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Active Suspension Evaluation Program

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Contents

1 Introduction

An Active Control System is generally defined as a system to which external power must be added to directly drive that system in real time. An active suspension is then a suspension which tries to respond to ground inputs in real time by regulating the force or displacement of a remotely powered actuator.

For practical reasons, Moog-Lotus (a joint venture company formed to develop active suspensions for production cars) further limits the definition of active suspensions [7] by categorizing into "active suspension, high frequency" (frequencies greater than 8Hz) and "active suspension, low frequency" (frequencies less than 8Hz). Other categories which have evolved in the literature include "semi-active" and "adaptive" suspensions. Semi-active suspensions include devices which may vary their characteristics in real time according to some control law, however, unlike a fully active system, these devices do not require external power input, except for the power required to operate the pilot mechanism. The essential difference between semi-active and fully active systems is that a semi-active system may only dissipate or store energy, whereas a fully-active system may impart energy to the suspension. Adaptive suspensions are very close in definition to semi-active systems since they also may vary their suspension characteristics according to some control law with no external power input, however, they are generally considered to respond much more slowly then semi-active systems. Adaptive systems may change stiffnesses or damping coefficients in response to global vehicle performance parameters such as load changes or wind side loads. An example of an adaptive system is the levelling system for airsprings on a highway coach. Finally, passive systems refer to conventional suspensions in which the characteristics (stiffness, damping, etc.) are constant and are established by the constitutive properties of the components.

In this report, current developments as well as relevant past work in active suspensions are discussed. Control algorithms are available from literature sources [14] and some of these will be discussed. References are also available describing developmental work of actual active systems [7], the best known of which is the Lotus active suspension.

2 Development of Active Suspensions

The concept of active suspensions has been around since the 1950's when early experiments with various forms of active control were carried out. A pendulous mass type levelling and banking control for a Citroen 2CV was developed around 1954. Westinghouse developed an active banking control system in 1965. More recently, systems have been developed in the laboratory and these include a two mass quarter car model developed by Sutton [18] (1979) as well as a single wheel apparatus developed at the University of Adelaide [13] (1971). The most recent and well-known of road vehicle active suspensions is the Moog-Lotus system in which production automobiles have been modified with active suspensions.

2.1 The Lotus System

The Lotus system was conceived around 1981 as a means of overcoming the high aerodynamic downward forces on Formula I racing cars [7]. The first fully active suspension prototype was installed on a Lotus Esprit and was an analog system. The second system was a hybrid (digital-analog) and all present prototypes are fully digital in order to provide maximum flexibility of control. The Lotus system is considered a "fully active, high frequency" suspension with suspension update rates of "a few milliseconds" [7], depending on the particular application. Currently, Moog-Lotus is working with many of the major automobile manufacturers to develop prototype active suspension cars. It is expected that production automobiles will be offered with a fully active suspension option in the 1990's.

Details of Lotus' system vary between prototype however there are many features common to all systems. Hydraulic struts controlled by servo-valves are used with operating pressures of around 2500psi to achieve very fast response. The struts are connected between the chassis and wheel in parallel with a load offset spring. The purposes of the offset spring are to carry the static load of the vehicle so that suspension power requirements are reduced and to provide an alternate suspension if the active system should fail.

A variety of sensors are used on the vehicle and in the active struts and the outputs from these sensors are used as input to control the velocity of the actuators. Transducers usually include a load cell at the top of each strut, an LVDT built into each strut measuring the relative movement between chassis and wheel, a vertical accelerometer on each wheel, longitudinal and lateral accelerometers at the body centre of gravity, a body yaw rate transducer, and vehicle velocity and handwheel angle transducers. Each transducer contributes to the vehicle control algorithm a value which is indicative of the vehicle ride or handling at that instant. In order to achieve good ride quality, transient forces into the body must be minimized and thus the load cell measures forces transmitted into the body. An LVDT must be used so that the suspension can correct for ride height. The lateral body accelerometer and handwheel angle are used to sense impending and existing cornering manoeuvres and thus allow the vehicle to correct for body roll. The longitudinal accelerometer can be used to correct for "brake dive" or "acceleration squat".

The basic operation of the Lotus active suspension ensures that both ride and handling may be improved over conventional suspensions. Ride is improved since the strut load cell senses road bumps and tries to retract or extend at the proper rate so that no change in load into the chassis occurs. This reduces the forces transmitted into the body and therefore acceleration levels are reduced and ride is improved. Because the wheel tries to follow all road irregularities, the transient forces on the tires are reduced and therefore handling should be improved (10-20% improvements in handling are claimed). The Lotus suspension also decouples four body modes and uses these as input to the control algorithm. By measuring the relative movement between the body and wheel (ie. LVDT signal) at all four wheel locations, relative body heave, pitch, roll, and warp may be sensed. Heave is then used as an indicator to provide body height adjustment; the pitch mode may be used to correct for vehicle dive or squat; the roll mode is used to correct for roll during cornering, and the warp mode is used to adjust vehicle oversteer/understeer. During suspension development Lotus also looked at driver preferences toward these four modes. They found that heave should be minimized (obviously to provide correct ride height), slight dive is useful to the driver during braking to sense impending wheel lock-up, zero roll on cornering was found to be most comfortable for drivers, and for the warp mode, slight oversteer gives the feel of good handling through corners.

The control algorithms were jointly developed by Lotus and Cranfield College of Aeronautics and are proprietary, and thus it is not possible to get all details of the algorithms, however, much work is published in the area of active controls for suspensions which gives sufficient insight into this area.

The disadvantages of any active suspension are its increased weight, complexity, expense, and decreased reliability and durability over conventional suspensions. Moog-Lotus, in its attempt to bring active suspensions to production automobiles, is addressing many of these problems. Current energy requirements for active suspensions are typically 6-10Hp. Their goal is to reduce this requirement to something similar to an air-conditioning unit (2-5HP). Much of the increased efficiency will be due to improvements to the servo-valves through reduced valve internal leakage and to development of more efficient and compact hydraulic pumps. Actuators are now being designed which combine all local functions in one unit. A suspension strut will contain the actuator, servo-valve, load cell, LVDT, load offset spring and local digital processing all combined into a compact unit. It is claimed that this will simplify installation, improve reliability and reduce the amount of vehicle wiring.

Future development will include improvement of control algorithms as well as integration of the active suspension with other active control systems within the vehicle such as anti-lock braking systems and anti-skid control.

3 Survey of Proposed Algorithms

Numerous algorithms have been proposed for use with active suspensions. Most of the models to date have been based on one degree of freedom or two degree of freedom (quarter car) models [10,18,3,4,21,20,2]. All of these models have been based on optimal control techniques to determine the optimum feedback gains for the system.

The following general technique is used by most of the references: A model is assembled which contains an active suspension element (this may be a strut which is capable of supplying any force at any given instant). A road profile is assumed and the system equations are derived. Next a "performance index" is defined which is the weighted sum of integral squared values. Such values as actuator force, tire deflection, and relative movement of the wheel to body are squared, multiplied by a weighting factor and integrated over time. The optimization problem tries to force the output to follow a desired output while also minimizing the performance index. An ideal desired output would have the body remain fixed while the unsprung mass tracks the road profile exactly. This problem is solved using optimal control techniques and the Riccati equation with the result being a vector of Kalman feedback gains. Using the Kalman feedback gains, a simulation may be run in which the force produced by the active element is the product of the Kalman feedback vector and the model state vector.

Thompson [10,13] produced some of the earliest work on active suspension algorithms. Thompson [10] describes a two degree of freedom model as discussed above. A performance index is selected based on actuator force, tire deflection and secondary suspension deflection. Weighting factors are selected based on some general assumptions and the resulting Kalman gains are found so that the performance index is minimized. Thompson assumes that full state information is available so that sprung mass velocity and road surface height are assumed to be known. A digital simulation was undertaken and the results showed much improved ride quality over a passive system however, with increased tire deflections suggesting decreased handling performance. However, Thompson notes that overall handling of the active system may still be improved due to the higher effective secondary stiffness which overcomes the negative effects of the poor road holding capabilities as seen by the increased tire deflections.

Wilson, Sharp and Hassan [21] considered Thompson's work and derived a two degree of freedom model where full state information is not available. Their performance index was based only on the secondary suspension deflection and the active element force. The control force was then based on the secondary suspension deflection and velocity. The control law was derived but no simulation was undertaken.

Sutton [18] (1979) constructed a two degree of freedom experimental active suspension with full state feedback from the system. This system was compared with the theoretical system. Some problems were encountered due to non-linearities of the servo-valves however, basic agreement was found between the theoretical and practical system, thus proving the potential of increased ride quality.

Thompson, Davis and Pearce [4] derive a two degree of freedom system in which preview control as well as state feedback control are used to control the active element in a similar manner to the above models. With preview control the road height is sensed prior to the wheel travelling over that position and therefore the actuator may begin to move in anticipation of a bump rather than after it is sensed. The implementation of this technique requires shifting of the previewed data (at a rate dependent on vehicle velocity) and summing it with a scaling factor to the actuator inputs. With preview control, there is potential for improved performance, however the practical realization of the height sensor design as well as implementation in the control logic lead to significant challenges.

In a four degree of freedom pitch plane (half car) model, Thompson and Pearce [5] use full state feedback with an optimal control strategy for their active suspension model. They showed that this model produces improved ride and much greater static stiffness (to resist body loads) over passive systems. Axle response was increased, however they also pointed out that the corresponding tire deflections were decreased thus resulting in improved road holding capabilities.

Malek and Hedrick [12] consider a seven degree of freedom (body heave, pitch, roll and four unsprung masses which move vertically) vehicle model since they feel this is the only way to predict the tire/road contact forces, and therefore handling as well as ride quality, for an active suspension. The model uses a linear combination of the full state feedback vector to generate a force control signal at each suspension strut. Their results show improved ride quality and the potential for better vehicle handling (ie. smaller peaks were seen for the tire transient loads).

Baraks and Sachs [17] also considered a seven degree of freedom model and compared active, semi-active and passive systems. The weighting factors which they utilized in their performance index (i.e. the integral squared values) were based on trade-off studies to determine the most desirable combination. The performance index was minimized while calculating the optimal control feedback vectors, with full state information being assumed, and the three systems were simulated and the results compared. They predict that the overall ride and handling performance, as determined from acceleration levels, is in the ratio 4.5:1.52:1 (passive:semi-active:active; active being the best). From these results, they also predict poor handling performance for the active system, but extremely good ride performance. The poor handling performance is a result of increased axle oscillations as well as increased transient tire deflections which seems in direct contrast to [12] which predicts lower tire transient loads.

One of the most extensive investigations of active suspension modelling was carried out by Fruhauf, Kasper, and Luckel [14]. In this seven degree of freedom vehicle model, they utilized the same optimization techniques as above, however, other aspects of the active system were included such as a servo-valve model and a perception filter (a vibration model of passenger sensitivity). Also different controller designs were compared for the active systems and a conventional suspension. Results showed that the active suspension provided both improved ride and improved handling, through lower transient tire forces.The results varied depending on the type of controller used and whether full state information was available or not.

4 Hardware Requirements

The Lotus system provides the most current information as to hardware configurations for fully active suspensions since it is currently the most advanced active suspension. Hardware requirements are also dependent upon the particular vehicle installation, therefore the following requirements are only approximations for a typical road vehicle.

All active suspension (high frequency) systems implemented so far have been hydraulic with high performance servo-valves. Actuator frequency response has been 25 Hz or better. Hydraulic system operating pressures of 2500 psi and power requirements of 6-10 Hp are typical for the Lotus system. Loads on the actuator depend on the physical placement of the actuator relative to the vehicle wheel, however loads of 1000-1500lb are common. Actuator maximum velocity is such that the maximum achievable vertical wheel velocity is 2m/s. The hydraulic systems are driven by variable displacement in-line piston pumps which are quite efficient over wide operating ranges. Also, accumulators have been utilized to compensate for flow surges necessary during rapid wheel movement and some form of oil coolers have also been employed to cool the return oil. "Helper springs" are added in parallel to each wheel as an emergency suspension and to reduce the energy requirements of the suspension. The additional mass added by an active suspension varied considerably between different car models (according to reference [15]) with the lightest model (Volvo 740) adding 50Kg and one of the heaviest (Corvette) adding 135Kg. Sensing requires approximately twenty channels all of which contribute to the control action at each wheel. Typical parameters sensed include: Load sensor-actuator to body, position sensor-body to wheel, accelerometer at each wheel hub, lateral and longitudinal accelerometers at the body centre of gravity, yaw rate of the body, steer wheel angle, vehicle velocity and possibly several other status indicators such as pump pressure, etc.

The Lotus experience shows the problems which may be encountered with active suspensions. Harshness over road joints was apparently a problem which may have been solved by appropriate tuning of the strut bushings. Noise from the hydraulic system was noticeable and this may be corrected by further refinement of the system, such as a quieter pump, re-sizing of some of the hydraulic lines, etc.

5 Conclusions

This report describes the current state of work associated with the development of active suspensions. Moog-Lotus,the forerunner in this area, has taken the concepts of active control and developed prototype active suspensions soon to be available on a production basis. Much of the work in active suspensions by Moog-Lotus is proprietary and therefore only general details are available.

Many references describing active suspensions are available and they point out the potential of active systems. Some general conclusions can be drawn from these references. Active systems are designed around the concepts of linear optimal control in which state feedback from the vehicle is used to control each of the active suspension elements. Different control laws may be used depending on the model assumed and different optimized solutions for the system will result leading to varying performances between active systems. Also, the designer must select initial weighting factors for their "performance index" (even before the problem is optimized) so that the same system will have many optimized solutions. Despite the variety of active control possibilities, all the references were unanimous in selecting active suspensions to have the best ride performance over passive or semi-active systems. They were not unanimous is selecting superior handling performance for active suspensions since axle oscillations increased in comparison with passive systems. However, the more complex models do indicate superior ride and handling as a result of lower body accelerations, lower tire transient forces, and better tire load distribution for active suspensions.

Another question which is frequently raised in the references concerns the relative merits of semi-active versus active suspensions. The references indicate that overall semi-active suspensions are almost as good as fully active suspensions (one paper claims semi-active is about 60% as good as fully active, whereas passive is only about 25% as good). If this is the case, in many situations it may be more economical to operate a semi-active suspension with reduced performance than to use a fully active system. The choice of semi-active versus active will depend on the particular application and the given driving conditions. For instance, where ride is very important, an active system may be justified whereas if handling is emphasized, a semi-active system may be adequate.

There still appears to be considerable scope for work in the area of predicting active suspension performance and optimizing the control strategies. All models reviewed were oriented towards ride quality since the only input to the models were random road roughness profiles. Many of the models assumed that full state information was available to the control system. This is not practically possible. Assuming less than complete state information generally results in a degradation of active suspension performance. Only a few references actually included the response of the servo-valve/hydraulics in their models while the others assumed that the active component responded instantaneously to control signals.

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