

# Development of Active Control Engine Mount System which Reduces Higher Harmonic Vibration

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## ABSTRACT

The range of three-cylinder drive can be increased in order to boost the fuel efficiency performance of V6 cylinder-on-demand engines. The use of three-cylinder drive increases the combustion pressure per cylinder, and also increases engine vibration not only at the fundamental order of combustion, but also at higher harmonic frequencies. A new active control engine mount (ACM) system was developed to respond to this higher harmonic vibration in order to satisfy commercial demands for noise and vibration (NV) performance. The operation of an ACM generates higher harmonic vibration other than the vibration produced by the engine. The new ACM system applies sine-wave drive control and multi-order frequency control in order to reduce these two forms of higher harmonic vibration. In addition, the use of a regenerative circuit has reduced heat production, helping to enable a reduction in size of the electronic control unit to be reconciled with reliability. Tests of the system in an actual vehicle showed that NV performance was increased even when an expanded range of three-cylinder drive was employed.

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## 1. Introduction

ACM systems utilizing map control of vacuum actuators<sup>(1)</sup> and adaptive control of electromagnetic actuators<sup>(2)</sup> as the drive method have been put into practical application. Honda's ACM, developed for use with V6 engines fitted with cylinder-on-demand systems, use a drive method that applies feed-forward control to a highly responsive linear solenoid without the use of specialized sensors<sup>(3)</sup>, realizing a level of NV performance that belies three-cylinder drive. The ACM has been employed on the market since the 2004 model year INSPIRE.

The cylinder-on-demand system is a technology that closes one bank of valves during periods of low-load operation, such as at constant speed or during deceleration, in order to reduce pumping loss and increase fuel efficiency. However, due to the reduction in the number of combustion cylinders, three-cylinder operation reduces the 3<sup>rd</sup> order of engine speed, the engine's fundamental order, to the 1.5<sup>th</sup> order and increases combustion pressure per cylinder, resulting in increased engine vibration<sup>(3)</sup>.

Conventional ACM systems mainly reduce the 1.5<sup>th</sup>-order component of engine vibration during three-cylinder

operation, and there has been no necessity for ACM to control the 3<sup>rd</sup>-order component, which is the higher harmonic component.

The development of a new type of ACM system discussed in this paper was conducted to provide a new control system able to respond to an increase in the amplitude of 1.5<sup>th</sup>-order and 3<sup>rd</sup>-order engine vibrations consequent upon an expansion of the range of three-cylinder drive in order to increase the fuel efficiency performance of the cylinder-on-demand system. The aim of the development was to achieve a level of NV performance equivalent to that of the previous system, at which users are unaware that three-cylinder drive is in operation.

## 2. Development Goals

The cylinder-on-demand system with an expanded range of three-cylinder drive will be termed the new cylinder-on-demand system, and the ACM that realized a degree of displacement that cancelled the vibration of the new cylinder-on-demand system will be termed the new form of ACM.

The power of the new form of ACM was increased by

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reducing coil resistance against the previous ACM in order to increase current responsiveness; this increased electromagnetic energy, thus boosting ACM output.

Figure 1 shows the load transmitted to the body from an engine bracket during three-cylinder drive in vehicles fitted with the conventional and new cylinder-on-demand systems. In the vehicle fitted with the new cylinder-on-demand system, there is greater engagement of three-cylinder drive in the range in which torque is necessary than in the vehicle fitted with the previous system. Because of this, the 1.5<sup>th</sup>-order and 3<sup>rd</sup>-order loads are both greater, and depending on the operating range, the 3<sup>rd</sup>-order load can reach a level at which NV targets are not satisfied. It was therefore necessary to drive the ACM using a form of control that was able to respond to 3<sup>rd</sup>-order vibration in addition to 1.5<sup>th</sup>-order vibration, in order to reduce the transmitted loads.

Figure 2 shows the force generated by the previous ACM and the new form of ACM in isolation when the units are driven by a current-impressing device under

identical conditions and a load corresponding to the weight of the engine is applied. Both ACMs produce a higher harmonic component, but the higher harmonic component is greater in the new form of ACM in proportion to the degree to which the 1<sup>st</sup>-order component increases in response to the fundamental order of engine vibration. If the new form of ACM was used to cancel engine vibration in this state, the fundamental order of engine vibration would be reduced, but the vibration of the ACM would produce vibration at higher harmonic frequencies. The reason for this is that the ACM could not be operated to render the force generated by the ACM into a sine wave.

Based on the above, the targets established for the development of the new form of ACM were, in addition to increasing ACM power in order to respond to an increased amplitude of engine vibration, to reduce the higher harmonic vibration from the engine and ACM, the new and conspicuous factor generating a decline in NV performance, to a level acceptable in a marketed vehicle.

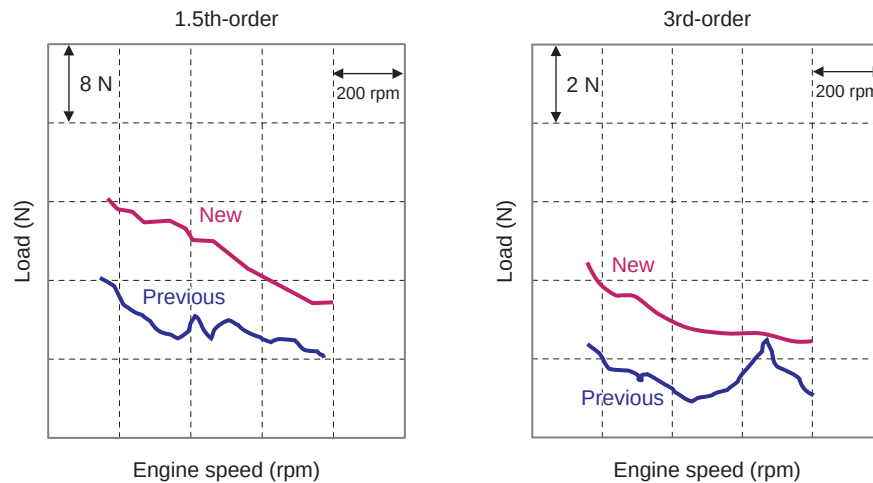


Fig. 1 Load transmitted to body from engine bracket during 3-cylinder stop mode

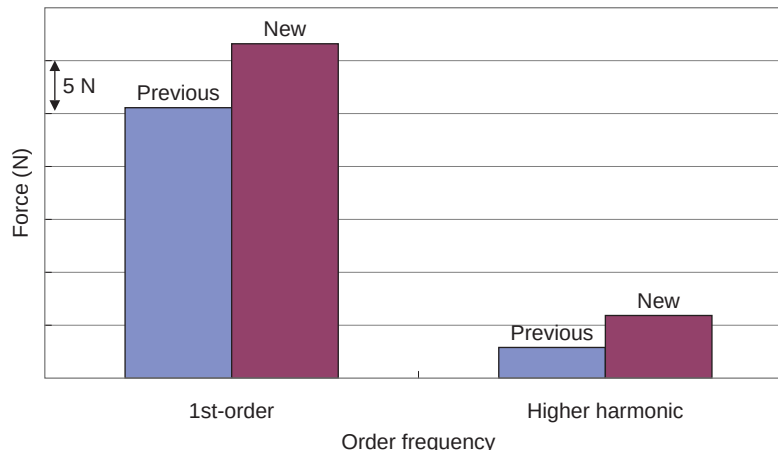


Fig. 2 Order frequency of output force from developed and previous ACM

### 3. Configuration of ACM System

#### 3.1. System Overview

Figure 3 shows an example of the ACM system when fitted in a vehicle. ACMs are fitted at both the front and rear of a V6 engine provided with the cylinder-on-demand system, and the electronic control unit (ECU) that controls the ACM is located in the vehicle cabin.

Figure 4 shows the system configuration. The ACM ECU is connected to the engine control unit (PGM-FI), to help ensure that it receives the necessary signals to track engine vibration.

Figure 5 shows the configuration of the ACM. The ACM is made up of a liquid seal section and a linear solenoid section. Hydraulic pressure is varied through the use of an armature in the linear solenoid section to induce vibration in an exciter plate in the liquid seal section. This results in vibration of the mounting rubber. By this means, the dynamic spring constant of the ACM can be varied, helping to enable the load transmitted from the engine brackets to the body (sub-frame) to be reduced.

#### 3.2. Generation of Higher Harmonic Component from ACM Output

When a sinusoidal current was impressed on the ACM, a higher harmonic component was generated from the ACM output. The ACM output is determined by the movement of the exciter plate. The displacement of the exciter plate,  $X$ , can be found using Eq.(1). Figure 6 shows a simple model of the exciter plate and the linear

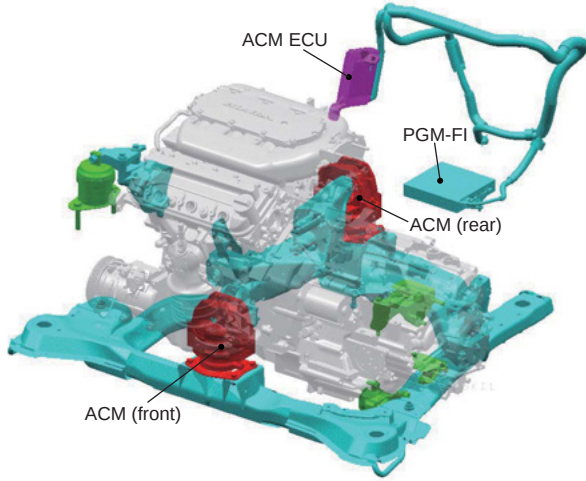


Fig. 3 ACM system configuration

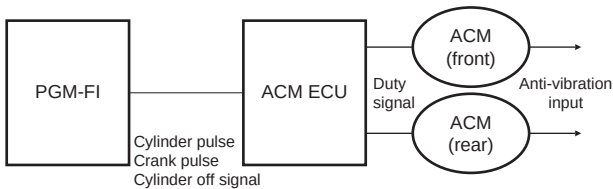


Fig. 4 Block diagram of ACM system

solenoid, used for deriving Eq. (1).

$$F_{act}(i, X) = M\ddot{X} + \{Ce + Cj(i)\}\dot{X} + \{Ke + Kj(i)\}X + \mu(i, \dot{X})F_n(i, X) + F_{BH}(i) \quad (1)$$

$F_{act}$  : Magnetic force

$F_n$  : Horizontal component of magnetic force

$F_{BH}$  : B-H hysteresis

$M$  : Total moving mass

$Ce$  : Attenuation coefficient of exciter plate

$Cj$  : Attenuation coefficient which changes with current

$Ke$  : Spring constant of exciter plate

$Kj$  : Spring constant which changes with current

$\mu$  : Coefficient of operation friction on bearing

$i$  : Drive current

$X$  : Displacement of exciter plate

The parameters displaying nonlinear characteristics in Eq. (1) are (1) the attenuation characteristics  $Ce$  and  $Cj$ , (2) the sliding resistance of the bearings,  $\mu F_n$ , and (3) the B-H hysteresis,  $F_{BH}$ , and these parameters are factors in the generation of the higher harmonic component.

The developed system allows this nonlinearity of the hardware, and applies a new method of control in order to reduce the higher harmonic component.

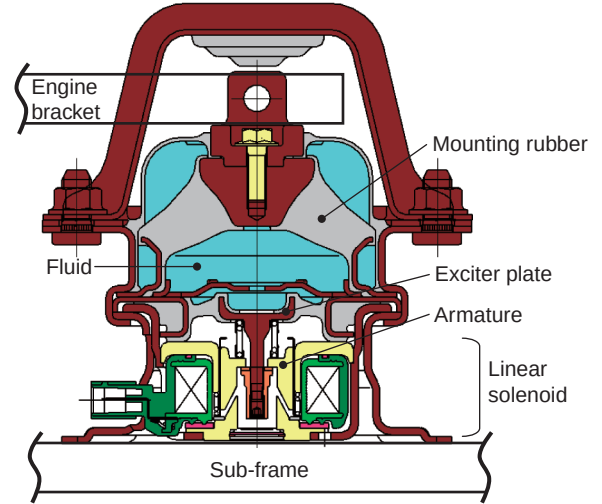


Fig. 5 Cutaway view of ACM

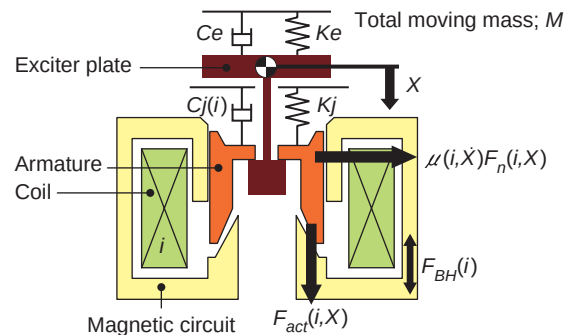


Fig. 6 Exciter plate displacement model

## 4. Control for Reduction of Higher Harmonic Component

### 4.1. Sine-wave Drive Control

Figures 7 and 8, respectively, show the magnitude of the frequency order components of the higher harmonic output and the phase difference of the higher harmonic wave with the 1<sup>st</sup>-order component when the ACM is driven by impressing a sinusoidal current. The main components of the higher harmonic output are the 2<sup>nd</sup> and 3<sup>rd</sup> orders, and its phase difference is reproducible as linear or nonlinear against the frequency. Therefore, if a current was synthesized so that the 2<sup>nd</sup>- and 3<sup>rd</sup>-order components of the impressed current were reduced, sine-wave drive of the ACM would be possible, and the higher harmonic output could be reduced.

If  $I_1$ ,  $I_2$ ,  $I_3$ ,  $\theta_2$ , and  $\theta_3$  represent, respectively, the magnitude of the 1<sup>st</sup>-, 2<sup>nd</sup>- and 3<sup>rd</sup>-order currents, and the phase of the 2<sup>nd</sup>- and 3<sup>rd</sup>-order currents,  $f$  represents the frequency of the 1<sup>st</sup>-order current, and  $t$  represents the period of ACM drive,  $ICMD$  in Eq. (2) gives the impressed current necessary for sine-wave drive of the ACM.

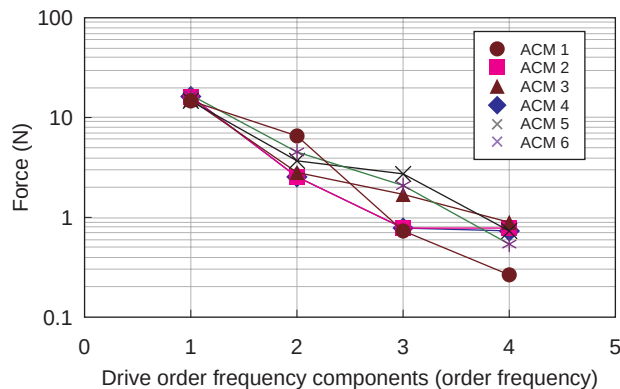


Fig. 7 Components of higher harmonic wave

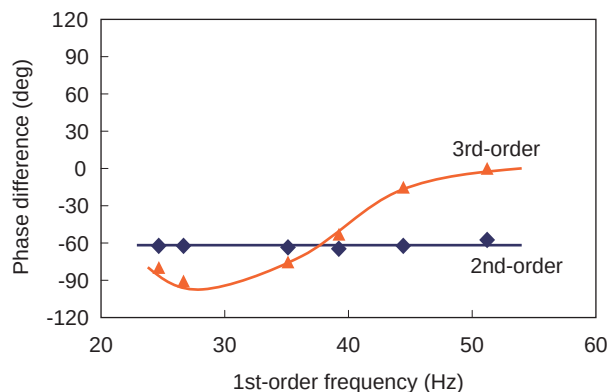


Fig. 8 Phase difference of higher harmonic wave with 1st-order

$$ICMD = I_1 \sin \omega t + I_2 \sin(2\omega t + \theta_2) + I_3 \sin(3\omega t + \theta_3) \quad (2)$$

Here,

$$\omega = 2\pi f \quad (3)$$

$I_1$  is implemented in the ECU as a map of engine speed and estimates of engine vibration. Because the values of  $I_2$ ,  $I_3$ ,  $\theta_2$  and  $\theta_3$  vary in response to the magnitude and frequency of the 1<sup>st</sup>-order current, they are implemented as a map (ICMD map) of the magnitude and frequency of the 1<sup>st</sup>-order current.

It was necessary to develop a high-precision current control to drive the ACM following Eq. (2). Equations (4) to (7) show the method used for current control.  $I_{ACT}$  is the actual current value for each ACM drive cycle. The power to be supplied to the linear solenoid,  $DUTY$ , is calculated to render the values of  $I_{ACT}$  and  $ICMD$  identical. Current feedback control is the basic framework of this method of current control, but because  $ICMD$  varies with each ACM drive cycle, traceability could not be ensured using only the feedback terms  $DSOLP$  (the proportion term) and  $DSOLI$  (the integration term). Therefore, using the fact that Eq. (2) is already known, the feed-forward term  $DSOLFF$  is added.

In addition, the ACM drive circuits providing feed-forward and feedback control of current should be sufficiently responsive to be able to reduce the current to 0 A within the frequency of the 1st-order current even under conditions in which inductance impedes the ability to reduce the current. This is because, due to the structure of the ACM, if a direct current component remains, the armature will be drawn up and the vibrating center of the exciter plate will be offset, reducing the level of cancellation displacement against the impressed current.

Therefore, situations when it is necessary to increase the current and when it is necessary to decrease the current are responded to by switching the drive circuit.

Figure 9 shows the ACM drive circuit. The drive circuit is made up of a FET (T1, T2) half-bridge circuit, a FET (T3) that switches responsiveness when the

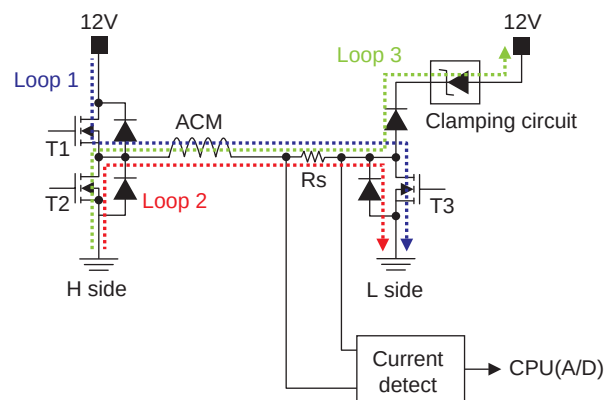


Fig. 9 ACM drive circuit

current is reduced, and a circuit that detects feedback current (shunt resistor  $R_s$ ). Figure 10 shows the current waveform during ACM drive. When the current is increased, PWM control is applied to T1 and T2 to switch to the current pathways shown as Loop 1 and Loop 2. When the current is decreased, PWM control is applied to T3 to switch to the current pathways Loop 2 and Loop 3.

Because current responsiveness is determined by the magnitude of the voltage impressed on the ACM, current responsiveness in the current pathway Loop 3 was increased by increasing the voltage impressed on the ACM to a level higher than the source voltage, and adding a clamping circuit that regenerates energy and supplies it to the power source.

The command to switch the drive circuit is provided by the *DUTY* code. When it is positive, Loop 1 and Loop 2 are selected, and when it is negative, Loop 2 and Loop 3 are selected. In addition, because responsiveness varies in relation to deviation ( $ICMD - IACT$ ) when the drive circuit is switched, the proportional gain,  $K_p$ , and the integration gain,  $K_i$ , are switched in Loops 1, 2, and 3.

$$DUTY = DSOLFF + DSOLP + DSOLI_{(n)} \quad (4)$$

$$DSOLFF = (K_p + K_i) \times \{ICMD_{(n+1)} - IACT_{(n)}\} \quad (5)$$

$$DSOLP = K_p \times \{ICMD_{(n)} - IACT_{(n)}\} \quad (6)$$

$$DSOLI_{(n)} = K_i \times \{ICMD_{(n)} - IACT_{(n)}\} + DSOLI_{(n-1)} \quad (7)$$

#### 4.2. Unit Tests

Figure 11 shows the reduction of the higher harmonic wave during ACM operation in unit tests, and Fig. 12

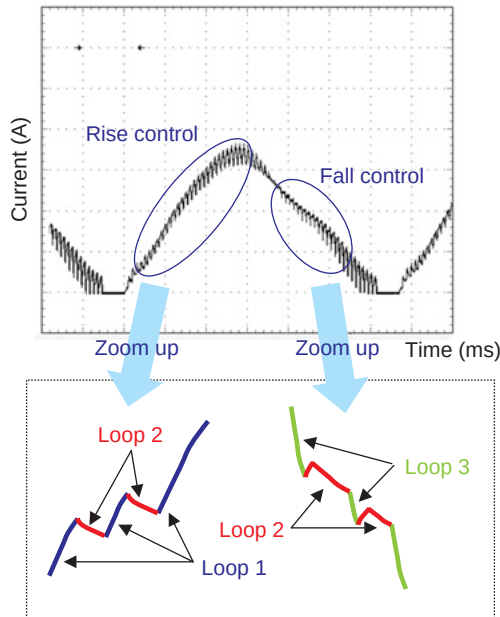


Fig. 10 Driving current waveform

shows the force waveform generated by the ACM at this time. The use of the new current control method has reduced the higher harmonic components (2nd- and 3rd-order) against drive using a sinusoidal current.

#### 4.3. Reduction of Higher Harmonic Wave and Multi-order Frequency Control as Related to NV in an Actual Vehicle

Using sine-wave drive control, it was possible to apply sine-wave drive to the ACM.

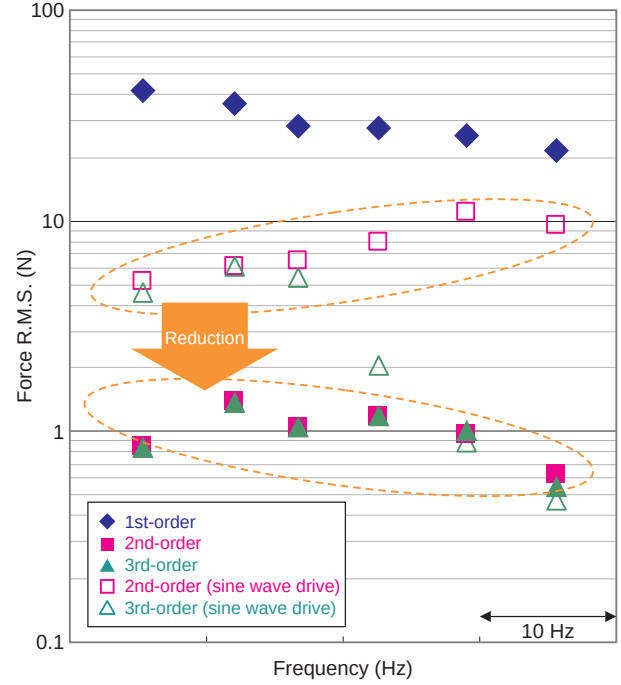


Fig. 11 Reduction of higher harmonic wave

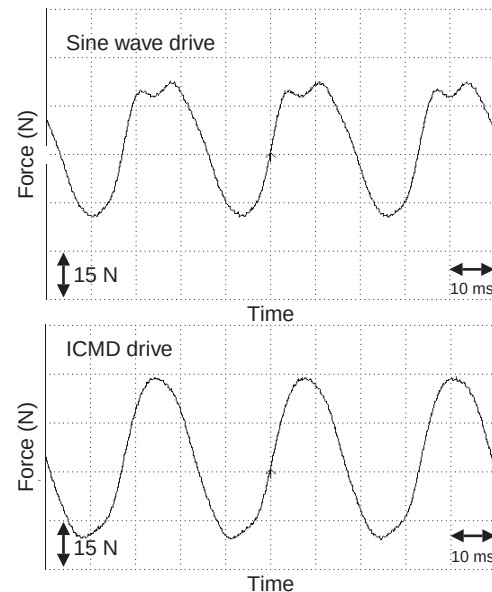


Fig. 12 Force waveform

Engine vibration can be considered to be a synthesis of the fundamental order and the higher harmonic components. Given this, if the ACM could be driven using a synthesis of the ACM sine-wave drive current form effective against the fundamental order and the ACM sine-wave drive current form effective against the major higher harmonic components, it would be possible to reduce engine vibration at multiple frequency orders.

When Eq. (2) is substituted for  $ICMD_m$ , the ACM sine-wave drive current form effective against the fundamental order of engine vibration, because the frequency of the current of each order is double  $ICMD_m$ ,  $ICMD_h$ , the ACM sine-wave drive current form effective against the major higher harmonic components, can be expressed as Eqs. (9) and (10), in which  $f$  in Eq. (3) has been transformed into  $2f$ , and  $ICMD$  in Eq. (8) is the current form for input to feed-forward and feedback control when reducing engine vibration at multiple frequency orders.  $I''_1$ ,  $I''_2$ ,  $I''_3$ ,  $\theta''_2$ , and  $\theta''_3$  represent, respectively, the magnitude of the 1st-, 2nd- and 3rd-order currents, and the 2nd- and 3rd-order current phases, all in relation to the higher harmonic components.  $\theta$  represents the phase of  $ICMD_h$  in relation to  $ICMD_m$ .  $I''_1$  and  $\theta$  are implemented in the ECU as a map of engine speed and estimated engine vibration.  $I''_2$ ,

$I''_3$ ,  $\theta''_2$ , and  $\theta''_3$  are calculated from an ICMD map into which  $I''_1$  and  $2f$  have been input.

In addition, because the current form is calculated by the ECU for each ACM drive cycle, the lowest point for  $ICMD$  in Eq. (8) can be offset, and the offset is corrected to make the lowest point 0 A.

Figure 13 shows the control block.

$$ICMD = ICMD_m + ICMD_h \quad (8)$$

$$ICMD_h = I''_1 \sin(\omega''t + \theta) + I''_2 \sin(2\omega''t + 2\theta + \theta''_2) + I''_3 \sin(3\omega''t + 3\theta + \theta''_3) \quad (9)$$

Here,

$$\omega'' = 2\pi(2f) \quad (10)$$

## 5. Effect on NV in an Actual Vehicle

Figure 14 shows the effect of the new system in reducing the transmitted load during three-cylinder drive when the ACM is in operation. The new form of ACM reduces the transmitted load for the 3rd-order component of engine vibration to less than half the figure when the ACM is not in operation, and is also effective in reducing the higher harmonic wave during three-cylinder drive.

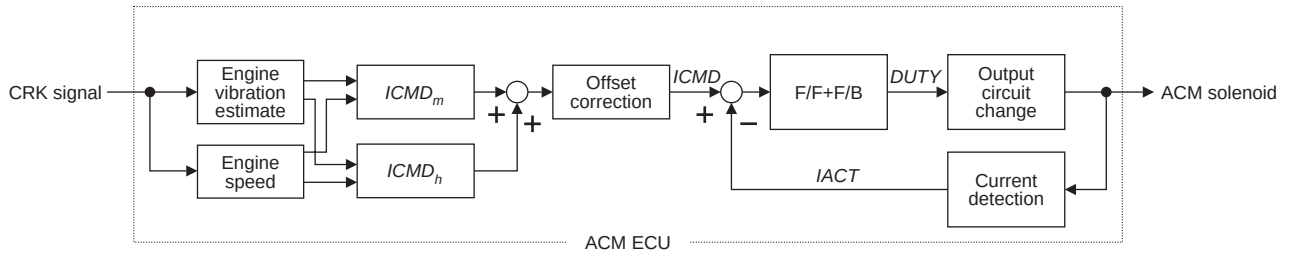


Fig. 13 Control block diagram

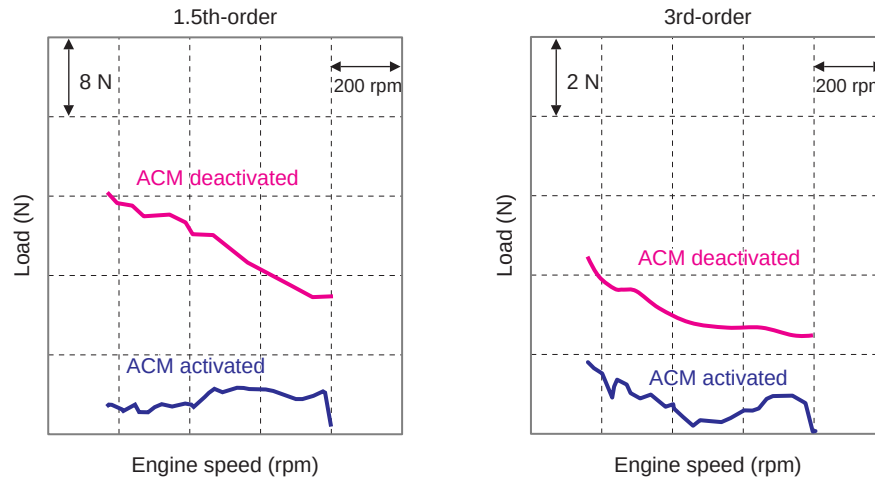


Fig. 14 Effect of new ACM system

Table 1 Specifications of developed ECU

| Items         | Developed ECU                                                                     |
|---------------|-----------------------------------------------------------------------------------|
| PCB and frame |  |
| Power (max)   | 72 W (12 V × 6 A)                                                                 |
| Circuit loss  | 6 W                                                                               |
| Size          | 86 × 98 × 35 mm                                                                   |
| Weight        | 295 g                                                                             |

## References

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## 6. Reduction of ECU Loss and Achievement of Size Reductions

Increasing the power of the ACM involved an increase in the maximum output of the ECU from the 60 W of the previous specification to 72 W, while the optimization of the drive circuits through the use of regenerative circuits and other measures reduced circuit loss to approximately 6 W against approximately 15 W in the previous specification. This helped to enable the weight of the heat dissipating frame to be reduced by 44% and the size of the ECU by 35%, reconciling increased power with reduced size (Table 1).

## 7. Conclusion

An ACM system that employs feed-forward and feedback current control was developed in order to respond to an increase in the amplitude of engine vibrations resulting from the use of a new cylinder-on-demand system. The following results were obtained:

- (1) A level of NV performance was achieved such that users are unaware of the operation of three-cylinder drive in the new cylinder-on-demand system.
- (2) A control method making possible sine-wave drive of the ACM was developed, and the higher harmonic vibration generated by the ACM was reduced.
- (3) A multi-order frequency control method was developed that allowed the synthesis of sine-wave drive current forms to be effective against the fundamental order and the higher harmonic components of the engine vibration cycles, reducing the higher harmonic vibration transmitted from the engine brackets to the vehicle body.
- (4) Optimization of the drive circuits reduced loss, helping to enable increased ACM power to be reconciled with the reduction in size of the ECU.

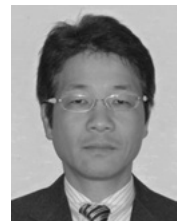
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