Preview Control of Vehicle Suspension System Featuring MR Shock Absorber

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Abstract. This paper presents control performance evaluation of optimal preview control algorithm for vehicle suspension featuring MR shock absorber. The optimal preview control algorithm has several advantages such as high control performance over that which is best for a non-preview system. In order to achieve this goal, a commercial MR shock absorber, Delphi Magneride\textsuperscript{TM}, which is applicable to high class passenger vehicle, is adopted and its field-dependent damping force and dynamic responses are experimentally evaluated. Then the governing equation of motion for the full-vehicle model is established and integrated with the MR shock absorber. Subsequently, optimal controller with preview control algorithm is formulated and implemented for vibration suppression of the car body. Control performance of the preview controller is evaluated for the full-vehicle model under random road condition. In addition, the control performances depending on preview distances are evaluated.

1. Introduction
The vehicle dynamic characteristics can be normally improved by suspension systems. So far, a passive oil shock absorber is widely employed for vehicle suspension system. However, its performance is limited by the uncontrollable damping force. Recently, active shock absorber is gradually used to enhance ride comfort as well as steering stability. However, design complication and high cost prevent the popularization of the advanced active suspension systems. Therefore, alternative mechanisms for vehicle suspension systems have been studied to replace the passive and active shock absorbers. For the last decade, the research work on ride comfort and steering stability of a vehicle system using semi-active suspension has been significantly increased. Among several potential candidates, magnetorheological (MR) fluid, whose rheological properties can be rapidly changed by applying a magnetic field to the fluid domain, has been most actively studied for the shock absorber of the semi-active suspension system which can offer a desirable performance without requiring large power consumption and expensive hardware. Carlson et al. [1] proposed a commercially available MR damper which is applicable to on-and-off-highway vehicle suspension system. Spencer Jr. et al. [2] proposed a dynamic model for the prediction of damping force of a MR damper. Choi et al. [3] manufactured an MR damper for a small-sized passenger vehicle and presented control characteristics of the damping force.
In the past, the feedback vibration control algorithms have been widely studied. However, research works on the feedforward control algorithms such as preview control are relatively rare. Preview control of suspension involves the acquisition and use of information concerning the road profile ahead of the vehicle. Hac et al. [4] obtained general analytical solutions including the effects of preview information on ride comfort, road holding and working space of the suspension and power requirements. Thompson et al. [5] proposed spectral decomposition methods to compute accurate RMS values with preview control. Mazbanrad et al. [6] proposed stochastic optimal preview control algorithm of a vehicle suspension on a random road. Gopala et al. [7] proposed semi-active preview control algorithm and half-car model considering the hysteretic nonlinear spring.

In this study, optimal preview control algorithm for the vehicle vibration is constructed by adopting the semi-active MR suspension system. Then preview control performances are evaluated under random road conditions.

2. Vehicle model with MR shock absorber

In this work, damping characteristics of a commercial MR shock absorber, Delphi Corporation’s Magneride™, which is used for high-class passenger vehicle is experimentally evaluated and modelled. Figure 1 presents the measured field-dependent damping force of MR shock absorber with respect to piston velocity. As expected, as the current increases the damping force increases. Figure 2 shows the dynamic bandwidth of MR shock absorber.

Figure 1. The field-dependent damping force of MR shock absorber.

Figure 2. Dynamic bandwidth of MR shock absorber.

Figure 3. Mechanical model of the full-vehicle MR suspension system.
measured dynamic bandwidth of the damping force in frequency domain. It is identified that the dynamic bandwidth of the proposed MR shock absorber is about $38\text{Hz}$ at $-3\text{dB}$. The MR shock absorber is modelled based on these characteristics. We can construct a mathematical state-space model for a full-vehicle MR suspension system equipped with four MR shock absorbers shown in figure 3:

$$\dot{x} = Ax + Bu + Dw,$$

$$u = [F_{MR1} F_{MR2} F_{MR3} F_{MR4}]^T,$$

$$x = [z_{u1} z_{u2} z_{u3} z_{u4} z_\theta \phi \dot{z}_{u1} \dot{z}_{u2} \dot{z}_{u3} \dot{z}_{u4} \dot{z}_\theta \dot{\phi}]^T,$$

where $x$ is the state vector, $u$ is the control input vector, $w$ is the road input vector. $A$, $B$ and $D$ are the system matrix, input matrix and disturbance matrix, respectively.

3. Preview control

The performance index $J$ is established for ride comfort and vehicle stability by minimizing the acceleration of C.G., suspension travel, tire force and control input [8].

$$J = \lim_{T \to \infty} \frac{1}{2T} \int_0^T \left( x^T Q_1 x + 2x^T N u + u^T R u + 2x^T Q_2 w + w^T Q_2 w \right) dt$$

where $Q_1$, $N$, $R$, $Q_{12}$ and $Q_2$ are time-invariant weighting matrices. From this performance index, the optimal control inputs are determined as follows:

$$u(t) = -R^{-1}\left( N^T + B^T P \right) x(t) + B^T r(t)$$

where $r(t)$ is the preview function and $P$ is the positive definite symmetric matrix solution of the algebraic Riccati equation;

$$P A_n + A_n^T P - P B R^{-1} B^T P + Q_n = 0,$$

$$A_n = A - B R^{-1} N^T, \quad Q_n = Q_1 - N R^{-1} N^T$$

The preview function $r(t)$ is given by

$$r(t) = \int_0^{t_p + t_d} e^{-A_\sigma \tau} \left( PD + Q_{12} \right) \begin{bmatrix}
H(t_p - \sigma) w_i(t + \sigma) \\
\cdots \\
H(t_p - \sigma) w_i(t + \sigma) \\
\cdots \\
H(t_p - \sigma) w_i(t + \sigma)
\end{bmatrix}^T d\sigma,$$

$$A_\sigma = A - B R^{-1} (N^T + B^T P),$$

$$H(t_p - \sigma) = \begin{cases} 1 \quad \text{for} \ t_p - \sigma \geq 0 \\
0 \quad \text{for} \ t_p - \sigma < 0 
\end{cases}$$

where $t_p$ is the preview time of front tire, $t_d$ is the preview time of rear tire. In equation (3), control input $u$ directly represents the damping force of $F_{MR}$. Therefore, the following semi-active actuating condition is imposed.

$$u_i(t) = \begin{cases} u_i \quad \text{for} \ u_i(\dot{z}_{u_i} - \dot{z}_{u_i}) > 0 \\
0 \quad \text{for} \ u_i(\dot{z}_{u_i} - \dot{z}_{u_i}) \leq 0 
\end{cases}, \quad i = 1, 2, 3, 4$$

In order to investigate the effect of preview control algorithm, a computer simulation is undertaken under the random road condition using MATLAB. Figure 4 presents vertical displacement of C.G. (center of gravity) point under random road condition. The RMS (root mean square) value of
uncontrolled case is 0.440, optimal control case is 0.314 and optimal preview case is 0.255. From this result, it can be obviously found that unwanted vibrations well suppressed by adopting the optimal preview control algorithm to the MR suspension system. Figure 5 shows the RMS of vertical acceleration at C.G. point vs. preview time. It is observed that the RMS value is sharply decreased over the first 0.1 sec and a little increased when preview time is greater than 0.2 sec.

4. Concluding remarks
In this work, a preview control for vibration control of MR suspension system was proposed and its effectiveness was verified under random road condition. After evaluating damping force characteristics of a commercial MR shock absorber, the full vehicle model with MR shock absorber was constructed. The optimal preview control algorithm was formulated based on MR suspension system. It has been demonstrated that the proposed optimal preview control algorithm with MR suspension system can provide much better vibration control performance compared with the conventional optimal control algorithm. It is finally remarked that the investigation of control performance considering sensor and actuator dynamics will be carried out in near future.

Acknowledgment
This work was supported by Acceleration Research (Center for ER Fluid Technology and Application) of MOST/KOSEF. This financial support is gratefully acknowledged. The authors also thank to GM Korea for providing the MR damper.

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Figure 4. Control performances under random road condition
Figure 5. RMS vs. preview time