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Passive and Semi-active Shock Reduction for Prototype HSRMD Avoiding Human Damage

Hyo-Jun Kim[1,#]

1 Department of Mechanical Engineering, Kangwon National University, Kyo-dong, Samcheok, Kangwon, South Korea, 245-711
Corresponding Author / E-mail: hjkimm@kangwon.ac.kr, TEL: +82-33-570-6322, FAX: +82-33-574-2993

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This paper presents the prototype shock reduction system (SRS) for the human supporting recoil mechanism device (HSRMD) subjected to impact force. Based on the parametric study of the HSRMD module, in order to reduce the force transmitted to the mounting body from the HSRMD, the passive and semi-active type shock reduction systems are studied. Parameters of the passive type SRS are determined by an optimization process under constrained conditions on the basis of the simplified HSRMD–SRS-human interaction model. The semi-active type SRS is devised using a MR damper with a feasible control scheme considering the disturbance characteristics. The performance of both systems is evaluated in a series of experiments using precisely constructed test setup. Finally, the transmitted force and linear impulse are estimated in the HSRMD-operator interaction condition for further developing process.

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1. Introduction

The problems of reducing or diminishing transmitted force and excessive vibration under the impacted structure are important factors in the structural design. Therefore, dynamic absorbing system designs that reduce impulsive force have been studied and applied in many engineering fields. In order to stabilize the total system due to an impulsive disturbance, a reduction in the amount of force transmitted to the system is required in the level maintaining system.

There have been many studies related to vertical disturbances in the vehicle dynamics area. From the ground input, the reduction of transmitted force to the operator has been studied using passive, semi-active and active control methods including the works of Lee *et al.*,[1] Vassal *et al.*,[2] Kim *et al.*[3] and Yagiz *et al.*.[4]

In the recent past, various control schemes using smart material such as electrorheological (ER) and magnetorheological (MR) fluid have been adopted for this purpose. Chooi *et al.*[5] studied modeling of the MR damper which is a noticeable device, especially as an automotive shock absorber. Sapinski *et al.*[6] studied an autonomous control system for a 3 DOF pitch-plane suspension model using a MR shock absorber.

In other subjects, Chehab *et al.*[7] investigated the efficiency of mounting systems with respect to foundations supporting hammer-presses and conducted comprehensive parametric studies considering the powerful short-term impact loads.

In the case of a subject closer to this study, Golysheva *et. al.*[8] studied a passive system of vibration protection in hand-held percussion machines. They rely on systematic impacts for the treatment of hard materials. Some operators suffer from HAVS(Hand-Arm Vibration Syndrome), VWF(Vibration White Finger) and other conditions caused by hand-transmitted vibration. After the study, in order to improve this problem of hand-held percussion machines, they showed that the proposed vibration attenuation system significantly reduced hand-transmitted vibration using a combination of vibration isolation and dynamic absorption.

In the case of the high impulsive force device penetrating an object by an immediate explosive shot, the force transmitted to the mounting system becomes a more important issue. In addition, in the case of a device with higher performance, a larger impact force can be produced in the aspect of kinetics. In the case of a portable device supported by the human body directly without special mounting structures, there is a possibility of causing serious problems to the individual. Furthermore, the interaction between a human body and the device is one of the essential performance factors in actual operating conditions. Therefore, in order to reduce the force transmitted to the human body from the device, a study of achieving the mechanism of the shock reduction system (SRS) should be followed in the development of the device.

In this study, isolation of the prototype human-supporting recoil mechanism device (HSRMD) is performed considering the dynamic characteristics of the device. This is a special application system and the related results are rare. On the basis of the study using the dynamic model of the device and the experimental results, the overall isolation system including the shock reduction system is modeled. In order to realize the SRS, the passive and semi-active type system is considered. To determine the design parameters of the passive system, an optimization process is performed. This is also a kind of reference system with respect to the semi-active type system. Following that, the semi-active system using MR damper is devised using a feasible control scheme considering the actual conditions avoiding a complexity of the system. Both systems are implemented and the performance is evaluated through experiments based on the precisely devised test setup.

2. Description of application system

There are some devices that penetrate an object by instant explosive gas. From ancient times, this has been a feasible method to send a heavy ball flying away. In order to project a heavier ball further, a more powerful explosive force was used. As a result, in general, these devices are supported by solid mounting structures. Considering durability and utility conditions, the reduction of the reaction force are important factors in the design process of these devices.

The recoil mechanism is a typical method to satisfy this requirement. In a device using explosive gas, recoil operation is generally one of the automatic operating mechanisms that allows autoloading. These mechanisms use the recoil force to provide energy to cycle the movement of an internal component in the device. But in the device, when a ball is propelled by explosive gas, the forward force of the ball has an opposite force that pushes the device backward. Due to this recoil effect, the recoil force pushes the device back into the mount structure. The other function of the recoil mechanism is to transform the extremely high interior ballistic forces acting upon the recoiling parts into tolerable loads transmitted to the supporting structure, in other words, the recoil-based moving mechanism inside the device absorbs some of the recoil force. The design objective of these kinds of devices is attenuation of high peak loads into longer duration with much lower peak values through the dynamic action of the moving-recoiling parts.

As shown in Fig. 1, the prototype HSRMD in this study contains the recoil mechanism. However it is small enough for hand-held and human-support device which is different from the case of huge artillery. The parameters of the HSRMD are determined to satisfy the target performance (maximum flying distance, cycle time of operation, interaction of internal mechanism, etc) in the design process.

Fig. 2 shows simulation results of the force generated by the device with respect to ±20% variation of barrel mass and ±40% stiffness variation of the barrel spring relative to designed parameters, using the HSRMD analysis module. As shown in Fig. 2(a), the variation range of barrel mass shows minor effect on the force. Also the barrel spring variation shows that it is insufficient in reducing the force transmitted to mount body as presented in Fig. 2(b).

As mentioned earlier, the supporting structure for the prototype HSRMD is the human body without any special mounting structure. The impulsive force from the device raises the possibility of causing serious problems to the mounting body. Instant or repeated exposure of the body to such a high impact force may result in severe injury or symptoms of physiological disorders.

Unfortunately, as shown in Fig. 2(a) and Fig. 2(b), the conventional recoiling mechanism designed for target performance is not enough to reduce the force transmitted to the mounting body. Therefore, it is necessary to apply an additional dynamic absorbing system in the prototype HSRMD.

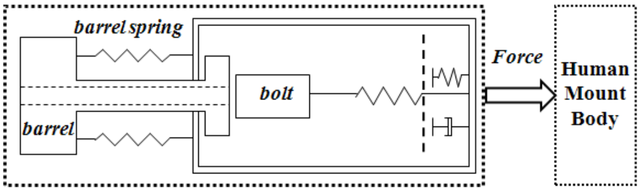
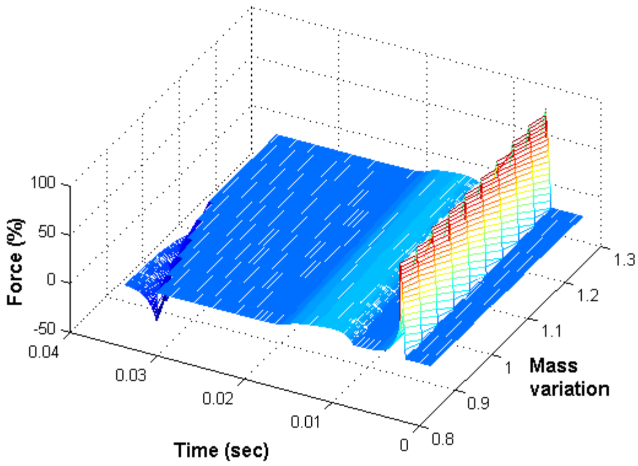
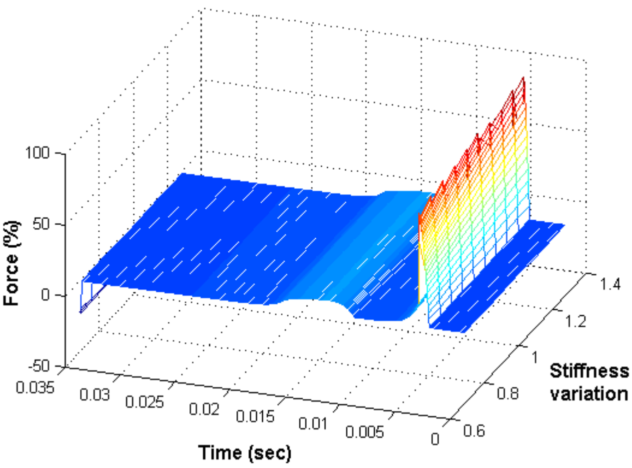


Fig. 1 Conceptual diagram of HSRMD system



(a) Barrel mass variation



(b) Barrel spring variation

Fig. 2 Comparison of forces with barrel mass and spring variation

3. Design of shock reduction system

3.1 Passive shock reduction system

In this section, for the purpose of reducing the force transmitted to the mount body from the prototype HSRMD, a simplified overall isolation system model as shown in Fig. 3 is constructed with the passive shock reduction system. Considering the results of previous section, the feasible method to suppress a transmitted force is using the dynamic absorber between the HSRMD and mounting body. The dynamic model of the HSRMD is too complex to apply in the optimization process, thus the HSRMD module is described as a lumped mass having an impulsive force input. In addition, because there are some difficulties in the analytical approach including the huge mathematical model of a complex human body, the mounting system considers only the dominant lowest horizontal mode on the basis of the previous works of Kim *et al.*[9] and Kim.[10] This section focuses on the optimization of the passive SRS having equivalent stiffness (Ks) and equivalent damping coefficient (Cs) based on Fig. 3.

In order to determine the design parameters of the passive SRS considering characteristics of mounting body, an optimization process[9,11] is performed as follows.

The state-space equation of the overall isolation system is expressed as:

$$\dot{X} = AX + BF_i \tag{1}$$

where,

$$X = \begin{bmatrix} x_s & \dot{x}_s & x_u & \dot{x}_u \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k_s}{M_s} & -\dfrac{c_s}{M_s} & \dfrac{k_s}{M_s} & \dfrac{c_s}{M_s} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_s}{M_u} & \dfrac{c_s}{M_u} & -\dfrac{k_s+k_u}{M_u} & -\dfrac{c_s}{M_u} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & \dfrac{1}{M_s} & 0 & 0 \end{bmatrix}^T$$

Where M_s is total mass of the HSRMD module, M_u is the mount body mass, k_s is the equivalent stiffness and c_s is the damping coefficient of the passive SRS, x_s represents the HSRMD displacement, x_u is the mount displacement, F_i is the impulsive force input and k_u is the mount stiffness.

The function of the passive shock reduction system is to reduce the damage transmitted from the HSRMD to the operator within the limited buffering displacement range. To this end, in order to decide the optimal stiffness k_{op} and damping coefficient c_{op} related to k_s, c_s of the passive SRS, the performance index J is defined as Eq. (2) using the state variables.

$$J = \lim_{T\to\infty}\frac{1}{T}E\left[\int_0^T \left(\dot{x}_4^{\,2} + \rho\left(x_1 - x_3\right)^2\right)dt\right] \tag{2}$$

where, ρ is weighting factor.

Eq. (2) can be rearranged in the form of Eq. (3) by using the state vector and the symmetric, positive definite matrix Q having dimensions of 4x4.

$$J = \lim_{T\to\infty}\frac{1}{T}E\left[\int_0^T X^T Q X dt\right] \tag{3}$$

Where the elements in the upper triangle can be written as:

$$Q_{11} = \frac{k_s^2}{M_u^2} + \rho,\quad Q_{12} = \frac{k_s c_s}{M_u^2},\quad Q_{13} = \frac{k_s\left(k_s+k_u\right)}{M_u^2} - \rho,$$

$$Q_{14} = -\frac{k_s c_s}{M_u^2},\quad Q_{22} = \frac{c_s^2}{M_s},\quad Q_{23} = -\frac{c_s\left(k_s+k_u\right)}{M_u^2},\quad Q_{24} = -\frac{c_s^2}{M_u^2}$$

$$Q_{33} = \frac{\left(k_s+k_u\right)^2}{M_u^2} + \rho,\quad Q_{34} = \frac{c_s\left(k_s+k_u\right)}{M_u^2},\quad Q_{44} = \frac{c_s^2}{M_u^2}$$

The performance index of Eq. (3) can be represented as follows.

$$J = Trace\left\{Q\Sigma\right\} \tag{4}$$

where,

$$\Sigma = E\left[X^T X\right] = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} \end{bmatrix}$$

The covariance propagation equation to the state-space representation of Eq. (1) satisfies the Eq. (5).

$$A\Sigma + \Sigma A^T + B\Xi B^T = 0 \tag{5}$$

where assumed that the impulsive disturbance F_i having intensity Ξ satisfies the following Eq. (6) and (7).

$$E\left[\dot{F}_i(t)\dot{F}(t+\tau)\right] = \Xi\delta(t-\tau) \tag{6}$$

$$E\left[\dot{F}_i(t)\right] = 0\left(t \ge 0\right) \tag{7}$$

The components of solution σ_{ij} can be obtained as follows.

$$\sigma_{11} = \frac{\xi_{11}}{\mu_{11}} + \frac{2k_s^2 k_u m_s m_u + k_s^3 m_u^2}{2c_s k_s k_u^3 m_s^2},\quad \sigma_{12} = 0$$

$$\sigma_{13} = \frac{\xi_{13}}{\mu_{13}} + \frac{k_s k_u m_s m_u + k_s^2 m_u^2}{2c_s k_u^3 m_s^2},\quad \sigma_{14} = -\frac{1}{2k_u m_s}$$

$$\sigma_{22} = \frac{c_s^2 k_u + k_s^2 m_s + 2k_s k_u m_s + k_u^2 m_s + k_s^2 m_u}{2c_s k_u^2 m_s^2}$$

$$\sigma_{23} = \frac{1}{2k_u m_s},\quad \sigma_{24} = \frac{c_s^2 k_u + k_s^2 m_s + k_s k_u m_s + k_s^2 m_u}{2c_s k_u^2 m_s^2}$$

$$\sigma_{33} = \frac{\xi_{33}}{\mu_{33}},\quad \sigma_{34} = 0,\quad \sigma_{44} = \frac{c_s^2 k_u + k_s^2 m_s + k_s^2 m_u}{2c_s k_u^2 m_s^2}$$

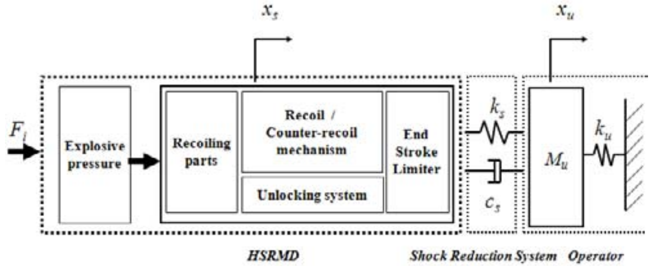


Fig. 3 Schematic diagram of simplified overall isolation system

where,

$$\xi_{11} = c_s^2 k_s k_u m_s + k_s^3 m_s^2 + 3k_s^2 k_u m_s^2 + k_u^3 m_s^2 + c_s^2 k_s k_u m_u + 2k_s^3 m_s m_u$$
$$\xi_{13} = c_s^2 k_u m_s + k_s^2 m_s^2 + 2k_s k_u m_s^2 + k_u^2 m_s^2 + c_s^2 k_u m_u + 2k_s^2 m_s m_u$$
$$\xi_{33} = c_s^2 k_u m_s + k_s^2 m_s^2 + k_s k_u m_s^2 + c_s^2 k_u m_u + 2k_s^2 m_s m_u + k_s^2 m_u^2$$
$$\mu_{11} = 2c_s k_s k_u^3 m_s^2$$
$$\mu_{13} = 2c_s k_u^3 m_s^2$$
$$\mu_{33} = \mu_{13}$$

From the above components of the solution, σ_{ij}, the performance index J of Eq. (4) is represented in the following form.

$$J = \frac{k_s^2}{2c_s k_u m_s^2} + \frac{c_s}{2m_s^2 m_u} + \left(\frac{1}{2c_s k_s} + \frac{1}{2c_s k_u}\right)\rho \tag{8}$$

From the calculations minimizing the performance index of Eq. (8) concerning stiffness and damping, respectively, the optimal stiffness coefficient k_{op} and damping coefficient c_{op} of the passive shock reduction system can be obtained as follows.

$$k_{op} = \sqrt[3]{\frac{k_u m_s^2 \rho}{2}} \tag{9}$$

$$c_{op} = \sqrt{m_u \left\{ \frac{k_s^2}{k_u} + \left(\frac{m_s^2}{k_s} + \frac{m_s^2}{k_u}\right)\rho \right\}} \tag{10}$$

3.2 Semi-active shock reduction system

In general, shock absorbing systems are categorized by how the device operates under passive, active and semi-active type systems. Despite the performance of the active system, it requires high power consumption and is costly. The passive type has a simple structure but it may be modified concerning parameter variations of the target system. Therefore, as an alternative method, the studies of the semi-active type system such as the controllable variable-orifice hydraulic damper, MR (magnetorheological) damper and ER (electrorheological) damper have recently been presented.

From the works of Chooi *et al.*,[5] differing from the conventional shock absorber, MR damper has the advantage of being able to continuously adjust to the mechanical properties of the device with a controllable MR fluid inside. With an electronic system, the damping force can be continuously regulated by controlling the strength of the applied magnetic field. The paper showed an analytical approach of matching physical parameters to the double-tube MR damper in the developing process. MR dampers are also feasible considering the fault-tolerance in controlling the system. If there is a failure in the electronic system, the MR damper can still operate as a conventional-passive damping element within certain performance parameters.

In this section, in order to design the prototype shock reduction system, the semi-active type controllable damper which uses the MR fluid is adopted. Unfortunately, related results subjected to impact force are rare. In general, several control theories can be adopted on the basis of the system model in Fig. 3 for the purpose of reducing the force transmitted to the mounting body from the HSRMD. In the case of Yao *et al.*[12] using skyhook control of vehicle suspension system or Tsang *et al.*[13] using the LQR algorithm to stabilize building subjected to earthquake, the magnitude and wave length of disturbance are not fixed. Different from them,[12-14] a pattern of the impulsive disturbance from the HSRMD can be standardized. A practical requirement for prototype

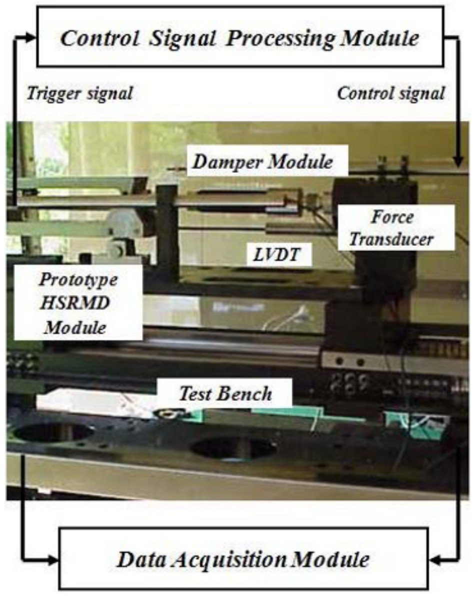


Fig. 4 Experimental setup

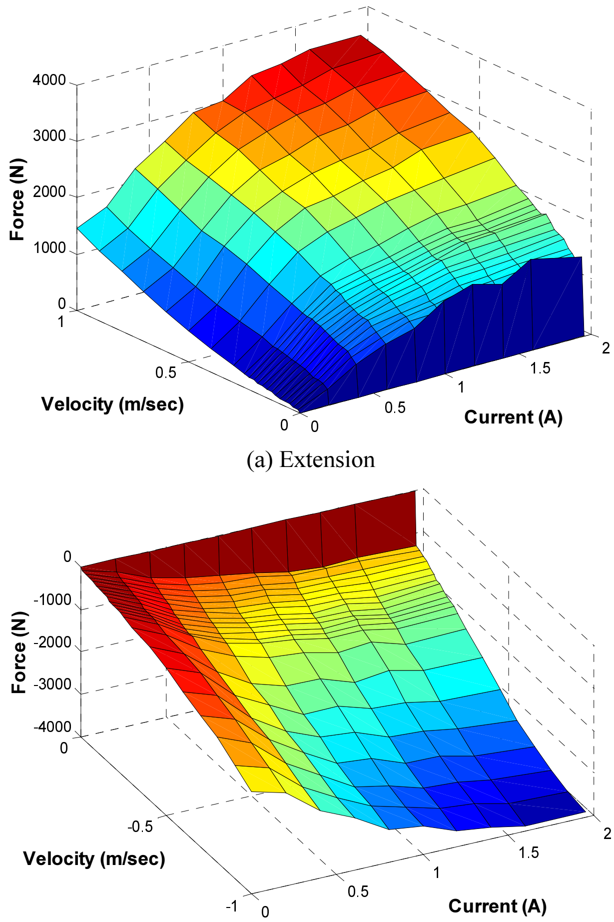


Fig. 5 Characteristic curve of MR damper

HSRMD is that the developing SRS should be as simple as possible under actual implementation. In this study, the reverse control scheme is applied in order to minimize additional equipment for controlling the device. The scheme is based on the repeatability of the force generated by the HSRMD. It just uses trigger signal without any extra sensor system.

On the basis of investigation of test results including force profile, duration time and delay between triggering and starting time of force, the corresponding control signal is formulated reversely using the trigger signal of the HSRMD. This control structure is shown in Fig. 4 of the schematic diagram of the experimental setup. Fig. 5 shows the tested characteristic curve of the MR damper used in experiment. Fig. 5(a) and 5(b) represent the extension and compression mode respectively. The damping forces of each mode are tested in a velocity range up to 1 m/sec with 0 - 2A current values.

4. Experimental work

In this section, on the basis of previous results, the prototype shock reduction system for the HSRMD has been implemented for both the passive and semi-active type systems. In order to precisely evaluate the practical performance of the designed systems, an experimental setup was constructed including a carefully devised test bench with the HSRMD module, the prototype shock reduction module and sensors - data acquisition - analysis module as shown in Fig. 4 at the rigidly mounted condition. There is the difference of this test condition from actual/modelled operating mode as shown in Fig. 1 and Fig. 2. It is due to the prototype HSRMD being partially assembled by major working parts. For practical implementation of the designed SRS module, it would be better to devise a supplementary experimental setup (with fully assembled HSRMD) as a middle stage between the presented method and the actual HSRMD-operator system.

In this study, there is a restriction of the buffering displacement in the shock reduction system, that is, the target specification is 10 mm. From the weighting factor $\rho(=7.2\times10^5)$ satisfying the restriction, the design parameters k_{op} and c_{op} of the passive shock absorber are decided as $k_{op}=5.293\times10^3\,(N/m)$ and $c_{op}=1.501\times10^3$ $(N\cdot\mathrm{sec}/m)$, respectively, by numerical analysis on the basis of the optimal design process in section 3.1.

Fig. 6 shows the experimental results of the forces transmitted to the mount structure with and without the passive shock reduction system (which is matched to previous results). In order to more easily compare them, the magnitude of the force is represented by a percentage-force relative to the original system case. As shown in the results, the maximum force with the passive shock reduction system represented about an 81% reduction rate from 21650(N) to 4113(N).

Fig. 7 presents three cases of test results of the original operation, non-optimal passive shock reduction system and semi-active system using MR damper, respectively. Non-optimal means unmatched SRS to previous optimal values. As shown in the figure, the maximum force with the semi-active type shock reduction system represented about an 80% reduction rate from 21980(N) to 4396(N). The performance of this semi-active type system becomes equivalent to the optimal passive type system in Fig. 6. The peak values are slightly different from that caused by the variable charge condition with explosive powder. As depicted in Fig. 7 of non-optimal passive type shock reduction system, if the parameters of the developing HSRMD were changed (for example, mass is changed), the optimal passive damper system should be modified. This means that the previous optimal system is non-optimal for the new system. But in the case of a semi-active type system, it can be easily done without any excessive hardware modification.

From the result of Fig. 8, the buffering stroke in both shock reduction systems matches the target specification. In the case of the passive type system, the returning time of the shock absorber is slow. General shock absorbing dampers are capable of converting the kinetic energy at the moment of impact into heat using flow resistance in both bounce and rebound operation. Considering the efficiency of the SRS for the HSRMD, this experimental result suggests that this shock absorber has the feature of approximately

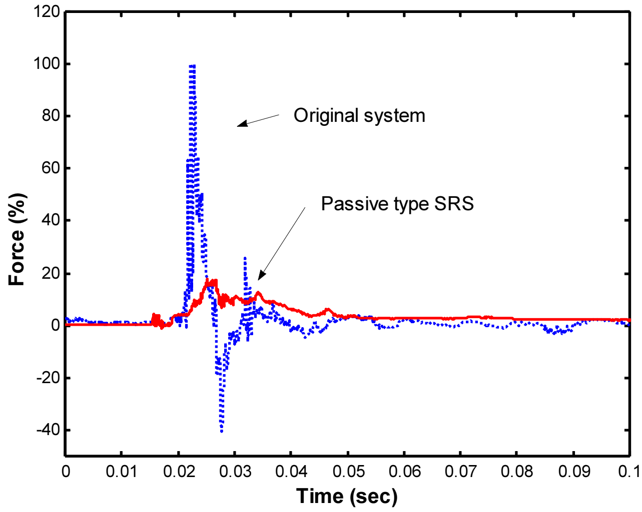


Fig. 6 Comparison of transmitted forces to mount

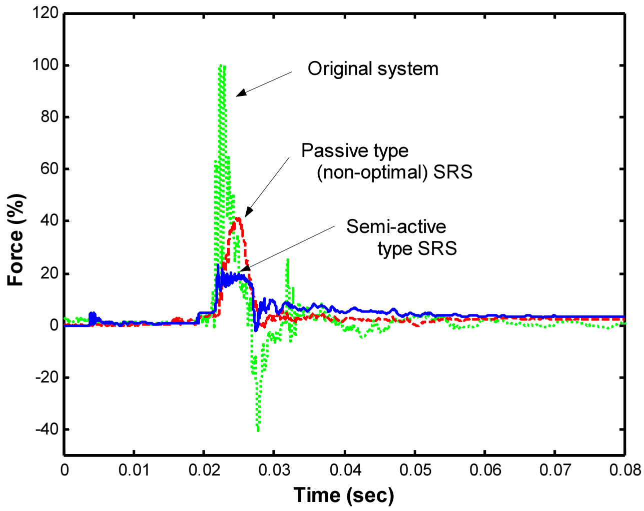


Fig. 7 Comparison of transmitted forces to mount

undamped in extension, that is, it has a different action between compression and extension operations for a quick return.

Fig. 9 depicts the predicted interaction (transmitted) force and linear impulse values in human-HSRMD interaction condition. These results are calculated by adopting the simplified shear model of human being in previous work of Kim[10] using data of Fig. 6 and Fig. 7 in the case of original, optimal passive, non-optimal passive and semi-active type shock reduction system, respectively. As mentioned before, both the optimal passive and semi-active type system have similar performance relative to the unisolated original system, although there are slight differences. Fig. 9 shows the feasibility of the semi-active type shock reduction system having the benefits of easy tuning for further modification of the prototype HSRMD.

Despite the fact that a practical performance test is impossible because the prototype HSRMD is partially assembled, this method gives meaningful results to the design process for further development. These results imply that the undesirable human damage (injury, symptoms of physiological disorders, etc.) induced by the impulsive disturbance from the HSRMD can be diminished.

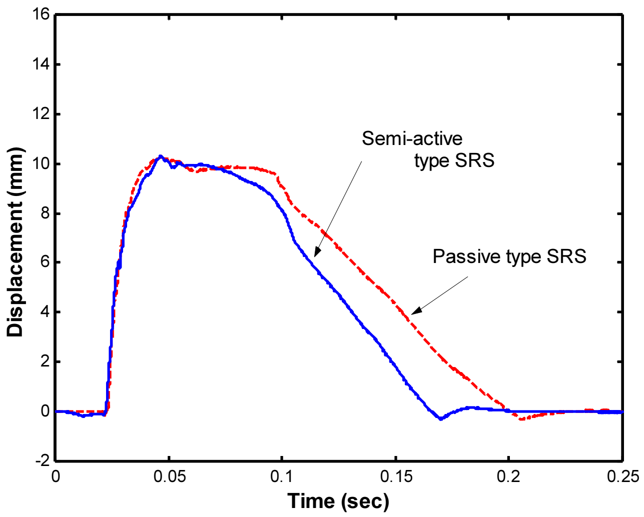


Fig. 8 Comparison of buffering displacement

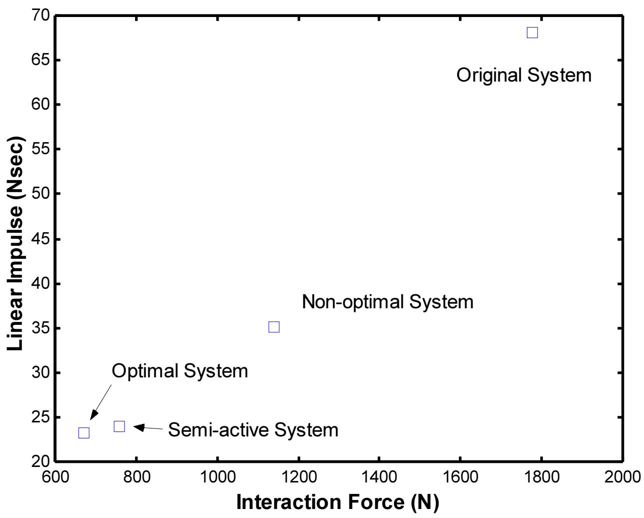


Fig. 9 Comparison of interaction force and linear impulse values

5. Conclusions

In this study, the systematic approach to the shock reduction system for the prototype HSRMD is performed considering limitations of the conventional recoiling mechanism. In order to reduce the force transmitted to human body from the HSRMD, two prototype shock reduction systems have been devised and presented. The design parameters of the first passive type SRS were determined by the optimization process using a simplified overall isolation system model. From solutions satisfying the constraints, the passive SRS using the hydraulic shock absorber was constructed. The second semi-active type SRS using MR damper was devised considering the feasibility of actual implementation.

Both systems were implemented in the experimental setup with the prototype HSRMD. From a series of experiments, the designed SRSs for the HSRMD result in 80 percent reduction rate of the maximum force compared to the unisolated original system. From estimation of human-HSRMD interaction condition, these results imply that the undesirable human damage can be diminished.

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