Semi-active ride control of human seated model and robustness analysis.

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Abstract: The objective of this paper is to synthesize a novel hybrid semi-active control algorithm as well as to compare the semi-active relative to conventional passive system in terms of human body unweighted RMS acceleration values.

A theoretical model of the human seated model is developed in order to simulate the vertical motion of the truck driver. The seated human model is attached on the truck seat model and semi-active control is applied between the excitation base and the moving mass of the truck seat.

Algorithm robustness to parametric variations as well as to real-life implementation issues such as feedback signals noise are investigated as well. The results indicate that the injected noise slightly affects the system performance.

The vertical acceleration of the human body is significantly reduced using the novel hybrid control algorithm relative to passive system. Hence, the human comfort due to vertical vibrations is substantially increased. Similar results are observed when random excitation (using spectral densities) is employed.

1. INTRODUCTION

The truck seat ought to be able to isolate the human body from road-induced disturbances. Amongst controlled truck seats a semi-active suspension, usually composed of a controlled damper in parallel with a passive spring, offers a relatively low-cost and reliable solution. A number of control schemes have been proposed for semi-active suspensions over the years.

A human body represented as a linear two degree of freedom (d.o.f.) model in standing position, has been developed (Matsumoto and Griffin, 2003; Wei and Griffin, 1998). Simulations were found to have very good agreement with experimental data over a wide frequency range (0-20Hz).

A detailed measurement of human response to vibration was carried out (Yoshimura et al, 2005) as well as the modelling of the seated human body for the assessment of the vibration experienced. A simplified model having 10 d.o.f. was constructed to model the whole body motion with satisfactory agreement with experimental data. This work concluded that the developed model can be essential for the assessment of the vibration because it can evaluate the relative displacements between vertebrae.

A double inverted pendulum was developed to simulate the motion of the head neck complex (HNC) due to trunk vibrations. Four volunteers were exposed to vibrations and the experimental data were in good agreement with the model. Viscoelastic parameters for the head and neck including spring stiffness and damping were identified using optimisation methods (Fard et al, 2003).

The aim of this paper is to present the benefits of the semi-active suspension relative to passive system. Also, robustness analysis is also performed injecting high levels of white Gaussian noise into the control algorithms in order to simulate very harsh real operation conditions.

2. MODELLING OF THE HUMAN SEATED

The seated human model is developed using four different subsystems namely the seat model, cushions, driver body and the head-neck-complex (HNC). The numerical parameters are obtained from the literature while the governing equations of motion are also described in the following sections. The fourth order Runge-Kutta algorithm is used with variable time step for numerical integration in Matlab/Simulink environment. The entire seated human model is presented in Fig. 1.

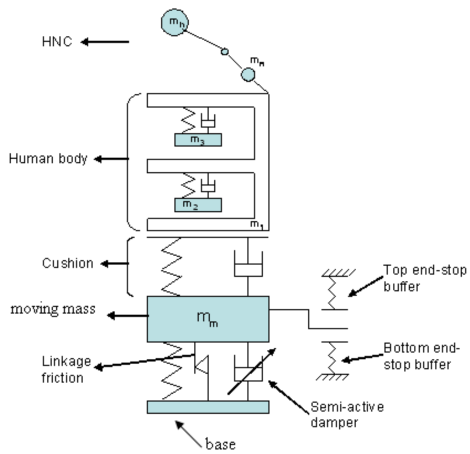

Fig. 1. Schematic diagram of human seated model

The governing equations of motion are:

$$m_3\,\ddot{x}_3 = C_3\,(\dot{x}_1 - \dot{x}_3) + K_3\,(x_1 - x_3) = f_3 \quad (1)$$
$$m_2\,\ddot{x}_2 = C_2\,(\dot{x}_1 - \dot{x}_2) + K_2\,(x_1 - x_2) = f_2 \quad (2)$$
$$m_1\,\ddot{x}_1 = C_c\,(\dot{x}_5 - \dot{x}_1) + K_c\,(x_5 - x_1) - f_2 - f_3 \quad (3)$$

$$m_m\,\ddot{x}_m = F_c + K_5\,(x_b - x_m) - C_c\,(\dot{x}_m - \dot{x}_1) - K_c\,(x_m - x_1) - F_{bw} - F_{buffer} \quad (4)$$

$$\dot{F}_{bw} = (k - K_s)\,\dot{z} - \gamma\,|\dot{z}|\,F_{bw} - \beta\,\dot{z}\,|F_{bw}| \quad (5)$$

$$F_{buffer} = \begin{cases} k_1^t(x_b - x_s - d) + C_1\dot{z} & \text{if } (x_b - x_s) > d \\ k_1^b(x_b - x_s + d) + k_3^b(x_b - x_s + d)^3 & \text{if } (x_b - x_s) < -d \end{cases} \quad (6)$$

The system non-linearities are modelled in (5) and (6) using the Bouc-Wen equation to describe the linkage suspension friction and the end-stop buffers to protect the system from high amplitude vibration, respectively. Detailed analysis of the subsystems used to form the novel human seated model and the analysis for the head neck complex (double inverted pendulum) using Gibbs-Appel approach.

3. PASSIVE DAMPER MODEL

The piecewise linear model of the passive viscous damper used in the simulation is described by the following equation:

$$F_d = \begin{cases} C_{bound}\ \dot{X}, & \text{if } \dot{X} > 0 \\ C_{rebound}\ \dot{X}, & \text{if } \dot{X} > 0 \end{cases} \quad (7)$$

Different damping coefficients have been used for the closure and rebound strokes and the equivalent damping ratios chosen are 0.15 and 0.35, respectively while $\dot{X}$ is the relative velocity between the base excitation and the seat moving mass.

4. SEMI-ACTIVE CONTROL ALGORITHMS

4.1 Balance Control by Cancelling (BCC)

Balance control by cancelling the dynamic spring forces is applied between the seat moving mass and the excitation base in order to isolate the human for vertical vibrations.

A hybrid version of balance control is presented in the following control scheme aimed at cancelling the dynamic spring forces.

$$F_c = \begin{cases} -b_1\,K_s(x_b - x_m) + b_2 C_{min}\dot{X}, & \text{if } F_c\,\dot{X} \le 0 \\ b_3 C_{min}\dot{X}, & \text{if } F_c\,\dot{X} > 0 \end{cases} \quad (8)$$

A "passive" viscous damping term is added to the control forces to reduce transients particularly when inputs are near to the system naturally frequency. Studies (not shown here) have indicated that the optimal values of b_2 and b_3 should be 20% of critical passive damping when the vehicle travels on smooth or gravel roads. Smaller or higher values of b_2 and b_3 result in larger dynamic spring forces (stiffening the suspension) and higher vibration levels. However, the optimum value of those parameters alters when the vehicle wheels come into contact with bumps or potholes.

A time delay should be implemented in order to simulate a real damper operation because the transmission from ON to OFF state is not instantaneously. Thorough analysis of the effect of the time delay to vehicle performance is also described by Tsampardoukas et al (2007a, 2007b) for heavy articulated vehicles. In this paper a first order time delay is implemented in the simulation model to reach 64% of the final state from the initial condition. The value of this time delay (Tc=11ms) is always fixed at every vehicle velocity or excitation frequency and it is applied on every control algorithm. The variation of time constant is an issue for future examination and experimental verification.

4.2 Skyhook control

Classical skyhook control (Karnopp, 1974) is used at each wheel, the logic trying to restrain the vehicle chassis to a reference point in space. Each semi-active damper on the vehicle is controlled independently. The objective of the controller is to reduce the acceleration levels at the vehicle chassis by adding large damping forces in order to reduce the absolute velocity of the sprung mass.

$$F_c = \begin{cases} C_{sky}\ \dot{x}_m, & \text{if } F_c\,\dot{X} \le 0 \\ b_3 C_{min}\dot{X}, & \text{if } F_c\,\dot{X} > 0 \end{cases} \quad (9)$$

Where $\dot{x}_m$ is the absolute velocity of the seat moving mass. The value of b_3 should be 20% of critical passive damping in order to emulate the passive damping force when the control system is OFF. The damping ratio at the

ON state defining the skyhook damper rate (C_{sky}) is equal to 0.7 of the critical value (ζ=1).

4.3 Modified Balance Control (MBC)

The modified balance control (MBC) is a novel algorithm aimed to combine the balance control with the ground hook in order to isolate the system from the base excitation. This control method cancels the dynamic spring forces beneath the truck seat and at the same time applies high damping force in order to reduce the absolute velocity of the excitation base. The construction of the current control logic is presented in Eq. (10).

$$F_c = \begin{cases} -b_1\, K_s(x_b - x_m) + C_g\, \dot{x}_b, & \text{if} \quad F_c\, \dot{X} \le 0 \\ b_3 C_{min} \dot{X}, & \text{if} \quad F_c\, \dot{X} > 0 \end{cases} \tag{10}$$

In this simulation study the parameters of the control algorithm such as b_1, b_3 are defined as 1 (100% cancellation) and 0.2 (20% of critical damping).The parameter C_g is the same as used in skyhook control algorithm.

5. SIMULATION RESULTS

5.1 Frequency response

The frequency response analysis is essential to examine the system response to various excitation frequencies and to identify the system performance at resonance. The main objective of the semi-active control logic is to reduce the unweighted RMS values of human seated model. The passive system for the human body indicates (Fig. 2) that the resonance occurs at 6Hz.

Various semi-active control algorithms are employed in order to isolate the seated human from vertical vibrations. The results indicate that only the skyhook and MBC control algorithms are able to reduce the vertical acceleration of the human body and thus to improve human ride. At the same time BCC control method reduces slightly the system performance relative to passive system.

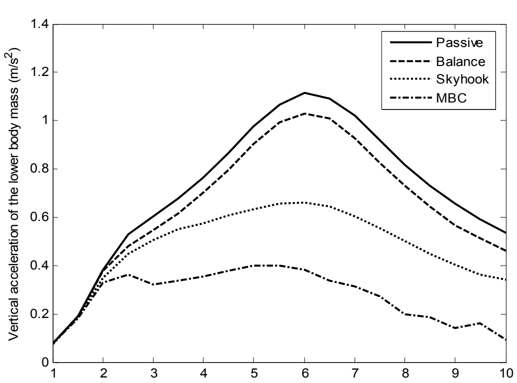

Fig.2 Vertical acceleration of the lower body mass (m/s^2)

The response of the seated human body with the novel MBC is considerably improved relative to passive system and skyhook, reducing the RMS acceleration values (this method applied underneath the moving mass of the seat). The acceleration reduction achieved at resonance (6Hz) between the MBC and passive system is about 67% and the same reduction relative to skyhook is about 33% as it is presented in Figure 2. Considering that the frequency range of interest is between 1Hz and 8Hz , MBC control strategy is the optimum solution in terms of human body comfort. Similar response is observed for the upper mass of the human body as well as for the human head and neck. Hence the figures neglected from this paper.

The investigation for the control effort is essential in order to observe any possible limitation of each control algorithm. Figure 3 present the maximum values of every control method relative to passive damper. The results show that the maximum applied force with MBC is extremely increased relative to other control methods but the values are easily obtained with a medium size controllable damper (e.g MR damper). Hence, no limitations exist in terms of control effort and practical implementation is possible.

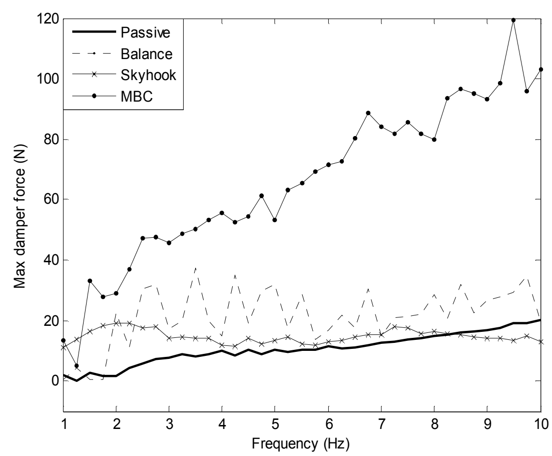

Fig.3 Maximum required control force

Consequently, the frequency response analysis indicates that MBC control method is able to improve the human ride relative to passive as well as classical skyhook control method. MBC method is the optimum control logic in order to reduce the unweighted RMS acceleration values of the human body relative to passive at resonance.

Similar performance is also observed when the system excited with random profile and thus additional figures are neglected from this paper.

5.2 Robustness analysis

Instrumentation noise (due to electromagnetic interference, electrical component damage or any other reason) is a real-life issue. The noise margin chosen (e.g 20%) is based on the fact that internal wiring within a truck is based on sound electrical engineering practice and relevant electromagnetic compatibility standards. Feedback signals are typically hardwired using shielded cables properly grounded (to prevent earth loops), and additional low-pass filtering stages are present in the conditioning on-board electronics. Furthermore, dedicated circuitries are present and appropriate board layout to increase the immunity to radio-frequency noise. This allows to say that also in a harsh environment, as it is the case of a truck, the noise margin can be reasonably chosen at 20%.

The algorithm robustness to injected white noise into the control loop is therefore examined. A significant level of white Gaussian noise was added to feedback signals, i.e., measured values (e.g relative and absolute velocity in Skyhook case) in order to simulate very harsh environment. The RMS values of the relative velocity (e.g Skyhook case) at excitation frequency of 6Hz with injected noise and without it, is available in Figure 4. The same white noise is injected to feedback signals to the rest of the controllers such as Balance and MBC.

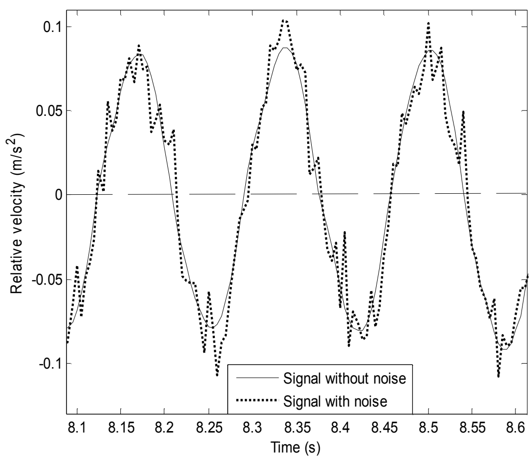

Fig.4 Signal with and without noise

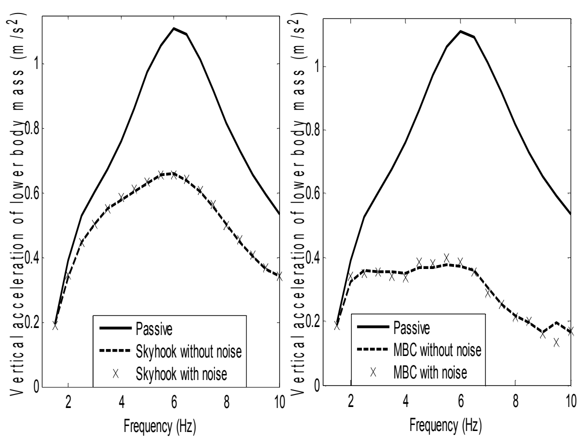

Fig.5 System performance with added noise

Figure 5 presents the system performance when noise is injected in skyhook and MBC control algorithm. The result allows us to say that both semi-active systems are robust and could be used in the real applications without suffering from failure due to excessive noise.

Experimental implementation using a real truck seat should be also performed in order to test these control algorithms in real test conditions. Hardware in the loop test cases should be also examined in order to validate every controller and to predict (if it possible) any possible failures not only due to excessive injected noise but also from other cases that may lead to system failure (e.g. loosen wire of the Magnetorheological damper).

6. CONCLUSIONS

MBC control method is developed and applied to a multibody system in order to investigate the system frequency response. The results clearly indicate that this method is the optimum robust solution in terms of human comfort. This method is also compared relative to classical skyhook approach improving further the system response in terms of ride.

BCC control method, however, is the worst solution to reduce the acceleration values because cancelling the dynamic spring forces low damping motion may occurs.

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