Australian Journal of Basic and Applied Sciences, 9(30) Special 2015, Pages: 46-53

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

A Comprehensive Study on Suspension System and Tilting Vehicle

[1]S.B.A. Kashem, [2]T. Saravana Kannan, [3]T.A. Choudhury, [4]M.A. Chowdhury, [5]Sajib Roy, [6]A.A. Safe, [7]M. Ektesabi, [8]R. Nagarajah

[1,2,4]*Faculty of Engineering, Swinburne University of Technology Sarawak, Kuching 93500, Sarawak, Malaysia.*
[3]*Faculty of Science and Technology, Federation University Australia, Churchill, VIC 3842, Australia.*
[5]*Faculty of Engineering , East West University, Dhaka, Bangladesh.*
[6]*Faculty of Engineering , Chittagong University of Engineering and Technology, Chittagong, Bangladesh.*
[7,8]*Faculty of Science, Swinburne University of Technology, Hawthorn, VIC 3122, Australia.*

ARTICLE INFO

Article history:
Received 13 November 2013
Accepted 23October 2013
Available online 30November 2011

Keywords:
Vehicle; Semi-active; Suspension; Damper; Car; Adaptive; Intelligent; review; comparison.

ABSTRACT

Nowadays, many researchers are working on active tilting technology to improve vehicle cornering. The concept of 'active tilting technology' has become quite popular in narrow tilting road vehicles and modern railway vehicles. In this paper, the development of active tilting technology has been reviewed. To tilt the vehicle inward during cornering, tilting actuators are used as an element of the active suspension system. Leading automotive companies have started to use intelligent suspensions in their high-end automobiles' to tilt vehicle. But much more research and developments are required in design, fabrication and testing the suspension system and many challenges need to be overcome in this area. This paper high lights different type of suspension systems which are being widely used. It has been realized that semi-active suspension system is suitable for road vehicles due to its performance and reliability.

To Cite This Article: S.B.A. Kashem, T. Saravana Kannan, T.A. Choudhury, M.A. Chowdhury, Sajib Roy, A.A. Safe, M. Ektesabi, R. Nagarajah., A Comprehensive Study on Suspension System and Tilting Vehicle. ***Aust. J. Basic & Appl. Sci.,*** *9(30): 46-53, 2015*

INTRODUCTION

Vehicle performance during cornering has been improved by most of the car manufacturers by using electronic stability control (ESC). Car manufacturers use different brand names for ESC, such as, Volvo named it DSTC (Dynamic Stability and Traction Control); Mercedes and Holden called it ESP (Electronic Stability Program); DSC (Dynamic Stability Control) is the term used by BMW and Jaguar but despite the term used the processes are almost the same. To avoid over steering and under steering during cornering, ESC extends the brake and different torque on each wheel of the vehicle. But ESC reduces the longevity of the tire as the tire skids while random braking. To overcome this problem a vehicle can be tilted inwards via an active or semi-active suspension system.

The concept of 'active tilting technology' has become quite popular in narrow tilting road vehicles and modern railway vehicles. Now in Europe, most new high-speed trains are fitted with active tilt control systems and these trains are used as regional express trains (Goodall, R., 1999; Goodall, R., 1999). To tilt the train inward during cornering, tilting actuators are used as an element of the secondary active suspension system. These actuators are named as bolsters. In a road vehicle actuators are also used to affect the vehicle roll angle via an active suspension system. Since the beginning of the 1950s, there has been extensive work done in developing the Narrow Tilting Vehicle by both the automotive industry and academic researchers (Karnopp, D. and R. Hibbard, 1992; Hibbard, R. and D. Karnopp, 1996; So, S.G. and D. Karnopp, 1993; Saccon, A., 2008; Frezza, R. and A. Beghi, 2003).

This particular small and narrow geometric property of the vehicle poses stability problems when the vehicle needs to corner or change a lane. There are also two types of control schemes that have been used to stabilize the narrow tilting vehicle. These control schemes are defined as Direct Tilt Control (DTC) and Steering Tilt Control (STC) systems as detailed in (Kidane, S., *et al*., 2006; Piyabongkarn, D., 2004). A typical passenger vehicle body can be tilted up to 10° as the maximum suspension travel is around 0.25 m. Then, the lateral acceleration of the tilted vehicle caused by gravity can reach a maximum of about 0.17g (Wang, J. and S. Shen, 2008). Since the lateral acceleration produced by normal steering manoeuvres is around 0.3–0.5 g, the active or semi-active suspension systems have the potential of improving vehicle ride handling performance. Semi-active or active suspension

Corresponding Author: S.B.A. Kashem, Faculty of Engineering, Swinburne University of Technology Sarawak, Kuching 93500, Sarawak, Malaysia.

Australian Journal of Basic and Applied Sciences, 9(30) Special 2015, Pages: 46-53

systems can act promptly to tilt the vehicle with the help of semi-active dampers or actuators. However, the active suspension systems need to avoid over-sensitive reaction to driver's steering commands for vehicle safety. Recently Bose Corporation presented the Bose suspension system (Jones, W., 2005) in which the high-bandwidth linear electromagnetic dampers improved vehicle cornering. It is able to counter the body roll of the vehicle by stiffening the suspension while cornering. Car giant Nissan has developed a four wheeled ground vehicle named Land Glider. The vehicle body can lean into a corner up to 17 degrees for sharper handling considering the speed, steering angle and yaw rate of the vehicle. In addition, in the works stated above and other research, the effect of road bank angle is neither considered in the control system design nor in the dynamic model of the tilting standard passenger vehicles (Bin Abul Kashem, S., 2014; Kashem, S.B.A., 2012; Gohl, J.B., 2003; Rajamani, R., *et al*., 2003; So, S.G. and D. Karnopp, 1997; Sang-Gyun, S. and D. Karnopp, 1997; Li, Y., 1968; Mourad, L., 2011; Roqueiro, N., 2011; Amati, N., *et al*., 2012; Edelmann, J., 2011; Kashem, S.B.A., 2008). Not incorporating the road bank angle creates a non-zero steady state torque requirement. So this phenomena needs to be addressed while designing the tilt control and the dynamic model of the full car model. To lean a vehicle which incorporates the road bank angle, the response time of the actuator or semi-active damper plays an important role.

Vehicle suspension system plays an important role in vehicle tilting. A brief description of different suspension systems is given in section 2.

Vehicle suspension system:

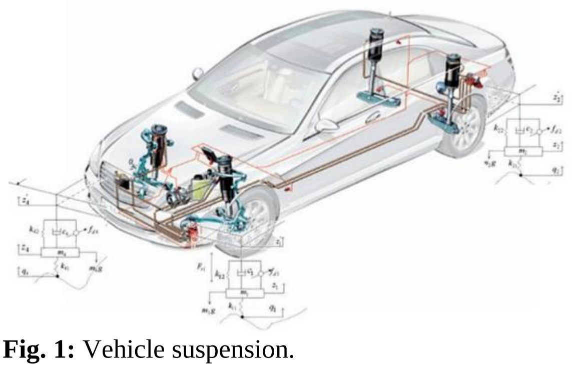

Fig. 1: Vehicle suspension.

A suspension system is an essential element of a vehicle to isolate the frame of the vehicle from road disturbances. Figure 1 shows a car suspension system. It is required to maintain continuous contact between a vehicle's tyres and the road. The most important element of a suspension system is the damper. It reduces the consequences of an unexpected bump on the road by smoothing out the shock. In most shock absorbers, vibration energy is converted to heat and dissipates into the environment. Such as, in the viscous damper, energy is converted to heat via viscous fluid. In hydraulic cylinders, the hydraulic fluid is heated up. In air cylinders, the hot air is emitted into the atmosphere. But the electromagnetic damper is different; here the vibration energy is converted into electricity via an electric motor (induction machine or DC motor or synchronous machine) and stored in a condenser or battery for further use (Suda, Y., *et al*., 2004).

Suspension systems are categorized as passive, active and semi-active considering their level of controllability. Although all the types of the suspension systems have different advantages and disadvantages, all of them utilize the spring and damper units.

Passive suspension systems are composed of conventional springs and oil dampers with constant damping properties (Figure 2). In this model m_1 and m_2 represent the un-sprung mass and sprung mass respectively, k_1 is the tyre stiffness coefficient or tyre spring constant, k_2 is the suspension stiffness or suspension spring constant. c_0 and c_t are the suspension damping constant and the tyre damping constant respectively, Fr is friction of suspension, q, z_1, z_2 represents road profile input, displacement of un-sprung mass and displacement of sprung mass respectively.

Passive suspension system:

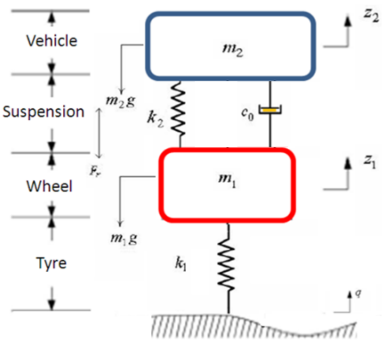

Fig. 2: Passive suspension system.

In most instances, passive suspension systems are less complex, more reliable and less costly compared to active or semi-active suspension systems. The constant damping characteristic is the main disadvantage of passive suspension systems. For a passive suspension, the use of soft springs and moderate to low damping rates is needed but the use of stiff springs and high damping rates is needed to reduce the effects of dynamic forces. Designers utilize soft springs and a damper with low damping rates for applications that need a smooth and comfortable ride such as in a luxury automobile.

On the other hand, sports cars incorporate stiff springs and a damper with high damping rates to gain greater stability and control at the expense of comfort. Therefore, the performance in each area is limited for the two opposing goals (Gillespie, T., 2006). There is always a compensation need to be made between ride comfort and ride handling in the passive suspension system as spring and damper characteristics cannot be changed according to the road profile.

Semi-active suspension System:

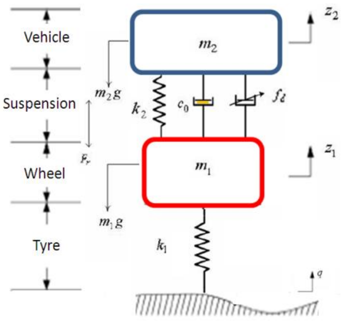

Fig. 3: Semi-active suspension system.

The semi-active suspension system was first proposed by Karnopp *et al*. in 1973. In this model, Figure 3 is a semi-active suspension model. Here f_d can generate an active actuating force by an intelligent controller. Since then, semi-active suspension systems have continued to acquire popularity in vehicular suspension system applications, due to their better performance and advantageous characteristics over passive suspension systems. In semi-active suspension systems, the damping properties of the damper can be changed to some extent. The adjustable damping characteristics in semi-active dampers are achieved through a variety of technologies, such as: Electro-Rheological (ER) and Magneto-Rheological (MR) fluids, solenoid-valves and piezoelectric actuators. It has been widely recognized that a semi-active suspension system provides better performance than a passive system. As it is safe, economical and does not need a large power supply, semi-active suspension has recently been commercialized for use in high-performance automobiles (Irmscher, S. and E. Hees, 1966; Konik, D., *et al*., 1996; Nakayama, T., *et al*., 1996; Yi, K. and B.S. Song, 1999; Sankaranarayanan, V., *et al*., 2008). However, there still exist many challenges that have to be overcome for these technologies to achieve their full potential. MR degradation with time, sealing problems and temperature sensitivity are some crucial issues of the MR dampers that need development.

Active suspension system:

The active suspension system (Figure 4) actuates the suspension system links by extending or contracting them through an active power source as required. Conventionally, automotive suspension designs have been a compromise between the three contradictory criteria of road handling, suspension travel and passengers comfort. In recent years the use of active suspension systems has allowed car manufacturers to achieve all three desired criteria independently.

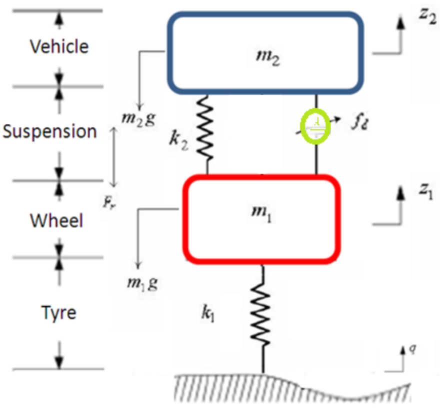

Fig. 4: Active suspension system.

A similar approach has also been used in train bogies to improve the curving behaviour of the trains and decrease the acceleration perceived by passengers. But this makes the system expensive and increases the design complexity and energy demands.

From the above discussion, it is apparent that a semi-active suspension system is more appropriate for implementing and evaluating the performance of various control strategies.

Active tilting technology:

The concept of 'active tilting technology' has become quite popular in narrow tilting road vehicles and modern railway vehicles. Now in Europe, most new high-speed trains are fitted with active tilt control systems and these trains are used as regional express trains. Some of the vehicles use actuator or active suspension system to tilt the vehicle.The description of tilting road vehicles technology is given in the following sections.

Narrow titling road vehicle:

Narrow vehicles are characterized by a high centre of gravity and relatively narrow track width compared to the standard production vehicle. These vehicles would be more efficient and pragmatic considering parking problems and traffic congestion in urban areas. They would also reduce energy consumption. These new cars are small, approximately half of the width of a conventional car (less than 2.5m in length, 1m in width and 1.5m in height). All over the world traffic congestion is a growing problem. Furthermore, the average number of occupants including the driver of a single vehicle in USA is 1.57 persons.

Australian Journal of Basic and Applied Sciences, 9(30) Special 2015, Pages: 46-53

Fig. 5: Narrow commuter vehicle.

The narrow commuter vehicle shown at Figure 5 can be categorised by two types depending on their tiling mechanisms. The first one Figure 6(a) uses an active suspension system to tilt the whole vehicle and the second one Figure 2-4(b) has an actively controlled tilting passenger cabin and a non-tilting chassis frame or rear assembly. An actuator fitted to the rear assembly controls the tilt action of the passenger cabin according to the design criteria. The non-tilting assembly of the vehicle typically consists of several power train components so therefore it contributes considerably to the mass and inertia of the vehicle. Moreover, the non-tilting chassis has to support the roll torque which has been applied to tilt the passenger cabin by the actuator. As a result, the suspension of the vehicle wheel needs to be quite stiff which may affect the ride comfort. Furthermore, the energy consumption of this tilting mechanism is also very high.

This particular small and narrow geometric property of the vehicle poses stability problems while cornering or lane change. There are also two types of control schemes that have been used to stabilize the narrow tilting vehicle. These control schemes are defined as Direct Tilt Control (DTC) and Steering Tilt Control (STC) systems as detailed in (Rajamani, R., 2006). In the DTC system, the driver steering input is connected to the front wheel steering mechanism directly. In a DTC system, dedicated actuators control the tilt of the vehicle (such as having an active suspension). In this system, the link between the wheels and the steering wheel is no longer mechanical. In an STC system, on the other hand, STC or steering tilt control, no additional actuator is used, and the tilt of the vehicle is controlled by the steering angle input from the driver. The steering input is used to follow the desired trajectory as well as stabilize the tilt mode of the vehicle. This is particularly a steer-by-wire system. In this system, the driver steering input signal is read by the controller and the controller determines the tilt angle. Since the beginning of the 1950s extensive research has been done on both types of control systems by the automotive industry and researchers.

(a)

(b)

Fig. 6: (a) Vehicle tilt by suspension, (b) Vehicle tilt by actuator.

Motorised tilting vehicles have been studied and developed since the pioneering prototype proposed by Ernst Neumann in 1945–1950. The Ford Motor Company developed a two-wheeled lean vehicle in the middle of the 1950s. It was gyroscopically stabilised with retractable wheel pods for parking. In the 1960s, the MIT presented a tilting vehicle which was equipped with an active roll control. The design was similar to a motorcycle. At the beginning of the 1970s, General Motors developed a tilting vehicle called the ‘Lean Machine’. It had a fixed rear frame and a tilting body module that was controlled by the rider. The rider had to balance the tilting body using foot pedals.

More recently, Brink Dynamics developed a three wheeled car named Carver with a rotating body and non-tilting rear engine. BMW and the Universities of Bath and Berlin were presented Clever in 2003. It consists of a non-tilting two-wheel rear axle and a single front wheel that tilts with the main body. The rear body remains in contact with the ground in the same way as a conventional automobile rear axle but the main body is connected to the rear frame by a suspension layout enabling it to lean like a motorcycle.

The manufacturer Lumeneo presented the Smera and Piaggio presented MP3. At the Tokyo motor show 2009 Nissan revealed the Land Glider, which is a four wheeled narrow vehicle. Of all the above the Carver One was sold commercially between 2006 to mid-2009 and the MP3 has been on the market for sale since 2006.

From an academic point of view researchers have done an extensive amount of work on these cars. D. Karnopp suggested that the narrow tilting vehicle would have to lean into a corner and also explained the optimum desired lean angle in his research. Dean Karnopp and his co-workers have also carried out a significant amount of research into dynamic modelling of tilting vehicles. Karnopp and Hibbard have proposed that a tilt actuator can be employed to tilt a narrow tilting vehicle to a certain desired tilt angle with the help of the direct tilt control strategy. It is apparent that their research lays down the basic ideas for designing a direct tilt control system. However in some of their research, they are unable to take into account the lateral position acceleration of the vehicle while calculating the desired tilt angle calculation. This caused the controller to require a high transient torque.

There are a few publications which have presented the idea of a virtual driver in a narrow tilting vehicle. These virtual drivers are able to follow a path without falling to one side. Saccon *et al*. (2008) developed a dynamic inversion of a simplified motorcycle model. This model is able to obtain a stabilizing feedback through the standard Linear Quadratic Regulatory control system. This model allows the controller to calculate the state and input trajectories according to a desired output trajectory of the tilting vehicle. To avoid the direct deal with the lean instability, Frezza and Beghi (2003) took the roll angle as control input instead of the steering angle input from the driver. They have defined the path tracking as an optimization problem of the controller design.

Snell (1998) proposed to start the tilting action with the STC system then to switch to the DTC system to maintain the tilting position. A three wheeled prototype of a narrow tilting vehicle was developed at the University Of Bath, UK. It employed hydraulic actuators to tilt the cabin with the help of DTC technology which has a high power requirement (Poelgeest, A., 2007). Kidane *et al*. (2008), applied hybrid control schemes with both STC and DTC. This work employed a feed forward plus PID controllers to stabilize the tilt of the vehicle and a look-ahead error of the trajectory model was used as the driver model. Chiou proposed a double loop PID to control and to maintain the tilting position and the rate of the vehicle (Chiou, J., *et al*., 2009).

Defoort (2009) and Nenner *et al*., (2008) worked with the trajectory-tracking and robust stabilization problems of a rider-less bicycle. They developed a dynamic model that considers geometric-stabilization mechanisms. They also derived a combined control system consisting of a second-order sliding mode controller and disturbance observer. In their research they adopted a simplified tricycle model as the dynamic model of a bicycle.

In addition, in the research works stated above and in other authors' researches, the effect of road bank angle is not considered in the control system design and in the modelling of the dynamic model of narrow tilting vehicles. The result of not incorporating road bank angle is a non-zero steady state torque requirement. It also significantly increases transient torque requirements. Sang-Gyun So and D. Karnopp (1993) considered the road bank angle in their work, but it has no effect on the final form of the control input. The authors specified that the lateral acceleration of the vehicle be obtained from the sensor readings mounted on the vehicle. But it is evident that the reading of an accelerometer of a narrow tilting vehicle would be contaminated by the tilt angle, the road bank angle and the angular acceleration of the vehicle.

Tilting standard production vehicle:

To improve vehicle performance during cornering or sudden lane change advance electromechanical and electronic systems are used, for example, antilock braking systems, electronic brake force distribution, active steering and electronic stability programs. Nowadays, some researchers have focused on active steering control to improve vehicle cornering (Marino, R., 2007; Li, B. and F. Yu, 2009; Du, F., *et al*., 2010). Recently, a system was presented by Bose Corporation, namely, the Bose suspension system. This system consists of a power amplifier and a linear electromagnetic motor at each wheel that is controlled by a set of control algorithms. The high-bandwidth linear electromagnetic dampers of this system respond quickly enough to achieve better ride performance. To date the prototype of the Bose suspension system is installed in standard production vehicles and able to achieve superior comfort and control simultaneously. According to the manufacturer, the Bose suspension system can counter the body roll of the vehicle by stiffening the suspension while cornering. It can also change the ride height dynamically and is capable of performing the four quadrant operations and the high bandwidth operation. But it uses less than one third of the power of the air conditioning system of a typical vehicle. However, to date no commercial tests or design details are available to the world from the Bose Corporation which would allow an accurate and unbiased comparison with other competitive suspension systems.

Vehicle performance during cornering has been improved by most car manufacturers using electronic stability control (ESC). Car manufacturers use different brand names for ESC, such as Volvo call it DSTC (Dynamic Stability and Traction Control); Mercedes and Holden call it ESP (Electronic

Stability Program); DSC (Dynamic Stability Control) is the term used by BMW and Jaguar but whatever the term used the processes are almost same. To avoid over steering and under steering during cornering, ESC extends the brake and different torque on each wheel of the vehicle. But ESC reduces the longevity of the tyre because the tyre skids during random braking. To overcome this problem a vehicle can be tilted inwards via an active or semi-active suspension system.

Car giant Nissan has developed a four wheeled ground vehicle for the future which is half-scooter and half-car. The electric-powered Land Glider shown at Figure 7 is approximately half the width of a family car and is designed for busy city streets.

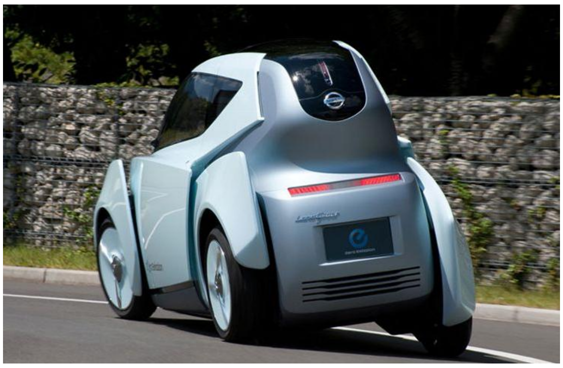

Fig. 7: Nissan Land Glider.

It uses a steer-by-wire system to control the vehicle manoeuvrer and has small motors mounted at each wheel. A computer in the Land Glider automatically calculates the amount of lean required to corner considering the speed, steering angle and yaw rate of the vehicle. The vehicle body can lean into a corner up to 17 degrees for sharper handling. In addition, in the works stated above and other authors' researches, the effect of road bank angle is considered neither in the control system design nor in the modelling of the dynamic model of the tilting vehicles.

Conclusion:

For a long time, active and semi-active suspension systems have been employed as a practical application for modern control theory. In this literature review different suspension systems have been reviewed. It has been explained that the semi-active suspension system is the most suitable for road vehicles. A brief literature review on automotive tilting technology has also been done in this chapter. This highlights that a direct tilting method needs to be developed to tilt the standard passenger vehicle inward during cornering while considering the road bank angle.

REFERENCES

A broadband controller for shunt piezoelectric damping of structural vibration. Smart Mater. Struct., 2003. 12(1): 18.

Active LQR and H 2 shunt control of electromagnetic transducers. Proc. 42nd IEEE Conf. on Decision and Control, 2003: p. 2294.

Active vibration control of a suspension system using an electromagnetic damper. Proc. Inst. Mech. Eng., 2001. 215(8): 865.

Amati, N., *et al*., 2012. Dynamic modelling and experimental validation of three wheeled tilting vehicles. Vehicle system dynamics, 49(6): 889-914.

Bin Abul Kashem, S., S. Roy and R. Mukharjee, 2014. A modified skyhook control system (SKDT) to improve suspension control strategy of vehicles. in Informatics, Electronics & Vision (ICIEV), 2014 International Conference on. 2014.

Chiou, J., *et al*., 2009. Tilting motion control in narrow tilting vehicle using double-loop PID controller. in Proceedings of the 7th Asian Control Conference, 978-89-956056-1/09. 2009: IEEE.

Damping of structural vibrations with piezoelectric materials and passive electrical networks. J. Sound Vib., 1991. 146(2): 243.

Defoort, M. and T. Murakami, 2009. Sliding-mode control scheme for an intelligent bicycle. Industrial Electronics, IEEE Transactions on, 56(9): 3357-3368.

Du, F., *et al*., 2010. Robust Control Study for Four-Wheel Active Steering Vehicle. in International Conference on Electrical and Control Engineering, ICECE,. 2010: IEEE.

Edelmann, J., M. PlÃ¶chl and P. Lugner, 2011. Modelling and analysis of the dynamics of a tilting three-wheeled vehicle. Multibody System Dynamics, pp: 1-19.

Electromagnetic shunt damping. Aim 2003: Proc. 2003 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, 2003: p. 1145.

Frezza, R. and A. Beghi, 2003. Simulating a motorcycle driver. New trends in Nonlinear Dynamics and Control and their Applications, pp: 175-186.

Gillespie, T., 2006. Development of semi-active damper for heavy off-road military vehicles.

Gohl, J.B., 2003. Narrow Tilting Vehicles: Modeling and Steering Based, Tilt Control. University of Minnesota.

Goodall, R., 1999. Tilting trains and beyond. The future for active railway suspensions. 2. Improving stability and guidance. Computing & Control Engineering Journal, 10(5): 221-230.

Goodall, R., 1999. Tilting trains and beyond-the future for active railway suspensions. 1. improving passenger comfort. Computing & Control Engineering Journal, 10(4): 153-160.

Hibbard, R. and D. Karnopp, 1996. Twenty first century transportation system solutions-A new type of small, relatively tall and narrow active tilting commuter vehicle. Vehicle system dynamics, 25(5): 321-347.

Irmscher, S. and E. Hees, 1966. Experience in semi-active damping with state estimators. in proceeding of AVEC.

Jones, W., 2005. Easy ride: Bose Corp. uses speaker technology to give cars adaptive suspension. Spectrum, IEEE. 42(5): 12-14.

Karnopp, D. and R. Hibbard, 1992. Optimum roll angle behavior for tilting ground vehicles. ASME DYN SYST CONTROL DIV PUBL DSC, ASME, NEW YORK, NY(USA), 44: 29-37.

Karnopp, D., M.J. Crosby and R.A. Harwood, 1973. Vibration Control Using Semi-Active Force Generators. ASME Pap, (73 -DET-122).

Kashem, S.B.A., M. Ektesabi and R. Nagarajah, 2012. Comparison between different sets of suspension parameters and introduction of new modified skyhook control strategy incorporating varying road condition. Vehicle system dynamics, 50(7): 1173-1190.

Kashem, S.B.A., S. Raju and I. Raza, 2008. Modified physical configuration to compensate parasitic effects in high speed systems, in Proceedings of ICECE 2008 - 5th International Conference on Electrical and Computer Engineering. Dhaka, Bangladesh, pp: 741-744.

Kidane, S., *et al*., 2006. Road bank angle considerations in modeling and tilt stability controller design for narrow commuter vehicles. in Proceedings of the American Control Conference, Minneapolis, Minnesota, USA: IEEE.

Kidane, S., *et al*., 2008. A fundamental investigation of tilt control systems for narrow commuter vehicles. Vehicle system dynamics, 46(4): 295-322.

Konik, D., *et al*., 1996. Electronic damping control with continuously working damping valves (EDCC)â€”system description and functional requirements. in International Symposium on Advanced Vehicle Control. Aachen, Germany.

Li, B. and F. Yu, 2009. Optimal model following control of four-wheel active steering vehicle. 2009: IEEE.

Li, Y., J. Meiry and W. Roeseler, 1968. An active roll mode suspension system for ground vehicles. Journal of Basic Engineering, 90: 167.

Marino, R., S. Scalzi and F. Cinili, 2007. Nonlinear PI front and rear steering control in four wheel steering vehicles. Vehicle system dynamics, 45(12): 1149-1168.

Mourad, L., F. Claveau and P. Chevrel, 2011. A Lateral Control Strategy for Narrow Tilting Commuter Vehicle Based on the Perceived Lateral Acceleration. in 18th IFAC World Congress Milano (Italy), September.

Multimodal passive vibration suppression with piezoelectric materials and resonant shunts. J. Intell. Mater. Syst. Struct., 1994. 5(1): p. 49.

Nakayama, T., *et al*., 1996. Development of semi-active control system with PUDLIS. in In Proceedings of International Symposium on Advanced Vehicle Control, AVEC'96. Aachen University of Technology.

Nenner, U., R. Linker and P.O. Gutman, 2008. Robust stabilization of an unmanned motorcycle. in Robotics, Automation and Mechatronics, IEEE Conference on, Chengdu, China. 2008: IEEE.

New method for multiple-mode shunt damping of a structural vibration using a single piezoelectric transducer. Proc. SPIE, 2001. 4331: 239.

Passive vibration control via electromagnetic shunt damping. IEEE/ASME Trans. Mechatronics, 2005. 10(1): p. 118.

Piyabongkarn, D., T. Keviczky and R. Rajamani, 2004. Active direct tilt control for stability enhancement of a narrow commuter vehicle. International Journal of Automotive Technology, 5(2): 77-88.

Poelgeest, A., K. Edge and J. Darling, 2007. Development of a Steer Tilt Controller for a Three Wheeled Tilting Vehicle. Proceedings of the ASME International Mechanical Engineering Congress and Exposition, IMECE, Seattle, USA.

Rajamani, R., 2006. Vehicle dynamics and control. Springer Verlag, New York.

Rajamani, R., *et al*., 2003. Dynamics of narrow tilting vehicles. Mathematical and Computer modelling of dynamical systems, 9(2): 209-231.

Roqueiro, N., M.G. de Faria and E.F. Colet, 2011. Sliding Mode Controller and Flatness Based Set-Point Generator for a Three Wheeled Narrow Vehicle. in 18th IFAC World Congress Milano (Italy), September.

Saccon, A., J. Hauser and A. Beghi, 2008. A virtual rider for motorcycles: An approach based on optimal control and maneuver regulation. IEEE.

Sang-Gyun, S. and D. Karnopp, 1997. Switching strategies for narrow ground vehicles with dual mode automatic tilt control. International journal of vehicle design, 18(5): 518-32.

Sankaranarayanan, V., *et al*., 2008. Semiactive suspension control of a light commercial vehicle. Mechatronics, IEEE/ASME Transactions on, 13(5): 598-604.

Snell, A., 1998. An active roll-moment control strategy for narrow tilting commuter vehicles. Vehicle system dynamics, 29(5): 277-307.

So, S.G. and D. Karnopp, 1993. Methods of controlling the lean angle of tilting vehicles. DSC, 52: 311-319.

So, S.G. and D. Karnopp, 1997. Switching strategies for narrow ground vehicles with dual mode automatic tilt control. International journal of vehicle design, 18(5): 518-32.

Suda, Y., *et al*., 2004. Study on electromagnetic damper for automobiles with nonlinear damping force characteristics:(Road test and theoretical analysis). Vehicle System Dynamics, 41: 637-646.

Synthetic impedance for implementation of piezoelectric shunt-damping circuits. Electron. Lett., 2000. 36(18): 1525.

Vibration isolation using a shunted electromagnetic transducer. SPIE: Smart Structures and Materials 2004: Damping and Isolation, 2004: p. 506.

Wang, J. and S. Shen, 2008. Integrated vehicle ride and roll control via active suspensions. Vehicle System Dynamics, 46(S1): 495-508.

web11. http://www.carver-engineering.com/. August, 2012.

web12. http://www.MP3.piaggio.com/. August, 2012; Available from: http://delphi.com/manufacturers/auto/other/ride/magneride.

web13. http://www.dailymail.co.uk/sciencetech/article-1263509/Meet-electric-powered-Land-Glider-half-width-normal-car.html. August, 2012.

web14. http://www.bmwblog.com/2009/10/09/bmw-unveils-clever-concept/. August, 2012.

web16. http://lynk.ly/stories/view/1479328. August, 2012; Availablefrom:http://delphi.com/manufacturers/auto/other/ride/magneride/.

web17. http://www.i4u.com/9754/carver-one-first-tilting-three-wheeler-market. August, 2012; Available from: http://delphi.com/manufacturers/auto/other/ride/magneride.

web28, http://www.motortrend.com/auto_shows/tokyo/2009/. August, 2012.

web7. http://www.conceptcarz.com/vehicle/z11633/Carver-One.aspx. August, 2012.

web8. http://www.maxmatic.com/ttw_moto.htm. August, 2012;Available from:http://delphi.com/manufacturers/auto/other/ride/magneride/.

web8. www.port.ac.uk. August, 2012.

web9.http://www.seriouswheels.com/cars/top-1997-Mercedes-Benz-F-300-Life-Jet-Concept.htm. August, 2012.

Yi, K. and B.S. Song, 1999. A new adaptive sky-hook control of vehicle semi-active suspensions. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 213(3): 293-303.