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ABSTRACT

The University of Texas Center for Electromechanics (UT-CEM) has been developing active suspension technology for off-road vehicles since 1993. The UT-CEM approach employs fully controlled electro-mechanical actuators to control vehicle dynamics and passive springs to efficiently support vehicle static weight. The project described in this paper is one of a succession of projects toward the development of effective active suspension systems, primarily for heavy off-road vehicles. Earlier projects targeted the development of suitable electromechanical actuators. Others contributed to effective control electronics and associated software. Another project integrated a complete system including actuators, power electronics and control system onto a HMMWV and was demonstrated at Yuma Proving Grounds in Arizona. Test results, described in previous papers, showed significant reductions in vehicle sprung mass accelerations with simultaneous increases in cross-country speed when compared to conventional passive suspension systems. Additionally, vehicles with EM suspensions have proved to have increased payload capacity and reduced fuel consumption.

The paper presents a brief history and overview of the active suspension program at UT-CEM including the evolution of the actuator design. A description of the vehicle used for this particular demonstration is included along with a discussion of the unique equipment needed to implement an active suspension on a conventionally powered truck. Finally, the paper presents the results of off-road terrain testing for a modified vehicle with active suspension compared to a passively suspended vehicle of the same design. Concluding remarks include performance comparisons, lessons learned and plans for future development and testing.

INTRO/OVERVIEW

UT-CEM has been developing active suspension systems since 1993 based on an approach that was patented in 1997 [1]. During that time active suspension systems have been developed for both on and off-road vehicles and for tracked and wheeled military vehicles. Each of these systems incorporated UT-CEM's unique near constant force active suspension system that greatly enhances ride quality while minimizing pitch and roll under all conditions. Numerous studies comparing the benefits of active, semi-active and passive suspension systems have been completed and three entire vehicles have been outfitted, by UT-CEM, with active suspension for testing. In 2001, based on the results of those studies and the first two successful integration efforts, Northrop Grumman of Canada (NGCC) licensed the active suspension system for the military field of use from the University of Texas and initiated efforts to develop a commercial product. The results of the first two highly successful test programs, on a High Mobility Multi-Wheeled Vehicle (HMMWV) and an Advanced Technology Transit Bus (ATTB), have been previously reported in the literature [2,3,4,5]. The third full vehicle integration program on a Stewart and Stevenson (S&S) Light Medium Tactical Vehicle (LMTV) is the subject of this paper.

BACKGROUND INFORMATION

VEHICLE AND OBJECTIVES

Stewart and Stevenson, located outside of Houston in Sealy, Texas, is the Army's supplier of the two and half ton and five ton military tactical trucks known as the Family of Medium Tactical Vehicles (FMTV). Current production numbers for this line of vehicles are approximately 2,500 units per year for everything from the basic two and half ton capacity four wheeled cargo truck to the six wheeled chassis used for the High Mobility Artillery Rocket System (HIMARS). For this first integration project on their production vehicles, S&S, NGCC and UT-CEM agreed to use a current LMTV/A1 production model in the S&S test fleet. The passive suspension truck, shown in figure 1 below, has a curb weight of 7,980 kg (17,600 lbs) and utilizes solid axles with multiple leaf springs, conventional dampers and heavy duty sway bars for its suspension system. Flexible rubber bump stops limit the axle motion in jounce. This arrangement provides the Army with an ultra-reliable, robust, and cost effective suspension system. The system, like all passive systems however, does have performance limits both in the areas of ride quality and load capacity. While the passive design meets the current Army truck specifications, the team was interested in demonstrating a dramatic improvement in performance in the areas of off-road mobility, handling, and load capacity. Specifically the project goals were to: improve off-road “ride limited” speed by a minimum of 50%; improve vehicle stability during turning maneuvers; and simultaneously accommodate payload variations of up to three and a half tons, (a 40% increase in cargo capacity). In addition to these specific performance improvements, the team also desired to maintain or improve all of the other vehicle performance parameters and its ultra-reliability. These, along with developing a design that could ultimately be manufactured cost effectively, were critical goals if the system was to become commercially viable.

THE TEAM

Under the previous programs completed on the HMMWV and ATTB, UT-CEM was responsible for every major aspect of the program from design, to integration and testing. To push the active suspension system closer to a commercial product the team agreed to work closely together and to spread the hardware development tasks in a way that optimized the experience of each group and would result in a system that was on the path to a commercial product. Stewart and Stevenson took responsibility for providing the vehicles, integrating the auxiliary power unit, completing the passive suspension modifications, and supporting the system integration and testing. Northrop Grumman was responsible for the development and fabrication of the power electronics and power management system while CEM was in charge of the actuator development, controls, Electronically Controlled Active Suspension System (ECASS) integration and testing.

ECASS COMPONENTS AND INTEGRATION

COMPONENT OVERVIEW

The Electronically Controlled Active Suspension System for a conventional vehicle consists of three primary subsystems: the electromechanical actuators and ride adjustment components; sensors and controllers; and a power supply and distribution system. The actuators and ride height adjustment hardware fits into the wheel wells of the vehicle replacing the passive dampers (shock absorbers) at each wheel with active electromechanical actuators. (The vehicle’s static weight is carried by passive leaf springs in both cases.) While the dampers in a passive system merely absorb and dissipate energy, the active system can apply a force in either direction, effectively lifting or lowering the vehicle chassis with respect to the wheels. The output force is determined by the controller which continuously monitors vehicle motion through sensors located at the wheel locations and maintains near-constant force on the vehicle chassis, adding or removing force as required.

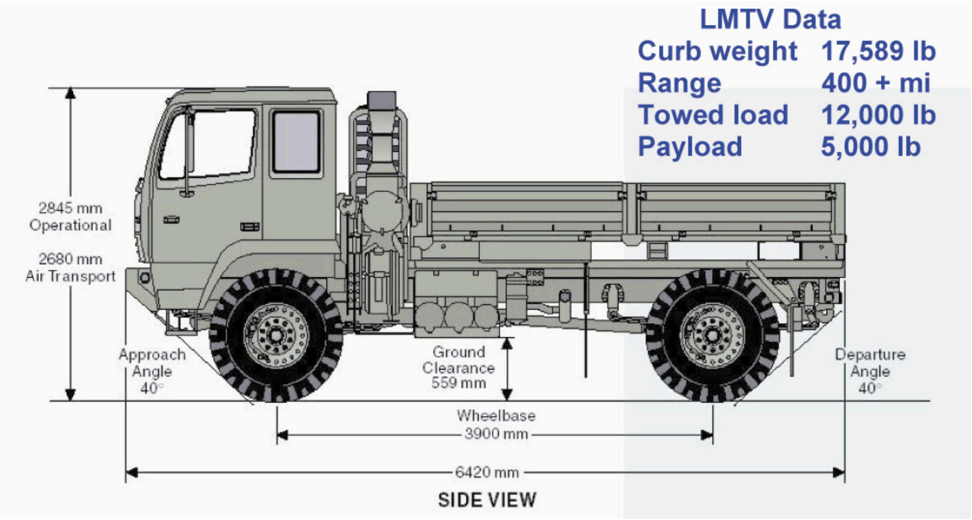

Figure 1. Baseline Stewart and Stevenson LMTV

Primary power for the system, on the LMTV, is provided by an auxiliary generator system driven by the vehicle's diesel engine. Power to each actuator is delivered by individual servo amps developed by NGCC. A capacitor bank is used to store regenerated energy delivered by the actuator back to the power supply. It should be noted that in the case of a hybrid electric vehicle, the suspension system can tap into the vehicle's on board power bus and energy storage system both for primary power and for regeneration, significantly reducing the hardware and costs required to integrate ECASS. While alternative active suspension approaches have required significant energy input, greatly diminishing their acceptance by the military, the UT-CEM approach actually minimizes off-road energy usage by minimizing vehicle body motion and regenerating during damping, as explained in previous papers [6].

ACTUATOR DESIGN

Previous proof-of-principle ECASS demonstrations on a HMMWV and ATTB were major advancements in active suspension technology and demonstrated a combination of performance improvements and power efficiencies not previously reported in the literature for active systems. Nevertheless, integration of some features necessary for fully capable military systems were beyond the scope of those first demonstrations. For example, the HMMWV system used a conventional steel spring (rather than an adaptable spring, such as gas springs), which limited its ability to handle large load fluctuations. It also utilized UT-CEM's first generation ECASS actuator technology, based on a rack and pinion gear reduction driven by a PM motor. For the LMTV demonstration, CEM implemented a new actuator technology that packages better than the original HMMWV rack and pinion actuator and is referred to as the reduced length actuator (RLA). A comparison of the RLA design to the rack and pinion design is shown in figure 2 with the actual system implemented on the LMTV demonstration project shown in figure 3.

SYSTEM INTEGRATION

As noted previously, the integration of the system on the LMTV was performed primarily by S&S and UT-CEM. S&S was responsible for installing a power supply and making vehicle modifications. To provide power to ECASS they chose a pair of off the shelf 8 kW Auragen generators. The primary unit was driven off the power take off unit while the secondary unit was belt driven by the vehicle engine like a conventional alternator. Suspension modifications on the LMTV included the removal of the vehicle's anti-roll or sway bar and replacement of the standard leaf springs with softer versions that fit in the same space. Mounting brackets to accommodate the ECASS actuator design were also installed by S&S. UT-CEM developed and integrated the suspension actuators, sensors and control system along with integrating the NGCC produced electronic components. All power electronics were installed under the bed of the truck to maintain the full cargo capacity of the vehicle. The sensor interface box and controller were installed inside the cab of the vehicle behind the seats with no impact on the space available to the driver or passenger but with easy access for modification during the development effort.

TEST RESULTS

TEST OBJECTIVES

The system integrated on the LMTV was designed to improve vehicle performance in three primary ways. First and foremost was to improve speed over off-road terrain by a minimum of 50%, going from a current peak speed of 19 km/hr (12 MPH) over a 3.8 cm (1.5") RMS course to a speed of 29 km/hr (18 MPH) over the same course with active suspension. Inherent in this goal was the desire to improve driver and passenger comfort by reducing the transmitted vibration (referred to as "absorbed power" by the military) at all speeds in off-road terrain. The second major objective was to improve vehicle stability during turning maneuvers. The final goal was to accommodate a payload increase of 40% from two and half tons to three and half tons while maintaining ride quality and ride height.

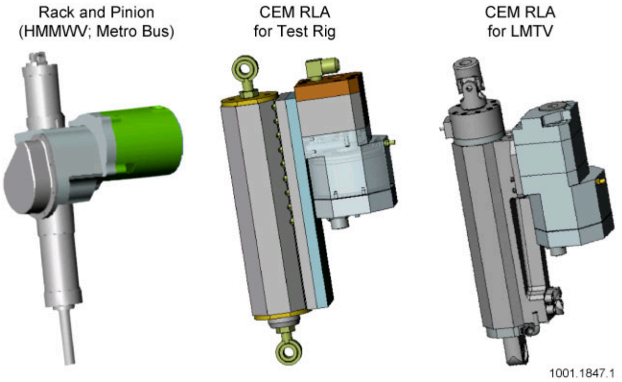

Figure 2. ECASS linear actuator technology showing original rack and pinion actuators used on HMMWV and reduced length actuators (RLA), with significant packaging advantages.

Figure 3 ECASS Actuator on LMTV

All of these objectives have been demonstrated as described below to the extent possible on UT-CEM's tuning track. As a result of these demonstrations, the Army, S&S, and NGCC have elected to go forward with more extensive testing of an upgraded system on the Army's Yuma Proving Grounds course to gather independent data in 2005. Following those tests an additional technical paper discussing those test results will be published.

OFF-ROAD SPEED AND RIDE QUALITY

Ride quality for military vehicles is typically described in terms of "absorbed power". This is a filtered measurement of the acceleration measured at the driver's location in a vehicle and is designed to provide an indication of the comfort (or discomfort) that a driver would feel traveling over rough terrain. The method used for calculation of absorbed power is prescribed by Pradko, Lee and Kaluza [7]. Typical military specifications currently dictate a maximum absorbed power level of 6 watts as the "ride limiting" value. In practice, this ride limiting value translates to the worst ride that a solder would be willing to tolerate for an extended period. This absorbed power value is then used to determine the highest acceptable speed that a vehicle could travel over a specific terrain. In the case of the passive LMTV the vehicle specification requires that the LMTV travel over 3.8 cm (1.5") RMS terrain at a minimum speed of 19 km/hr (12 MPH) without exceeding the 6 watts of absorbed power. Future vehicle specifications for next generation systems such as the Future Combat System (FCS) and Future Tactical Truck System (FTTS) have proposed even higher speeds over 5.1 cm (2.0") RMS. In anticipation of these future specifications, testing at UT-CEM was conducted primarily on a 2" RMS course, the data for which is presented here. This data, in figure 4 verifies a fifty percent increase in ride limiting speed from 19 km/hr (12 MPH) to 28 km/hr (18 MPH) over 5.1 cm (2.0") RMS terrain. Driver acceleration data taken over the same course at 24 km/hr (15 MPH) and shown in figures 5 and 6 also clearly indicates the 30-70 percent reduction in peak accelerations when comparing the ECASS equipped vehicle to an identical truck with passive suspension. All tests were conducted with a two and a half ton payload in both vehicles.

VEHICLE STABILITY

Like most large military trucks, with a relatively high center of gravity, the roll forces on the LMTV can become quite large under specific conditions. While these are typically managed by the stiff leaf springs and sway bars, the roll is still significant under hard maneuvers such as lane changes at high speeds. ECASS can minimize roll under these conditions, as well as pitch during braking, by utilizing the actuators to counteract the roll forces providing a noticeable improvement in handling. While UT-CEM does not have a formal skid pad, space is available to set up a one hundred foot step slalom course.

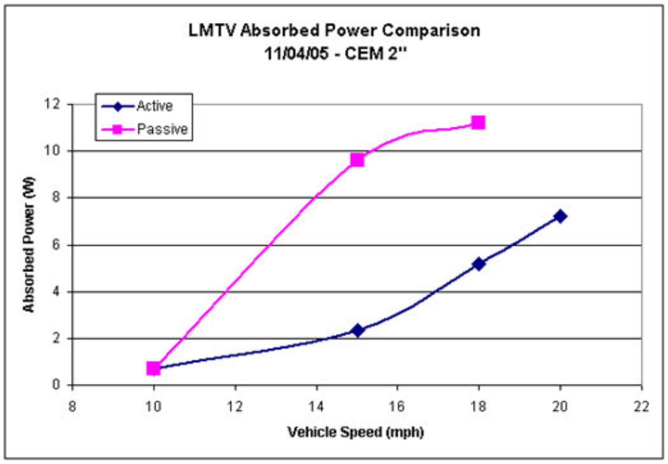

Figure 4 Absorbed power test results comparing LMTV with passive and active suspension.

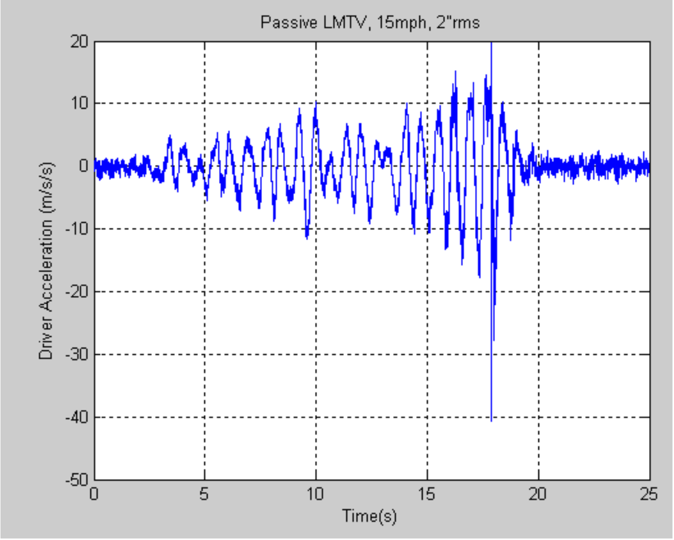

Figure 5 Acceleration test data for Passive LMTV over 2" RMS terrain.

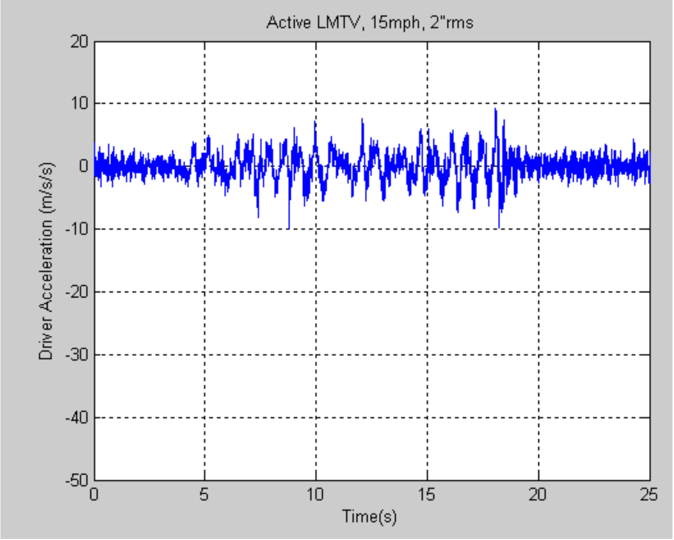

Figure 6 Acceleration test data for ECASS equipped LMTV over 2 in. RMS terrain.

Figure 7. 100' Slalom Testing of passive LMTV indicating ~3 degree tilt at ~28 mph equating to peak lateral accelerations of ~0.35g

Figure 8. 100' Slalom Testing of ECASS equipped LMTV with no measurable tilt at ~28 mph equating to peak lateral accelerations of ~0.35g

Demonstration tests were completed on this course comparing both the passive and ECASS equipped LMTV and indicated that the passive vehicle rolled two to three degrees during slalom testing, after accounting for the crown in the road, while the ECASS equipped vehicle exhibited no measurable roll as indicated. These tests are illustrated in figures 7 and 8. In addition to utilizing the actuators to counteract the roll forces, ECASS can also be used to lower a vehicle's center of gravity for on-road operation, effectively reducing the roll forces seen by the suspension and further enhancing vehicle stability. While this capability was not utilized during the slalom testing presented here, it will be demonstrated during future test efforts.

INCREASED PAYLOAD CAPABILITY

As stated previously, accommodating an increase in the payload of the LMTV of forty percent from two and a half to three and a half tons was another significant goal on this project. The ECASS hardware installed on the LMTV was designed to accommodate increasing or decreasing loads and maintain a specific ride height by adjusting the static pressure in the passive springs. The ability to adjust ride height and accommodate varying loads was demonstrated, with testing limited to two and a half tons for a variety of reasons. Calibrated test weights, with appropriate tie down features, provided by S&S were designed for their current payload requirements of two and a half tons. While new weights could have been fabricated it was felt that the time and funding available to complete the testing was better utilized refining the systems and demonstrating the more difficult performance parameters associated with traversing off road terrain at high speeds. Future testing, described in the following paragraphs will be utilized in part to demonstrate the ability to accommodate the three and a half ton payload. It should also be noted that, as the program progressed, ECASS ability to increase payload capacity emerged as a more significant benefit as the need for additional capacity to accommodate the addition of armor, and its inherent additional mass, for both the HMMWV and LMTV was demonstrated during recent military conflicts.

CONCLUSIONS/FUTURE PLANS

The LMTV demonstration project described here met all of the primary goals and also garnered additional support from NGCC, S&S and the military community. Based on the success of the project, the team agreed to continue development of the ECASS system for the full line of S&S trucks including a continuation of the LMTV project described here that will: add additional suspension travel to the LMTV; further reduce the stiffness of the mechanical springs; and complete a series of formal tests at the Army's Yuma Proving Grounds (YPG) in 2005 to compare the off-road performance of a passive and active suspension LMTV. A second project is focused on evolving the system to production ready hardware that is suitable for the both the complete current lineup of FMTVs and the anticipated future line. While this is a broad program addressing safety, reliability, maintainability and cost requirements, the testing/demonstration aspect is focused on developing an active suspension version of the current five ton capacity vehicle that can accommodate an eleven ton payload and traverse off-road terrain at two to three times the speed of the current system. This is clearly a technology that can have significant impact the on the military's ability to transport supplies and munitions through hostile territory at higher speeds with fewer vehicles and a reduced logistical trail. These programs will be reported on in future technical papers as they are completed and results become available.

ACKNOWLEDGEMENTS

As noted, the LMTV ECASS project was a team effort and its success was a result of the efforts of many dedicated individuals from UT-CEM, NGCC, and S&S. In addition to the technical support provided by each of these organizations, funding support for this project and the follow-on effort noted here has been provided by: the State of Texas Technology Development and Transfer program and TACOM's Combat Hybrid Propulsion System Program, NGCC, and S&S.

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