Adaptive Magnetorheological Seat Suspension for the Expeditionary Fighting Vehicle

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Abstract. The Expeditionary Fighting Vehicle (EFV) is an amphibious vehicle designed to operate through harsh conditions and at much higher speeds than its predecessors. These unique capabilities and broadly varying operational conditions lead to a complex design and human factors scenario for the forward seating positions that cannot be solved using conventional passive seat suspension systems. Injurious shock loads transmitted to the occupants when traversing over water in high sea states and/or at high speeds, as well as harmful shock and vibration transmitted to the occupants when the vehicle is travelling over land, pose a threat to occupant health and significantly limit mission duration. In this study, a semi-active magnetorheological (MR) seat suspension is developed which adapts to broadly varying operational conditions, as well as occupant weight, to provide optimal protection of EFV occupants. It is shown that this MR seat suspension system will reduce the shock and vibration transmitted to the occupant by up to 33% and 65%, respectively, as compared to the existing passive suspension.

1. Introduction

The Expeditionary Fighting Vehicle (EFV), the newest United States Marine Corps (USMC) amphibious vehicle, is designed to operate over harsh off-road terrain as well as in oceans and rivers. Travelling over water (Figure 1), the EFV is capable of much higher speeds (3x) than its predecessors, which has led to high shock loads being transmitted to the occupants when operating in high sea states. These shock loads are particularly problematic in the forward seating positions for the driver and troopcrew commander. Harmful shock and vibration may also be transmitted to the occupants when the vehicle is travelling over land and traversing rough terrain. These operating conditions, combined with the requirement to handle both ballistic and UNDEX shock, make for a complex design and human factors scenario. The transmission of such high and repetitive shock loads into the seats drastically increases the risk of occupant pelvic or spinal injury. Moreover, health risks, fatigue, and discomfort are also associated with lower amplitude vibration that may be transmitted into the seat during normal operating conditions. Furthermore, the fact that these seats are occupied by USMC personnel of widely varying weights complicates the design solution. Current attempts at addressing these issues with passive seat suspensions have been unsuccessful because passive systems can only be optimally tuned for one excitation.
level and occupant weight. A semi-active magnetorheological seat suspension was developed in this study to adapt to these different vibration and shock spectra. The key technologies behind this system are retrofit-capable MR fluid shock absorbers and a compact control electronics module featuring a control algorithm developed specifically for this EFV seat application. MR shock absorbers have the advantage that their damping levels can be adjusted automatically in real-time with low power control signals, and accomplish this controllability with no more moving parts than conventional hydraulic dampers, so that MR dampers are highly reliable. While passive suspensions, such as those currently installed in the EFV seat, can be designed to mitigate either water-borne shock loads or lower level land-mode excitations, passive dampers cannot be optimally tuned to mitigate both simultaneously. In contrast, the MR suspension system can be adaptively tuned to simultaneously mitigate both shock and vibration. In the present study, a retrofittable semi-active MR vehicle seat (SAMVS) system for the EFV was developed and semi-active control performance was analyzed for both land and water operations.

2. System Design

2.1. Loading and Evaluation Criteria

There were 5 shock conditions for which this system was designed to mitigate. In order of increasing severity, these are: 1) underwater explosive (UNDEX) shock (52.8 g, 5ms half-sine pulse), 2) ballistic shock (19 g, 15ms half-sine pulse), 3) typical wave shock (6-8 g, 50ms half-sine pulse), 4) basic shock (19 g, 15ms terminal saw-tooth pulse), and 5) maximum wave shock (16 g, 50ms half-sine pulse). Since the maximum wave shock is the most severe, this excitation was used for determining the maximum MR damper force necessary to prevent end-stop impact (damper bottom-out). Shock performance was evaluated using two metrics: 1) peak lumbar loads, and 2) the ISO 2631-5 shock “dosage”. Peak lumbar loads should be kept as low as possible and should at all times be kept below the injury thresholds presented in JSSG-2010-7 [1]. The ISO 2631-5 shock dosages are typically used to calculate health effects and occupant exposure durations [2]. For vibration excitation, PSD data generated using MIL-STD-810F Method 514.5, Annex A, Category 20 [3] were utilized. These PSD profiles consist of a wideband random noise superimposed with swept narrowbands. From this PSD data, eight sample vertical acceleration time histories were determined for inclusion into the design analysis. For performance evaluation for these vibration cases, ISO 2631-1 was utilized. The acceleration at the occupant interface was filtered to give a frequency-weighted acceleration time history per the ISO standard. A simple RMS of the weighted acceleration was used as a vibration performance metric [4]. Similarly to the ISO 2631-5 shock dosage, performance between design options was compared by showing percent changes in this ISO 2631-1 weighted RMS acceleration value.

2.1. MR Damper Design and System Integration

An MR damper was designed to provide an on-state force, $F_{on}$, of 6 kN at a piston velocity, $v$, of 1.7 m/s with a dynamic range (ratio of on-state to off-state force), of 3.52; thus, an off-state viscous damping, $C_o$, of 1,000 N·s/m. This MR damper (Figure 2) was designed to use Lord Corporation’s MRF-132 fluid, have a fully extended length of 10 inches and an outer cylinder diameter of 2.8 inches such that it can be retrofitted into the existing EFV seat. This damper was then fabricated using 6061 aluminum and anodized as shown in Figure 3.
2.2. Semi-Active Control

A multi-mode control algorithm has been developed specifically for this EFV seat application. This control algorithm has two primary modes, one which is intended for normal, low amplitude excitation and one which is intended to optimally mitigate shock loading. The objective of the first mode is to combine the benefits of a highly damped and lightly damped system to both suppress the seat suspension resonance while optimally isolating higher frequency vibrations. When a shock condition occurs, real-time sensor feedback automatically triggers the controller into the 2nd (shock mitigation) mode. In this mode, the MR dampers are optimally controlled to provide the minimum amount of load possible without causing harmful end-stop impact. In this shock mode, the recoil of the suspension is also controlled to return the occupant to the static position as quickly as possible while keeping rebound accelerations to a minimum and preventing an extensional end-stop impact. It should be noted that this controller will automatically switch between these modes based upon real-time sensor feedback. Furthermore, the control gains for all control modes automatically adapt for occupant weight (calculated by the controller), thus providing optimal protection for all occupants.

3. Results and Discussion

For design and performance evaluations, a mathematical model of a seated human was coupled with the nonlinear model of an MR seat suspension. The biodynamic model used for this analysis is described in detail in Ref. [5] and has been updated for the inertial properties of the EFV seat.

Figure 4 shows the analytical response of the MR damper to the max wave impact condition discussed above for four different conditions. The first of these assumes that the seat has no suspension. The second condition includes an MR damper simply turned on to a constant applied magnetic field level (thus uncontrolled). The third condition utilizes an MR damper that is semi-actively controlled using the adaptive control algorithm discussed above. Finally, the fourth condition simulates the current passive suspension being used for the EFV seat. In Figure 4, the upper plot shows that the each of the conditions with suspensions utilize approximately the same amount of stroke at onset of the shock. These data also show, however, that the controlled
SAMVS system returns to its static equilibrium position (zero inches) faster than the other suspended conditions. This is because the MR damper can lower its force upon recoil (as shown in the bottom plot) and allow the occupant to return to the normal seated position sooner, which is important for line-of-sight concerns. Figure 5 presents the analytical occupant lumbar load response to the maximum wave impact condition for these same four conditions. Figure 5 also shows that the controlled SAMVS system provides significantly lower lumbar loads than the existing passive suspension, both in compression (negative) at the onset of the shock, and upon recoil. The controller is optimal in the sense that it fully utilizes available suspension stroke for all conditions, while also providing an optimal recoil. The ISO 2631-5 shock dosages were calculated for the five design shock cases discussed above. Figure 6 shows that the theoretical controlled SAMVS system provides significantly reduced shock dosages over both a seat with no suspension and the existing seat with a passive suspension which is tuned for shock. The controlled SAMVS system reduces the ISO 2631-5 shock dosage by up to 33% over the passive suspension because the controller optimally adjusts the damper to mitigate the harsh compression and recoil. Similarly, the ISO 2631-1 weighted RMS accelerations were calculated for the eight design vibration load cases discussed above. Figure 7 shows that the theoretical controlled SAMVS system significantly reduces vibration transmitted to the occupant, and can reduce land-mode vibration transmitted to the occupant by up to 65% as compared to the existing passive suspension, because the MR damper is turned off during low amplitude excitations to provide very low transmissibility. The MR damper is only turned on to mitigate the suspension resonance and to ensure that end-stop impacts are avoided when larger amplitude bumps occur. The passive suspension is fixed at a high damping level for shock so that it provides poor vibration isolation.

4. Summary
This study has demonstrated the feasibility and benefits of the SAMVS system. The key technologies behind the SAMVS system are retrofit-capable magnetorheological (MR) fluid dampers and a control algorithm developed specifically for the EFV seat application. While passive suspensions, such as those currently installed in the EFV seat, can be designed to mitigate either the water-borne shock loads or the lower level land-mode excitations (but not both), the SAMVS system enables a unique single solution for both shock and vibration environments. This study has shown that, with a real-time controller developed specifically for this application, the SAMVS system can reduce the shock dosages applied to the occupant by up to 33% in water mode and reduce the vibration transmitted to the occupant by up to 65% as compared to the current passive suspension system.

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