Proc. Schl. Eng. Tokai Univ., Ser. E
28 (2003) 27-31

Simulation Study on Active Seat Suspension for a Small Vehicle

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(Received on 31.3.2003 & accepted on 28.5.2003)

Abstract

To improve the riding comfort of the driver's seat, we have proposed an active suspension system for a heavy-duty truck. In this study, the control mechanism of the active seat suspension was designed for a small vehicle such as a community car, using an optimal control method. An operability improvement for senior citizens, vibration isolation for babies and riding comfort improvement on unpaved road can be expected. In order to examine the effectiveness of the system, simulations were performed.

Key Words: Active Seat Suspension, Riding Comfort, Community Vehicle, Electric Vehicle, Numerical Simulation, Feedback Control, and Feedforward Link

1. Introduction

The "community car" has been attracting attention as a transportation vehicle aimed at increasing the comfort of and convenience in daily life in the 21st century. In particular, several manufacturers have marketed small one or two-seater electric automobiles in recent years. Recyclability is taken into consideration, and some electric automobiles guarantee safety comparable to that of standard-sized cars; they are also equipped with sufficient functions to serve as a means of transportation within a local area or for brief trips. Furthermore, a system of using IC cards, based on the assumption that electric automobiles will be owned in partnership for purposes such as commuting and shopping, has been put into practical use. In addition, the spread of "silver vehicles," marketed mainly for elderly people, has been notable recently. It is expected that the demand for small electric automobiles will increase yearly, and the development of increasingly-value-added products is expected. Under such circumstances, consideration is given to aspects of the development of a driving-environment support system, such as alleviation of vibration and shock in the consideration of elderly drivers or a baby in the car, improvement of comfort on unpaved roads, and reduction of driving fatigue.

We have examined the improvement of ride quality and the reduction of riding fatigue by active control of the seat suspension of heavy vehicles such as trucks [1)~4)]. The purpose of this study is to examine the effectiveness of active seat suspension when it is applied to small cars and the problems associated with its practical use, based on the knowledge accumulated thus far. A small active seat suspension, which is easy to install, is designed and manufactured for one-seater electric automobiles. The section corresponding to the seat surface is supported by a coil spring and an actuator, and the motion of the suspension is limited to vertical vibrations using a linear slider. For the actuator, a maintenance-free voice coil motor used as a direct drive is adopted.

ISO 2631 and Janeway et al. proposed that, generally, vibration, which affects riding comfort in a vehicle, is largely caused by accelerations between 4 and 8 Hz in the vertical direction. Therefore, in this study, we perform numerical simulations with the aim of reducing vertical directional acceleration within this frequency range. In an actual driving test, a test road in which the concavity and convexity of an actual road surface are simulated using hard rubber is prepared. So the basic control performance of vertical vibrations of the seat surface during the travel simulation is examined.

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Fig.1. Small electric vehicle.

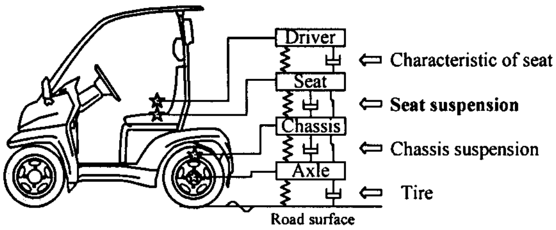


Fig.2. Vibration transfer path of the vehicle.

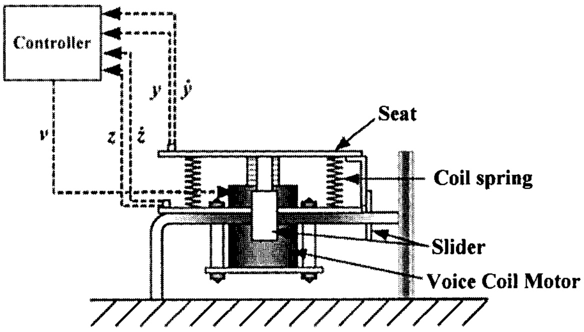


Fig.3. Active seat suspension control system.

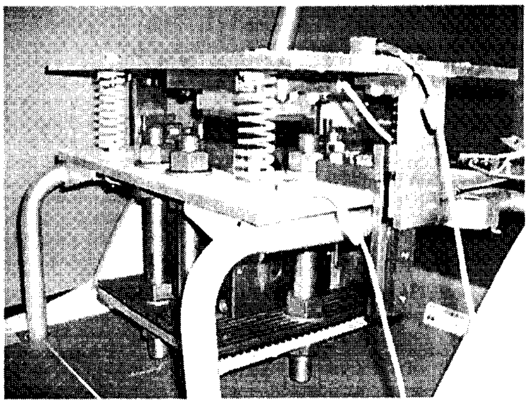


Fig. 4. Photograph of active seat suspension.

2. Analytical model

Figure 1 shows a photograph of small electric vehicle. The seat is suspended on the chassis frame and the axles (Fig.2), so the coupled vibration of the whole structure should be considered when analyzing the vibration of the driver's seat. However, since the seat mass, including the driver's mass, is relatively small compared with that of the chassis, the floor vibration is assumed to be transferred to the seat by means of cascade connection. In this study, experiment device and the control system of the active seat suspension, which is designed and manufactured, are shown in Figs.3,4. The seat is supported by four sets of a coil spring with a voice coil motor installed by parallel to the spring assembly. The flexibility of the cushion on the seat frame is not taken into account in the basic research for the control performance, so the analytical model of the seat is represented as a one-degree-of-freedom system. The friction between the driver's hands and the steering wheel is neglected in this study. The driver's mass is corrected by deducting the leg mass from the body mass. The control theory is applied to obtain signals (absolute displacements and velocities of the seat surface and the floor) and the control voltage is calculated by using the optimal control theory. This voltage signal is input to the voice coil motor, and the control force is generated.

3. State equations

The equation of motion of the analytical model is

$$m\ddot{y} + c(\dot{y} - \dot{z}) + k(y - z) = u \tag{1}$$

m : Sum of seat and driver masses [kg]
k : Spring constant of seat suspension [N/m]
c : Damping coefficient of seat suspension (including the friction produced by the linear slider) [Ns/m]
y : Absolute displacement of seat [m]
z : Absolute displacement of cabin floor [m]
x : Relative displacement of suspension ($x = y - z$)[m]
u : Control force [N]

The voice coil motor used in this study consists of a circuit containing a magnet and a coil which actually generates force. The motor does not include a linear bearing to support the coil's motion. The control force, considering the characteristics of an actuator, is approximated using eq. (2), where v is an input voltage. Here, a_m and b_m are characteristic constants, which were determined to adjust consistency in the displacement of the actuator between actual values (from a static condition to the time when an off-set voltage is applied to when the actuator actually moved) and simulated values.

$$u = -\frac{\dot{y} - \dot{z}}{b_m} + \frac{a_m v}{b_m} \qquad (2)$$

The state equation of the seat suspension system is introduced from the equation of motion, that is,

$$\dot{\boldsymbol{y}}_s = \boldsymbol{A}_s \boldsymbol{y}_s + \boldsymbol{b}_s v + \boldsymbol{d}_s \boldsymbol{z}_f \qquad (3)$$

where

$$\boldsymbol{y}_s = \begin{bmatrix} y & \dot{y} \end{bmatrix}^T \ , \ \boldsymbol{z}_f = \begin{bmatrix} z & \dot{z} \end{bmatrix}^T$$

$$\boldsymbol{A}_s = \begin{bmatrix} 0 & 1 \\ -\dfrac{k}{m} & -\dfrac{1 + b_m c}{b_m m} \end{bmatrix}$$

$$\boldsymbol{b}_s = \begin{bmatrix} 0 & \dfrac{a_m}{b_m m} \end{bmatrix}^T \ , \ \boldsymbol{d}_s = \begin{bmatrix} 0 & 0 \\ \dfrac{k}{m} & \dfrac{1 + b_m c}{b_m m} \end{bmatrix}$$

To simulate a road for traveling, hard-rubber obstacles 30 mm wide, 15 mm high, and 150 mm long are placed at an equal interval (150 mm) as shown in Fig.5 and are used as disturbances on the road. In this study, the signal, which corresponded to the actual data, was generated by shaping a random signal analytically.

The transfer function of the shaping filter used to produce the floor vibration due to white noise is approximated by an expression of the second-order system:

$$G_f(s) = \frac{s^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^{\ 2}} \qquad (4)$$

Figure 6 shows the power spectrum of acceleration on the floor of a vehicle. Figure 6(a) shows measured values, and Fig.6(b) shows numerically simulated values in which parameters were determined such that the simulated values fit with the measured values(ω_f =31.4 rad/s, ζ_f =0.12). In this study, since we aim at improving riding comfort in the frequency range of 4-8 Hz, the filter was designed to fit this range (colored section in the figure). The parameter used here is that the acceleration disturbance has a dominant frequency of 5 Hz. This value takes into account the natural frequency of the entire vehicle due to the chassis suspension, which is approximately 5 Hz when the driver's body weight is 60 kg. Therefore, the worst disturbance is the input under these traveling conditions.

The state equation of the shaping filter is derived from the transfer function as follows:

$$\dot{\boldsymbol{z}}_f = \boldsymbol{A}_f \boldsymbol{z}_f + \boldsymbol{d}_f w \qquad (5)$$

where

$$\boldsymbol{A}_f = \begin{bmatrix} 0 & 1 \\ -\omega_f^{\ 2} & -2\zeta_f \omega_f \end{bmatrix} \ , \ \boldsymbol{d}_f = \begin{bmatrix} 0 & 1 \end{bmatrix}^T$$

w is the Gaussian white noise with a mean of zero, that is,

$$E\{w(t)\} = 0 \qquad (6)$$

$$E\{w(t) w^T(\tau)\} = W\delta(t - \tau) \qquad (7)$$

E denotes the mathematical average, δ denotes Dirac's delta function and W is the intensity of white noise.

So the state equation of the augmented system including the shaping filter is obtained.

$$\dot{\boldsymbol{y}}_p = \boldsymbol{A}_p \boldsymbol{y}_p + \boldsymbol{B}_p v + \boldsymbol{D}_p w \qquad (8)$$

where

$$\boldsymbol{y}_p = \begin{bmatrix} \boldsymbol{y}_s & \boldsymbol{z}_f \end{bmatrix}^T \ , \ \boldsymbol{A}_p = \begin{bmatrix} \boldsymbol{A}_s & \boldsymbol{d}_s \\ 0 & \boldsymbol{A}_f \end{bmatrix},$$

$$\boldsymbol{B}_p = \begin{bmatrix} \boldsymbol{b}_s & 0 \end{bmatrix}^T \ , \ \boldsymbol{D}_p = \begin{bmatrix} 0 & \boldsymbol{d}_f \end{bmatrix}^T$$

4. Control theory

In the case of the model used in this study, the basic method is feedback control, which uses state values of the seat surface. However, when the detection of disturbance coming from the road surface is easy, as in this case, improvement in the control performance can be expected by the application of a feedforward compensation-predicting disturbance, compared with the case of only feedback control. As the control purpose is to minimize the vertial acceleration of the seat under the constraints of the relative displacement x of the suspension and the input voltage to the voice coil motor, the criterion function is given as follows:

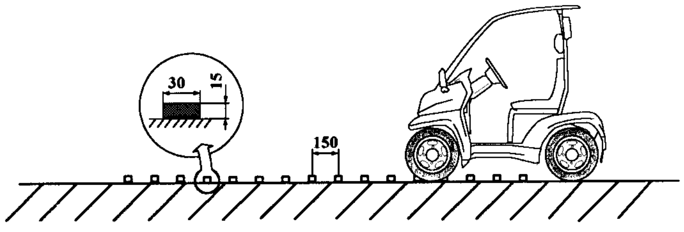
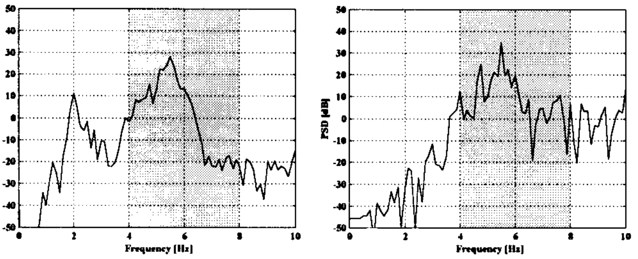


Fig. 5. Test road.



(a) Measured value (b) Simulated value

Fig. 6. Power spectral density of floor acceleration.

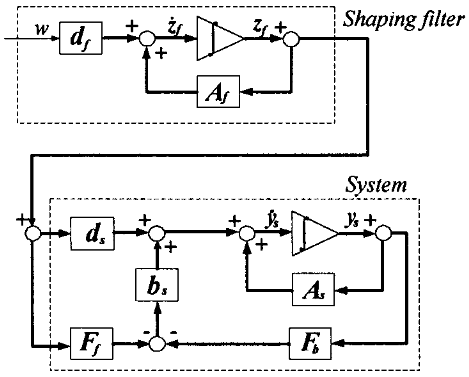


Fig. 7. Block diagram of the control system.

$$J = E\left(q_1 x^2 + q_2 \dot{y}^2 + q_3 y^2 + r v^2\right) \qquad (9)$$

q_1, q_2, q_3 and r are the weighting parameters.

According to the optimal regulator theory[5], the optimal control law to minimize the criterion is

$$v_{opt} = -\boldsymbol{F}\boldsymbol{y}_p = -\begin{bmatrix} \boldsymbol{F}_b & \boldsymbol{F}_f \end{bmatrix} \begin{bmatrix} y_s \\ z_f \end{bmatrix} \qquad (10)$$

To obtain the optimal feedback gain $\boldsymbol{F}$ of the control system, the MATLAB CONTROL SYSTEM TOOLBOX lqr of the MATHWORKS,Inc. was used. Figure 7 shows the block diagram of the control system.

5. Simulation

The simulation of the active seat suspension was performed when the disturbance shown in Fig.6 was the input.

The specification of the simulation system is shown as follows (measured values): m =49.5kg (deducting the leg mass from the body mass =60kg) + 12.6kg (seat mass), k =42500Ns/m, c =800Ns/m, a_m =0.043m/Vs, b_m =0.0036m/Ns. The performance of the control was compared among the following three cases: without control, with feedback control, and with feedback control and feedforward compensation. Here, the weight coefficient in eq. (9) is set constant, and only the weight coefficient r with respect to v is changed. By doing so, a trade-off curve of the standard deviation of the absolute acceleration of the seat surface relative to the standard deviation of the controlling voltage was obtained as shown in Fig.8. The standard deviation of acceleration without control is also shown for reference (dashed line). From the figure, comparison of the seat acceleration, when the standard deviation of the control voltage is about 4 V (the maximum value in the specification), with that of the passive controls showed that improvement by 47% and 69% is possible by feedback control and feedback control with feedforward link, respectively.

Figure 9 shows examples of time histories of absolute seat accelerations obtained from the simulation when the standard deviation of the control voltage is about 4 V for the cases without control, feedback control, and feedback control with feedforward link. The figure shows that improvement in riding comfort is possible by the active control of seat suspension, based on the evaluation of time domain. The figure also shows that the feedback control with feedforward link, given the disturbance characteristics, can reduce the absolute seat acceleration by more than 20% at the maximum.

Figure 10 shows the power spectrum density of the absolute seat acceleration shown in Fig.9 in evaluating the frequency domain, the acceleration in the vertical direction at 4-8 Hz, which significantly affects comfort, is sufficiently reduced.

In the simulated results, seat acceleration is sufficiently reduced by the control. This confirmed that feedforward -compensation to the feedback control functions well, thereby indicating that the simple model incorporating one-degree -of-freedom can produce effective controls.

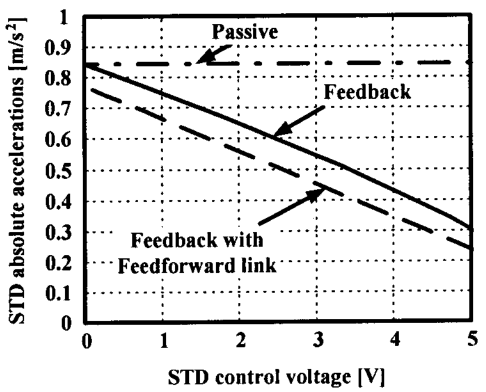
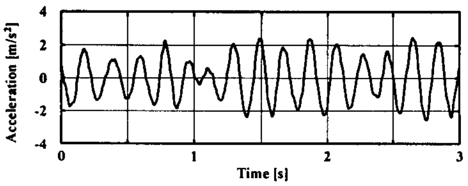
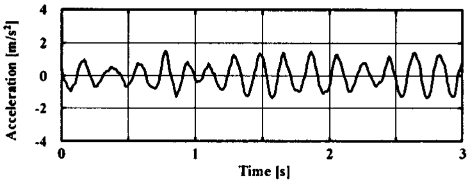


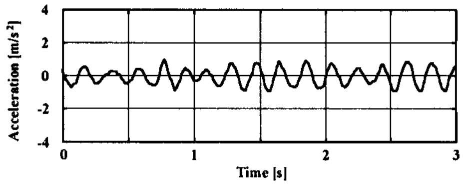
Fig. 8. Trade off curve of control voltage vs. seat acceleration in the case of using feedback controller and feedforward link controller.



(a) Passive control

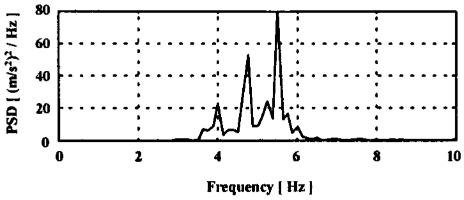


(b) Feedback controller

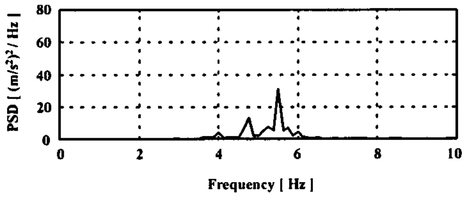


(c) Feedback with feedforward controller

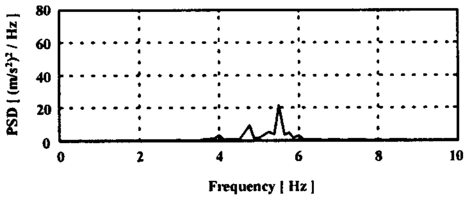
Fig. 9. Time histories of seat acceleration.



(a) Passive control



(b) Feedback controller



(c) Feedback with feedforward controller

Fig. 10. Power spectral densities of seat acceleration.

6. Conclusion

In this study, we proposed the application of an active seat suspension to small vehicles. We also investigated the efficacy and control performance of the models using simulations. From the results, we confirmed that acceleration in the frequency range of 4-8 Hz, which is an uncomfortable vibration component, can be reduced using active seat suspension which improves riding comfort.

In the future, we plan to perform experiments and to pursue practical aspects of the system, such as mounting an actuator power source onto the system, reducing power consumption, and pursuing the robustness of the system for changes in body weight of the driver considering that automobiles are shared.

Acknowledgments

The authors would like to thank Mr. Yoshihiro Abe and Mr. Shinya Hasegawa for providing the data used in this study, as well as for his guidance.

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