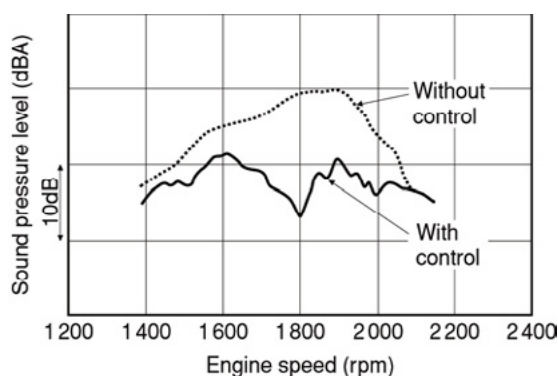


Fig. 15 Reduction of sound pressure in completed vehicle at three-cylinder drive

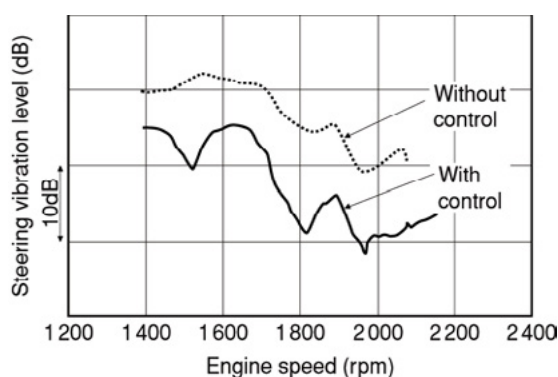


Fig. 16 Reduction of steering vibration in completed vehicle at three-cylinder drive

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References

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8. Conclusion

The following is the summary of this active control engine mount development:

- (1) An ACM system equipped with an exclusive linear solenoid type actuator with high efficiency and low heat generation, and a vibration estimating type feed forward control system by crank rotation pulse signal, which is the existing signal, was developed.
- (2) Amplitude characteristics that exceed the engine vibrations in the active driving condition were satisfied; adequate isolated vibration value was obtained, thereby enhancing the marketability of V6 cylinder-on-demand engine in noise and vibration performance.
- (3) A packaging similar to that of the conventional hydraulic engine mount was realized by shortening the overall height of the hydraulic engine mount and the exclusive compact actuator.
- (4) For reliability for low heat generation in the actuator, a coupling structure between armature and the excitation plate that allowed coaxial misalignment and deflection in the coupling was established, which ensures a sufficient durability.

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