A Study of Active Seat Suspension Using Voice Coil Motor: Fundamental Consideration on Change of Thrust

by

Ayato ENDO[*1], Keigo IKEDA[*1], Ryosuke MINOWA[*2],
Hideaki KATO[*3] and Takayoshi NARITA[*4]

Abstract

In recent years, an ultra-compact vehicle that can take only a small number of people, have been developed. However, the ride comfort of such mobility is low. Ride comfort of this vehicle is considered to be affected by disturbance vibrations. We have proposed vibration control using active seat suspension has been proposed as a method to improve ride comfort in these vehicles. The active seat suspension system consisted of a device mounted on the seat of the ultra-compact vehicle. As the vehicle has a small interior area, it requires compact controllable active seat suspension. Therefore, an actuator that can provide high thrust with a short stroke is required. We proposed a voice coil motor as an actuator for use in the active seat suspension system. The gap between the permanent magnet and coils of the voice coil motor can be reduced to increase the thrust of the motor. However, reducing the gap increases the thrust variation and deteriorates control performance. Therefore, in this study, we researched the influence of the gap on voice coil motor characteristics using electromagnetic field analysis. Furthermore, motion simulation was performed to research the influence of the change in the characteristics of the voice coil motor on the vibration reduction effect. Thus, we proved that changes in the gap affect the thrust and thrust variation to the highest degree. Moreover, we showed that reducing the gap and increasing the maximum thrust improves the vibration reduction effect.

Keywords: Voice coil motor, Active seat suspension, Ultra-compact vehicle, Electromagnetic field analysis

1. Introduction

In recent years, the need for an environmentally friendly transportation system has increased for realization of a low carbon society. The use of public transportation has been recommended. However, it is impossible to reach this destination by only using public transportation[1]. Therefore, an ultra-compact vehicle, which is a one or two seaters electric vehicle, has been proposed in some countries. Ultra-compact vehicle can be achieved, when the body size is smaller than a usual Japanese small car and the rated output power is less than 8 kW[2]. This vehicle is proposed for short-range movement. Moreover, the ultra-compact vehicle is considered for the use in car sharing system[1].

The question we have to ask here is whether the ride comfort of the ultra-compact vehicle is sufficient. When an input to the vehicle due to uneven roads as disturbance, acceleration of the vehicle is in inverse proportion to its weight. Though many researchers proposed an active seat suspension for generally vehicles[3-5], there is no consideration of the active seat suspension for ultra-compact vehicle. Accordingly, Oshinoya et al. proposed the "active seat suspension" for improving ride comfort of the vehicle[6-11]. The active seat suspension is a vibration control device that is installed in the seat. It could be easily installed in the ultra-compact vehicle. The proposed system by Oshinoya et al., a voice coil motor (VCM) was installed as an actuator in the active seat suspension system. The VCM is highly efficient because it involves a direct-drive mechanism. We showed a reduction of vibration in the vehicle using the active seat suspension[12-17].

Miniaturized active seat suspension was required because the space inside an ultra-compact vehicle is small.

*1 Graduate Student, Course of Science and Technology
*2 Graduate Student, Course of Mechanical Engineering
*3 Junior Associate Professor, Department of Prime Mover Engineering
*4 Assistant Professor, Department of Prime Mover Engineering

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Fig. 1 Ultra-compact vehicle with a passenger on-board.
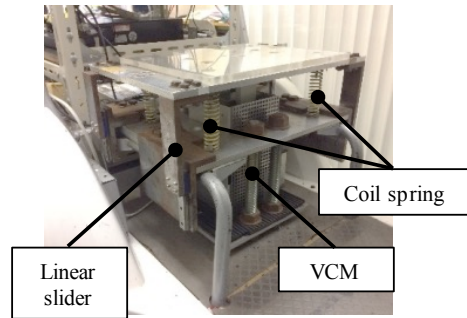
Fig. 2 Seat of the ultra-compact vehicle.

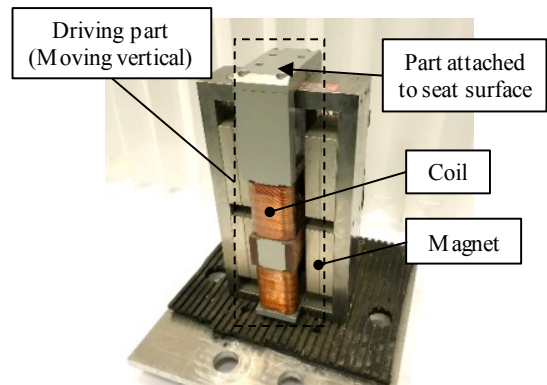

Fig. 3 Active seat suspension.

Fig. 4 Voice coil motor.

Therefore, it is necessary to design a short-stroke VCM, which requires high thrust, to reduce vibration and thus improve the comfort of the seat. One method of increasing the thrust of the VCM is to reduce the gap between permanent magnets and coils of the VCM. However, shortening of the gap causes a variation in the thrust of the VCM[18,19]. A constant thrust force was assumed in this research. However, the control performance was affected when changing the thrust force of VCM, in the case when a complex and large disturbance was applied to the vehicle. In this paper, we researched the relation between thrust characteristics and the gap of VCM using an electromagnetic field analysis. Moreover, we studied the effect of thrust variation on the vibration control using motion simulation.

2. Thrust Characteristics of VCM

2.1 *Overview of analysis*

Figure 1 shows the seat of the ultra-compact vehicle, and Fig. 2 is an enlarged figure of the seat. The seat of the ultra-compact vehicle is very small. Figure 3 shows the active seat suspension used in this study. The VCM was located at the center of the active seat suspension as actuator (Fig. 4). The seat surface was supported by four coil springs and allowed to vibrate only in vertical directions via a linear slider. Figure 5 shows the driving mechanism of the VCM. This VCM was comprised of four permanent magnets, a yoke, and a moving part including two coils, which were located between two permanent magnets. When the current was
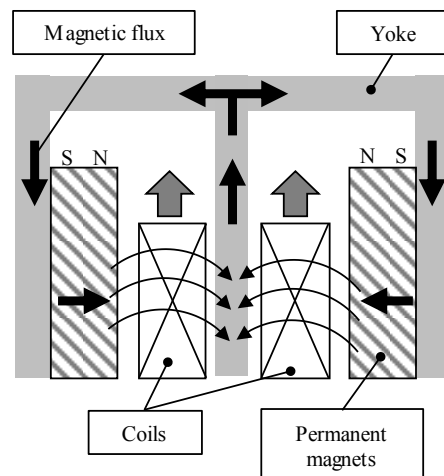

Fig. 5 Driving mechanism of the voice coil motor.

applied to the coils, VCM generated the thrust force according to Fleming's left hand rule.

In this paper, we researched whether the gap between the coils and permanent magnets affects characteristics of the VCM. At first, the effect of gap change of VCM to the variation of thrust was analyzed by the electromagnetic field. Figure 6 shows the VCM models used for this analysis. The gap was varied to create models with different gaps (1.5, 3.0, 6.0, and 9.0 mm). Table 1 shows the specifications of the VCM used for this analysis. We studied the change of thrust by moving the driving part, when the coils are activated under an applied current of 1 A.
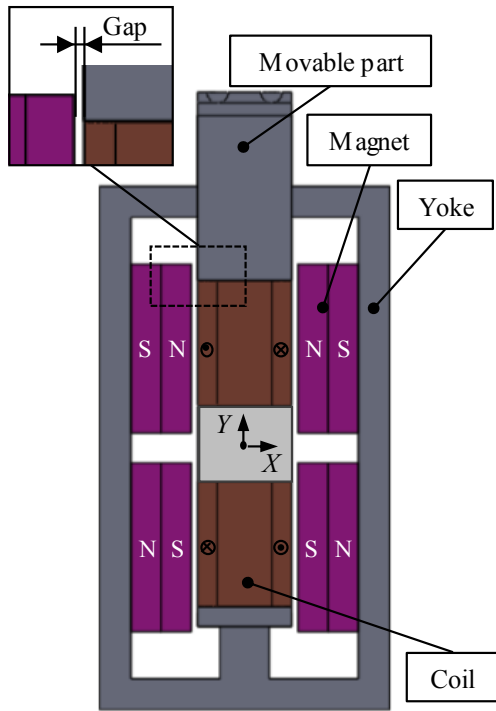
Fig. 6 Model of the voice coil motor.

Table 1 Specifications of the voice coil motor.

Permanent magnet (PM)	NEOMAX-46BH
Number of PMs	4
Remanence of PM	1.2 T
Number of coils	2
Number of turns	990
Material of yoke	SS400

Fig. 7 An example of thrust variation caused by displacement (The gap size was 3.0 mm in this case).

2.2 *Characteristic of VCM for each gap condition*

Figure 7 shows an example of the change of thrust due to the movement of the driving part of the VCM with a gap size of 3 mm. The maximum thrust was obtained at the displacement of 0 mm, and the thrust is reduced with increasing displacement. Figure 8 shows the average thrust and the peak-to-peak of thrust. Peak-to-peak is the difference between maximum and minimum of thrust. The thrust variation at a gap of 9.0 mm was smaller than that at a gap of 1.5 mm, although thrust was the smallest under all stroke conditions. Figure 9 shows the magnetic flux density of VCM for gap sizes of 1.5 and 9.0 mm. We focused on the flux density in coils. The magnetic flux density at a gap of 1.5 mm in the coil was higher than that at a gap of 9.0 mm. However, the change of magnetic flux density in the case of the 9.0 mm gap was smaller than in the case of the 1.5 mm gap, when the displacement was larger than 25 mm. The above results indicate that the change of thrust was reduced, when the gap is extended, because then the magnetic flux density is reduced.

We confirmed that the movement of the driving part changed the thrust. However, the maximum thrust remained constant when the system controlled the vibration. When we applied a large disturbance into the moving ultra-compact vehicle, the system could control the thrust in order to reduce the vibration. Therefore, we analyzed the control performance in a real driving situation using the results of this section.
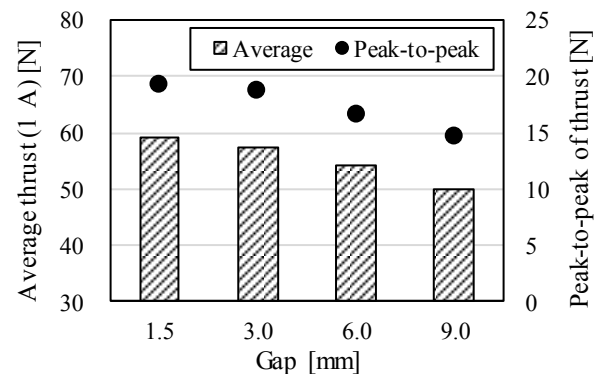

Fig. 8 Average and peak-to-peak of thrust.

3. Effect of Thrust Characteristics on Vibration Control

3.1 *Analysis condition*

We performed the dynamic motion simulation to clarify the effect on the reduced vibrations when the thrust characteristics were changed. In analysis, we controlled the vibration of the seat by the active seat suspension system equipped with the model as described in Section 2. Figure 10 shows a model of the ultra-compact vehicle equipped with an active seat suspension. No cushion is used, and it is assumed that the vibration of the seat surface is directly transmitted to the driver and that the driver and the seat move in the same way. Therefore, we assumed the upper side of the floor as

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(a) Gap: 1.5 mm,
Displacement: 0 mm

(b) Gap: 1.5 mm,
Displacement : 25 mm

(c) Gap: 9.0 mm,
Displacement : 0 mm

(d) Gap: 9.0 mm,
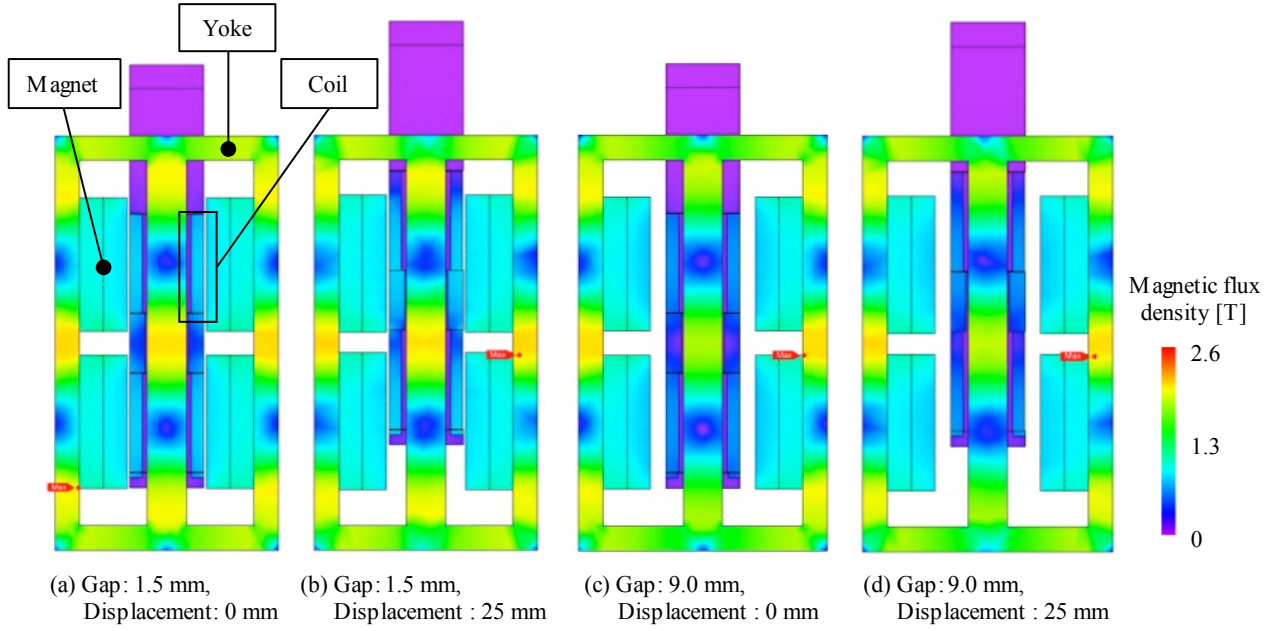Displacement : 25 mm

Fig. 9 Magnetic flux density of the voice coil motor.
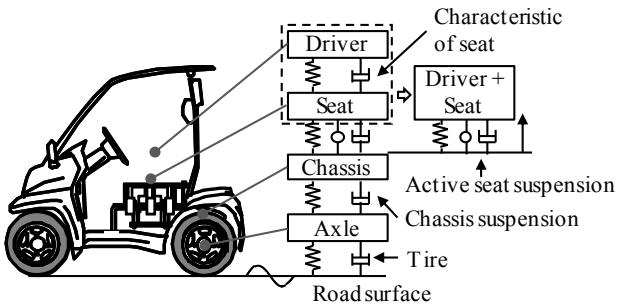

Fig. 10 Model of ultra-compact vehicle with active seat suspension.

Table 2   Parameter of active seat suspension.

Parameter	Unit	Value
m	kg	64.2
k	N/m	24911
c	N·s/m	160
y	m	-
i	A	-
K	N/A	-
L	H	0.03
R	Ω	8
y_i	m	0.1

one degree of freedom of the system. Then, the target of vibration control system was modeled as shown in Fig.11. There, m is the sum of the masses of seat and driver including his legs, k is the spring constant (as the sum of the four springs), c was the apparent damping coefficient considering the friction of the linear slider, internal damping of spring

Table 3   Specifications of the experimental vehicle.

Vehicle	Everyday COMS Basic
Manufacturer	Toyota Auto Body Co., Ltd.
Weight	325 kg
Length	1935 mm
Whole width	955 mm
Height	1600 mm
Wheelbase	1280 mm
Drive system	Wheel motor

and concomitant of mechanical elements, y is the absolute displacements of the seat, i is the control current, K is the thrust constant of the actuator, and y_i is initial displacement of simulation. Moreover, Table 2 shows parameter of active seat suspension and Table 3 shows specification of experimental vehicle.

In this analysis, we applied the optimal control theory to control the vibration using active seat suspension. Figure 12 shows the control system used in the analysis, where

$$\boldsymbol{y} = \begin{bmatrix} y & \dot{y} & i \end{bmatrix}^{\mathrm{T}}$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 \\ -\dfrac{k}{m} & -\dfrac{c}{m} & \dfrac{K}{m} \\ 0 & -\dfrac{K}{L} & -\dfrac{R}{L} \end{bmatrix}$$

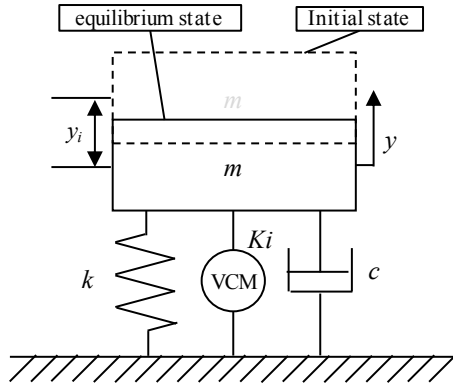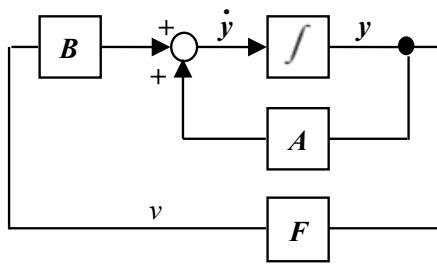Fig. 11 Model of active seat suspension for this analysis.

Fig. 12 Optimal control system for this analysis.

Table 4 Feedback gain.

Gap [mm]	f_1	f_2	f_3
1.5	4514.9	310.0	10.7
3.0	4433.0	313.6	10.7
6.0	4218.4	325.4	11.0
9.0	3929.8	336.3	11.1

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & \dfrac{1}{L} \end{bmatrix}^{\mathrm{T}}$$

$$\mathbf{F} = \begin{bmatrix} f_1 & f_2 & f_3 \end{bmatrix}$$

f_1, f_2 and f_3 are the feedback gains for y, $\dot{y}$ and i. v is the input voltage [V]. The feedback gain was calculated based on the optimal control theory. Weighting coefficients were chosen by referring to previous researches[11-14]. Table 4 shows feedback gains for this study. In a practical driving situation, high-thrust and responsiveness are mostly required, when the vehicle passes a road bump. Therefore, we investigated control responses when initial displacement was set to 100 mm.

Figure 13 shows the driving environment assumed in this analysis. The initial displacement is selected as the worst driving situation, passing a bumpy road. Initial displacement was decided by assuming general bumps (about 100 mm).
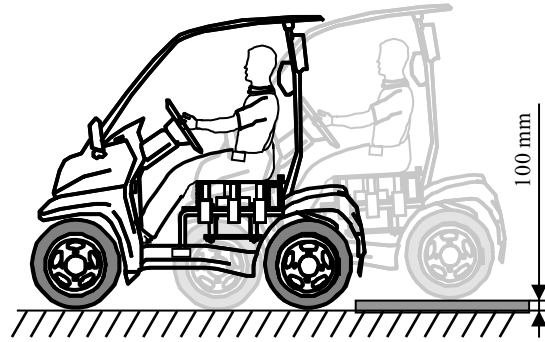

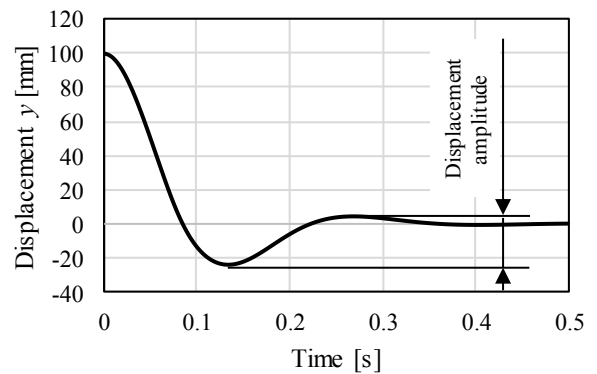Fig. 13 Driving environment assumed in this analysis.

Fig. 14 An example of time history of displacement (gap 3.0 mm).

3.2 Relationship between gap and vibration control

Figure 14 shows an example of time history of displacement for the case with a gap of 3.0 mm. In this study, the vibration reduction effect was evaluated by the displacement amplitude shown in Fig. 14. Figure 15 shows the displacement amplitude for each gap. The displacement amplitude was most suppressed at a gap of 1.5 mm. From the analysis results in the previous section, the average thrust of 1.5 mm was large, although the change of the thrust was also large. Therefore, we showed that the vibration reduction effect is the highest when the average thrust is the largest.

4. Conclusion

In this paper, we investigated appropriate VCM characteristics for an active seat suspension in an ultra-compact vehicle. We evaluated changes in control performance by the VCM when the vehicle passes over a bump. As a result, it was possible to elucidate a design of the VCM that could demonstrate good control performance. In the future, we plan to investigate the characteristics of VCM to improve the effect of vibration reduction on various types of roads. In addition, we will investigate a high-thrust and energy-efficient VCM for the active seat suspension.
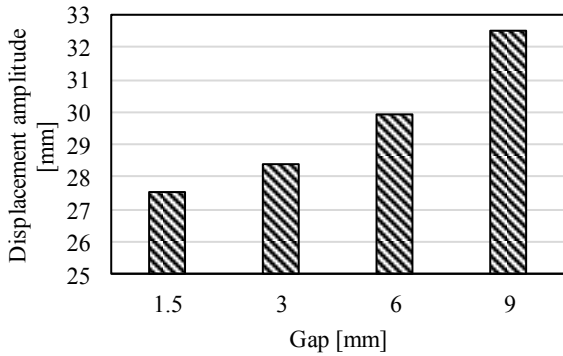
Fig. 15 Displacement amplitude of each gap.

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