LORD Corporation

Vehicle Suspension Design

White Paper

A brief discussion of suspension system trades.

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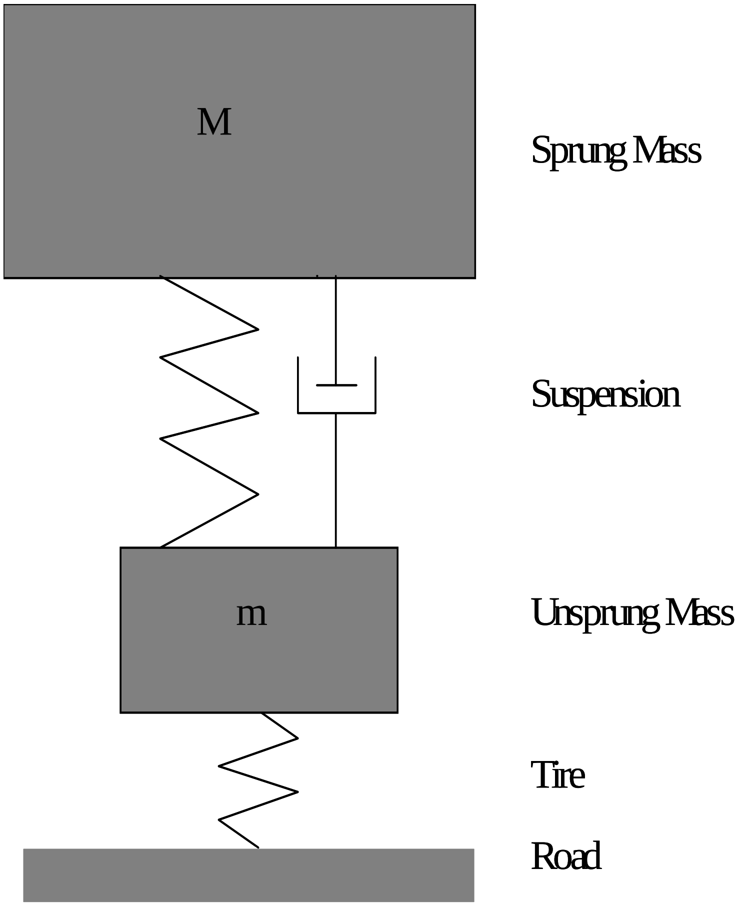
The purpose of the suspension system of a wheeled ground vehicle is to locate the wheel/transfer propulsion energy, isolate the vehicle chassis and occupants from the ground induced shock and vibrations, and simultaneously provide vehicle stability through the dynamic vehicle-to-ground interface.

The suspension system of a ground vehicle consists of a variety of components headed by the suspension spring and shock absorber (or damper). The suspension system also includes the linkages that constrain and define the tire motion relative to the vehicle chassis and any suspension travel limiting devices.

The spring and damping characteristics of the tires also greatly affect the operation of the suspension system but are generally considered independently.

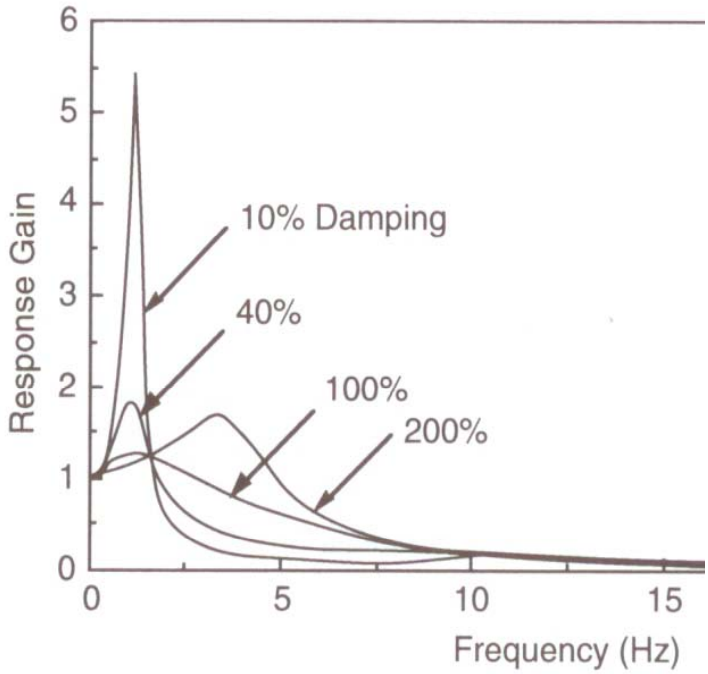
The simplest way to consider the effect of the spring and damper on the mass of the vehicle chassis is to look at a simplified diagram representing a single corner of a vehicle. The resulting mass-spring-damper system is shown below.



The chassis mass (or sprung mass) and the tire mass (or un-sprung mass) are represented by the labeled blocks. The suspension system is represented by the upper spring and damper, and the tire by a separate (lower) spring. The system is excited by the elevation profile of the road acting through the tire. For the simplified case where the springs and damper are linear, the vertical response of the chassis can then be determined for sinusoidal inputs of the road elevation.

If the tire were infinitely stiff, and no damping were included in the system (including friction), the sprung mass would theoretically oscillate with infinite amplitude in response to a sinusoidal road input at the system's natural (or resonance) frequency.

The figure below shows the comparative effects on the output gain for damping of 10, 40, 100 and 200 % of critical damping.



With the damping ratio at 10 % the sprung mass will oscillate with amplitude greater than 5 times that of the input. With critical damping (the 100% curve), the suspension becomes too stiff for the sprung mass to oscillate at all. It can be noted also, that as the damping ratio increases, the damped natural frequency increases from its un-damped value. Passenger cars generally have a vertical natural frequency of from 1.0 to 1.5 Hz and a damping ratio of from 0.2 to 0.4 .

Vehicle suspension systems, of course, are not linear. Suspension travel is limited and the limiting devices have their own characteristics. Spring rates themselves are not linear, particularly with air and gas springs. Dampers are generally designed with different rates in compression (or jounce) and extension (or rebound) in order to help keep the tire-to-ground contact more constant, and the dampers often have pressure limiting valves to prevent damage to the dampers at high force levels.

An additional form of suspension non-linearity is brought about by the geometry of the linkages that connect the tire/wheel assembly, chassis, and suspension spring and damper. The vehicle natural frequency and damping ratio are based on the effective vertical spring and damping rates as applied at the tire center. Yet the spring and damper are rarely mounted vertically, and they are generally mounted inboard of the tire center. This latter fact reduces the required stroke of the spring and damper, but at the penalty of requiring proportionately higher force capability. The suspension kinematics also generally cause the tire to move longitudinally, laterally, and to roll relative to the chassis as the tire moves through the range of suspension travel. These motions can have significant effects on the vehicle stability and handling.

Independent versus Solid Axle Suspensions

An independent suspension system is one in which the vertical motion of any wheel does not cause motion of any other wheel. In other words, each wheel is free to oscillate in a vertical direction, “independently” of the other wheels.

One important non-independent suspension configuration is the *solid axle suspension*. Modern large trucks still tend to use solid axles with leaf springs (especially on all drive axles). When one wheel of a “live” solid axle (i.e. a driven solid axle) suspension system hits a road irregularity, the opposite wheel is also affected in both its vertical and camber motions. Solid axle suspensions have proven to be cheap and robust but they also result in significantly increased un-sprung mass and therefore adversely affect ride quality and handling.

Independent suspension systems have become the high performance standard for the automotive industry. The improvements possible in ride, stability, and handling along with the packaging flexibility have made independent suspension nearly the standard for modern passenger cars. The front suspension on passenger cars often employ a coil spring and tube shock absorber in either a double A-arm or a MacPherson strut configuration (both resulting in an independent front suspension). The rear suspension may also be an independent double A-arm or strut design, or may use a solid axle (either powered or dead) with position locating links. Passenger cars and light trucks also often employ an anti-roll bar (or stabilizer bar). Usually this lateral torsion bar (or spring) is mounted between the two front wheels and is attached in such a way as to transfer spring load across the vehicle to help minimize chassis roll motion.

Vertical Wheel Travel

The amount of vertical suspension travel, as measured at the wheel center, is of crucial importance in the off-road capability of a vehicle. Since it is imperative not to hit the suspension travel limits, due to the extreme forces encountered, it can be seen that small jounce travels must be coupled with higher spring rates in order to prevent hitting the bump stops. Damping can assist in slowing the wheel, but smaller travel gives less time for the damper to help. Correspondingly, larger wheel travel permits a lower spring rate coupled with appropriate damping to provide significantly increased ride quality. In general, it is more difficult to obtain as large a wheel travel with a solid axle suspension as with an independent suspension.

Magneto-Rheological Active Damping

An intermediate choice for an advanced suspension system, between a passive and a fully active suspension, is a semi-active suspension system. A semi-active suspension system replaces the standard damper with an electronically controllable MR damper. Semi-active suspension system controllable dampers have been built and tested using control of the fluid viscosity using magneto-rheological (MR) fluids (termed MR active damping systems). The semi-active suspension system does not supply power, or add energy, to the suspension system. Instead, it dynamically modulates the damping force at each wheel to minimize chassis disturbances. The MR active damping system provides a very fast system response (<5ms), with infinite variability, and no moving parts.

The response time of the active damper, along with the control algorithm (and sensor suite) is crucial for optimum performance of the system. The MR active damper system has a clear advantage in the response time domain with a fluid viscosity transition time of under 2 ms.

Under license from LORD Corporation, the Delphi MagneRide suspension system that has appeared on over 14 passenger car models is an MR active damping system. The cost and reliability of this system has been developed to acceptable standards for the automobile industry; over 400,000 automobiles are on the road today with MagneRide active damping, with new models introduced every year.

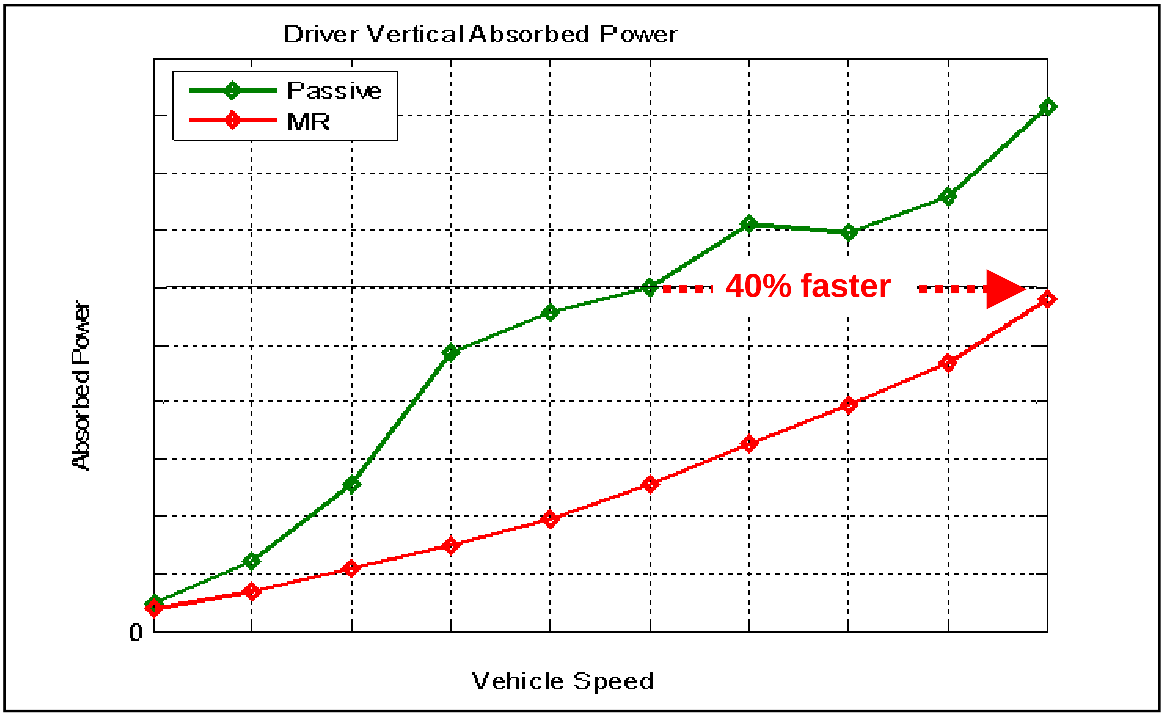
MR active damping system has also been demonstrated on 14 different military vehicle platforms. These include HMMWV, FMTV, Stryker, FTTS, M915, and other technology demonstrator platforms. Test results on these vehicles have shown the following performance advantage over passive shock absorbers:

1. Increased driver limited cross-country speed (6 watt limit) by 30% to 50% (due to significant reduction in absorbed energy).
2. Reduced peak accelerations by 50% to 70% for large dynamic events (half round, or curb hits)
3. Reduced vehicle roll rates by 30%.
4. Significantly improved stability and handling, while also providing a more stable body/hull allowing more combat effective weapons platforms.

A key element of the system is the control algorithm. MR active damping employs skyhook, end-stop, and stability/handling control.

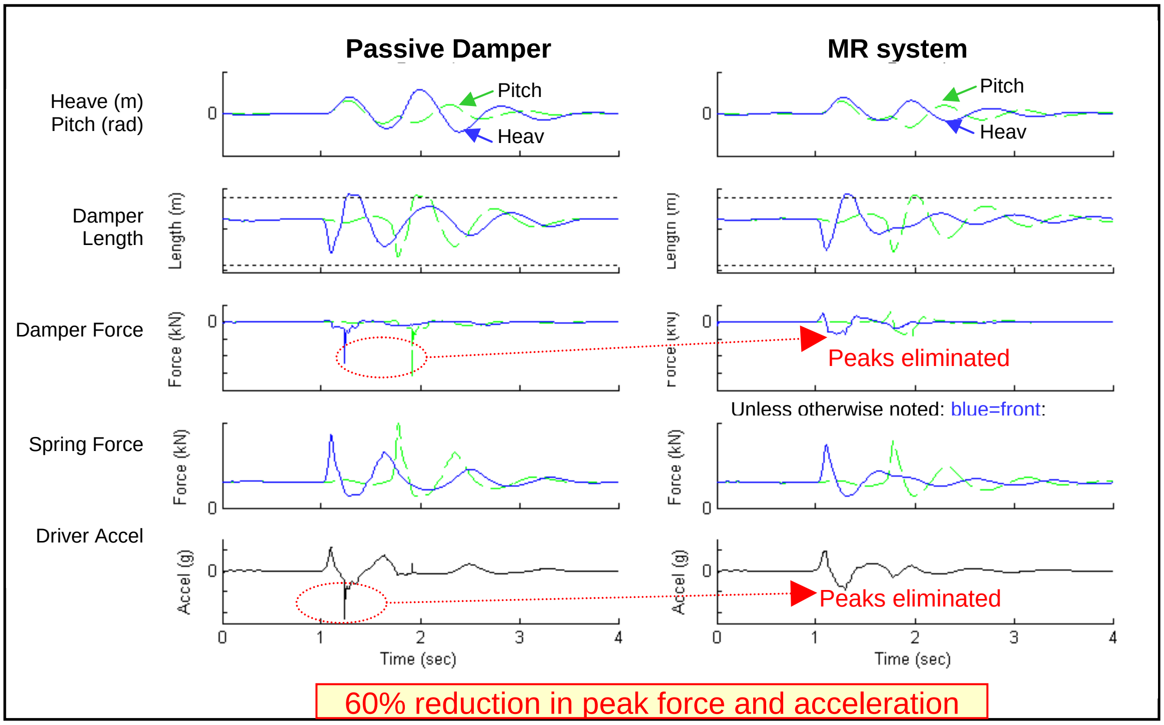
Skyhook control

A primary function of the control algorithm is called skyhook control, where the objective of the system is to minimize vehicle body motion while traversing terrain. Skyhook controls vehicle roll, pitch, and heave. In this mode, the variation in wheel contact pressure should be minimized. Skyhook control reduces the driver absorbed energy by about 50% over off-road terrain. The figure below shows the performance benefit realized in tactical wheeled vehicle over passive.



<u>End stop control</u>

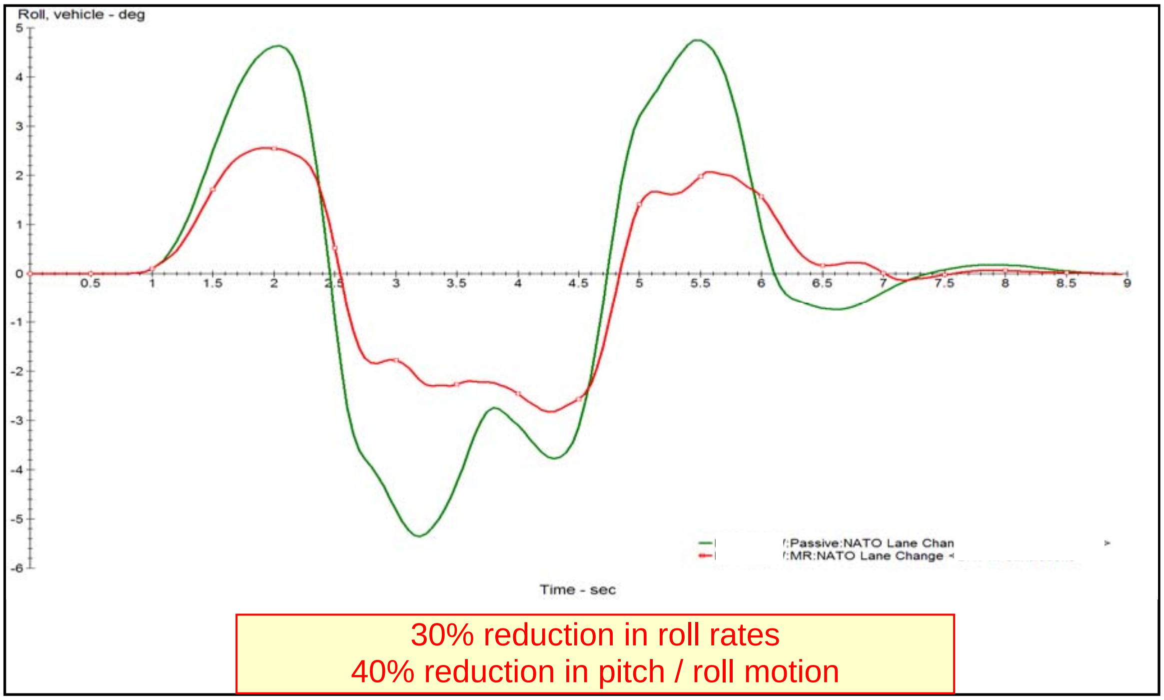
LORD patented end-stop routines further ensure ride quality by greatly reducing peak loads due to large dynamic excursions. In traditional, passive systems the suspension 'bottoms out' thereby causing very high dynamic loading into the sprung and un-sprung masses. The MR active damping end-stop routine will sense a high velocity, predict an end-stop event, and adjust the damping force so as to efficiently absorb the energy over the space and time available. This function has shown peak accelerations / dynamic loading reductions up to 60 or 70%



60% reduction in peak force and acceleration

Handling and stability control

The inherent handling and stability control function of the system controls roll, over / under steer, and braking dive. In NATO lane change testing, vehicle roll rates have been reduced by 30%, providing a 40% higher safe speed through the maneuver. The figure below shows the reduced roll angle in the dynamic lane change event for a tactical wheeled vehicle.



30% reduction in roll rates
40% reduction in pitch / roll motion

MR Strut: MR Active Damping Coupled With a Variable Spring

The semi-active suspension system provides excellent cross-country ride improvement for its designed vehicle weight, but for a vehicle with significantly varying weight missions, the semi-active suspension should be coupled with an automatic variable ride height system. This allows the designed jounce and rebound suspension travel percentages to be maintained regardless of vehicle weight.

Recently such a strut was designed, fabricated, and lab tested under the guidance of the Office of Naval Research (ONR). The semi-active strut was built around an MR fluid based controllable damper with an overlapping concentric air cylinder spring. The ride height system was accomplished through the adjustable air cylinder. Extensive simulations with this system on JLTV showed driver limited cross-country ride speed increased by 80-100% over a total vehicle weight range of 12,000 to 22,000 lbs.

LORD Corporation offers an integrated MR active damper and variable spring strut for military vehicle primary suspensions. This variable spring is pneumatic and can be in the form of an air-cylinder or air-bag. This strut concept is in production for cab mounts of agricultural tractors.

Passive Suspension

The use of traditional springs and dampers results in what is known as a passive suspension system. The design of passive suspension systems has always been a balancing act between the desired vehicle ride performance and the intrinsic vehicle stability and handling characteristics. This tradeoff has been assisted by the use of dual rate shock absorbers which allow the use of low damping in jounce, with the resulting lowered acceleration input to the chassis, while having as much as three times the damping ratio in rebound, in order to quickly remove the extra energy stored in the spring and permit a more consistent tire-to-ground contact. “Soft” springs (resulting in a lower natural frequency) are also desirable for good ride quality. However, this produces more suspension travel and is not suitable for handling, harsher roads (or cross-country), nor for changes in vehicle loading. In such a case, adding (or subtracting) vehicle load will quickly use up the available jounce (or rebound) travel. Changing the vehicle’s total weight also changes the designed natural frequency and damping ratio making it difficult to maintain desired ride and stability performance over the full range of operational weights.

Active Suspension

An active suspension system is defined as a system in which the suspension spring and dampers are replaced with force generating actuators (generally some form of auxiliary spring is included to provide the required static support of the vehicle). These actuators may be hydraulic, pneumatic, or electromechanical. An electronic controller senses various states of the chassis and suspension system (often including sprung and un-sprung mass accelerations chassis roll and pitch rates, and suspension stroke position) and controls the actuators to reduce chassis vertical, pitch, and roll accelerations.

Active suspensions have been demonstrated on a variety of on-road and off-road vehicles with differing levels of success. The varying levels of success are attributed to the different bandwidths of the actuators and to the active suspension control algorithms implemented. Limited active suspension versions have recently appeared on a couple of production cars. Some military demonstration versions of active suspension have concentrated on off-road performance of a variety of military vehicles. Recent tests of these systems have reported, in some cases, to more than double the driver limited cross-country speed.

Although active suspension shows great performance promise, it comes at the expense of significantly increased system complexity, space claim, weight, power draw, and cost. The active system must still carry the static vehicle load and is required to continuously supply power for each of the suspension actuators; the failure mode is not desirable.