# A revolutionary advance in the design of vehicle suspension systems

**Real time electronic control of wheel point vertical forces**

# A quantum leap in the design of vehicle suspension systems

**Since the invention of the wheel** people have tried to soften the bumps and jolts of the road by fitting a spring of some kind between the axle of the wheel and the main body of the vehicle itself. The springs ("compliances") store energy and have to be prevented from bouncing by "dampers" that turn the spring energy into heat that is blown away. Suspension components have in turn controlled the design of vehicle body structures - and even of wheels and tyres.

**A few years ago hydraulic "active suspensions" were developed** (principally by Lotus in the UK). These were designed to eliminate the inevitable pitch and roll actions of a spring suspension by rapidly changing the length of a rigid strut between each axle and the body of a vehicle. An active suspension of this type might be imagined to lift each wheel over a bump and to push it down into a hole as required. But it was necessary for precisely–controlled physical movement to take place continually - and since each movement took time to complete, its ability to deal with small disturbances at high speed was limited. A certain amount of springing had to be retained to cope with this. The peak power demand problems and the complexity of the hydraulics also made the equipment expensive and impractical for high-volume use.

**A more advanced design of active suspension is now available**, using a breakthrough technology of electronic force control. There is now a completely new electromagnetic suspension component that can respond in a fraction of a millisecond. Wheel forces may now be selectively isolated from or coupled to the vehicle, to any required degree, instant by instant, for every inch of the vehicle motion, even at full speed.

**The component is a very high speed force modulator**, unlike any other type of actuator. Nothing has to move for it to control the forces transmitted to the vehicle by the wheels. In effect, this turns a passenger car, a truck, an off-road vehicle or a military machine into a precisely-stabilised platform, moving under real-time electronic control. The electronically-controlled suspension component is mechanically simple and inherently reliable. It is so designed that it doubles as a gas spring that automatically adjusts to road conditions, temperature variations, vehicle load distribution and so on. Further, when driven in reverse, it turns motion energy into electricity. In fully-active mode it draws power from the vehicle to control the vertical forces at each wheel point, for the safest and smoothest ride possible. In semi-passive mode it takes power from the vertical motions of the wheels and uses this to control the attitude and position of the vehicle, returning any surplus energy to a central source.

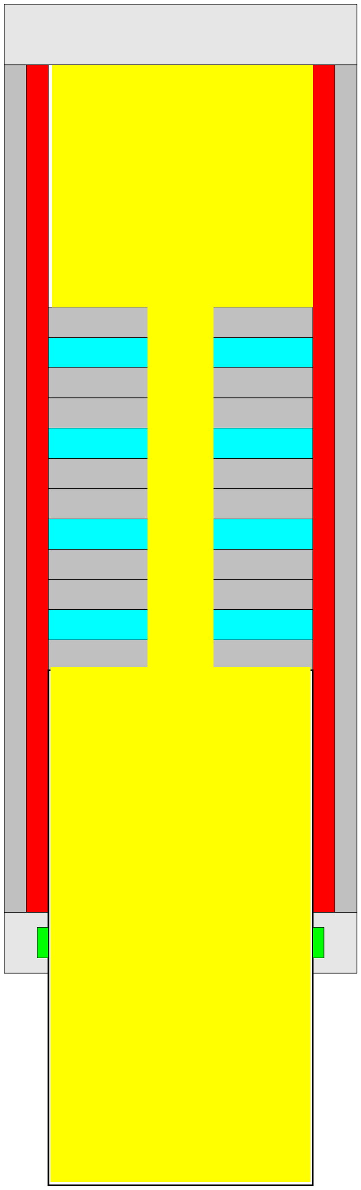
One simple component thus revolutionises suspension system design. Under precise electronic control **it acts as:-**

- **A force generator that compensates instantly for the disturbing effects of the road surface**
- **A gas spring that is automatically tuned to optimise vehicle attitude and ride height**
- **An energy-recycling damper that reacts instantly to vehicle accelerations**
- **A vehicle attitude control element, whether the vehicle is moving or stationary**
- **A vehicle height control element, whether the vehicle is moving or stationary**
- **A "fail-soft" subsystem, maintaining function through several grades of degradation**

This revolutionary “fly by wire” suspension component will strongly influence the future design of vehicle chassis, wheels and tyres, steering systems and electrical equipment. The resulting improvement in vehicle stability has many significant safety benefits. Since it also offers improved fuel economy and an order of magnitude improvement in ride quality, it will add greatly to the value of any kind of vehicle.

# A simplified schematic of the ServoRam™ actuator

**is shown on the right. It consists of an outer mild steel case (grey) lined with electrical coils (red) and fitted with aluminium end pieces. The case and coil system is the stator element of an electrical machine.**



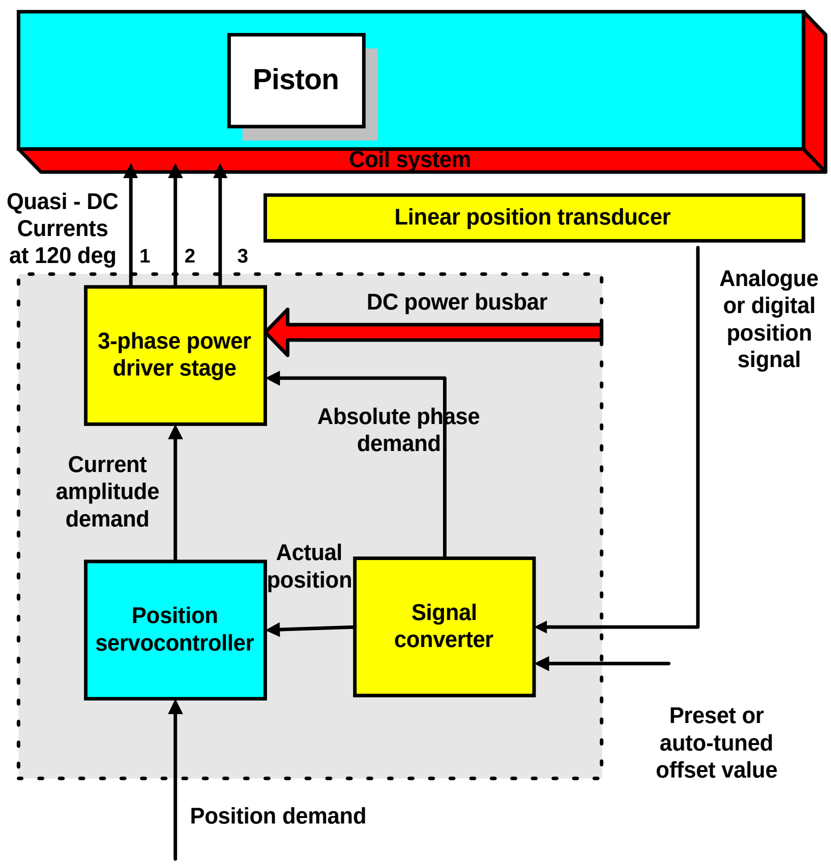
A piston element or armature moves along the axis of the stator, bearing on the inner surface of a thin dielectric tube that lines the coil assembly. (This liner tube is not shown in the diagram.) The piston consists of a stack of planar rings forming magnetic force elements. Each magnetic element is made up of a magnetic ring (light blue) and two mild steel polepieces (grey). The stack of piston elements drives a thrust tube that emerges from one end of the actuator.

The thrust tube is fitted with a sliding seal (green) that makes the whole assembly airtight. The tube is hollow and the space within it communicates with the remainder of the volume of the actuator through a hole in the centre of the “piston”. In operation the actuator is filled with gas (air) that forms a spring whose rate may be chosen according to the ratio of the enclosed volumes of the device when contracted or extended. The pneumatic force may be adjusted by varying the gas pressure at any time.

The actuator is unique in that it produces an electromagnetic force and a pneumatic force acting simultaneously on the same output element. A linear transducer (not shown) measures the position of the piston, so that the unit may be precisely controlled by any standard electronic drive of the type used for industrial rotary three-phase servomotors.

The electromagnetic actuator has zero mechanical hysteresis, since the force is applied directly to the output element. It has zero electrical hysteresis – a microamp in one direction produces a positive force, a microamp in the opposite direction produces a negative force, so that the force output is an exactly linear function of the current input. There is zero transport lag – nothing moves except the armature itself and as soon as the current is in the coils, the output force is present. The small control time constant allows the force to be changed at a rate of thousands of Newtons per millisecond.

# Control of a ServoRam™ actuator




The coils in the stator of the machine are designed to be energised by an electronic drive unit for a conventional rotary three-phase servomotor. This operates by converting the incoming power into a DC rail voltage (if it is not DC already) and then deriving three other DC potentials. These are so arranged that they are symmetrical about a voltage equal to half the DC rail and change as though they were 120 degrees out of phase with one another. As a result the windings of the machine are energised by three Quasi-DC currents.

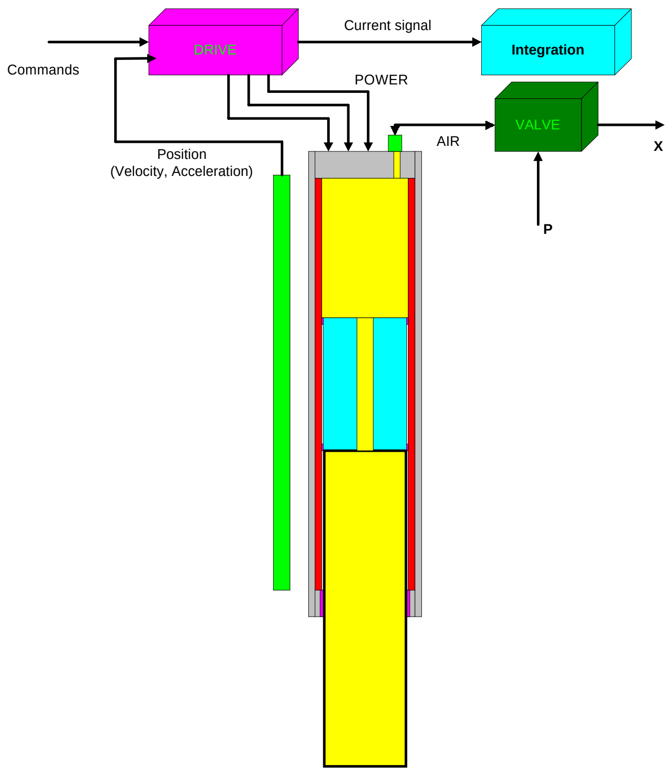
The phase of these currents is locked to the position of the piston, so that the thrust is always optimised. So that the phase of the stator currents can be locked to the armature position, it is necessary for there to be a position transducer – usually along the central axis of the ram.

The magnitude of the current (the amplitude of the sine function or the peak value of the trapezoid) determines the value of the thrust. It is set by the parameters of a servo control loop around a commanded position of the armature. An ancillary circuit processes an output signal that represents the magnitude and sign of the drive current. This controls the pressure in the gas spring with which the actuator is associated, so as to minimise the system power consumption.

# One of the primary objectives of a suspension system

**One of the primary objectives of a suspension system** is to make the passenger compartment insensitive to the vertical motions of the wheels, whilst allowing the wheels to remain firmly in contact with the ground. That is to say, within reasonable limits, the vertical position of the passenger compartment should be kept stable – and when it has to move (to follow a large vertical excursion), it should move as smoothly and gently as possible.

**Newton's first law of motion** says that there cannot be any vertical acceleration unless the vertical force acting on the vehicle is changed. That is to say, if the ride is to be a smooth one, the vertical forces at the wheel points must remain constant.




We start by discarding the conventional idea of a suspension system and suppose that the vehicle is supported on very soft, undamped gas springs at the four wheel points.

The passenger compartment will therefore continue to travel at the same height whilst the wheels move randomly (within the reasonable limits of their travel) across uneven ground. The vehicle body will be disconnected from the ground. It will travel on an air cushion. It will glide as though it is travelling on a level surface.

Of course, this ideal concept ignores the inevitable seal and bearing friction of the pneumatic elements and their thermodynamic losses, both of which will act to degrade the isolation of the gas springs and to transmit some of the wheel forces to the vehicle. The gas springs themselves also exert a restoring force that varies with vertical wheel movement.

**But consider that the suspension elements are ServoRams™ of the type described above. Electromagnetic forces may then be used to compensate, over a wide bandwidth, for all the unwanted forces in a real system.** (As the extremes of wheel travel are approached the actuators are designed to transfer force smoothly to the body of the vehicle so as to provide a comfortable ride.)

**It should be especially noted that, because the ServoRam is able to respond in real time – in less than a millisecond, or about one inch of travel at 60 mph - there is absolutely no need for any look-ahead optical system.**

Because the centre of mass of a vehicle is usually above the plane of the wheel points, a vehicle has a tendency to roll when turning and to pitch fore and aft when changing speed. Conventional suspension systems are arranged to have non-zero spring rates to resist this motion. But the ServoRam™ actuator can produce very powerful fast-acting electromagnetic forces to hold the plane of the vehicle stable, instant by instant as the motion proceeds. Accelerometers at each individual wheel point can be arranged to command changes to the instantaneous values of the ram forces, producing a very strong anti-roll and anti-dive action. Because the total upward force produced by the four wheel-units remains the same, the vehicle body continues at the same height.

**It should be noted that the actuator does not produce a constant electromagnetic force.** The electromagnetic force is modulated instant by instant so as to maintain the net force at the wheel point at a such a value that the body height and attitude does not vary. That desired value of the net force changes only slowly in comparison to the electromagnetic signal – in hundreds of milliseconds rather than in fractions of a millisecond. Although the vehicle occupant may have the impression that the suspension unit responds only gradually, that is not the case at all.

**The gas spring pressure at each wheel point** is continually optimised, averaged over a period of several seconds by a simple algorithm, so as to reduce the electrical power demand. This technology, which was originally developed for the use of the ServoRam in simulators and later for its industrial use, automatically corrects for changes in load distribution and for leaks, valve imperfections and temperature changes. In vehicle use the algorithm has the effect of automatically trimming the ride height if it has been set too low for the roughness of the terrain.

**Because the ServoRam™ does not need to move,** or to move another object, in order to change the state of the system, it is not subject to the normal bandwidth limitations of actuators that do. That is to say, there is no 3 db per octave roll-off as a result of velocity limitations, nor any 6 db per octave roll-off caused by inertial effects.

## The same actuator may be used in a semi-passive or first stage fallback mode as a highly-controllable damper

In this configuration it is the velocity-related coupling between the two parts of the actuator that is modulated to maintain the passenger compartment at a uniform height and attitude.

As the actuator piston moves it generates electrical voltages in the control coils. If the coils are left open circuit, no current can flow and there is no reaction force on the piston, but if the coils are presented with a short circuit the reaction force can be very great, dependent on the piston velocity. Thus by controlling the impedance of a load presented to the coils it is possible to control the velocity of the actuator – to control the damping of its motion.

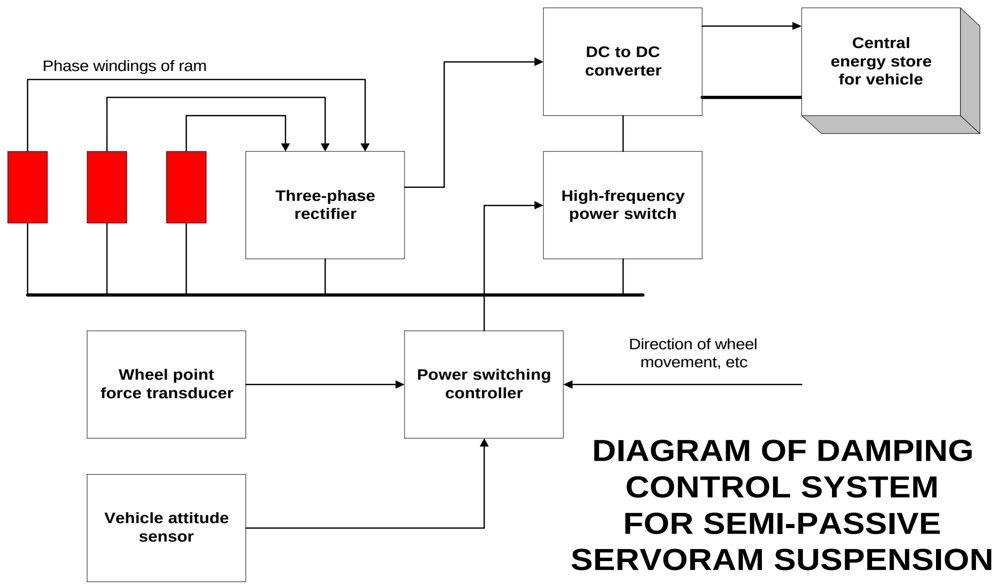



**DIAGRAM OF DAMPING CONTROL SYSTEM FOR SEMI-PASSIVE SERVORAM SUSPENSION**

It should be remembered that the outer part of the ServoRam™ is not fixed – it is connected to the body of the vehicle. So when we refer to "damping" we actually mean the degree of coupling between the vertical motion of the wheel and that of the vehicle itself. The damping coefficient of a ServoRam™ can be changed in a fraction of a millisecond by altering the mark/space ratio of a high-frequency switching transistor that is effectively connected across the phase windings.

It is possible to make slow changes in the mean height of the vehicle by adjusting the gas spring pressure at each wheel point. But it will be obvious from the previous paragraph that the attitude of the vehicle can also be controlled rapidly and precisely by varying the damping coefficient of each ServoRam™ suspension unit. For example, the appropriate suspension units may be stiffened against upward motions of the wheels to resist an unwanted pitch or roll motion but relaxed on every wheel downward motion so that the wheel may retain its grip on the road.

**The ability to control vertical damping forces *instantly and asymmetrically* is a unique feature of the ServoRam™ suspension system**.

When moving over a nominally-level surface, the vehicle travels on its gas spring suspension. For small amplitude motions that do not disturb the mean attitude of the vehicle, the damping coefficient is kept low, so as to produce a smooth ride. But, as the vehicle begins to change its mean height or attitude outside pre-determined limits, the damping is increased ***asymmetrically***, so as to stiffen the suspension against the undesired motion.

In the same way that the gas spring pressure is controlled by the mean direction of current in the windings of the ServoRam™ in active mode, the mean direction of the damping current may also be sensed and used in the same way to trim the average spring settings for each wheel.

A simple algorithm that controls the position of the vehicle in height and attitude thus harnesses in a unique way the forces applied to the wheels by the road surface.

It will be understood that the suspension unit does include a compliant element at the lower extreme of its travel, so as to produce a residual restoring force if the active control system, the damper control system *and* the gas spring control system should *all* fail simultaneously.

Conventional vehicle dampers convert motion energy into heat, which is thrown away into the slipstream. In contrast, the output of the ServoRam™ damper is in the form of electrical energy, a large part of which may be fed back into a central store – e.g. the vehicle battery - via a current transformer and conserved.

***By using a combination of the active and passive suspension control technologies, it is also possible to arrange for the power collected by the damping system to be used to drive the wheel units in fully active mode during the return stroke. This increases the force holding the wheels in contact with the road and produces a smoother ride.***

## Vehicle attitude control

The empirical evolution of vehicle suspension components has set cars and trucks apart from all other forms of transport.

When an aeroplane flies, it banks into a corner. So does a speedboat or a submarine. So does a cycle or a motor cycle – and even a modern passenger train. But passenger road vehicles try to stay horizontal. Many high-sided trucks and off-road vehicles overturn as a direct consequence.

But a vehicle with ServoRam™ suspension may easily be adapted to lean into a bend or to compensate for reverse road camber, since the control system can recognise the side forces and adjust the suspension height on individual wheels as appropriate.

The ServoRam™ suspension also permits the ride height to be reduced (consistent with the smoothness of the road surface) so as to reduce vehicle drag as road speed increases. Further, the vehicle may, just as easily, be arranged to "kneel" or drop to a more convenient height when stationary for the loading and unloading of goods or for the entry and exit of disabled persons.

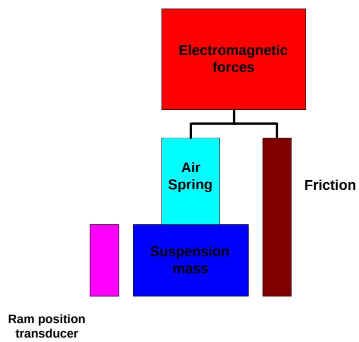
## Advantages of the ServoRam™ suspension system

**The ServoRam™ combines in one simple and robust mechanical element: -**

- **An active suspension system using a minimum energy principle based on Newton's First Law.**
- **A regenerative damper with extremely rapid and precise control of coupling between wheels and chassis.**
- **Almost instantaneous response to external forces that attempt to modify vehicle ride height and attitude.**
- **A continuously tuned and self-levelling gas-spring suspension.**
- **A flexible system for control of ride height and attitude in response to changing speed and road conditions.**
- **A multi-layer fail-safe system.**

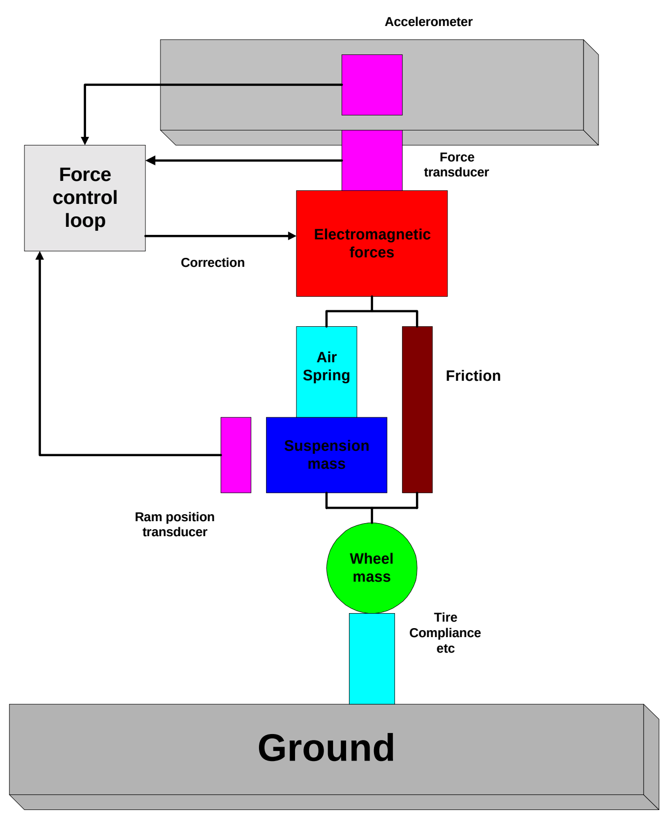
# Notes on the control of the ServoRam™ active suspension unit

The equivalent diagram of the ram is shown below.




The suspension mass (piston and thrust tube, plus couplings or fittings) is separated from the body of the stator by an air spring, but this separation is degraded by the friction in the piston bearings and seals. The electromagnetic forces act directly between the piston and the stator **and override the other forces.**

In use, the ram is placed between the wheel point (on the vehicle chassis) and the wheel stub axle, so as to carry all the vertical forces. The lateral forces are carried by the wishbones.

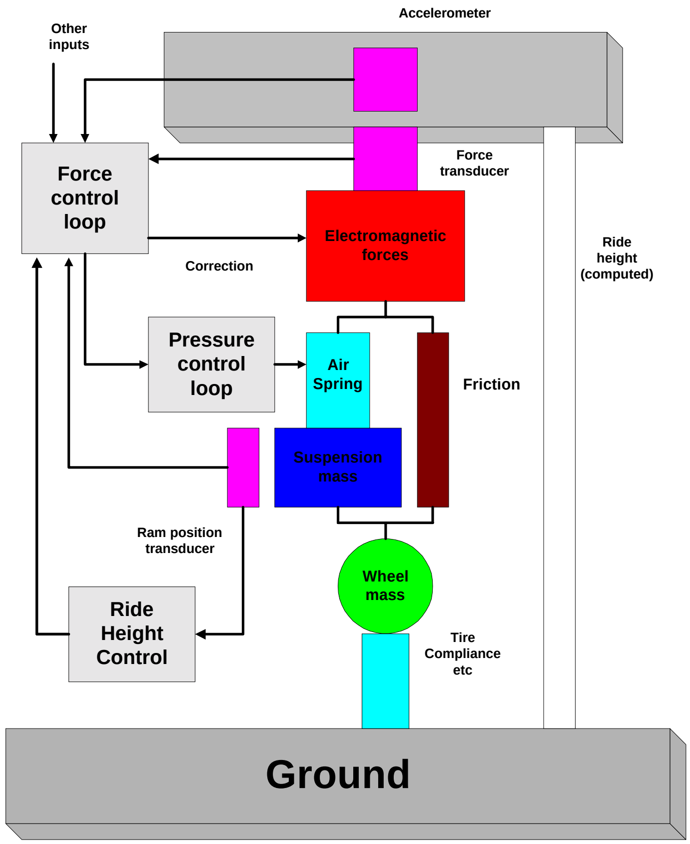



It will be recognised that, within the limits of the ram travel, the forces transferred from the wheel to the chassis may be precisely controlled by the electromagnetic forces. A force-measuring transducer may be used to control the current to the coil system, so as to maintain the total upward force at a constant value, irrespective of the wheel vertical motion.

The desired value of this "constant" force may be determined in turn by the output from a wheel-point accelerometer, so as to hold the vehicle steady against pitch and roll motions, for example.

**Gas spring pressure control**

The force control loop also produces a signal that is processed to control the pressure in the gas spring system. If a predominantly downward–acting force is required of the electromagnetic system, the pressure is increased, and vice-versa.




## Ground clearance control

The ride height of the vehicle at each wheel point can be computed from the average extension of the ram. It is therefore possible to modify the attitude or ground clearance of the vehicle by an external input to each ram controller. The suspension ram moves to its new average position and the air spring pressure is automatically adjusted to suit.

In a similar manner, a series of strong downward-acting (body-lifting) electromagnetic forces to all wheels, caused by the reaction of the vehicle to rough terrain, will automatically cause the gas spring pressures to increase and the ride height to increase. A programmed bias arrangement may be introduced to allow the vehicle to move automatically to low ground clearance on a smooth road surface.

## Gas spring pressure control for a semi-passive ServoRam™suspension system

It may be obvious that very similar gas spring pressure control techniques may be used for the ram when no external power is supplied and the unit is a controlled damper. The energy for the attitude and ride height control system then comes from the vertical forces applied to the wheels by the road surface – that is to say from the energy of the vehicle motion. To raise the vehicle the damping is increased when the wheel moves upwards and it is decreased when the wheel moves downwards.

The mean direction and magnitude of the currents drawn from the ram can therefore be monitored in the same way as for a fully-active suspension system and the gas spring pressure may be adjusted in the appropriate sense, according to a similar algorithm.