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ABSTRACT

The University of Texas Center for Electromechanics (UT-CEM) conducted a set of simulations and full-scale experiments to determine suitable shock load design requirements for in-hub motors for hybrid electric combat vehicles. Both modeling and experimental results indicate several realistic scenarios in which wheel hubs experience accelerations of 80 to 120g, sometimes at very low vehicle speeds. This paper focuses the experimental determination of suitable design goals for in-hub motors (wheel motors), describing the experimental test rig, experiment procedures, and experimental results. The paper also discusses implications of these results on wheel motor design, leading to the conclusion that a realizable and feasible design goal for wheel motor shock rating is 150g, with a 10 to 20 ms pulse width.

BACKGROUND

Strategic considerations frequently impose severe volume constraints on combat vehicle designers, usually to meet airlift requirements such as C-130 transportability. For wheeled vehicles, wheel motors provide major volume advantages and also eliminate mechanical power linkages, which provides greater design freedom.

Mobility goals for advanced, high-mobility hybrid electric fighting vehicles frequently include the ability to travel cross-country at speeds exceeding 48 km/h (30 mph) and frequently up to 64 km/h (40 mph) on 3.8 to 5 cm (1.5 to 2 in.) RMS terrain. This capability increases the tempo of battle, improves survivability by providing quick dash speeds, and exploits recent investments in C4I (command and control, communications, computers, and intelligence) that enable managing battles at high speeds.

Suspension technology to meet cross-country speed goals with wheeled vehicles has been demonstrated previously by The University of Texas at Austin Center for Electromechanics (UT-CEM). These higher speeds inevitably lead to increased shock loads on wheel motors. This is particularly true in heavy combat when the crew drives hard and is too busy to pay close attention to terrain.

Simulations, using estimated tire/run-flat parameters, have shown that shock impacts on tires may transmit >100g loads to the wheel hubs. This paper documents experimental validation of the high shock loads experienced by wheel hubs under typical operational scenarios.

HIGH SHOCK SCENARIOS

The first step in determining wheel motor shock load design requirements was to hypothesize situations that lead to high shock loads. Then experiments were designed to replicate these scenarios. The following scenarios were considered plausible and realistic:

- 48 to 64 km/h (30 to 40 mph) travel in a field covered with grass 15 to 20 cm (6 to 8 in.) tall, vehicle strikes hidden log or rock 15 cm high; tire at normal off-road inflation pressure
- 48 to 64 km/h travel in grassy field or low speed night-time operation, vehicle wheel engages equivalent of hidden pothole or ditch 50 to 100 cm (20 to 40 in.) wide and 15 cm deep; tire at normal off-road inflation pressure
- 96 km/h (60 mph) road march, vehicle wheel strikes pothole; tire at normal on-road inflation pressure; catch-up speeds during road march can be 16 to 24 km/h (10 to 15 mph) above average road march speed
- 80 km/h (50 mph) dash for cover in firefight, vehicle wheel strikes hidden log or rock; tire at normal off-road or on-road inflation pressure
- Single punctured tire (on run-flat), 48 to 80 km/h (30 to 50 mph) dash for cover in firefight, vehicle wheel strikes hidden log or rock
- Punctured tire (on run-flat), vehicle drives off vertical curb or step of 15 to 38 cm (6 to 15 in.) at modest or high speed (>32 km/h, or >20 mph) and lands on hard surface

The run-flat situations were considered plausible because typical run-flat requirements recognize travel at 48 km/h (30 mph) and above until conditions permit changing tires. For a typical 18,000 kg (20 ton), 8 x 8 combat vehicle, traveling with all eight tires on run-flats would probably result in significant speed limitations; however, the vehicle would probably be able to operate at nearly full speed with only one tire on its run-flat. Consequently, high-speed events on run-flats are realistic for individual wheels in an 8 x 8 vehicle.

This paper focuses on the results obtained from the *pothole* tests because the high shock loads were experienced under these conditions at unexpectedly low speeds. Results from the *curb* tests (simulating a log, rock, or curb event) are summarized.

TEST APPROACH

UT-CEM developed a shock load test rig to be towed behind a high-mobility, multi-wheeled vehicle (HMMWV), as shown in Figure 1. In order to avoid subjecting the HMMWV to potentially damaging test conditions, this setup allows the HMMWV to straddle the obstacles that the trailer traverses. The sprung to unsprung mass ratio of the trailer was designed to be ~6.6, which is comparable to the typical ratios of 5.5 to 8 for 18,000 kg (20 ton) 8 x 8 combat vehicles (dependent on vehicle design and load). The trailer is equipped with an airbag spring and a shock absorber. The natural frequency of the trailer suspension is within the range of desirable natural frequencies for the FCS vehicle. The trailer wheel hub was instrumented with 100g force-balanced accelerometers on the x and y axes.

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Figure 1. HMMWV towed tire test rig at UT-CEM

The test was designed to represent severe on- and off-road situations that are realistic but not overly improbable, as described above. A *log* was represented by a 15 cm steel half-round, a *pothole* by a variable-width recession 15 cm deep with a steel assembly forming a step at the far side of the recession (Figure 2). Other components of the test apparatus were made of wood. It is worth noting that none of the tests resulted in observable tire or rim damage.

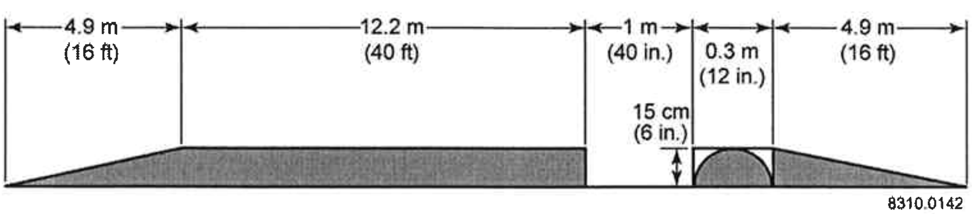

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Figure 2. Diagram of pothole test apparatus (15 cm high)

POTHOLE TEST RESULTS

The *pothole* test represents the scenarios in which the vehicle is traveling either on- or off-road at various speeds when a tire engages a pothole or ditch. Therefore, the test matrix for the *pothole* tests consisted of speeds 8 to 48 km/h (5 to 30 mph) at 8 km/h increments and tire pressures of 275, 207, 172, 138, 103, 69, and 0 kPa (40, 30, 25, 20, 15, 10 and 0 psi).

Multiple trials were performed for each combination of speed and tire pressure. The averaged results of the tests are shown in Figure 3 with trend lines. The results show that the shock load is highly dependent on how the tire engages the far end of the obstacle. The suspension springs are designed to support the sprung mass at 1g of acceleration. When the tire becomes airborne, the suspension springs force the unsprung mass downward at acceleration much greater than 1g (the unsprung mass is ~6 times lighter than the sprung mass), which adds to the gravitational acceleration acting on the CG of the sprung-unsprung mass system. At slow travel, the tire falls into the pothole and makes contact with the ground, absorbing part of the vertical acceleration into the suspension system, before engaging the far side. This lessens the impact of the shock. At high speeds, the tire engages the far end of the pothole only lightly, which results in a glancing blow. This can result in a very mild event. For a given pothole width, there is a matching speed where the tire makes a direct impact on the far side of the pothole, resulting in a severe event with high accelerations (Figure 4).

Other tests, such as the *curb* test, typically resulted in shock loads that increased with vehicle speed. For example, 100g shock loads are obtainable by running into a 15 cm (6 in.) curb at 48 km/h (30 mph). The significance of the pothole tests is that a 100g load has been shown to occur at 16 km/h (10 mph). For a 102 cm (40 in.) wide *pothole*, the speed-match impact occurs at approximately 16 km/h (10 mph).

The pothole test results can be summarized by the following:

- For cross-country travel with off-road tire pressures (69 to 138 kPa, or 10 to 20 psi), shock loads of 60 to 95g are experienced.
- For on-road travel with on-road tire pressures 138 to 207 kPa (20 to 30 psi), the shock loads from a pothole increase to 80 to 100g.
- In both cases, the event can be classified as severe impact, but no tire damage occurred.
- The typical pulse width of the shock impact event was 10 to 20 ms.

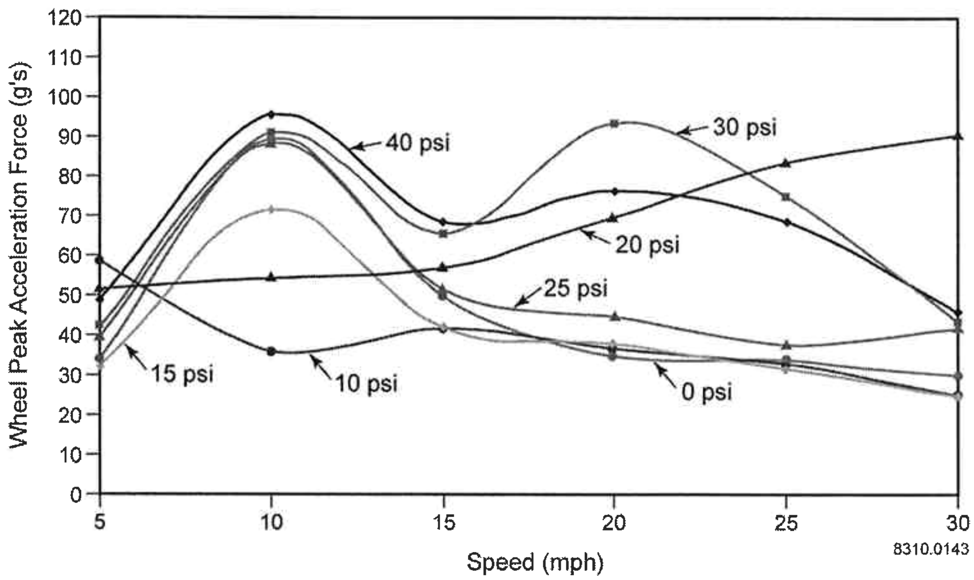

Figure 3. Wheel peak acceleration vs. speed for various tire pressures for pothole tests

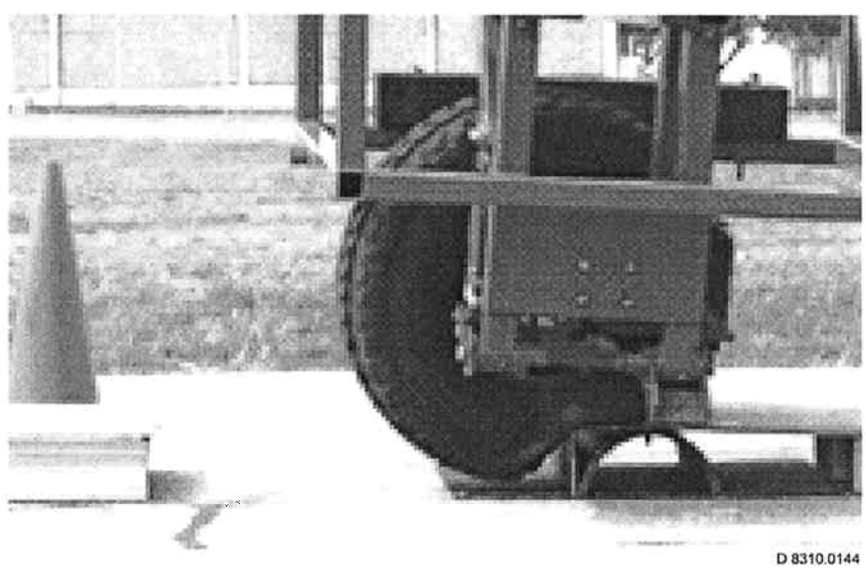

Figure 4. "Speed-match" impact at 10 mph and 30 psi

SUITABLE WHEEL MOTOR DESIGN GOAL

Although this paper focuses on the pothole tests because they resulted in high shock conditions at very low speeds, other tests also resulted in high shock loads measured at the wheel hub. For completeness, *curb* test results are also presented (Figure 5), showing peak shock loads of over 100g. Again, no visible tire or rim damage occurred during these tests. It seems reasonable to accept a design goal for wheel motors that ensures motor survivability under any conditions that the tire and rim survive. Assuming a safety margin of 1.5, shock loads of 100g require that the shock design goal be 150g.

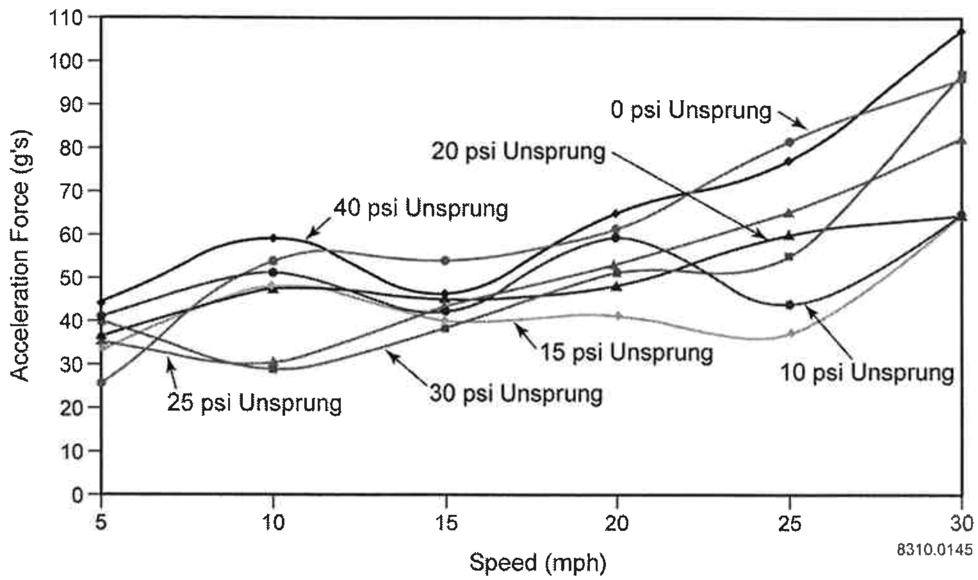

Figure 5. Wheel peak acceleration vs. speed for various tire pressure, 15 cm curb impact tests

FEASIBILITY OF HIGH SHOCK TOLERANT WHEEL MOTORS

Under the *Combat Hybrid Power Systems* program sponsored by the U.S. Army Tank Automotive Research, Development and Engineering Center, UT-CEM conducted an investigation into the feasibility of wheel motors that can withstand 150g shock loads. Although a detailed discussion of these results is beyond the scope of this paper, the results indicated that 150g shock-tolerant wheel motors are feasible, can be lightweight, and can be compatible with 20 ton 8 x 8 combat vehicle designs. The results of the design study are summarized here. The design goals included:

- 18,000 kg (20 ton), 8 x 8 vehicle with trailing arm suspension
- physical shock rating of 150g
- 120 km/h (75 mph) top speed; low speed tractive effort >1
- integrated brakes, gear reduction, coolant lines and central tire inflation lines
- 50 cm (20 in.) rims; sprung to unsprung mass ratio >6
- optimization of the entire wheel propulsion system (motor, gear reduction, brakes, wheel assembly, tire, support system, spindle, etc.)

The design study indicated that a permanent magnet machine is a good choice for the motor, although supporting the brittle magnets at 150g requires careful design. A strong emphasis must also be placed on a lightweight design since small masses are easier to support under high-shock loading than large masses. The total mass for the wheel propulsion system (including tire, rim, brakes, gear reduction, etc.) that meets all requirements is approximately 270 to 320 kg (600 to 700 lb), depending on design details and material choices.

One design alternative is shown in Figure 6. The design required careful optimization, but no new materials or technology breakthroughs. A 12-month development period, including testing, would be sufficient time to complete the final design, build and test.

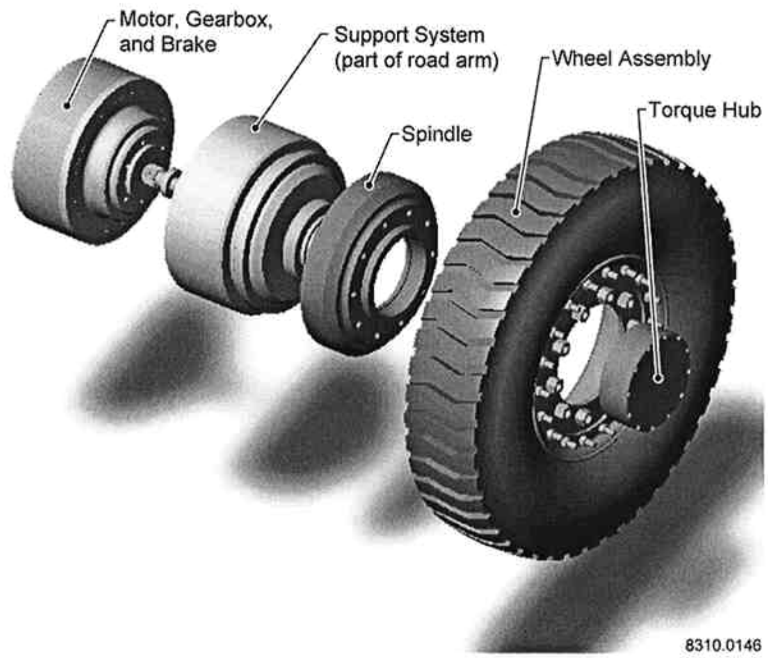

Figure 6. Wheel propulsion system design

CONCLUSIONS

Through a series of tests with a single wheel trailer, it has been shown that a vehicle can encounter 75 to 105g shock loads with pulse widths of 10 to 20 ms in field conditions. These shock loads do not require high speeds or unrealistic conditions. Conventional tires, with run-flats, can withstand impacts that create >120g wheel hub accelerations without tire or rim damage. Adding a suitable safety factor, a 150g shock load design goal for wheel motors appears appropriate, feasible, and achievable.

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