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New Suspension Mechanism Using Camber Thrust for a Formula Car

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Abstract**—**The basic ability of a vehicle is to "run", "turn" and "stop". The safeness and comfort during a drive on various road surfaces and speed depends on the performance of these basic abilities of the vehicle. Stability and maneuverability of a vehicle are vital in automotive engineering. The stability of a vehicle is the ability of the vehicle to revert back to a stable state during a drive when faced with crosswinds and irregular road conditions. Maneuverability of a vehicle is the ability of the vehicle to change direction during a drive swiftly based on the steering of the driver. The stability and maneuverability of a vehicle can also be defined as the driving stability of the vehicle. Since the fossil fueled vehicle is the main type of transportation today, the environmental factor in automotive engineering is also vital. By improving the fuel efficiency of the vehicle, the overall carbon emission will be reduced, thus reducing the effect of global warming and greenhouse gas on the Earth. Another main focus of the automotive engineering is the safety performance of the vehicle, especially with the worrying increase of vehicle collision every day. With better safety performance of a vehicle, every driver will be more confident driving every day. Next, let us focus on the "turn" ability of a vehicle. By improving this particular ability of the vehicle, the cornering limit of the vehicle can be improved, thus increasing the stability and maneuverability factor. In order to improve the cornering limit of the vehicle, a study to find the balance between the steering systems, the stability of the vehicle, higher lateral acceleration and the cornering limit detection must be conducted. The aim of this research is to study and develop a new suspension system that will boost the lateral acceleration of the vehicle and ultimately improving the cornering limit of the vehicle. This research will also study environmental factor and the stability factor of the new suspension system. The double wishbone suspension system is widely used in a four-wheel vehicle, especially for high cornering performance sports car and racing car. The double wishbone designs allow the engineer to carefully control the motion of the wheel by controlling such parameters as camber angle, caster angle, toe pattern, roll center height, scrub radius, scuff, and more. The development of the new suspension system will focus on the ability of the new suspension system to optimize the camber control and to improve the camber limit during a cornering motion. The research will be carried out using the CAE analysis tool. Using this analysis tool we will develop a JSAE Formula Machine equipped with the double wishbone system and also the new suspension system and conduct simulation and conduct studies on the performance of both suspension systems.

Keywords**—**Automobile, Camber Thrust, Cornering force, Suspension.

I. Introduction

THE turning ability of the vehicle is vital in improving the overall driving stability of the vehicle. By improving the cornering ability of the vehicle, the overall driving stability will also improve thus giving the driver a safer driving experience and swifter control of the steering. The double wishbone suspension system is a favorite choice by car manufacturers for conventional vehicle due to the characteristic of the double wishbone suspension system that allow the engineer to manipulate various parameters such as the camber angle, caster angle, toe pattern, scrub radius and many more to achieve a higher cornering limit and better cornering performance of the vehicle [1], [2]. However, when a cornering force is applied to the tire during a cornering motion, conventional double wishbone suspension system will tilt the tire to the opposite side of the turning direction, thus increases the cornering resistance that will affect the overall cornering performance [3], [4]. Therefore, it is considered to be a method that can be used to control the camber [5], [6].

In recent years, many advance technologies [7] such as the AYC (Active Yaw Control) [8], [9], ACC (Active Camber Control) [10], SH-AWD [11], [12] system using electronic control technology have been developed to improve the cornering performance and more importantly the overall driving experience of the vehicle. Unfortunately, these technologies can only be found on super car and concept car because these technologies are too costly and high maintenance is needed to be implemented on the everyday conventional vehicle. Other than that, most of the vehicle equipped with such technologies is often a four-wheel drive vehicle in order to have an optimum performance. These technologies are not suitable for two-wheel drive vehicle due to the limitation of the layout of the vehicle. In order to have an affordable suspension system that will optimize and improve the cornering performance of the vehicle that can fit in various types of vehicle, this research is proposed for a safer and better driving experience in the future.

Our aim of this research is to improve the cornering performance and the cornering performance of a vehicle by developing new suspension system. In recent years, many suspension systems are developed to improve cornering performance of a vehicle with the aid of electronic control technology which is very costly. Unfortunately, such systems can only be installed into limited types of vehicle such as four wheel drive and vehicle have a wide layout. The new suspension system is aimed to be developed to be affordable and also versatile enough to be fit into all kinds of vehicle. The new suspension system will not use any electronic control devices and will be compact enough to fit in all kinds of layout. The concept is to build a suspension system with a compliance control mechanism that can generate and effectively control the

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camber thrust and thus improving the cornering limit and the cornering performance during a turning motion. Our design is based on a light weight JSAE formula car design of the Kinki University Formula Project team. We will then recreate the JSAE formula car models equip with double wishbone suspension system and another will the new suspension system using the CAE analysis tool ADAMS/CAR 2012 by MSC Software Cooperation and perform simulations to study and compare the performance of the new suspension system and the double wishbone suspension system. We also aim to develop a simulation system using the ADAMS/CAR 2012 for future model. We will be able to simulate various experiments and tests using this simulation system. We can save up on precious time, budget and also not risking driver's life and also not risking crashing the formula car by avoiding dangerous test and experiments in real life.

II. Negative Camber Control Suspension System Using a Swing Arm Theory Proposal

A. Concept

A basic suspension system consists of shock absorbers and springs that connect a vehicle to its wheels and allows relative motion between the two and at the same time must be able to damp the vibrations must be able to support the overall mass of the vehicle. Usually hydraulic absorber are used in a suspension system, whereas there are various types of spring that are being used for example the leaf spring, the coil spring, torsion bar, rubber spring, air spring and gas spring. Furthermore, there suspension will control the flow of the various types of forces such as the driving force, breaking force and lateral force that are generated during a drive in order to maintain a good dynamic performance of the vehicle. This is also why the suspension system is also made out of various link mechanisms and rigid joints that connect the vehicle to the wheel. Throughout the history of the automobile, many tried and improved many suspension structure forms and ideas in order to achieve a better performance. Out of the many types of suspension system that was developed, we adopted the double wishbone suspension system as the ideal system for our research due to the high degree of design freedom the suspension system holds. Unfortunately, during a cornering motion, the conventional double wishbone has a problem with the tilting position of the tire. The suspension system will tilt the tire to the opposite side of the turning direction, thus increasing the cornering resistance of the vehicle that ultimately reduces the cornering performance of the vehicle.

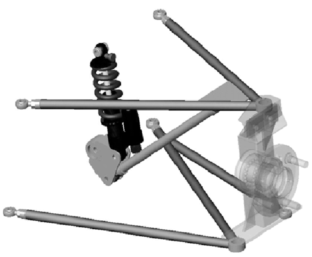
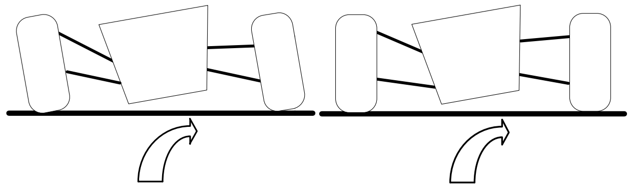


Fig. 1 Basic Built of a Standard Double-wishbone Suspension



(a) Conventional Double Wishbone (b) New Suspension

Fig. 2 Camber Change when making a turn

The double wishbone suspension system will be the base of the new suspension system in this research and the new suspension system is expected to solve this problem and thus improving the overall cornering performance and of the vehicle. The basic built of a double wishbone is shown in Fig. 1. The double-wishbone suspension can also be referred to as "double A-arms", though the arms themselves need not to necessarily be A-shaped but also L-shaped, or even a single bar linkage. The suspension is fixed to the vehicle body at the leg of the "A" with a bearing to enable an up and down movement of the wheel. The tip of the "A" is installed in the axle housing on the wheel with a ball joint. From this structure we can see that both the A-arms and the side rod stroke around the pivot shaft in other words the suspension jounces (rises). The A-arms will only revolve around the pivot shaft, even though force is applied in the other direction. Therefore, by controlling the geometry of both the A-arms, we can adjust the camber angle parameter and the position of the wheel center. Other than the links and arms, the double wishbone suspension system is also built out of springs and shock absorbers. By changing the layout geometry of the links and the mounting position, we can easily manipulate various parameters such as the camber angle, caster angle, toe pattern, scrub radius and many more to achieve a higher cornering limit and better cornering performance of the vehicle. Unfortunately, the conventional double wishbone suspension system has a tilting problem when cornering. The car will roll when making a turn and cause the tire to tilt. In other words, camber change occurred. We can control this by changing the built of the suspension system. The problem of the conventional double wishbone suspension system is that it will tilt in the same direction of the rolling motion of the car as shown in Fig. 2 (a). By manipulating the layout geometry of the links in the system we can change how the suspension system tilts as shown in Fig. 2 (b). Therefore, we can say that the layout geometry of the links and the camber change of the tire are closely related. Unfortunately, depending on the type of road surface, camber change might only occur on one side of the tire. Tilting the tire to the same direction of the cornering direction is the ideal motion because this motion will reduce the cornering resistance thus improving the cornering performance of the vehicle. When a camber change occurs, camber thrust is generated. Camber thrust is the force that is generated perpendicular to the direction of travel of a rolling tire due to its camber angle. If the tire leans and rotates at camber angle ϕ as shown in Fig. 3, the leaned over tire acts as a section of a cone APO with the center O, and tries to describe an arcs BB' with center O and a tight radius of R/sin ϕ . Therefore, camber thrust is the force that is generated when a point (point P) on the outer surface of a leaned and rotating tire, that would normally follow a path that is elliptical when projected onto the ground, is forced to follow a straight path while coming in contact with the ground due to friction. Camber thrust is approximately linearly proportional to camber angle for small angles. Therefore, this research will focus on a new suspension system which is called the Compliance Camber Control System, which will utilize this camber thrust to improve the cornering performance. Fig. 4 shows the mechanism to reduce the cornering resistance using the camber thrust. When a car makes a turn, the tire takes a slip angle as shown in Fig. 4 (a). By producing a camber thrust in the same direct of the cornering motion, it is possible to generate the lateral force that is needed during a turning motion with a small amount of resistance as shown in Fig. 4 (b). With this, the slip angle can be reduced. A smaller slip angle can reduce the cornering resistance and thus improving the cornering performance of the vehicle as shown in Fig 4 (c).

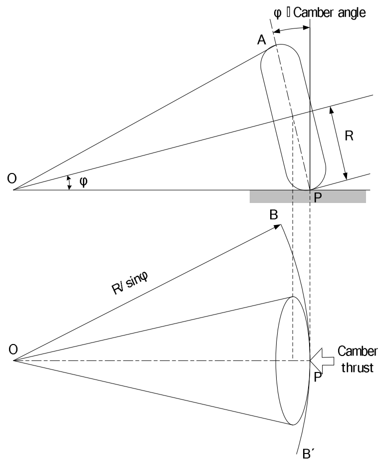
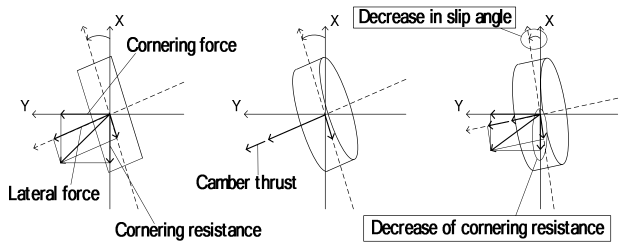


Fig. 3 Relationship of Camber Angle and Camber Thrust



(a) Cornering Resistance (b) Camber thrust (c) Resistance Decrease

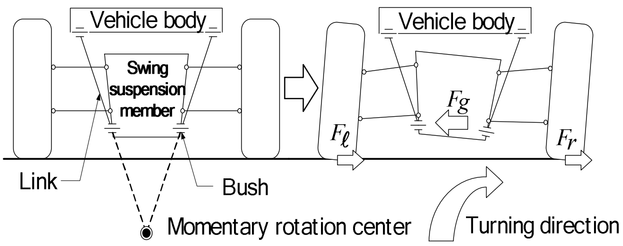
Fig. 4 Mechanism of cornering resistance reduction

B. Compliance Camber Control (CCC) System

The conventional double wishbone is installed with sets of arms to build a swing suspension member as shown in Fig. 5. The swing suspension member is then hanged from the vehicle body by two links on the left and right and two links on the front and back. The links fasten together using rubber bushes to enable the deflection in other words to enable compliance control as shown in Fig. 5 (a). Fig. 5 (b) shows the mechanism of Compliance Camber Control system.When the car makes a turn, cornering force F_l and F_r will act on the tires which is supported by the lower and upper control arm of the suspension system. A lateral force F_g, which is a combination of these cornering forces will eventually act on the swing suspension member. In other word, the lateral force $F_g$is the total cornering force that is acting on the suspension system when a car makes a turn.

When the lateral force acts on the swing suspension member, deflection of the rubber bush will occur and thus compliance will occur. The swing suspension member tilts with the lateral force with respect to the momentary center of rotation and cause the tire to lean and produce a camber angle. Camber thrust will be generated relative to the camber angle on both tires. The camber thrust will increase the cornering limit of the vehicle and thus ultimately increase the cornering performance of the vehicle. Basically, this is how the Compliance Camber Control System works.

We can increase the camber thrust even with the same cornering force by changing the hardness of the rubber bush. However, the geometry of the links must be adjusted so that the momentary center of rotation must always be lower than the ground level in order the Compliance Camber Control System to work effectively because if the momentary center of rotation is located above ground level, the swing suspension member will tilt the tire to the opposite direction and thus increasing the cornering resistance.

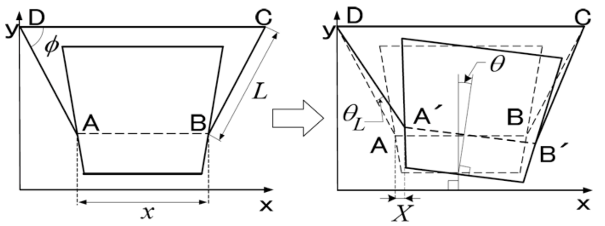


(a) Schematic of Links (b) Mechanism of CCC system

Fig. 5 Compliance Camber Control System

C. Geometry Change of the Swing Suspension Member

The instantaneous center of rotation of the extension of the intersection of the two links is taken as the point of origin. The swing suspension member will rotate about the point of origin. Fig. 6 shows the model of the swing suspension member. Figs. 6 (a) and (b) show the model without and with cornering force respectively. From Fig. 6, the swing suspension member will tilt θ degree with respect to the momentary center of rotation. The momentary center of rotation is the interception point of the extension of the two links. Here the horizontal displacement X of the swing suspension member and the angle displacement θ with respect to the momentary center of rotation will be derived geometrically. Firstly, we will derive the horizontal displacement X of the swing suspension member when the swing suspension member is tilted θ degree with respect to the momentary by the lateral force.



(a) Without Cornering Force (b) With Cornering Force

Fig. 6 Geometry Change of the Swing Suspension Member

Here the horizontal displacement of the swing suspension member X, displacement angle of the moment around the center of rotation θ, are represented by the following formulas that is derived geometrically.

$$X = L\left[\sin\left(\frac{\pi}{2}-\phi+\theta_L\right)-\sin\left(\frac{\pi}{2}-\phi\right)\right] \quad (1)$$

Here, L: length of the link, φ: mounting angle of the link, θ_L: displacement angle of the link, x: distance between the mounting position of the link of the swing suspension member. From (1), the horizontal displacement of the swing suspension member X is better smaller in order to reduce the overall effect of the transverse stiffness and the scuff change in the suspension system. To do so, the length of the link L must be made shorter, whereas the mounting angle of the link must be made bigger.

Y_1 and Y_2 can be derived from the right angle with the acute angle as shown in Fig. 7.

$$Y_1 = L\cdot\cos\left(\frac{\pi}{2}-\phi+\theta_L\right) \quad (2)$$

$$Y_2 = L\cdot\cos\left(\frac{\pi}{2}-\phi-\theta_L\right) \quad (3)$$

Thus,

$$Y = L\left[\cos\left(\frac{\pi}{2}-\phi-\theta_L\right)-\cos\left(\frac{\pi}{2}-\phi+\theta_L\right)\right] \quad (4)$$

$$Y = 2L\sin\left(\frac{\pi}{2}-\phi\right)\sin\theta_L \quad (5)$$

$$\sin\theta = \frac{Y}{x} = \frac{2L}{x}\sin\left(\frac{\pi}{2}-\phi\right)\sin\theta_L \quad (6)$$

$$\theta = \sin^{-1}\left(\frac{2L}{x}\sin\left(\frac{\pi}{2}-\phi\right)\sin\theta_L\right) \quad (7)$$

From (7), the tire camber angle which is affected directly by the displacement angle θ of the swing suspension system will be dependent on the θ_L, L, x, and φ. The length of the link L is better, longer because the Compliance Camber Control System will work more effectively if the momentary center of rotation is located below ground level.

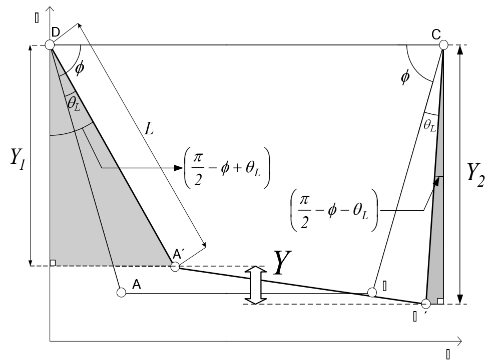
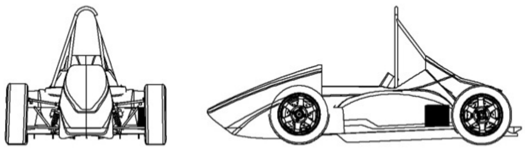


Fig. 7 Vertical Displacement Y of the Swing Suspension Member

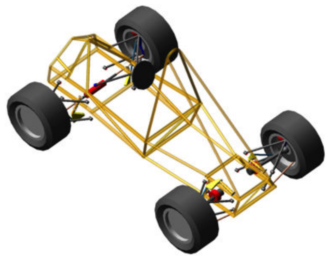
C. Verification of the Accuracy of the CAE Analysis

We have verified the accuracy of the analysis by comparing the actual measurement data of the lateral acceleration and the CAE analysis by the Adams/Car (Vehicle Motion Analysis Tool) of the steering wheel angle of the JSAE vehicle that have adopted the double-wishbone suspension system. The JSAE machine is the racing car built by the Kinki University Formula Project team for the Student Formula Japan 2012 race. Our actual JSAE machine is shown in Fig. 8. The model of JSAE formula car and the test course are shown in Figs. 9 and 10 respectively. Here Figs. 9 (a) and (b) show 3D CAD model and CAE virtual model respectively. Table I shows the dimension of the machine, is weighted at 235kg, has a wheelbase of 1600mm, tread of 1150mm, 1170mm and the weight distribution is 47% front and 53% rear. The tires are slick JSAE tires manufactured by Bridgestone. Measurements are conducted by equipping the machine with a GPS system, acceleration sensor and steering sensor. The measurement device is DL1 MK2 built by Race Technology.The vehicle will maintain a driving speed of 30km/h throughout the course. Using the DL1 the data were collected for the steering angle and the lateral acceleration during this test.The comparison result of the lateral acceleration and steering wheel angle is shown in Figs. 11 (a) and (b) respectively. From Figs. 11 (a) and (b) we can verify that both results are almost identical.

Fig. 8 Actual Model of JSAE Formula Car



(a) 3D CAD Model



(b) Virtual Model

Fig. 9 JSAE formula car

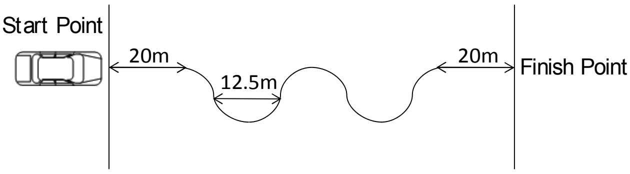
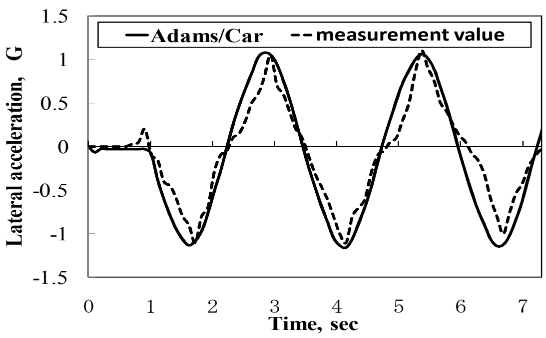


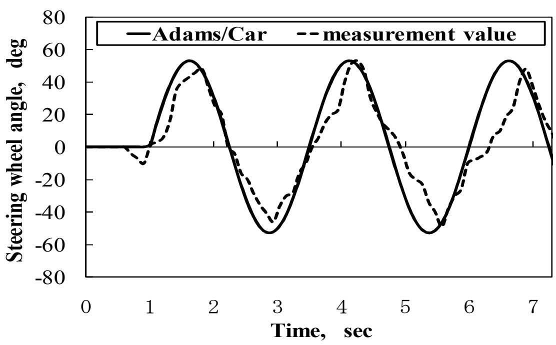
Fig. 10 JSAE formula car and Pylon slalom course

TABLE I
DIMENSION OF THE JSAE MACHINE

Dimensions	Front	Rear
Overall Length, Width, Height	2506mm, 1364mm, 1128mm	
Wheelbase	1600mm	
Track	1170mm	1150mm
Suspension Parameters	**Front**	**Rear**
Suspension Type	Double unequal length A-arm. Pull rod actuated spring and damper.	Double unequal length A-arm. Pull rod actuated spring and damper.
Tire Size and Compound Type	6180/510-13, Bridgestone	6180/510-13, Bridgestone
Wheels	6 inch wide, 1 pc Al Rim, 1.5 inch pos.offset, RAYS	6 inch wide, 1 pc Al Rim, 1.5 inch pos.offset, RAYS
Body Frame		
Frame Construction	Steel Tubular Space Frame	
Material	STKM 13A, STKM 11A steel round tubing.	
Powertrain		
Manufacturer/Model	Kawasaki GPZ500s 2 cylinder / EX500-D1	
Bore/Stroke/Cylinders/Displacement	77mm bore / 58mm stroke / 2 cylinder / 498cc	
Compression Ratio	10.8:1	



(a) Lateral acceleration



(b) Steering Angle

Fig. 11 Comparison result of CAE and Measured data

D. The Design Study of the New Suspension Mechanism

After successfully constructing a working and stable model, we can proceed to do a simulation.There are two types of simulation in ADAMS/CAR 2012. The Full Vehicle Analysis Simulation for the full vehicle assemblies and the Suspension

Analysis Simulation for the assemblies of the suspension subsystems, steering subsystems and the tires subsystem.Since our research focuses on the cornering performance of the vehicle equipped with the CCC system, we will use the Full Vehicle Analysis Simulation for our research. There are many types of event we can simulate with the ADAMS/CAR 2012 with various event modes. For example, constant radius cornering event, acceleration event, pylon slalom and many more. Since our research focuses on the cornering performance of the vehicle, we designed a pylon slalom course to conduct our test on the models. Fig. 12 shows the complete rear suspension subsystem (CCC system).

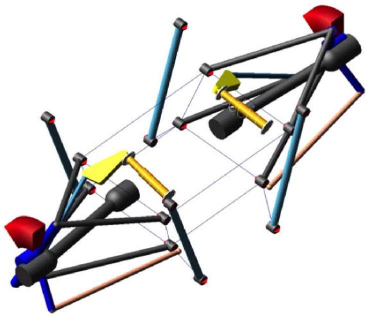


Fig. 12 Rear Suspension Subsystem (CCC System)

E. CAE Vehicle Motion Analysis of the New Suspension System

CAE Vehicle Motion Analysis is performed on the newly developed suspension system and the double-wishbone suspension system to compare the performance of the vehicle equipped with the suspension systems. The tires that are used in the simulation are created using the coefficients, number of the Magic Formula model. In order to create a comparison test on the cornering performance of the conventional double wishbone rear suspension system and the CCC rear suspension system, we decided that a pylon slalom test is the best way to compare the cornering performance of both systems. This is because of the characteristic of the pylon slalom course that constantly maneuver left and right and constantly cause camber change. The initial camber angle and toe angle of both models are set to zero degree. Other than that, the bushing and spring properties of both models are set to be the same in order to have a fair comparison of the system itself. We used the standard spring and bush properties given in ADAMS/CAR 2012. In this simulation the vehicle will accelerate until a constant velocity of 60km/h is achieved. When a constant velocity of 60km/h is reached, the model will enter the pylon slalom course, as shown in Fig. 13 and the vehicle is allowed to decelerate naturally until the end of the course. This way we can know that the system with a bigger resistance will decelerate at a faster rate. Other than that we can also observe the camber angle change, lateral acceleration and the roll angle.

From the simulation above, we managed to produce a few data that shows the CCC system has a better cornering performance than the conventional double wishbone suspension system. The results are shown in Figs. from 14 to 17. From Fig. 14, it can be seen that there are changes in the camber angle of the rear left tire throughout the course. CCC represents the model equipped with the CCC rear suspension system, whereas the Double Wishbone represents the model equipped with the conventional double wishbone rear suspension system. Even though the camber change is small, (0.02~0.03) degree, we can see that both system tilt the tire to a different direction. From the data above, the CCC system managed to tilt the tire to the same direction as the cornering direction whereas the conventional double wishbone suspension system tilt the tire to the opposite direction of the turning direction. This shows that the swing suspension member and the CCC links fasten with rubber bush managed to perform it sole purpose in the system. In other word, that the cornering force causes the system to control the camber angle of the tire with the CCC system. Next from the lateral acceleration result in Fig. 15, we know that the lateral acceleration of the CCC system vehicle is bigger compared to the conventional double wishbone vehicle. Since the CCC system managed to tilt the tire to the same direction as the turning direction, a camber angle is produced and thus a camber thrust is generated. Since we can assume that the initial cornering force of both models is almost similar, the result above shows that the camber thrust generated in the CCC system increased the overall cornering force of the CCC system and thus having bigger lateral acceleration acting on the vehicle.

Fig. 16 shows the relationship between the velocities of both models against distance traveled throughout the pylon slalom course. From the result, we can see that the deceleration rate of the CCC system vehicle is much lower than that of the double wishbone vehicle. In other words, the overall resistance of the CCC system is smaller and thus having a smaller deceleration rate compared to the double wishbone vehicle. Since the deceleration rate of the CCC system vehicle is smaller, the roll angle as shown in Fig. 17 is bigger, whereas the double wishbone vehicle has a smaller roll angle. A bigger roll angle is vital for the CCC system because a bigger roll angle will cause the swing suspension member and links to tilt the tire more and thus produce a bigger camber thrust during a turn.

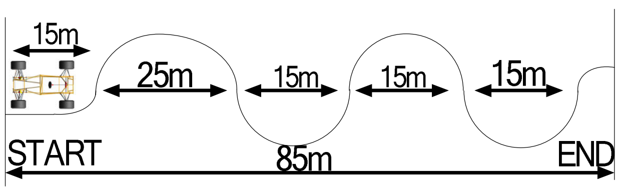


Fig. 13 Natural Deceleration Pylon Slalom Course

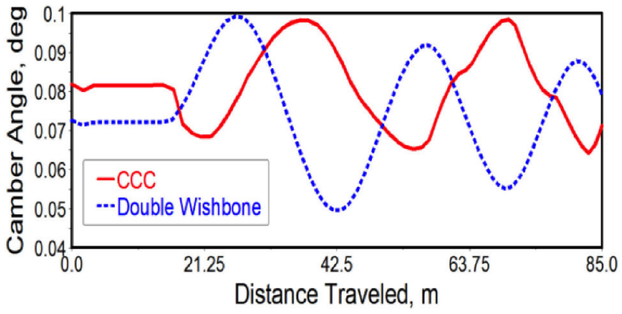


Fig. 14 Camber Angle of Rear Left Tire

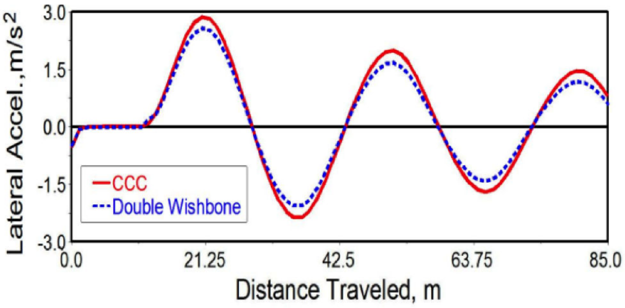


Fig. 15 Lateral Acceleration

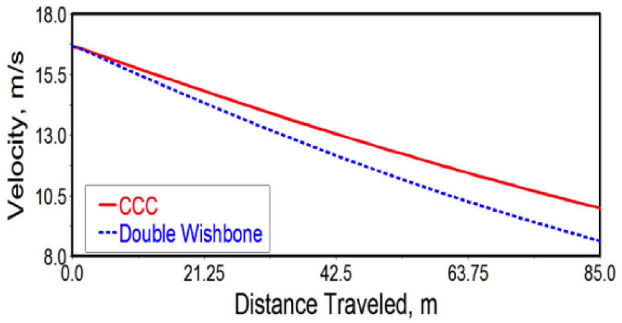


Fig. 16 Velocity versus Distance Traveled

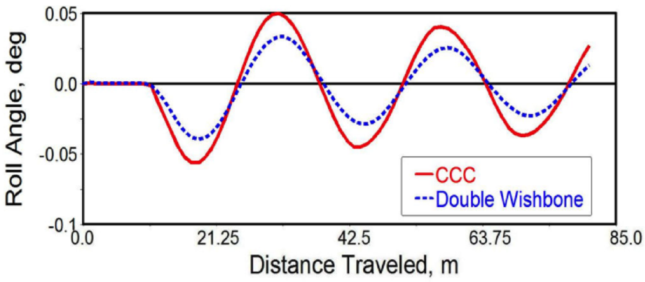


Fig. 17 Roll Angle

III. Discussions

From the simulation data above, we can conclude that the vehicle equipped with the CCC system has a better cornering performance compared to the vehicle equipped with the conventional double wishbone system. Unfortunately, the change in camber angle throughout the course is small (0.02~0.03) degree. We can assume that a bigger change in camber angle will exhibit a better cornering performance. Even though the camber change in our current models is relatively small, our CCC system managed to prove that we can improve the cornering performance by tilting the tire in the same direction of the turning direction. Other than that, in the simulation, our CCC system also proved that we can control the camber angle during a turn of a vehicle by using the compliance control of the rubber bush, CCC links and a swing suspension member and not the expensive electrical control hydraulic system. The next research is aimed to increase the camber change by adjusting various parameters of the CCC system such as the spring properties, bush properties, mounting angle of the links, the position of the momentary center of rotation of the swing suspension member.

IV. Summary/Conclusions

In this research, we managed to develop a functioning Compliance Camber Control system in the ADAMS/CAR 2012. We take a conventional double wishbone system and installed four links and a swing suspension member into it to build the CCC system. The one end of the four links will be fastened to support the whole suspension system at the lower control arm and the other end of the links is connected to the vehicle body. The swing suspension member is a cube like a cage that is fastened to the upper and lower control arm of the suspension system. All the links are fastened together with rubber bushes. The rubber bushes will enable the CCC system to compliance control the camber angle of the tire when a cornering force acts on the system. Other than that, we also managed to develop a design and development process using the ADAMS/CAR 2012 for the CCC system. We also study how to tackle various problems in designing and developing the CCC system using this software. For example, to identify an unstable model and how to troubleshoot problems such as the negative camber problem. Such studies are important to ensure a much smoother design and development process in the future. Finally, throughout this one year of research, we managed to create a functioning CCC system that tilts the tire to the same direction as the turning direction in ADAMS/CAR 2012. Even thought the camber change was relatively small, we managed to prove that with this CCC system we can improve the cornering performance of the vehicle even by a little bit compare to the conventional double wishbone suspension system. We hope to increase the camber change of our system in future research by studying the effect of various parameters such as the spring properties, bush properties, mounting angle of the links, the position of the momentary center of rotation of the swing suspension member. A bigger camber change will surely improve the cornering performance of the vehicle.

(1) Designed a new suspension system made of a body and 4 links swing suspension system that when it is compliance controlled, will act as a negative camber due to the cornering force during a cornering motion and thus can actively use camber thrust.

(2) The vehicle model equipped with the new suspension system was developed using Adams/Car. Based on the comparison of the results from the vehicle equipped with the new suspension system and the vehicle equipped with the

double-wishbone system, the new suspension system exhibited a better performance for both the lateral acceleration and the cornering rolling resistance.

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