International Journal of the Korean Society of Precision Engineering Vol. 4, No. 6. November 2003.

Analysis of Optimal Dynamic Absorbing System considering Human Behavior induced by Transmitted Force

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ABSTRACT

In this study, the optimal dynamic absorbing system for the gas operated HIF (high implusive force) device has been investigated. For this purpose, firstly, the dynamic behavior of human body induced by impulsive disturbances has been analyzed through a series of experimental works using the devised test setup. The characteristics of linear impulse has been compared under some conditions of support system. In order to design the optimal dynamic absorbing system, the parameter optimization process has been performed based on the simplified isolation system model under constraints of moving displacement and transmitted force. Finally, the performance of the designed dynamic absorbing system has been evaluated by simulation in the actual operating condition.

Key Words : Human behavior, Dynamic absorbing system, Impulse, Optimal design

1. Introduction

In general, the problem associated with reducing the transmitted impulsive force and the undesirable vibration is an important factor both in the structural design and in the stabilization of the overall system[7-10]. Therefore, the bumper structure design reducing the impact force has been studied and applied in many engineering fields. In order to stabilize the total system in spite of impact disturbance, the reduction of transmitted impulsive force is required to maintain the system safety.

As a research related to the dynamic absorbing system, Zhang et al.[1] derived the optimal damping factor of an absorbing system in the railway vehicle, and defined the equivalent mass ratio which is able to evaluate the efficiency. Hundal et al.[2] studied the design scheme which is able to induce the optimal response using the pneumatic shock isolator. After that, Alanoly et al.[3] performed the study that reduces the acceleration and relative displacement of the body mass through semi-active actuator. The semi-active actuator can be used for absorbing the force by controlling the internal fluid flow in the actuator with the variable orifice. Walsh et al.[4] studied on the absorber system with variable stiffness in order to minimize the excessive vibration which can occur in the rotatory machine using the on-off operation process.

In HIF devices penetrating an object by an instantaneous explosive shot, the transmitted force to the mount system becomes a more important issue. Besides, in case of the HIF devices with high performance, larger impact energy can be produced in the aspect of kinetics. Especially, in case of a portable HIF devices supported by human body directly without special mounting structures, there is a possibility of causing serious damages to the human body[8].

Therefore, in order to realize the mechanism of the dynamic absorbing system reducing the

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Accepted: April 30, 2003
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transmitted force to the human body from the HIF device, correct prediction for the transmitted impulsive force to the body should be followed in the development of the device.

Recently, a couple of works[5,6] in the fields of automobile engineering have been presented regarding the problems of human body behavior due to vibration and impact, however, the results are still insufficient especially when related to dynamic characteristics of human behavior at horizontal direction for the high impulsive force.

In this study, firstly, the portable HIF device operated by explosive gas pressure and human body mounted at the device are selected as the overall system concerned. Secondly, on the basis of experimental results and analyses between human behaviors and transmitted impulse occurring in an actual operating condition, modelling of the simplified isolation system is conducted by taking into account the dynamic characteristics of support body structure. Finally, the parameter optimization on the dynamic absorbing system for the HIF device is performed. Also, through the simulation with the designed dynamic absorbing system, the performance of reduction of the transmitted impulsive force is evaluated under an actual utility condition.

2. Analysis of dynamic characteristics of human body under an impulsive force

2.1 Human behavior induced by the impulsive force input

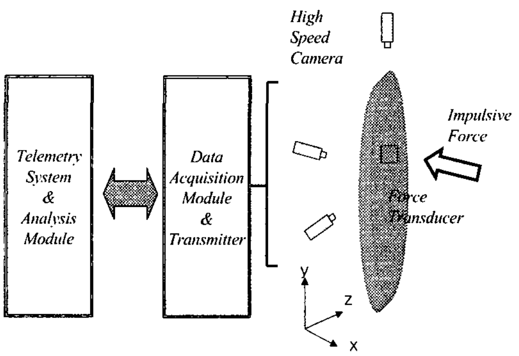

Fig. 1 Schematic diagram of experimental setup

In order to analyze the dynamic characteristics of human bodies having complicated structure subject to impact force from the HIF device, it is necessary to measure and to predict the human behaviors under an actual impulsive force input[11]. In this section, experiments were conducted as shown in Figure 1 on the devised experimental setup to investigate the dynamic characteristics between human bodies and device under an impulsive force input, and the corresponding analysis was performed.

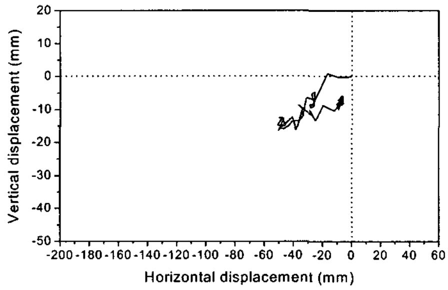

Fig. 2 Trajectory of shoulder position under single impulsive force input condition

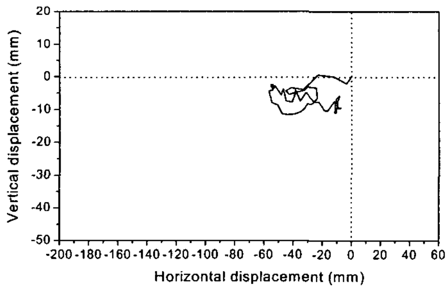

Fig. 3 Trajectory of forearm position under single impulsive force input condition

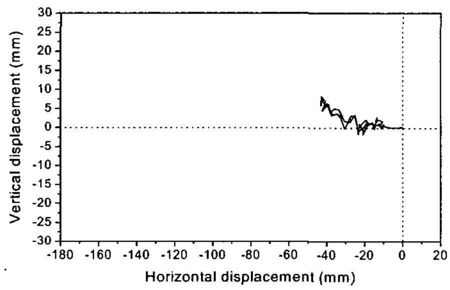

Fig. 4 Trajectory of HIF device position under single impulsive force input condition

Through the experiments of main part of human body for single or continuous impulsive input, the dynamic behaviors and the transmitted force of human body were measured by using the high-speed camera set and a force transducer. When an impulsive force input in HIF system acts upon an object, HIF device and human behavior represent three-dimensional trajectories.

However, in this study, trajectories of each point in x-y plane are demonstrated for the vertical cross-section giving dominant effect as shown in Figures 2 to 7. In Figures 2 to 7, x-axis and y-axis represent the horizontal and vertical directions of HIF device, respectively. For the trajectory of shoulder position shown in Figure 2, horizontal displacement shows the dominant behaviors compared with the vertical one which is less than 25% of horizontal displacement. As shown in Figure 3 for the trajectory of forearm position, horizontal displacement shows the dominant behaviors compared with the vertical one which is less than 15% of horizontal displacement. The HIF device due to impulse force input gives rise to rotational moment about the support point of a human body as shown in Figure 4. Therefore, the direction of vertical displacement is positive.

In the case of continuos impulsive force input as in Figures 5, 6 and 7, horizontal displacement value is three times the value of single impulsive force input case. Through the results of Figures 2 to 7, one can understand the impulsive force input transmitted to the human body from HIF device causes unnecessary human body and rotational motions of the HIF device. Therefore, a study is required for reducing the impulsive force transmitted to the human body.

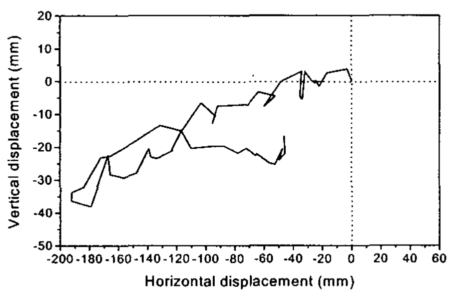

Fig. 5 Trajectory of shoulder position under continuous impulsive force input condition

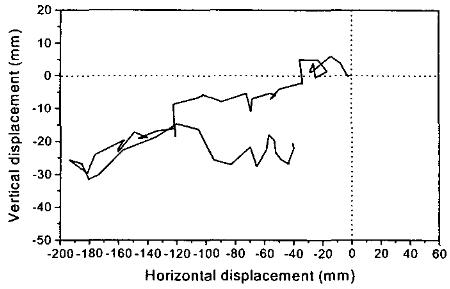

Fig. 6 Trajectory of forearm position under continuous impulsive force input condition

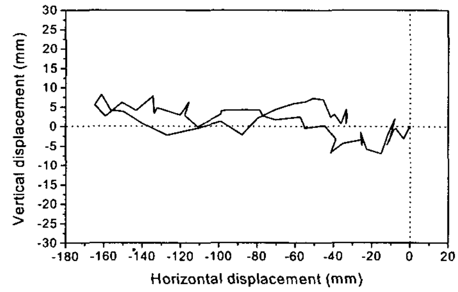

Fig. 7 Trajectory of HIF device position under continuous impulsive force input condition

2.2 Transmitted impulse to human body

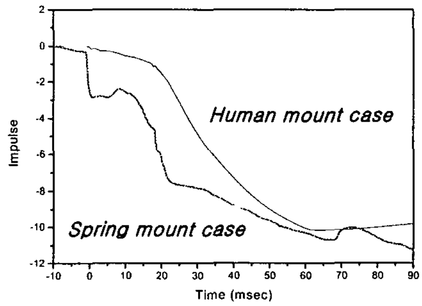

Fig. 8 Experimental result of impulse variation depending on the mount condition.

Figure 8 gives experimental results for impulse which causes human behavior through the experimental set-up shown in Figure 1. Since the transmitted impulse from HIF device has a big difference according to the mount conditions, experimental results in Figure 8 depict the impulse variation with respect to time between human mount and rigid spring mount. In general, for the design of bumper structure, it is required to consider the mount part, because internal components and size of HIF device have significant effects on the impact from HIF device.

3. Optimal design of an absorbing system

3.1 Optimal design of a dynamic absorbing system considering mount characteristics

In this section, an absorbing system considering the behavior of a human body as the mount of HIF device is designed for the purpose of reducing the transmitted impulsive force. Human behavior characteristics can be changed by user conditions, and there are some difficulties in constructing the mathematical model of complex human body structure. Therefore, in this study, the simplified absorbing system considering only some dominant lower horizontal modes on the basis of experimental results is constructed, and optimization process considering restriction condition is performed in order to determine the design parameters of absorbing system.

Governing equation of simplified absorbing system model is expressed by HIF device mass M_s, mount mass M_u, equivalent stiffness k_s and damping coefficient c_s.

$$\begin{bmatrix} M_s & 0 \\ 0 & M_u \end{bmatrix}\begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_u \end{Bmatrix} + \begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix}\begin{Bmatrix} \dot{x}_s \\ \dot{x}_u \end{Bmatrix} + \begin{bmatrix} k_s & -k_s \\ -k_s & k_s+k_u \end{bmatrix}\begin{Bmatrix} x_s \\ x_u \end{Bmatrix} = \begin{Bmatrix} F_i \\ 0 \end{Bmatrix} \quad (1)$$

where x_s means HIF device displacement, x_u is mount displacement, F_i is force input and k_u is mount stiffness.

In order to decide optimal parameter of the absorbing system, performance index considering both buffer displacement and transmitted force to the mount is defined as Equation (2).

$$J = \lim_{T\to\infty} \frac{1}{T} E[\int_0^T (\ddot{x}_u{}^2 + \rho(x_s - x_u)^2)dt] \quad (2)$$

where ρ is weighting factor.

Equation (2) can be rewritten in the form of Equation (3) using state variables.

$$J = \lim_{T\to\infty} \frac{1}{T} E[\int_0^T (\dot{x}_4{}^2 + \rho(x_1 - x_3)^2)dt] \quad (3)$$

Integration part of Equation (3) can be rearranged in the following form:

$$\dot{x}_4{}^2 + \rho(x_1 - x_3)^2$$
$$= [\,x_1\, x_2\, x_3\, x_4\,] \begin{bmatrix} \frac{k_s^2}{M_u^2}+\rho & \frac{k_s c_s}{M_u^2} & \frac{k_s(k_s+k_u)}{M_u^2}-\rho & -\frac{k_s c_s}{M_u^2} \\ \frac{k_s c_s}{M_u^2} & \frac{c_s^2}{M_s} & -\frac{c_s(k_s+k_u)}{M_u^2} & -\frac{c_s^2}{M_u^2} \\ \frac{k_s(k_s+k_u)}{M_u^2}-\rho & -\frac{c_s(k_s+k_u)}{M_u^2} & \frac{(k_s+k_u)^2}{M_u^2}+\rho & \frac{c_s(k_s+k_u)}{M_u^2} \\ -\frac{k_s c_s}{M_u^2} & -\frac{c_s^2}{M_u^2} & \frac{c_s(k_s+k_u)}{M_u^2} & \frac{c_s^2}{M_u^2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = X^{\top} Q X \quad (4)$$

where $X = [\, x_s \;\; \dot{x}_s \;\; x_u \;\; \dot{x}_u \,]^T$ and Q is symmetric and positive definite matrix.

Assuming that exciting force having intensity Ξ satisfies the following Equations,

$$E[\, F_i(t) \;\; F_i(t+\tau)\,] = \Xi\,\delta(t-\tau) \quad (5)$$

$$E[\, F_i(t)] = 0 \quad (t \geq 0) \quad (6)$$

performance index using Equation (3) and (4) can be represented as follows.

$$\begin{aligned} J &= \lim_{T\to\infty} \frac{1}{T} E[\int_0^T X^{\top} Q X\, dt] \\ &= Trace\{\, Q \textstyle\sum \} \end{aligned} \quad (7)$$

where

$$\textstyle\sum = E[\, X^{\top} X\,] = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} \end{bmatrix}$$

Covariance propagation to the state equation of the system concerned satisfies the following Equation (8):

$$A \textstyle\sum + \textstyle\sum A^{\top} + B \Xi B^{\top} = 0 \quad (8)$$

where

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

$$B = [\,0 \quad \frac{1}{M_s} \quad 0 \quad 0\,]^T$$

Therefore, components of the solution for the simplified absorbing system model can be obtained as follows:

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

$$\sigma_{12} = 0$$

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

$$\sigma_{14} = -\frac{1}{2k_u m_s}$$

$$\sigma_{21} = \sigma_{12}$$

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

$$\sigma_{23} = \frac{1}{2k_u m_s}$$

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

$$\sigma_{31} = \sigma_{13}$$

$$\sigma_{32} = \sigma_{23}$$

$$\sigma_{33} = \frac{\xi_{33}}{\mu_{33}}$$

$$\sigma_{34} = 0$$

$$\sigma_{41} = \sigma_{14}$$

$$\sigma_{42} = \sigma_{24}$$

$$\sigma_{43} = \sigma_{34}$$

$$\sigma_{44} = \frac{c_s^2 k_u + k_s^2 m_s + k_s^2 m_u}{2c_s k_u^2 m_s^2}$$

where

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

$$\xi_{13} = c_s^2 k_u m_s + k_s^2 m_s^2 + 2k_s k_u m_s^2 + k_u^2 m_s^2 + c_s^2 k_u m_u + 2k_s^2 m_s m_u$$

$$\xi_{33} = c_s^2 k_u m_s + k_s^2 m_s^2 + k_s k_u m_s^2 + c_s^2 k_u m_u + 2k_s^2 m_s m_u + k_s^2 m_u^2$$

$$\mu_{11} = 2c_s k_s k_u^3 m_s^2, \quad \mu_{13} = 2c_s k_u^3 m_s^2, \quad \mu_{33} = \mu_{13}$$

From the above components of solution σ_{ij}, performance index J in Equation (7) is represented in the following form:

$$J = Trace\{\, Q \textstyle\sum \} \qquad (9)$$
$$= \frac{k_s^2}{2c_s k_u m_s^2} + \frac{c_s}{2m_s^2 m_u} + \left(\frac{1}{2c_s k_s} + \frac{1}{2c_s k_u}\right) \times \rho$$

Optimal spring coefficient k_{op} and damping coefficient c_{op} of the dynamic absorbing system minimizing the performance index can be obtained by Equations (10) and (11).

$$k_{op} = \sqrt[3]{\frac{k_u m_s^2 \rho}{2}} \qquad (10)$$

$$c_{op} = \sqrt{m_u \times \left\{ \frac{k_s^2}{k_u} + \left(\frac{m_s^2}{k_s} + \frac{m_s^2}{k_u} \right) \times \rho \right\}} \qquad (11)$$

3.2 Analysis of dynamic absorbing characteristics

From the weighting factor satisfying constraint conditions based on the trade-off between transmitted impulsive force and buffering displacement, the design parameters of the absorbing system for the gas operated HIF device are decided as follows from Equations (10) and (11), respectively.

k_{op} = 2385 (N/m)
c_{op} = 520 (N·sec/m)

On the basis of the previous design parameters, the performance of the dynamic absorbing system was evaluated by simulation in an actual utility condition. Fig. 9 shows the simulation results of transmitted forces to mount system for the gas operated HIF device with and without the dynamic absorbing system. As shown in the figure, the maximum impulsive force to the mount reduces 79%, which is from 6050(N) to 1270(N), when the dynamic absorbing system is included. This result implies that the human behavior induced by the impulsive force disturbance can be diminished. Therefore, the enhancement of operating performance with more stable utility condition can be achieved.

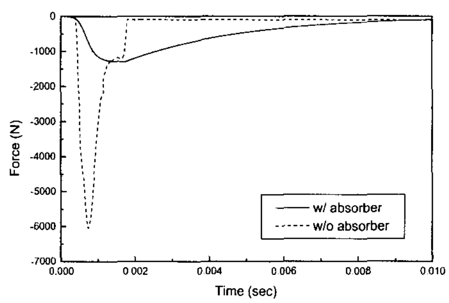

Fig. 9 Comparison of transmitted forces to mount system

4. Conclusions

In this study, in order to investigate the optimal dynamic absorbing system for the gas-operated HIF device, the HIF device and a human body as a mount structure were selected as the overall system concerned.

On the basis of experimental results and analyses between human behaviors and transmitted impulse occurring in an actual condition, modelling of the isolation system was conducted including the HIF device and the dynamic absorbing system considering the dominant characteristics of human mount.

In order to design the optimal dynamic absorbing system, the parameter optimization process has been performed based on the simplified isolation system model under the constraints of moving displacement and transmitted force. Finally, the performance of the optimally designed dynamic absorbing system has been evaluated by simulation with the actual operating condition

As a result of simulation, the HIF device with the designed dynamic absorbing system showed approximately 79% reduction rate in the maximum transmitted impulsive force to the mount.

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