

Analysis of Passive Vibration Measurement and Data Interrogation Issues in Health Monitoring of a HMMWV Using a Dynamic Simulation Model

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ABSTRACT

Integrated health monitoring technologies are being developed for military ground vehicles to enable condition based maintenance in the short term and prognostic health management in the long term. Technical issues related to health monitoring of a military HMMWV are examined using a dynamic simulation model. Both free and forced vibration response analyses are conducted to examine the effects of damage and operational conditions on the vehicle response. The higher frequency modal properties are found to be sensitive to frame and cross member damage whereas the lower frequency sprung modal properties are not. Changes due to adding up armor are found to be much larger than those due to damage. In addition, cross member damage affects the higher frequency modes whereas damage to the left or right frames causes changes to the modal behavior across the entire frequency range making this type of damage most detectable. Composite amplitudes at all transverse degrees of freedom are calculated using the modal deflection shapes to show that certain sensor locations, for example, on the rear cross members, are most sensitive to all vehicle motions. The sensitivities of the vehicle frequency responses to damage mechanisms are determined and observations are consistent with the free response analysis; however, the anti-resonant regions of the frequency response are also shown to be highly sensitive to localized changes in the model due to damage. The frequency response studies also show that suspension response is not observable from the chassis due to the filtering action of the suspension.

condition-based maintenance (CBM). By scheduling maintenance for vehicles based on their condition rather than on a fixed time interval, it may be possible to reduce the cost of maintaining these vehicles. Many researchers including Burdisso et al. [1] have investigated methods for estimating the condition of drivelines, chasses, and suspensions. Maintenance on vehicles that do not immediately require service could be postponed thereby reducing costs. Vehicles in poor condition could be scheduled for service immediately to prevent catastrophic failures that are expensive.

Health and Usage Monitoring Systems (HUMS) are already commercially available for CBM in rotorcraft, primarily for monitoring rotors and gear boxes [2,3]. Health monitoring systems for manufacturing machine tools are also available [4]. Condition monitoring in civil structures [5] and aircraft is also being investigated. One advantage of health monitoring in rotorcraft (and rotating machinery in general) in contrast to wheeled ground vehicles is that in rotorcraft there is a one-per-revolution event to which averaging of data can be synchronized leading to better statistical confidence in rotorcraft data than in ground vehicle systems. In wheeled vehicles, the synchronous event associated with the engine driveshaft/wheel rotation is not at all synchronized with variations in the terrain. Another advantage of health monitoring in rotorcraft is that all critical loads act on the rotor and within the gearbox leading to relatively localized faults (broken teeth, cracked rotor, etc.). In ground vehicle systems, loading is distributed across the wheel ends, suspensions, frame, etc. through bushings and other connections leading to distributed damage (bushing rupture, tie rod failure, frame cracks, etc).

INTRODUCTION

Integrated health monitoring technologies are being developed for military ground vehicles to enable

The long-term objective of health monitoring is to enable prognostic health management by predicting which vehicles and components will require maintenance ahead of time making it possible to automate the process of ordering replacement parts (autonomic

logistics). Prognosis can be used not only for condition-based maintenance but also to certify the readiness of vehicle fleets for warfighting prior to deployments.

Health monitoring technologies consist of sensing equipment, data acquisition hardware, and analysis algorithms that measure response data. At the system level, response data such as the roll rate and speed provide a measure of the usage of one vehicle with respect to the fleet to aid in maintenance scheduling. At the component level, response data such as the acceleration and strain in various subsystems can be monitored to identify damage and the rate of damage accumulation in specific subsystems such as the suspension and frame within a vehicle. This information is essential for prognosis, which is component oriented because damage laws are written for damage mechanisms at the component level. In some military vehicles, a vehicle data bus on the engine is available to measure speed, braking, and other conditions. In many platforms, a vehicle data bus is not available making it necessary to first determine operational conditions using response data. Component data can only be interpreted properly if operating conditions at the system level are known. For example, changes in vehicle speed must be identified for use in vibration-based damage detection algorithms because different vibration frequencies in the vehicle are excited as a function of speed.

Technical issues related to health monitoring of a military HMMWV are examined using a dynamic simulation model in this paper. An eighty-seven degree of freedom model is first developed using Bernoulli-Euler finite element models for the frame and cross members coupled with lumped parameter modeling of the wheels, suspension, and powertrain. The free vibration characteristics are then identified by solving the associated eigenvalue problem to determine the modal frequencies and deflection shapes. The free response characteristics are then examined to determine the sensitivity of modal vibration properties to (a) damage mechanisms in the suspension and frame due to bushing rupture and cracking, respectively, and (b) changes in carrying weight due to up armor. Frequency domain and time domain forced response characteristics are then examined as well to understand the effects of changes in operational conditions on the interpretation of vehicle health monitoring response data. The effects of uncertainty in the model coefficients are not considered.

MODELING APPROACH

Information was obtained in the open literature regarding American General's standard HMMWV. Figure 1 is a photo of the vehicle that has been modeled approximately. It has a length of 4.6 m, width of 2.1 m, height of 1.8 m, mass of 2340 kg, and a steel box frame with 5 cross members. Using these properties in addition to suspension data available from previous work on passenger trucks [6], a simplified dynamic model of the HMMWV was developed consisting of Bernoulli-

Euler beam elements for the frame and lumped elements for wheels, suspension, and powertrain. Bending and torsion of the frame are permitted and the body mass (and up armor mass) is lumped onto the frame for inertial loading. The stiffness of the body is ignored based on evidence in the literature that the body is made to be highly flexible for durability on uneven terrain. A single degree of freedom is used to model the powertrain although this model could be extended to include roll and pitch as well. Longitudinal and transverse degrees of freedom are used for the frame, suspension, and wheels to account for both types of motions and forces. The rear suspension is modeled to be somewhat softer than the front suspension as in most trucks. The resulting eighty-seven degree of freedom model schematic is shown in Figure 2. This model is used to qualitatively study technical issues related to health monitoring of wheeled vehicles. The intention of this work was not to validate all of the model's dynamic properties with tests.

The simulation model is of the form:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f\} \quad (1)$$

where $[M]$, $[C]$, and $[K]$ are the mass, viscous damping, and stiffness matrices, respectively. Proportional damping is assumed. $\{x\}$ is the response vector including translational and rotational displacements. $\{f\}$ is the excitation vector, which combines the displacements at the tire patch in the vertical (z) and tracking (x) directions per Figure 2 as well as the stiffness and damping of the tire in those directions. The model was programmed into MATLAB® for analysis. The analysis is very computationally efficient for use in studying a myriad of vehicle health monitoring scenarios.

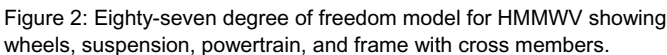


Figure 1: American General HMMWV for which model has been developed (courtesy of http://en.wikipedia.org/wiki/High_Mobility_Multipurpose_Wheeled_Vehicle).

ANALYSIS

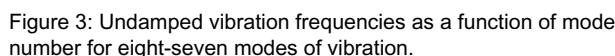
BASELINE FREE RESPONSE ANALYSIS

The eigenvalue problem associated with Eq. (1) for zero damping was solved to characterize the free vibration characteristics of the vehicle model. The eigenvalue formulation takes the following form:



where $\{X\}$ is the eigenvector (or modal vector in this case) and λ is the eigenvalue. The eigenvalue is equal to $-s^2$, where s contains the modal frequency, $\pm j\omega_n$. For the mechanical properties chosen, the eigenvalue problem in Eq. (2) was solved and the undamped natural frequencies obtained are plotted in Figure 3. Eighty-seven frequencies are shown corresponding to the eight-seven modes of vibration.

Figure 4 shows the first six modal vectors, $\{X\}$, corresponding to the first six modal frequencies in Figure 3. As expected, the first few modes of vibration at 1.19, 1.28, and 1.31 Hz are modes of the sprung mass acting nearly as a rigid body on the suspension. The next few modes at 7.16 and 9.13 Hz are flexible torsional and bending modes, respectively, of the chassis. Then one of the tire hop modes occurs at 10.3 Hz. These modal vectors show that at lower frequency modes of vibration, which are excited by low vehicle speeds over terrains with widely spaced features, the vehicle responds such



that the suspension and wheels are exercised primarily. In other words, damage to the suspension and frame will affect the lower frequency response whereas damage to the cross members will not affect this low frequency response because the cross members are not deforming at low frequency. This preliminary conclusion is verified in the following sections when damage is simulated in the vehicle suspension, frame, and cross members.

Damage mechanisms due to ruptured bushings, broken tie rods, and cracking in the frame and cross members are analyzed in this work. First, variations in modal frequencies due to each damage mechanism are analyzed in this section to determine the sensitivity of the dynamic response characteristics to damage.

The right rear suspension stiffnesses in the x and z direction (see Figure 2) were reduced by 5, 10, 20, and 30% to simulate bushing damage and the changes in natural frequency were calculated. The results are shown in Figure 5 for the first 11 modes in terms of a percent change in the natural frequencies. Modes 1 and 4 experience the largest percentage change (2-9% reduction for a 30% reduction in stiffness). The response of the vehicle near these two modal frequencies should be monitored to identify damage to the bushings of the suspension. In practice, these modes are excited in most operational conditions; however, this result demonstrates that the small changes in the resonant frequencies for even a 10% reduction in the suspension stiffnesses may be difficult to identify in the midst of sources of variability in the response data.

The stiffness of the first cross member element closest to the right frame rail was reduced by 50% and changes in the natural frequencies were again noted. The results are plotted in Figure 6 in terms of a percentage change in natural frequency. Note that the frequency shifts are very significant in the upper frequency range (above the 40th mode at 2500 Hz). In practice there is not usually much excitation from the terrain in this upper frequency