Journal of King Saud University – Engineering Sciences xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of King Saud University – Engineering Sciences

journal homepage: www.sciencedirect.com

Original article

Active camber and toe control strategy for the double wishbone suspension system

C. Kavitha [a], S. Abinav Shankar [b], K. Karthika [a], B. Ashok [b,*], S. Denis Ashok [b]

[a] Department of Electronics & Communication Engineering, Kumaraguru College of Technology (KCT), Coimbatore 641049, India
[b] School of Mechanical Engineering (SMEC), VIT University, Vellore 632014, India

ARTICLE INFO

Article history:
Received 29 August 2017
Accepted 15 January 2018
Available online xxxx

Keywords:
Active suspension system
Active camber control
Active toe control
Vehicle handling
Double wishbone suspension

ABSTRACT

The present research work proposes a method for improving handling characteristics of the vehicle by controlling camber and toe angle using double wishbone suspension arms in an adaptive manner. This is accomplished by two telescopic arms with actuators which changes camber and toe angle of the wheel dynamically to deliver best possible traction and manoeuvrability. Active suspension controllers are employed to trigger the actuators based on the camber and toe angle from sensors for reducing the existing error. Hence the arms are driven by the actuators in a closed loop feedback manner with help of a separate PID controller. A quarter car physical models with double wishbone suspension is modelled in SolidWorks and simulated using MATLAB for analysis. The simulation result shows an improvement of 58% in camber and 96% improvement of toe characteristics. A prototype of the proposed system is developed and subjected to the same test as the simulation system. The prototype achieved an improvement of 46.34% in camber and a 93.35% in the toe variation of the active system over the passive system. Further, the prototype was able to achieve 89% of camber reduction and 45% of toe reduction with respect to the simulation.

1. Introduction

The suspension system in a vehicle provides the passenger comfort and reduced vibrations to chassis components with the help of springs and shock absorbers along with the movable links connecting the chassis of a vehicle with the wheels and axles (Németh and Gáspár, 2012a, 2012b). The suspension system has three primary functions: isolating passengers and cargo from vibration and shocks caused by irregularities in the road for a comfortable ride, improving the mobility by providing lateral and longitudinal stability while resisting chassis roll and finally to improve the vehicle control by maintaining the proper steer and camber angles relative to the road surface, as well as to keep all the tires in contact with the road while manoeuvring (Tu et al., 2012). However, in the past few years, the suspension system has undergone various changes and developments due to advancements in technology, comfort and customer demand.

To meet the performance requirements there is always a compromise between comfort and dynamic properties of the suspension system. Hence the packaging parameters of the suspension system such as camber, caster, toe etc. are required to be set-up accordingly and these parameters are responsible for the way the system reacts (Hurel et al., 2013). By varying these parameters in an adaptive manner, the dynamic characteristics of the vehicle can be varied on a real-time basis. Among all these parameters, camber angle is one of the several attributes for a suspended wheel which maximizes lateral grip (Lu et al., 2006). Camber is the angle between the top and bottom of the tire and true vertical as viewed from the front side. The tire leaning in, toward the centre of the car, is a negative camber and the tire leaning out is called as positive camber. Another parameter that has a large effect on car's stability is toe angle (Shim and Velusamy, 2006). Toe is the measure of how far inward or outward the leading edge of the tire is facing, when viewed from the top and determines how the car reacts to steering inputs as well as the tire wear. When the car has a toe-in during acceleration the thrust force will tend to bring the wheels back into straight line but it will have drastic effects during turns and braking. When toe-out is present, during acceleration the thrust force

---

* Corresponding author.
E-mail address: ashok.b@vit.ac.in (B. Ashok).

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.jksues.2018.01.003
1018-3639/

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

will try to increase the toe-out which has a greater influence on the vehicles' stability.

In the quest to improve suspension performance, much work has been done recently in designing and analysing suspension systems that contain active components ranging from simple self-levelling suspensions to fully active systems. Addition of electronic controls to the suspension system gives engineers an opportunity to improve the vehicle dynamics characteristics even further (Kawamoto et al., 2008). The importance of this kind of suspension system is that it can perform according to the dynamic road conditions and give better handling on a real-time basis. Hence, the main idea of such active suspension system is to use the disturbances from the road condition/terrain as input to the electronic control unit (ECU) to make sure that the suspension system responds to achieve optimal handling (Tseng and Hrovat, 2015). There are various types of active suspensions employed in today's higher-end category vehicles. However, they include high cost, complexities due to added mass and advanced technologies besides requiring very frequent maintenance. Hence, the research on optimising suspension system under dynamic conditions came into the spotlight.

Balazs and Peter presented the advantages of variable geometry suspension system implemented in a nonlinear polynomial SOS (Sum of Squares) to analyse the coordination of steering and wheel tilting. Groenendijk (2009) proposed an idea of active toe control based on signals from longitudinal and lateral acceleration, steering angle and yaw rate sensors in a 4-wheel individual steering control system to achieve better dynamic behaviour of the vehicle. Tandel et al., (2014) have studied the implementation of a Proportional Integral Derivative (PID) controller on a suspension system with various combinations of spring parameters and damping constants to reduce the vertical body acceleration by minimizing the vehicle lift and road shocks. Arana et al., (2015) proposed a variable geometry suspension with an electro-mechanic actuator which controls the pitching of the chassis and the position of the upper-end eye of the strut system to improve suspension behaviour. Thacker and Bhatt (2015) have focused their research on suspension arm designs and proposed a design based on topology with material optimization for controlling the arms in finite element analysis to improve the performance of the system. Laws (2010) came up with the idea of the mechatronic suspension system with multiple active degrees of freedom to actively change the camber, along with active steer and suspension system to increase the vehicle's lateral forces leading to increased turning capabilities. Nguyen et al., (2015) presented the application of linear parameter varying (LPV) based control system to differential brake moment and the auxiliary front wheel steering angle to change the camber angles of the wheels with 4 semi-active dampers in order to improve the tracking of the road trajectory. Choudhery (2005) proposed the idea of variable camber suspension system using electro-mechanical devices to sense the lateral forces acting on the vehicle and employs the camber adjusters to provide necessary response to improve vehicle stability during turns and cornering. Pourshams et al., (2011) came up with the idea of using a pneumatic system for providing the variations in camber angle of a double wishbone suspension system to improve traction and vehicle safety. Esfahani et al., (2010) proposed the idea of varying the camber angle using hydraulic actuators to vary the geometry of suspension system components for better traction and stability. Németh and Gáspár (2015) have proposed an LPV based control design for a variable geometry suspension system to reduce the lateral force during wheel tilting and the strategy incorporates the non-linear tire characteristics to achieve better performance in vehicle dynamics.

From various past researches, it can be inferred that the active suspension control is accomplished by varying the camber, toe and damping coefficient of the suspension system on a real-time basis. By means of employing the electromechanical system, an active camber control is achieved to improve the vehicle's stability and traction (Evers et al., 2008). Although there are several works in the field of active suspension system, very few work has been attempted to control the suspension system through a mechatronic system involving a PID controller and linear mechanical actuators. There have been several attempts to control toe and camber angles separately in an active manner using several mechanisms with the objective of improving the vehicle dynamic characteristics. Past researches have proven the significance of an independent adaptive control system. However, the active control of camber and toe angles in a simultaneous manner has not been reported in any research work. Vehicles with double-wishbone systems have many benefits because the wheel parameters can be adjusted as per the requirements enabling a complete control of the suspension dynamics (Németh and Gáspár, 2012a, 2012b).

Within this context, this work aims to develop an active suspension system for the optimizing camber and toe angles under dynamic conditions to provide the maximum wheel contact and traction. This is accomplished by two telescopic arms with actuators which optimizes the camber and toe angle of the wheel dynamically to deliver the best possible traction and manoeuvrability. The incorporation of the mechatronic system to actuate the arms in a closed loop feedback manner is accomplished by incorporating a Proportional Integral Derivative (PID) controller. Thus, the proposed active suspension system tries to rectify the limitations of the passive suspension system keeping in mind the space constraints and also ensuring it at a very low cost.

2. Proposed active suspension control system

Proposed active suspension control (ASC) system consists of double wishbone suspension, electronic control unit, accelerometer sensors and servo actuators. The real-time change in camber and toe angles are interpreted by accelerometer sensors placed on the steering knuckle and the data is fed real-time to the ASC ECU (active suspension control electronic control unit) as shown in Fig. 1.

The suspension system setup is placed on a test rig providing the up and down road profile conditions similar to the bumps and potholes. When the wheel travels upward due to a bump, a negative camber is induced on the wheel and similarly, a downward movement creates the positive camber. Also, the toe angle is varied due to the movement of wheel assembly which affects the vehicle handling characteristics. The variation in the camber and toe angle is measured with help of two accelerometers and the corresponding signals are fed into the ASC ECU. According to the desired angle, the ECU actuates the two servo motors which drive two telescopic arms, one to balance camber angle and the other to adjust toe angle to the desired values. In order to reduce the position error between the desired and actual angle in the system a closed feedback is employed with help of PID controller. Also, the wheel travel is measured by a separate accelerometer and the corresponding values are stored.

3. Design parameters of the suspension system

For a suspension system design, various parameters in the suspension geometry have to be considered. A quarter-car model is employed in the present work for the suspension design and it includes the components of double wishbone suspension such as upper A-arm, lower A-arm, tie rod, steering knuckle and wheel is considered in present work. The suspension parameters such as instantaneous centre, upper arm length, lower arm length are

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

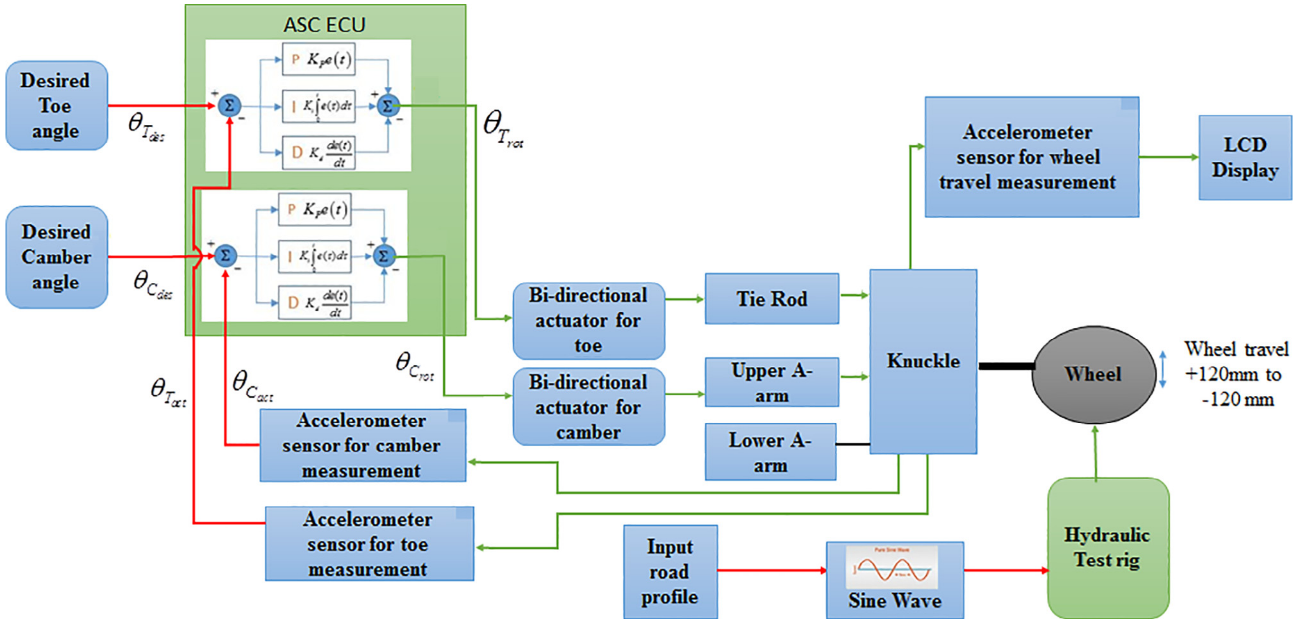

Fig. 1. Schematic representation of the proposed active suspension system.

determined from the mathematical model. For the parameter determination purpose, the specification for ride height, tire, camber angle, rim size, etc is considered as listed in Table 1. Although these parameters are fixed, they can be customized and varied according to the system requirements. The front view swing arm instantaneous centre (IC) is determined by the desired roll centre height and roll camber. Then lines are projected from the outer ball joints to IC to determine control arm lengths. The inner pivot point locations are obtained depending on the chassis and camber is adjusted to zero. Then the tie rod length is established based on the rack position and length. This is arranged in such a way that the initial toe is zero.

4. Active suspension system design

The proposed active suspension system design includes the development of 3D suspension model and the necessary control system to vary the real-time control applications. The following section discusses the design of the above-mentioned model design and control system development process.

4.1. Design of suspension model

A 3D model of suspension system is accomplished in SolidWorks which includes a quarter car physical model with double wishbone suspension by considering the estimated parameters shown in Table 1. The passive suspension system model includes a standard upper A-arm, lower A-arm, tie rod, steering knuckle, wheel hub and tyre. A hydraulic test rig is also designed to provide the wheel dynamic motion which replicates the bumps and potholes in the road under driving conditions.

Table 1
Design parameters of the suspension system.

Parameter	Value
Ride Height	205 mm
Toe Angle	0 degree
Camber Angle	0 degree
Caster Angle	4 degree
King Pin Angle	4 degree
Wheel	255/40R18

The designed active suspension system includes, modified upper A-arm and tie rod as compared with the existing passive system. The design of Upper A-arm is modified to control the camber angle by retraction and extension as shown in Figs. 3a and 3b respectively. Similarly, for controlling the toe angle, the tie rod is modified for retraction and extension operation as shown in Figs. 4a and 4b respectively. The variation in upper A-arm and tie rod length is accomplished through individual servo motors attached to them. However, the actuation of servo motors is controlled by a separate control system based on the real-time inputs from various sensors.

In order to compare the designed active suspension with the existing passive systems, a quarter car model is developed for both the passive and active systems as shown in Fig. 2. This allows the evaluation of the active model's performance against passive model. This allows the evaluation of the active model's performance against passive model.

4.2. Control system development for active suspension system

The proposed active suspension system is controlled by an electronic control unit which includes three multi-axis accelerometer sensors and servo actuators. The first accelerometer sensor is located on the knuckle for measuring the camber angle and the second sensor is located on upper arm fulcrum axis for obtaining

Fig. 2. Passive and Active Suspension system.

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

Fig. 3a. Upper A-arm (retracted).

Fig. 3b. Upper A-arm (extended).

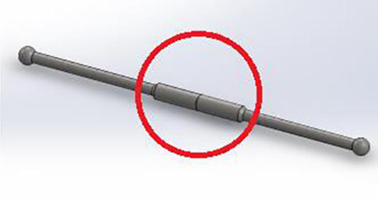

Fig. 4a. Tie rod (retracted).

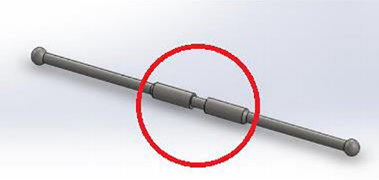

Fig. 4b. Tie rod (extended).

the toe angle. While wheel travel is measured by the third sensor located in the frame of the suspension system. Based on these real-time sensor values to the control unit, a control algorithm varies the output of the servo actuators. The control algorithm of the ASC ECU includes two PID controllers to vary the system output based on the real-time data from the sensors. Hence, the camber and toe angle is varied in an active manner by two individual PID controllers based on the real-time sensor values. The sensors located in suspension system provide the wheel parameters such as camber and toe angle to the PID controllers for comparison with the desired value. For the variation of camber and toe angles the corresponding length of the upper A-arm and tie rod is calculated. To accomplish the required length, the servo actuators vary the position of upper A-arm and tie rod dynamically based on the control signal provided by the PID controller as mentioned below in Eqs. (1) and (2) (Ashok et al., 2016).

$$(\mathrm{U_{PID}})_C = \mathrm{K_P}\,(\theta \mathrm{c_{req}} - \theta \mathrm{c_{actual}}) + \mathrm{K_I}\int_0^t (\theta_{\mathrm{Creq}} - \theta_{\mathrm{Cactual}})\mathrm{dt} + \mathrm{K_D}\frac{d}{dt}(\theta_{\mathrm{Creq}} - \theta_{\mathrm{Cactual}}) \tag{1}$$

$$(\mathrm{U_{PID}})_T = \mathrm{K_P}(\theta_{\mathrm{Treq}} - \theta_{\mathrm{Tactual}}) + \mathrm{K_I}\int_0^t (\theta_{\mathrm{Treq}} - \theta_{\mathrm{Tactual}})\mathrm{dt} + \mathrm{K_D}\frac{d}{dt}(\theta_{\mathrm{Treq}} - \theta_{\mathrm{Tactual}}) \tag{2}$$

The final control system output voltage $(\mathrm{U_{PID}})_C$ for camber given by Eq. (1) and $(\mathrm{U_{PID}})_T$ for toe given by Eq. (2) are provided to the respective servo actuators for varying the length of upper A-arm and tie rod. In the equations, $\theta \mathrm{c_{req}}$ denotes the desired camber value while $\theta \mathrm{c_{actual}}$ denotes the actual camber value and is the same for toe angles. The gain values in PID controller such as $\mathrm{K_P}$, $\mathrm{K_I}$ and $\mathrm{K_D}$ are tuned through the Ziegler- Nichols method, in order to give the better stability in the control system.

5. Simulation of the proposed active suspension system

The performance of the proposed active suspension system is simulated in SimMechanics. For the simulation of the proposed system, the designed active suspension model is imported into SimMechanics. The imported CAD model consists of mass, inertia, joint, constraints and 3D geometry of the active suspension system. SimMechanics formulates and solves the equations of motion for the complete mechanical system. For controlling the suspension system the designed control system which consists of sensors and servo actuators along with two PID controllers are included using Simulink library toolbox and mathematical functions. The imported model and the developed control system are simulated for the wheel travel input signal. The input signal is provided to the hydraulic cylinder jack for providing the road profile which causes wheel travel in the suspension system. The road profile input signal shown in Fig. 5 is provided in the form of a sine wave having the amplitude of 150 mm, identical to a road profile having bumps and potholes. For the road profile conditions, the wheel travel input is provided to the suspension system which leads to varying the camber and toe angle. Performance parameter such as camber and toe angle of the proposed suspension system is compared with the passive suspension for the sinusoidal input and the results are discussed in the following section.

5.1. Response of the suspension system to camber characteristics

Conventional passive suspension system and the proposed active suspension system were subjected to wheel travel in both positive and negative directions and the corresponding changes in camber characteristics were recorded. The camber angle response during the simulation process is plotted in Figs. 6a and 6b for passive and active suspension system respectively.

The camber characteristic varies in a sinusoidal fashion in response to the sinusoidal input at the wheel through the hydraulic lift. The maximum camber angle $(\theta_{C_{pas}})$ obtained from passive suspension system is 2.8 degrees and the maximum camber angle from active suspension system $(\theta_{C_{act}})$ is about 1.151 degrees. As the variation of camber angle is less for the proposed system, it ensures better handling and manoeuvrability of the vehicle. This provides better dynamic characteristics of the vehicle during real-time operations.

The camber angle characteristics with respect to the corresponding wheel travel of both passive and active system are shown in Figs. 7a and 7b. From the figure, it reveals that there is a significant reduction in the camber angle variation of the active suspension system over the whole span of wheel travel. However, in some regions of wheel travel, the camber angle for active suspension system is oscillating due to the vibrations encountered in the system. The vibrations are caused by the combined effect of inertial imbalance on the wheel centre plane and the counter forces produced by the wheel when it is travelling in different directions.

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

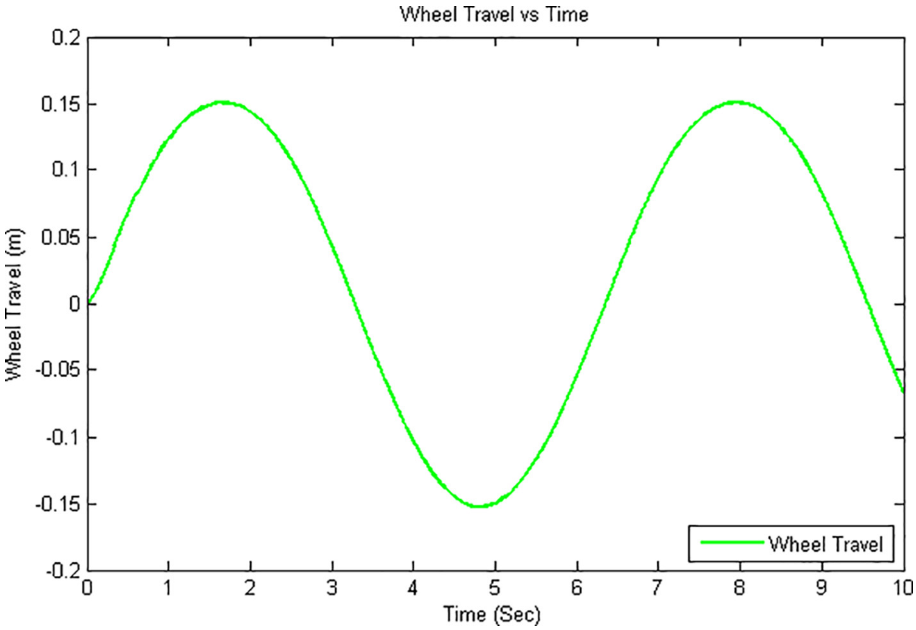

Fig. 5. Input wheel travel signal provided for the simulation.

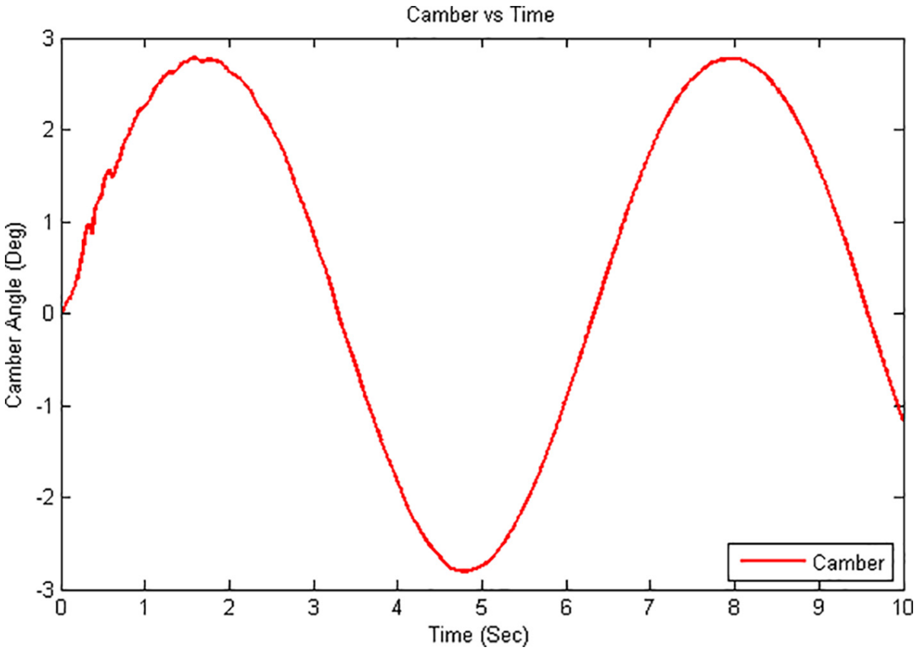

Fig. 6a. Camber vs Time (Passive system).

5.2. Response of the suspension system to toe characteristics

Similar to the camber analysis, both the systems were subjected to undergo wheel travel and the corresponding changes in toe characteristics are presented in the following section. The toe angle response of both the systems during simulation process is shown in Figs. 8a and 8b. The maximum toe angle $(\theta_{T_{pas}})$ obtained from the passive suspension system is -0.6 degrees while the active suspension system reduced the maximum toe angle change $(\theta_{T_{act}})$ to about -0.023 degrees. This ensures a larger area of wheel contact patch, which results in better wheel traction.

Toe characteristics of both the passive and active system with respect to the wheel travel are shown in Figs. 9a and 9b. The plots show a significant reduction in the toe angle variation of the active suspension system due to active control of the tie rod by the servo actuator. The maximum toe angle $(\theta_{T_{pas}})$ obtained from passive suspension system is about 0.6 degrees while the maximum toe angle from active suspension system $(\theta_{T_{act}})$ is about 0.023 degrees. Also, the confounding variations in the toe angle as seen in Fig. 9b is due to the same inertial effects and imbalance which affected the camber characteristics.

Comparing the response of the active system with the passive system from Figs. 6–9 under same testing conditions in a simulation setup, the capability of the proposed idea and its real-time performance is realized. The active system has an improvement of 58% in camber characteristics and 96% in toe

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

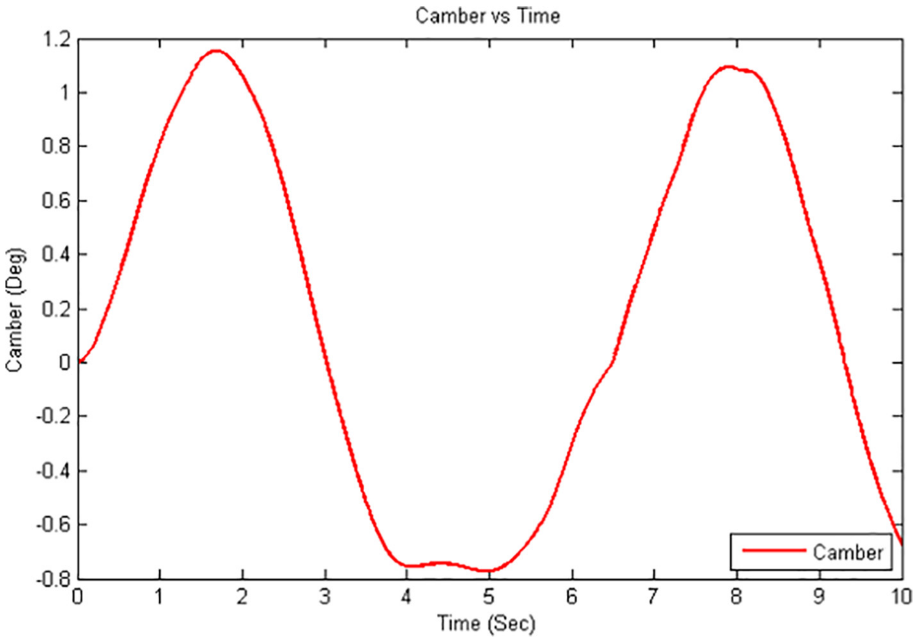

Fig. 6b. Camber vs Time (Active system).

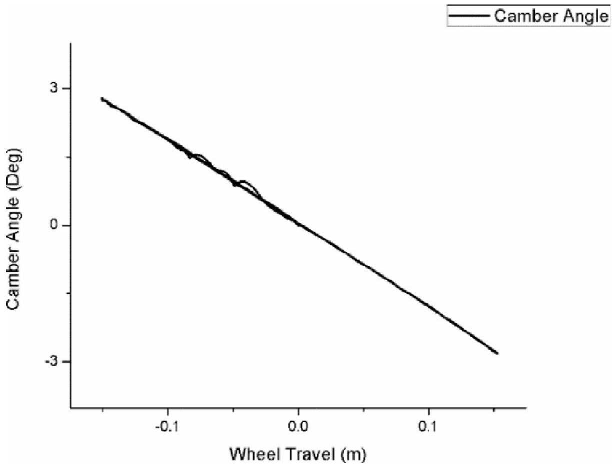

Fig. 7a. Camber response of passive system.

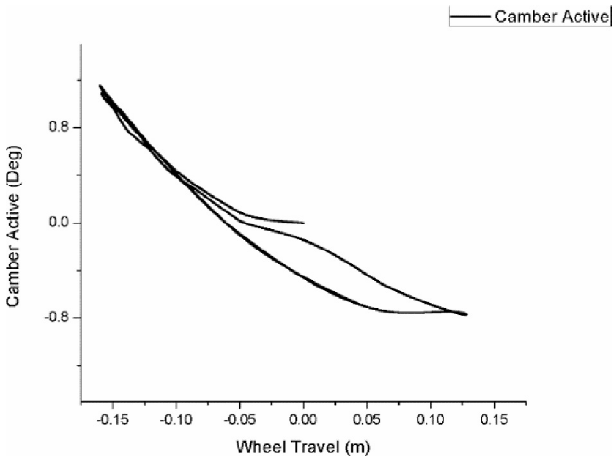

Fig. 7b. Camber response of active system.

characteristics over the passive suspension system which is evident from Table 2.

6. Prototype development of active suspension system

The simulation test showed that both the camber and toe angle can be controlled actively in real time conditions with the help of servo actuators. The active suspension system prototype as shown in Figs. 10a and 10b is developed for the real-time physical analysis with the help of quarter car suspension system along with accelerometers, control unit and servo actuators. The wheel was placed on a hydraulic jack along with a quarter car double wishbone suspension system. Quarter car suspension consisting of an upper arm, lower arm, tie rod, knuckle and the wheel assembly were mounted on a frame. The upper arm was sectioned into two parts and was connected back with a help of a power screw mounted longitudinally and was reinforced by cross members and the construction was such that the rotational motion of the power screw led to the change in the overall length of the arm. Similarly, the tie rod is also modified by attaching the servo actuators for active control.

The developed prototype includes four multi-axis accelerometer sensors, two mounted on the knuckle and one on upper arm fulcrum axis and one on reference body. These sensors give the wheel inclination (camber), toe and wheel travel data to the active suspension system electronic control unit (ASC ECU). The sensor values are compared with the desired value of camber and toe angle in the control system. For the variation in the camber and toe angle the corresponding arm length is computed. Hence, the length of the telescopic counterparts is changed with the help of two servo actuators for maintaining the camber and toe angle on a real-time basis.

7. Experimental analysis of developed active suspension system

The developed active suspension system is operated by varying the wheel travel with help of hydraulic jack. The wheel travel position is varied with respect to the desired position (0mm in this case) to120 mm in steps of 30 mm and reversed till -120 mm.

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

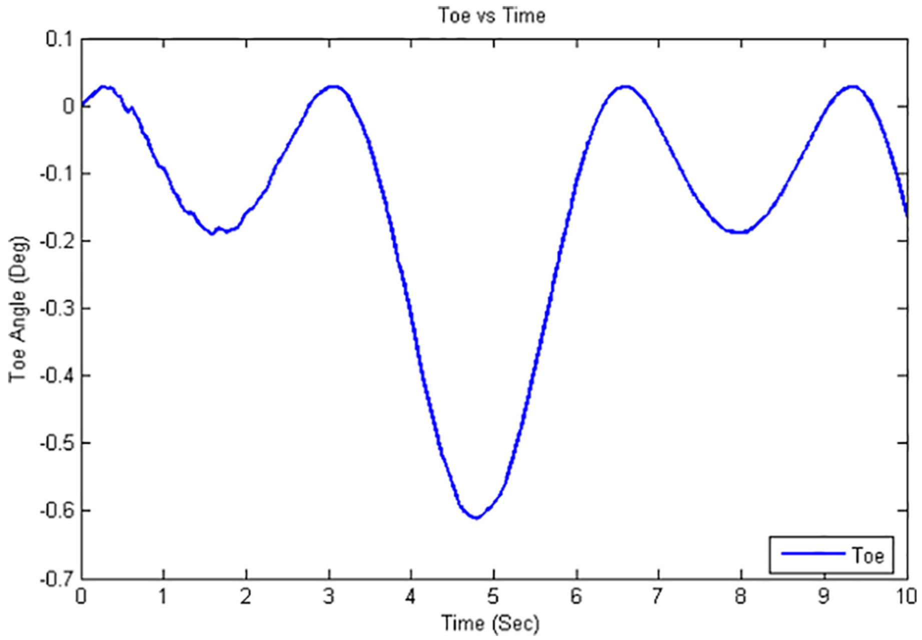

Fig. 8a. Toe angle vs Time (Passive system).

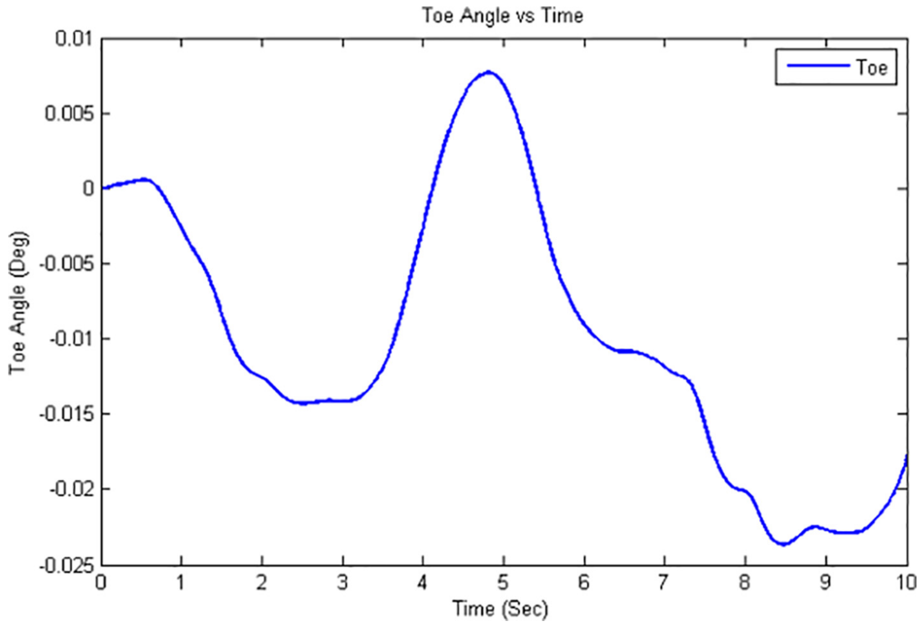

Fig. 8b. Toe angle vs. time (Active system).

The camber and toe angle readings were recorded for each position of the wheel travel with the help of corresponding sensors and the data is fed into the ASC ECU. The ASC ECU processes the data and decides the correct length of the upper A-arm and tie rod, to bring back the camber and toe angles to desired values at any point of operation dynamically. For comparing the active system results with a passive system, the setup is operated without the ASC ECU and the servo actuators similar to a passive suspension system.

7.1. Camber angle response of the active suspension system prototype

The proposed active suspension system is subjected to wheel travel by the hydraulic jack which induces changes in the wheel parameters. The camber angle response during the experimental process is interpreted by the accelerometer sensors and passed on to ASC ECU. The ASC ECU computes the data and actuates the arms, which results in a lesser deviation of the camber angle from the desired value. This helps the vehicle to maintain its manoeuvrability and stability in dynamic conditions. In order to benchmark the prototype, the suspension system is operated in passive mode and the corresponding camber characteristics are also recorded. The data collected from both the test is shown in Table 3 and the corresponding plot is shown in Fig. 11

Comparing the camber values of the systems, a significant decrease in the deviation of camber angle from 2.5 degrees in the passive system to 1.7 degrees in the active system is evident from the Fig. 11. Thus, the system successfully reduces the variation in

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

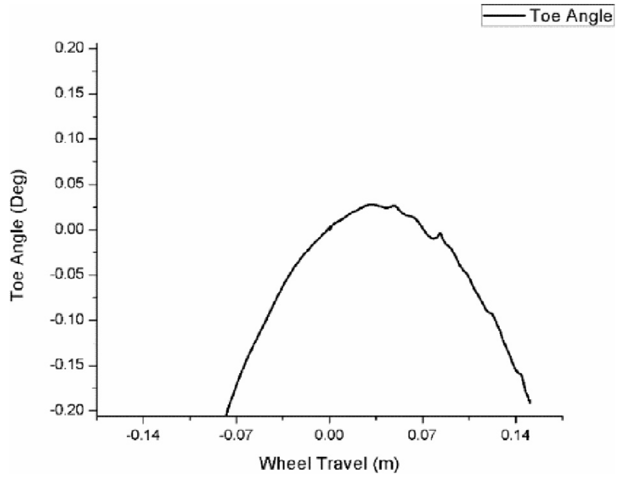

Fig. 9a. Toe response of Passive System.

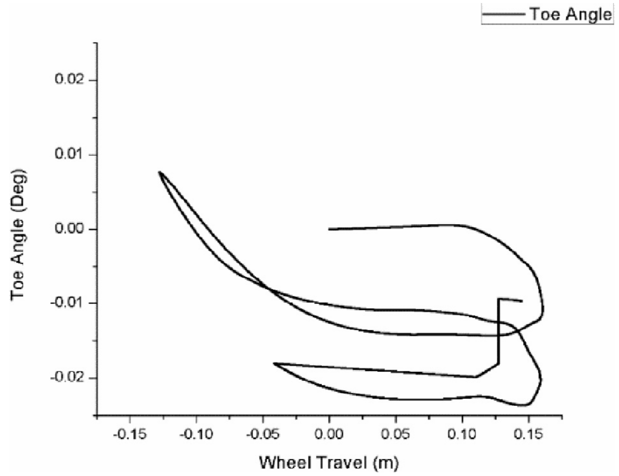

Fig. 9b. Toe response of Active System.

Table 2
Result of simulation test.

Wheel parameter	Passive System	Active System	% reduction
Camber Minimum	0	0	0
Camber Maximum	2.806	1.153	58.91
Toe Minimum	0	0	0
Toe Maximum	0.61	0.023	96.23

camber angle from the desired set point during wheel travel. Hence, there is a reduction in variation of camber angle of the active system is contrary to the passive suspension system. However, the variation of camber angle is higher in the passive system which leads to affects the vehicle stability. The positive outcome from the active suspension system prototype is an indication of the success of the proposed system to maintain the vehicle stability during operating conditions.

7.2. Toe angle response of the active suspension system prototype

During the experimental analysis of the prototype, the toe angle is interpreted from the sensors and the corresponding values are sent to the ASC ECU. The ASC ECU makes the computations and performs the actuation through servo actuators to maintain the desired arm length. This helps to achieve a lesser deviation in the

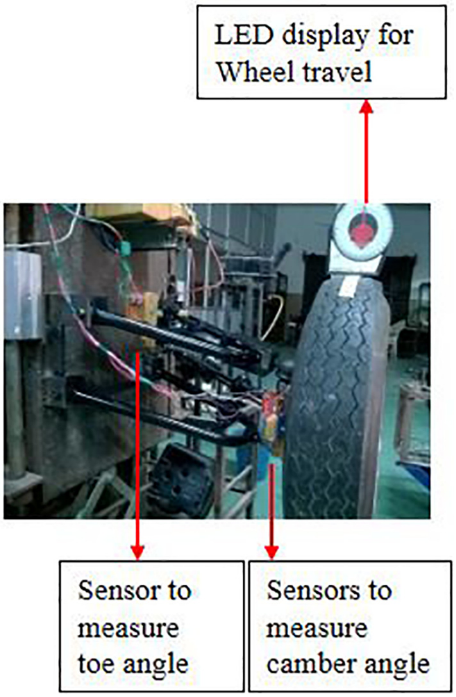

Fig. 10a. Front view of the prototype.

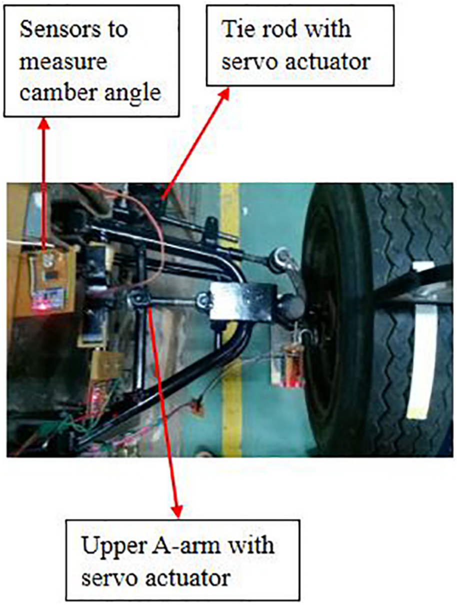

Fig. 10b. Top view of the prototype.

Table 3
Camber characteristics with respect to the wheel travel data points.

Position	Wheel Travel (mm)	Camber angle of Passive system	Camber angle of Active system
A	120	−2.3	−1.5
B	90	−1.9	−1.2
C	60	−1.1	−0.7
D	30	−0.5	−0.2
E	0	0.2	0.2
F	−30	0.4	0.1
G	−60	1.1	0.5
H	−90	1.7	1
I	−120	2.5	1.7

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

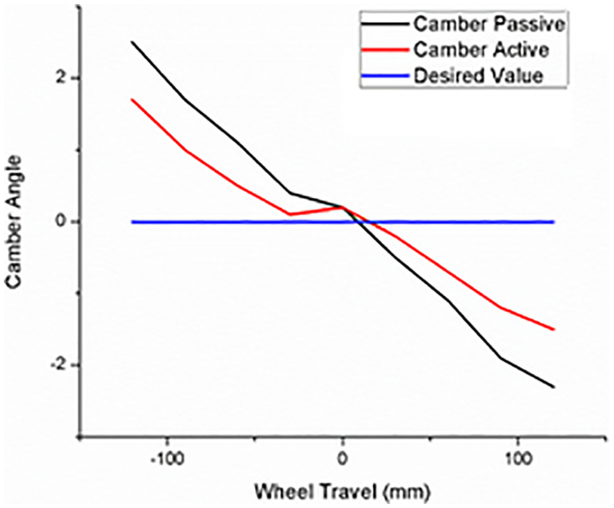

Fig. 11. Camber angle response of prototype.

toe angle from the desired value as shown in Table 4. Corresponding passive system values are also recorded by operating the system without the control unit and actuators for comparison.

From the experimentation, we can conclude that the active system significantly decreases the deviation of toe angle to just 0.04 degrees from a comparatively higher value of -0.6 in the passive system. The significant advantage of the active system over the passive system in reducing the variation of toe angle from the desired setpoint is shown in Fig. 12.

Table 4
Toe characteristics with respect to the wheel travel data points.

Position	Wheel Travel (mm)	Toe angle of Passive system	Toe angle of Active system
A	120	−0.2	−0.018
B	90	−0.15	0.01
C	60	−0.1	0.04
D	30	0.03	0.02
E	0	0	0
F	−30	0.03	−0.006
G	−60	−0.25	−0.003
H	−90	−0.367	−0.0010
I	−120	−0.6	0.0035

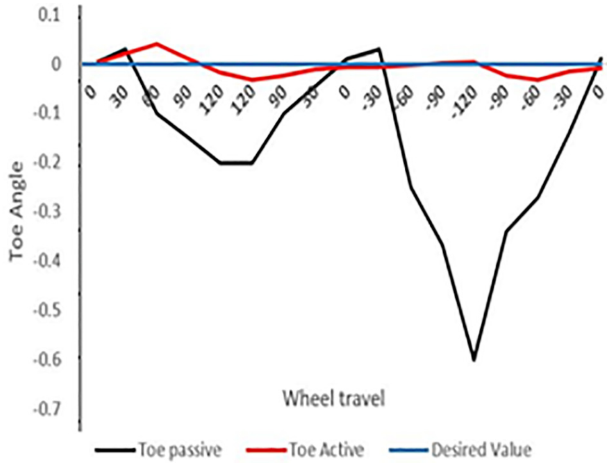

Fig. 12. Toe angle response of prototype.

8. Results of the suspension system

The results of comparison between the passive system and the developed active suspension system portrays the efficiency of the proposed system in improving maneuverability. The simulation results showed an improvement of **58%** in camber angle and **96%** improvement of toe angle characteristics while the prototype achieved an improvement of **46.34%** in camber angle and **93.35%** in the toe angle variation of the active system over the passive system. Further, the prototype was able to achieve **89%** of camber angle reduction and **45%** of toe angle reduction with respect to the simulation model.

This difference in output performance is due to external factors, sensor noise and the response time of the microcontroller. As the simulation model was able to perform without these interferences, it was able to produce better performance report than the prototype. With better sensors, noise reduction and a high-performance microcontroller, this issue can be sorted out and the prototype can be made to function as effective as the simulated model.

9. Conclusion

An active suspension system for a double wishbone type is proposed to minimize the variation in camber and toe angle dynamically during vehicle operation. The proposed system consists of servo actuators to vary the arm length for maintaining the camber and toe angle based on the accelerometer sensor input to the ASC ECU. Also, the signals are processed and actuation is executed only when there are changes in the system which makes it much less complex and energy efficient. This makes the system simple and robust while providing a quicker response as compared to the other mechanical type suspension systems. With the help of developed active suspension system stability, wheel traction, manoeuvrability and dynamic characteristics of the vehicle can be improved.

The idea of using PID controller and servo actuator to vary the length of arms to control the wheel parameter stands to be novel in its field and shows signs of benefitting the industry. The advantage of the proposed system over other systems is that it involves less complexity and is very economic. This makes this system suitable for adoption in passenger vehicles to improve maneuverability and comfort without any significant increase in cost. In the future research will be focused mostly on refining the method with non-linearity and also complex control mechanisms in order to improve the smoothness in the response of the particular system. The focus will also be put on improving and optimizing the frequency response of the system and in optimizing the prototype to perform equally with the simulated model.

References

Arana, C., Evangelou, S.A., Dini, D., 2015. Series active variable geometry suspension for road vehicles. IEEE/ASME Trans. Mechatron. 20 (1), 361–372.

Ashok, B., Ashok, S.D., Kumar, C.R., 2016. A review on control system architecture of an SI engine management system. Ann. Rev. Control 41, 94–118.

Choudhery, K., Variable camber suspension system, U.S. Patent 6874793, April 5, 2005.

Esfahani, M.I.M., Mosayebi, M., Pourshams, M., Keshavarzi, A., 2010. Optimization of double wishbone suspension system with variable camber angle by a hydraulic mechanism. World Acad. Sci. Eng. Technol. 61, 299–306.

Evers, W.J., van der Knaap, A., Besselink, I., Nijmeijer, H., 2008. Analysis of a variable geometry active suspension. In: International Symposium on Advanced Vehicle Control (pp. 350-355).

Hurel, J., Mandow, A., García-Cerezo, A., 2013. Kinematic and dynamic analysis of the McPherson suspension with a planar quarter-car model. Veh. Syst. Dyn. 51 (9), 1422–1437.

Kawamoto, Y., Suda, Y., Inoue, H., Kondo, T., 2008. Electro-mechanical suspension system considering energy consumption and vehicle manoeuvre. Veh. Syst. Dyn. 46 (S1), 1053–1063.

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003

Laws, S.M., 2010. An active camber concept for extreme manoeuvrability: mechatronic suspension design, tire modelling, and prototype development (Doctoral dissertation, Stanford University).

Lu, X.P., Guo, K., Lu, D., Wang, Y.L., 2006. Effect of tire camber on vehicle dynamic simulation for extreme cornering. Veh. Syst. Dyn. 44 (sup1), 39–49.

Groenendijk, M.J.P., 2009. Improving Vehicle Handling Behavior with Active Toe-control Master's thesis. Eindhoven University of Technology Department Mechanical Engineering Dynamics and Control Group Eindhoven.

Németh, B., Gáspár, P., 2012a. Challenges and possibilities in variable geometry suspension systems. Periodica Polytechnica. Trans. Eng. 40 (2), 81.

Németh, B., Gáspár, P., 2012b. Mechanical analysis and control design of a variable-geometry McPherson suspension. Int. J. Veh. Syst. Model. Test. 7 (2), 173–193.

Németh, B., Gáspár, P., 2015. LPV-based variable-geometry suspension control considering nonlinear tyre characteristics. IFAC-PapersOnLine 48 (26), 61–66.

Nguyen, M.Q., da Silva, J.G., Sename, O., Dugard, L., 2015. A state feedback input constrained control design for a 4-semi-active damper suspension system: a quasi-LPV approach. IFAC-PapersOnLine 48 (14), 259–264.

Pourshams, M., Mokhlespour, M.I., Keshavarzi, A., Talab, M.H., 2011, January. Design, Analysis and Manufacturing a Double Wishbone Suspension System with Variable Camber Angle by Pneumatics Mechanism. In: ASME 2011 International Mechanical Engineering Congress and Exposition (pp. 477-483).

Shim, T., Velusamy, P.C., Influence of suspension properties on vehicle roll stability SAE Technical Paper No 2006 2006–01-1950.

Tandel, A., Deshpande, A.R., Deshmukh, S.P., Jagtap, K.R., 2014. Modeling, analysis and PID controller implementation on double wishbone suspension using simmechanics and simulink. Procedia Eng. 97, 1274–1281.

Thacker, S., Bhatt, A. 2015, Research paper on Design and analysis Double Wishbone Suspension system using Finite Element Analysis.

Tseng, H.E., Hrovat, D., 2015. State of the art survey: active and semi-active suspension control. Veh. Syst. Dyn. 53 (7), 1034–1062.

Tu, F., Yang, Q., He, C., Wang, L., 2012. Experimental study and design of automobile suspension made of the magneto-rheological damper. Energy Procedia 16, 417–425.

Please cite this article in press as: Kavitha, C., et al. Active camber and toe control strategy for the double wishbone suspension system. Journal of King Saud University – Engineering Sciences (2018), https://doi.org/10.1016/j.jksues.2018.01.003