809. Geometry optimization of double wishbone suspension system via genetic algorithm for handling improvement

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(Received 17 February 2012; accepted 14 May 2012)

Abstract. Motion control, stability maintenance and ride comfort improvement are fundamental issues in design of suspension systems in off-road vehicles. In this paper, a double wishbone (DW) suspension system, mostly used in off-road vehicles, is modeled using ADAMS software. Geometric parameters of suspension system are optimized using genetic algorithm (GA) in a way that ride comfort, handling and stability of vehicle are improved. Simulation results of suspension system and variations of geometric parameters due to road roughness and different steering angles are presented in ADAMS and effects of optimization of suspension system during various driving maneuvers in both optimized and non-optimized conditions are compared. Simulation results indicate that the type of suspension system and geometric parameters have significant effect on vehicle performance.

Keywords: suspension system, geometric parameters, ride comfort, optimization, genetic algorithm, ADAMS.

Introduction

Vehicle ride comfort and handling stability are the main performance criteria for the modern off-road vehicles. When vehicle is in motion, the vibration from the road surface negatively impacts the ride comfort, handling stability and speed. Furthermore, this can also damage vehicle parts and components. The purpose of vehicle's suspension system is to isolate the vehicle from the uncomfortable vibrations transmitted from the road through the tires and to transmit the control forces back to the tires so that the driver can keep the vehicle under control [1]. Vehicle ride comfort analysis during different paths is performed through study of vehicle parameters such as slip angle, lateral acceleration and vehicle turning speed at transient and steady states. Geometry of suspension system can markedly vary the amount of role center height, camber & caster and toe in & out angles, which affects the ride and handling characteristics. Therefore, the vehicle models including the suspension geometry are used to investigate dynamics of vehicle. Jansen and Oosten [2] used a model with 36 degrees of freedom considering the suspension system geometry and connections. Thoresson [3] evaluated the use of mathematical optimization algorithm for optimization of vehicle suspension system with respect to ride comfort and handling. Significant improvement in the ride comfort as well as handling was observed. Tang and Guo [4] developed a five degree of freedom half-body vehicle suspension system and modeled the road roughness intensity as a filtered white noise stochastic process. Genetic algorithm and neural network control were used to control the suspension system. They also simulated and analyzed mechanical dynamic model of the five degrees of freedom half-body of vehicle suspension system using ADAMS. Ba et al. [5] improved the performance of double wishbone suspension in patrolling forest fire vehicle, based on advanced and efficient Functional Virtual Prototyping (FVP) technology and ADAMS software. They showed that through optimization of the suspension system, the key parameters and total suspension performance could be improved. Kang et al. [6] investigated the robust design optimization process of suspension system for improving vehicle dynamic performance (ride comfort, handling stability) using the target cascading method. The result indicated that the suggested design method of suspension system is effective and systematic. Ning et al. [7] analyzed kinematics and dynamics of suspension ride comfort on adaptability to different vehicles using ADAMS. Uys et al. [8] investigated to determine the spring and damper settings that will ensure optimal ride comfort of an off-road vehicle, on different road profiles and at different speeds. A full-3D model of a Land Rover Defender was developed in ADAMS. Els et al. [9] investigated the suspension requirements for good ride comfort and good handling, respectively. They focused on vehicles that require both good on-road handling as well as good off-road ride comfort. Pang et al. [10] established a time-domain virtual prototyping model of the 8×4 heavy vehicle based on ADAMS in order to match suspension stiffness and realize the optimization of vehicle ride comfort.

Motion control, stability maintenance and ride comfort are important issues in designing off-road vehicles. In off-road vehicles unlike passenger vehicles in which ride comfort is of the utmost importance, the main objective of suspension system design is stability maintenance and improving handling and ride comfort in highly bumped roads. In previous studies, just the ride comfort improvement was considered [11] or control systems such as applying direct torque and active steering system were used to improve vehicle stability and handling [12]. Moreover, effect of geometry and type of suspension system on the stability and ride comfort were not considered [13].

This paper studies effects of various geometric parameters of DW suspension system including caster, camber and kingpin angles on handling stability and ride comfort in off-road vehicles using ADAMS software in order to achieve improvements in stability and ride comfort through optimization of geometric parameters with GA. Firstly, the DW suspension system is modeled in ADAMS and then mechanism and geometry of suspension system is optimized by studying geometric parameters and angles of wheel and suspension system in different vehicle maneuvers during bump and roll inputs.

Suspension system geometry

Suspension system geometry in DW systems has significant effect on vehicle handling and ride comfort compared to other systems like Macpherson and pendulum [14]. Therefore, effect of geometric parameters of DW suspension system mostly used in off-road vehicles on handling and ride comfort is investigated here.

One of the main kinematic factors influencing vehicle guidance is camber angle, which is the angle between the vertical axis of the wheels used for steering and the vertical axis of the vehicle when viewed from the front or rear. It is used in the design of steering and suspension. If the top of the wheel is farther out than the bottom (that is, away from the axle), it is called positive camber; if the bottom of the wheel is farther out than the top, it is called negative camber. Camber angle alters the handling qualities of a particular suspension design; in particular, negative camber improves grip when cornering. This is because it places the tire at a better angle to the road, transmitting the forces through the vertical plane of the tire rather than through a shear force across it. In cars with DW suspensions, camber angle may be fixed or adjustable, but in Macpherson suspensions, it is normally fixed.

Caster angle is the angular displacement from the vertical axis of the suspension of a steered wheel in a vehicle, measured in the longitudinal direction. It is the angle between the pivot line (in a car - an imaginary line that runs through the center of the upper ball joint to the center of the lower ball joint) and vertical.

Toe is the symmetric angle that each wheel makes with the longitudinal axis of the vehicle, as a function of static geometry, and kinematic and compliant effects. This can be contrasted with steer, which is the anti-symmetric angle, i.e. both wheels point to the left or right, in parallel (roughly). Positive toe, or toe in, is the front of the wheel pointing in towards the centerline of the vehicle. Negative toe, or toe out, is the front of the wheel pointing away from the centerline of the vehicle [15]. Toe can be measured in linear units, at the front of the tire, or as an angular deflection. Fig. 1 shows the geometric parameters of tire in standard coordinated system.

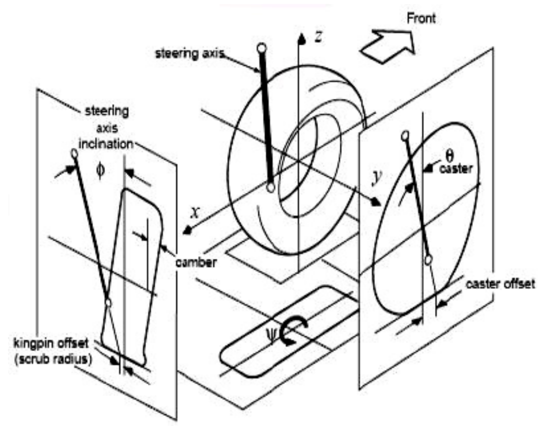


Fig. 1. Geometric parameters of tire

Altering each of geometric parameters of suspension system would affect other parameters. For step function input, it is shown that the generated forces in tire due to steering and camber angles may adversely affect the stability of the vehicle [14]. Fig. 2 schematically depicts the camber angle variations due to wheel oscillations at three different conditions.

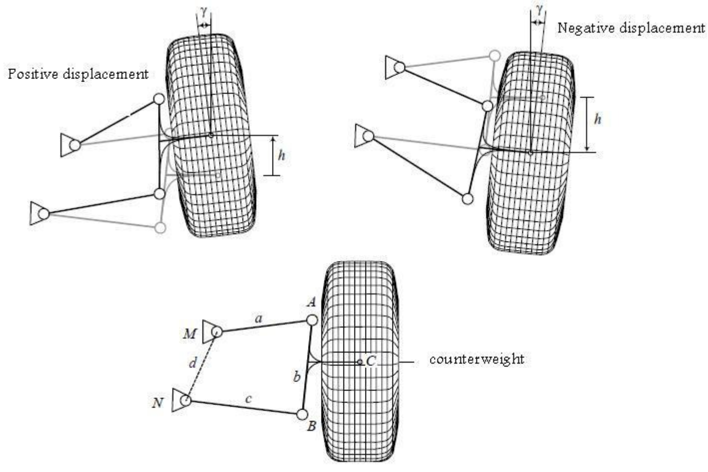


Fig. 2. Different types of camber angle resulted from wheel oscillations

Geometric model of double wishbone suspension system

In order to investigate effect of geometric parameters on the vehicle ride comfort, variation of camber angle due to vehicle roll and tire vertical deflection (bump) is taken into account for DW suspension system with short-long arm suspension (SLA) according to Fig. 3. The desired and optimal condition of it is when the upper arm is shorter than the lower arm and the camber angle is negative [16].

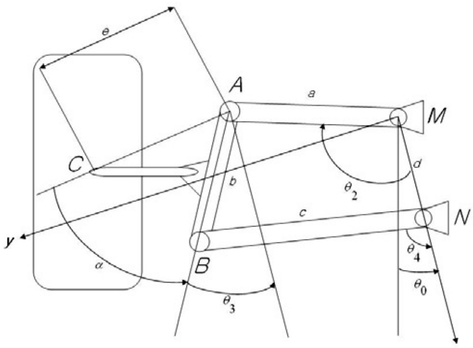


Fig. 3. Double wishbone suspension system and its geometric parameters [17]

According to Fig. 3, the suspension system is in a dynamic state of balance when the arms of DW suspension system make initial angles of $\theta_{40}, \theta_{30}, \theta_{20}$. The camber angle (γ) is defined as $\theta_{30} - \theta_3$. According to Fig. 2, θ_3 can be obtained based on wheel displacement height as:

$$\theta_3 = 2\tan^{-1}\left(\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right) \tag{1}$$

where:

$$D = \frac{c^2 - d^2 - a^2 - b^2}{2ab} - \frac{d}{a} + \left(1 + \frac{d}{b}\right)\cos\theta_2 \tag{2}$$

$$E = -2\sin\theta_2 \tag{3}$$

$$F = \frac{c^2 - d^2 - a^2 - b^2}{2ab} + \frac{d}{a} - \left(1 - \frac{d}{b}\right)\cos\theta_2 \tag{4}$$

By combining Eqs. (1) to (4), variations of camber angle based on wheel geometry and suspension system are acquired. Fig. 4 illustrates DW suspension system for steer and camber angle.

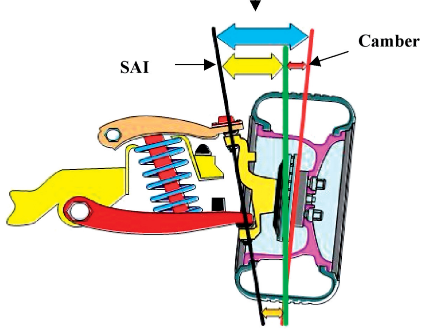


Fig. 4. DW suspension camber and steering angle [18]

As shown in Fig. 3, along of steer axis cuts the contact surface of wheel with ground at point (s_a, s_b, $-R_w$) as presented in Eqs. (5) to (7):

$$s_a = \frac{\cos\theta \sin\varphi}{\sqrt{\cos^2\varphi + \cos^2\theta \sin^2\varphi}} \tag{5}$$

$$s_b = \frac{-\cos\varphi \sin\theta}{\sqrt{\cos^2\varphi + \cos^2\theta \sin^2\varphi}} \tag{6}$$

$$R_w = \frac{\cos\theta \cos\varphi}{\sqrt{\cos^2\varphi + \cos^2\theta \sin^2\varphi}} \tag{7}$$

Thus it is possible to obtain caster angle variations, steering angle deviation and tire scrub based on suspension geometric specifications related to the camber angle.

Optimization of geometric parameters of DW suspension system using GA

A genetic algorithm (GA) is a heuristic search that mimics the process of natural evolution. It is routinely used to generate useful solutions to optimization and search problems. Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. Genetic algorithms find application in bioinformatics, phylogenetics, computational science, engineering, economics, chemistry, manufacturing, mathematics, physics and other fields. A typical genetic algorithm requires: a genetic representation of the solution domain and a fitness function to evaluate the solution domain.

The GA parameters for optimizing geometric parameters of DW suspension system are considered as shown in Table 1. In order to perform optimization using GA, objective function, variables and objective function constraints should be defined. Camber angle variations due to wheel oscillations can be optimized in a way that scrub is reduced and it is minimized at a specified height. For this purpose, camber variation and variation range of suspension geometric parameters are considered as objective function and constraint in GA, respectively. Optimization results of geometric parameters in off-road vehicle suspension system are given in Table 2.

Table 1. GA parameters

Parameter	Type/value
Population function	Double vector
Number of generation	1000
Selection function	Uniform
Mutation	Uniform/2%
Cross over	Two point

Results and discussion

In the first step, the DW suspension system is modeled as shown in Fig. 5 in order to investigate effects of geometric parameters and their optimization on vehicle stability and ride comfort. Then, equivalent mechanisms of suspension system with bump and roll inputs for tire vertical deflection of 50 mm and roll are depicted in Fig. 6 in order to provide sensitivity measurement of geometric parameters of optimized suspension system.

Table 2. Geometric parameters in off-road vehicle suspension system

Parameter	Unit	3rd suspension (optimized)	2nd suspension	1st suspension (simple)
Upper arm length	mm	224	221	222
Lower arm length	mm	273	273	364
Upper arm angle	mm	122	120	125
Lower arm angle	mm	107	109	106
Distance of body joints	mm	175	180	189
Distance of tire joints	mm	221	235	250
Initial camber	deg	-2	-1.5	-2
Initial caster	deg	4	5.5	5
Scrub	mm	35	25	30
Mechanical trail	mm	18	21	20
Toe in angle	deg	-3	-2	-2
Steering deviation angle	deg	11	4	8.5

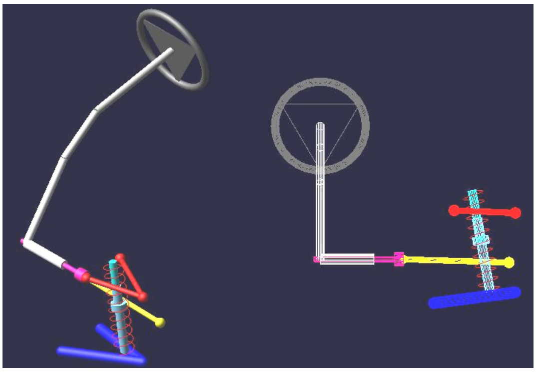
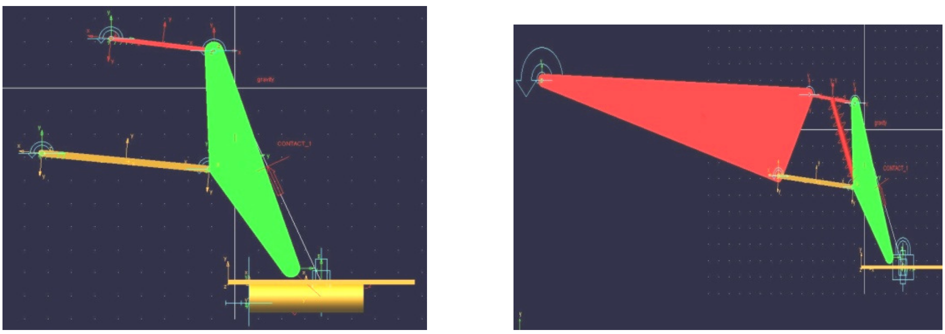


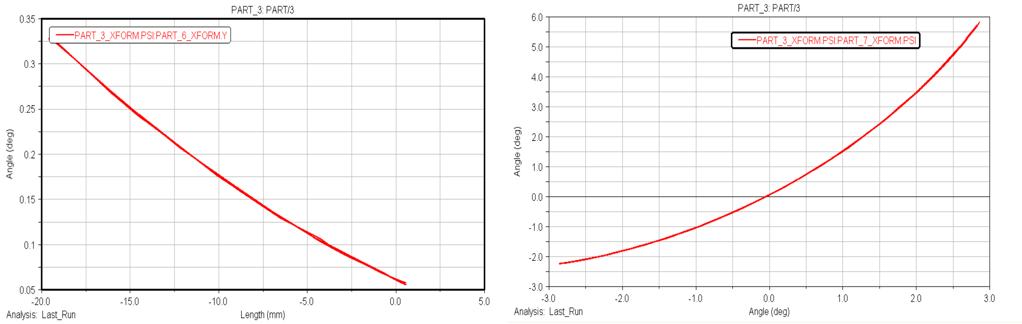
Fig. 5. The integrated DW suspension with steering system modeling



(a) (b)

Fig. 6. Equivalent mechanisms of DW suspension system in ADAMS: a) bump input; b) roll input

The variation of optimized camber angle is illustrated in Fig. 7. It is evident that the camber angle is negative when the wheel gets height during passing the bump or increasing of roll angle, which shows the trend of wheel towards the outside of vehicle and its instability. As can be observed, the camber angle variation is lower in off-road vehicles compared to the on-road vehicles, which indicates a better handling and stability of the vehicle with optimized DW suspension system.



(a) (b)

Fig. 7. Camber angle variation due to: a) bump; b) vehicle roll

Figs. 8 and 9 indicate the variation of toe in angle due to sinusoidal bump and scrub due to vehicle roll, respectively.

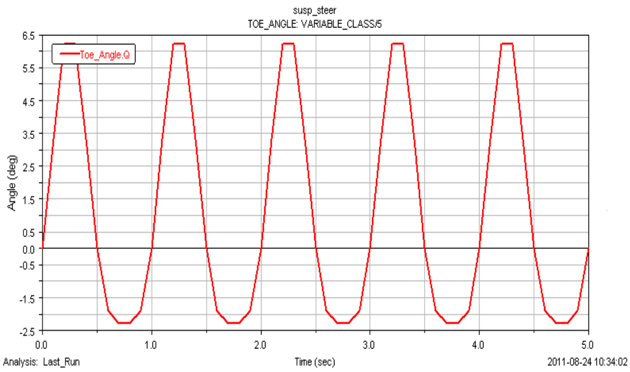


Fig. 8. Variation of toe in angle with sinusoidal bump input

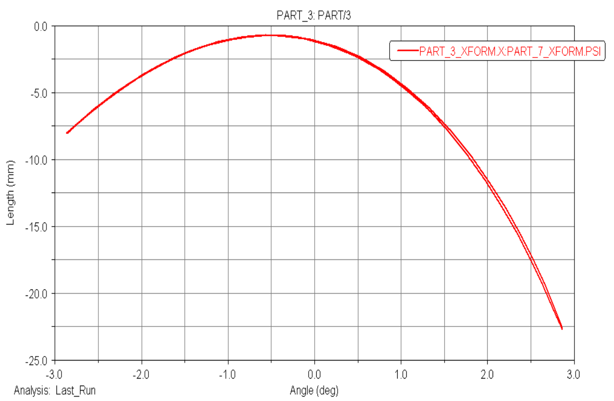


Fig. 9. Variation of scrub due to vehicle roll

It is possible to obtain effect of each of these geometric parameters at different lateral accelerations on its steering angle. Fig. 10 demonstrates effects of steering deviation, caster, camber angles and tire scrub on steering angle at tires' tip. To study effect of each parameter, other parameters are kept constant and others are tested in four cases (two positive and two negative).

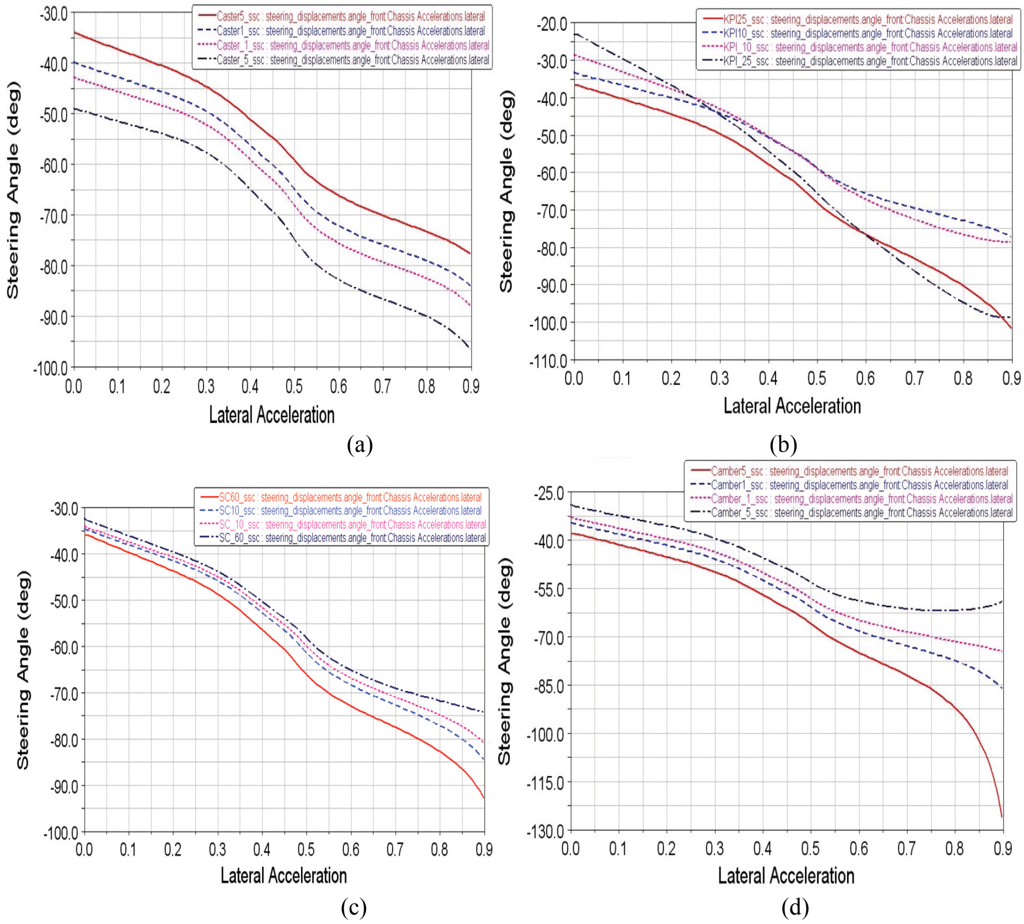


Fig. 10. Steering angle versus lateral acceleration:
a) different caster angles; b) different kingpin slopes; c) different scrubs; d) different camber angles

Fig. 11 depicts the camber angle variation at different vehicle rolls based on vehicle longitudinal dynamics (acceleration and braking) for front left- and right-hand side suspensions. In the case of low vehicle dive, camber angle for left- and right-hand side suspensions has minimum and maximum amount, respectively. Furthermore, it can be observed that by increasing roll angle or bump height, camber variations for both left- and right-hand side suspensions increases at the same rate and by enhancing vehicle dive angle in longitudinal dynamics the camber increases but its variations remain constant.

In the second stage, by modeling the complete vehicle in ADAMS as shown in Fig. 12, simulation results with initial longitudinal speed of 30 m/s in a dry road during double lane-change, lateral deviation from objective path, acceleration, lateral and turning velocity are compared in Fig. 13 for optimized with GA, modified with trial and error method and unmodified suspension systems.

As the results indicate, the optimized suspension system with GA represents the best response with respect to vehicle performance and follows the objective path with minimum deviation and heading error along with stability maintenance. The maximum side-slip and yaw rate which should be minimized as vehicle stability variables are less than 4 degrees and 10 rad/s, respectively, which results in lateral acceleration, to be under critical condition (less than 6 m/s^2). Also, maximum lateral deviation and heading error is always lower than 0.1 m and 4 degrees respectively, indicating suitable handling and steering comfort of vehicle during intensive maneuvers.

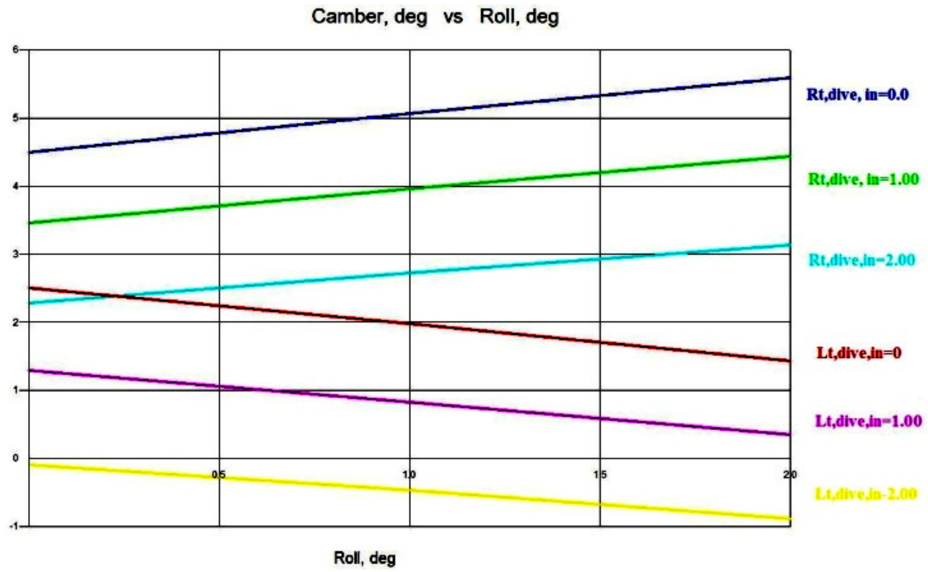


Fig. 11. Variations of camber angle due to roll and longitudinal dynamics

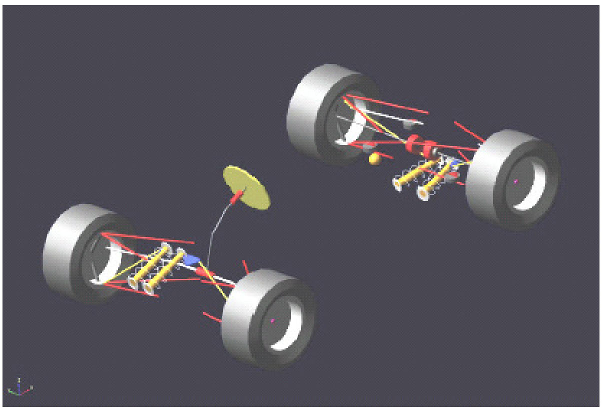


Fig. 12. Modeling of suspension system with steering in ADAMS

In addition, according to Fig. 6, two equivalent mechanisms with bump and roll inputs are modeled for optimized DW suspension system in order to realize sensitivity measurement of geometric parameters. The simulation results for state variables of vehicle such as yaw rate, side slip and lateral acceleration show that the optimized suspension system with GA exhibits the best response in terms of vehicle performance. Maximum side-slip is always lower than 4 degrees, indicating appropriate handling and steering comfort of vehicle during intensive maneuvers. However, lateral acceleration and side slip angle reach over than 0.6g and 4 degrees at non-optimized condition, which results in vehicle instability.

Conclusions

In this paper, modeling of a double wishbone suspension system in off-road vehicle is performed using ADAMS. Geometric specifications of suspension system are optimized using genetic algorithm aiming at minimizing camber angle variations. Moreover, sensitivity analysis and variations of geometric parameters of suspension system resulted from bump and vehicle roll inputs are presented for the optimal case. In the next stage, simulation of vehicle motion during turning maneuver for vehicle parameters is conducted using comprehensive modeling of vehicle in ADAMS. The simulation results are compared in three stages for the un-modified suspension system, modified suspension system with trial and error method and suspension system optimized through GA. The simulation results indicate that the suspension system type and its geometric parameters have considerable effect on ride comfort, handling, stability and prevention of vehicle rollover through quick speed maneuvers. It is observed that by optimizing geometric parameters of suspension system, the vehicle can follow the objective path with minimum deviation along with stability maintenance and improvement in ride comfort conditions.

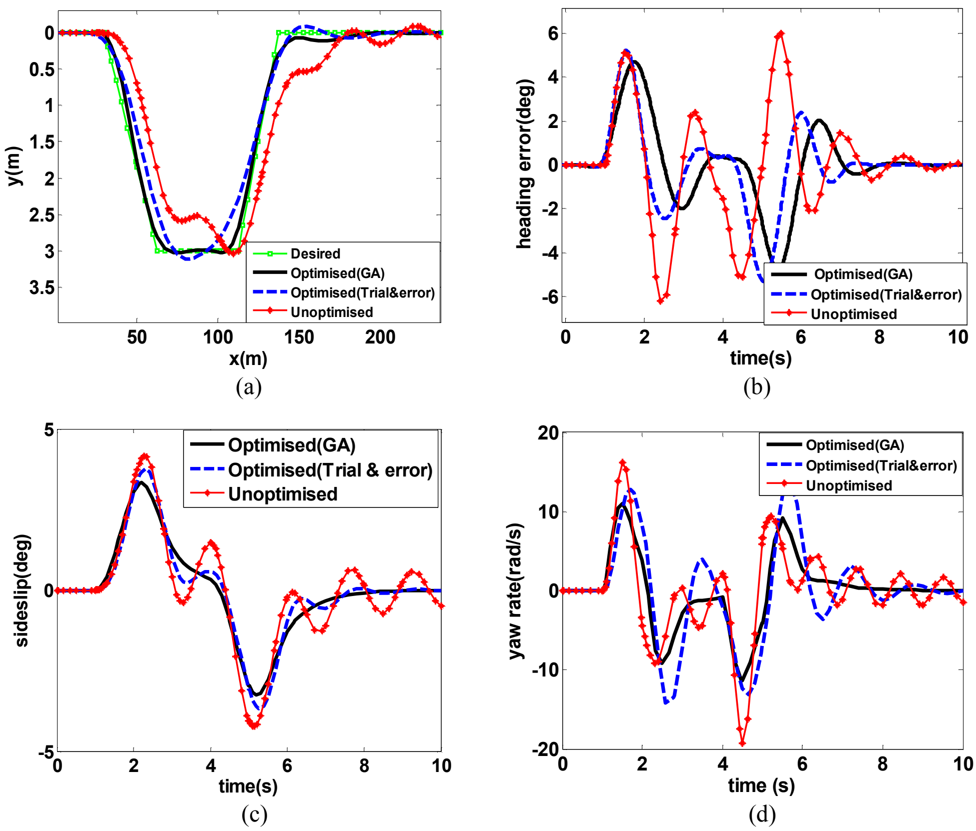


Fig. 13. a) Double lane-change maneuver path; b) vehicle heading error during double lane-change; c) vehicle side-slip angle during double lane-change; d) yaw rate variations during double lane-change

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