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DESIGN OF INDEPENDENT SUSPENSION MECHANISM FOR A TERRAIN VEHICLE WITH FOUR WHEELS DRIVE AND FOUR WHEELS STEERING

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ABSTRACT: In this paper a terrain vehicle with four wheels drive and four wheels steer intended to use for recreational purpose is presented. The main purpose is to design the suspension mechanism that fulfills requirements about stability, safety and maneuverability. Nowadays, as well as in the past, the development of the suspension systems of the vehicle has shown greater interest by designers and manufacturers of the vehicles. Research is focused to do a comprehensive study of different available independent suspension system (MacPherson, double wishbone, multi-link) and hence forth develop a methodology to design the suspension system for a terrain vehicle. Few chosen suspension systems are analyzed into the very details in order to find out the optimal design of it. During development process of the suspension system should be considered design constraints and requirements provided in the check list. Afterwards the simulation results for kinematics analyses of suspension mechanism are performed in Working Model 2D and MATLAB environments. Achieved results are discussed in detail in order to find the best solution that will fulfill pretentious requirement from developed suspension system. All these investigations and reviews related to the suspension system will be exploited in order to obtain the optimal suspension geometry to equip a terrain vehicle, with such system.
KEYWORDS: terrain vehicle, design, suspension mechanism, suspension geometry

INTRODUCTION

The primary function of the suspension system of the vehicle should fulfil pretentious requirements about stability, safety and manoeuvrability. The suspension system of the vehicle performs multiple tasks such as maintaining the contact between tires and road surface, providing the vehicle stability, protecting the vehicle chassis of the shocks excited from the unevenness terrain, etc. [1]. The suspension system works together with the tires, wheels, frame, suspension linkages, wheel hubs, brakes systems as well as steering system to provide driving comfort, stability, etc.

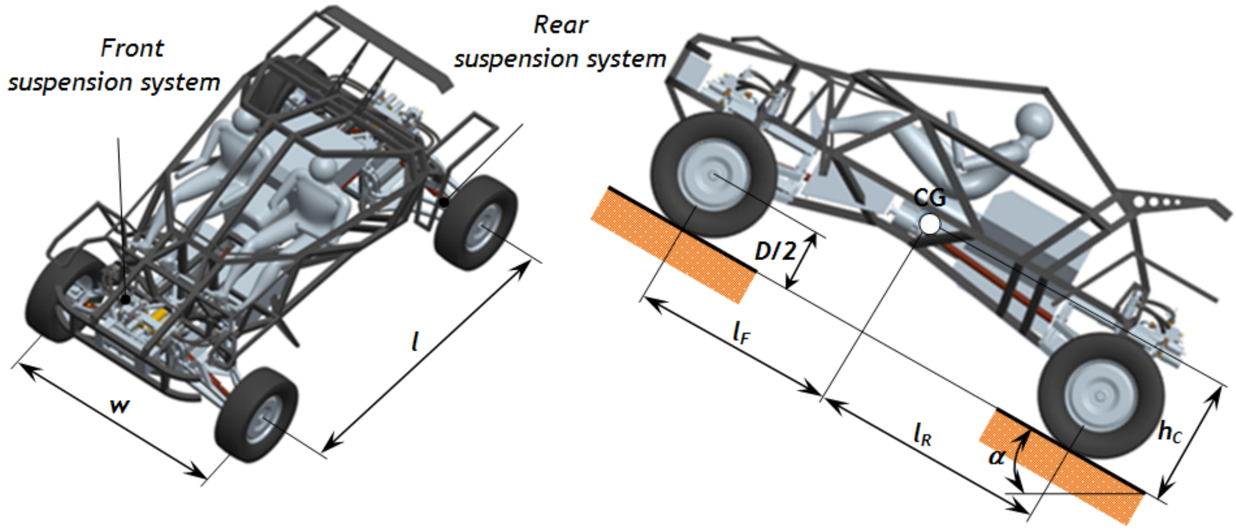

Figure 1 - Design of terrain vehicle modeled in Pro/ENGINEER environments

This system is the mechanism that physically separates the vehicle body from the wheels of the vehicle. The performance of the suspension system has been greatly increased due to the continued advancements in automobiles in the recently years. The suspension system will consider ideal if the vehicle body isolate from uneven road and inertial disturbances associated during situation of cornering, braking and acceleration.

The design of the vehicle suspension system may be different for front and rear axis (independent or dependent suspension) [2]. The main aim in this research is to conceive and design the suspension system for a terrain vehicle with four wheels drive and four wheels steer intended to use for recreational purpose. The terrain vehicle it is designed to operate mostly in roughness terrain as well as in paved roads. The design of the terrain vehicle is modeled in Pro/ENGINEER environment and is shown in Figure 1.

In order to meet the requirements counted in the project as better as much, in Table 1 are given check list with main characteristics, which should be respect during design.

Table 1 - Check list with characteristics which influence in the design of the suspension system

No.	Characteristics of terrain vehicle	Value	Unit	Remarks
1.	Engine: P_e	~ $4{\cdot}10^3$	kW	Limit
2.	Powertrain system:	Mechanical		Request
3.	Driving speed: v	0 - 180	km/h	Limit
4.	Maximal passing road slope: a	~ 50	deg	Wish
5.	Geometric dimensions: Wheelbase: l Track width: w Distance: l_F Distance: l_R	 2.80 2.10 1.40 1.40	m	Limit
6.	Total mass of the vehicle: m_{tot}	1150	kg	Limit
7.	Dimensions of front and rear wheels: Diameter: D Width: B	 0.80 0.25	m	Request
8.	Camber angle: γ	~ 0	deg	Limit
9.	Suspension system:	Independent suspension		Request
10.	Vertical motion of wheels: Rebound: z_{min} Rest position: z_{rest} Bound: z_{max}	 - 0.250 0 + 0.250	m	Request

For better understanding of the suspension design in following are discussed classification and types of the vehicle suspension systems.

CLASSIFICATION OF THE SUSPENSION SYSTEM

The suspension system is always derived by some mechanical way. Generally speaking, the designs of the suspension systems are classification in two main groups [1, 3]:

- *Dependent suspension system (solid axle) and*
- *Independent suspension system.*

Each group can be functionally quite different and they are studied and discussed accordingly [3, 4]. Recently, both suspension systems can be found on ordinary vehicles and commercial vehicles.

The dependent suspension system

The dependent suspension system is known as solid axle, when both wheels (left and right) are mounted the same solid axle (Figure 2). In this case, any movement of any wheel will be transmitted to the opposite wheel causing them to camber together. Solid drive axles usually are used on the rear axle of many passenger cars, trucks and on the front axle in many four wheel drive vehicles.

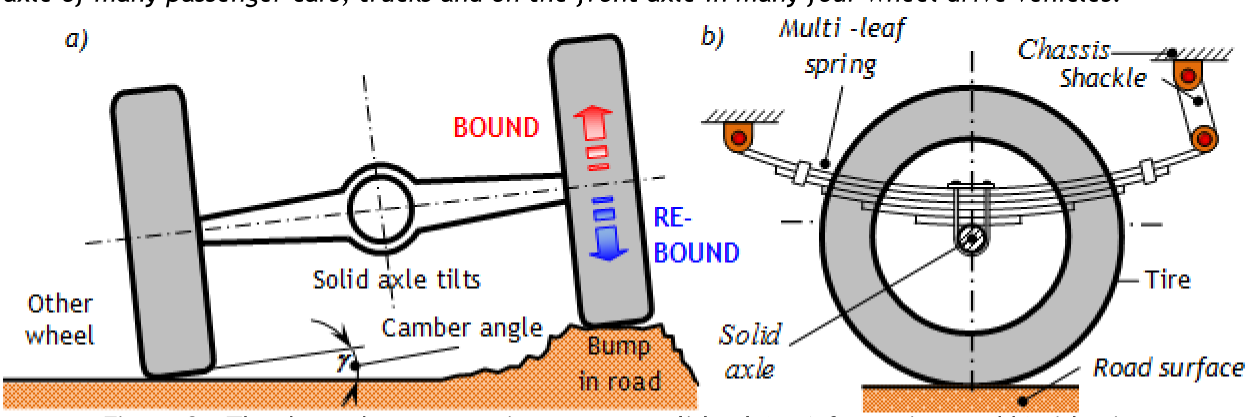

Figure 2 – The dependent suspension system (solid axle); a) front view and b) side view

The advantage of solid axles is considered the camber angle which is not affected by rolling of the vehicle body. Therefore, produce little camber in cornering, except for that which arises from slightly greater compression of the tires on the outside of the turn. In addition, wheel alignment is readily maintained, which contribute to minimize tire wear. The disadvantage of solid steerable axles is their susceptibility in shimmy steering vibrations, heavy mass, etc. The most types of solid axles are: Hotchkiss, Four link and De Dion.

The independent suspension system

The independent suspension system, allows one wheel to move upward and downward with a minimum effect on the other wheel (Figure 3). Mostly of the passenger cars and light truck use independent front suspension system, because provide much more space for installing vehicle engine, allow much more displacement of wheel, better resistance in steering vibration (wobble and shimmy) as well as offer higher performance in passenger comfort. As disadvantages of the independent suspension system can be considered the complexity of the design and manufacturing cost due to increasing number of parts.

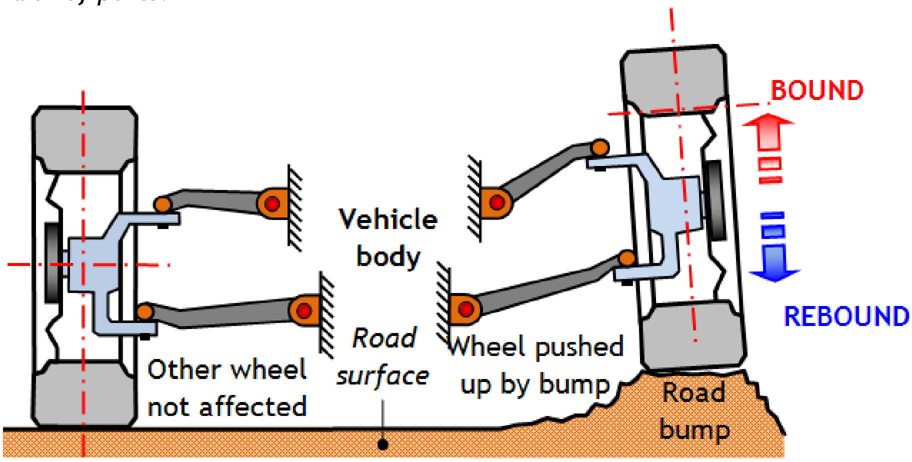

Figure 3 – The independent suspension system (front view)

Over the years, many types of independent suspension system have been tried to develop such as MacPherson, double wishbone, multi-link, trailing arm and swing axle. Many of them have been discarded for different reasons, with only basic concepts, MacPherson strut, double wishbone and multi-link suspension system, have found application in many types of the vehicles.

*The **MacPherson** strut consists of a single control arm and a strut assembly (spring and shock absorber) which allows tire and wheel to move upward and downward. The major components of the system are shown in Figure 4.a. It may be used on both the front and rear axles. This suspension system design allows reducing number of parts, lower un-sprung mass as well as smooth driving comfort.*

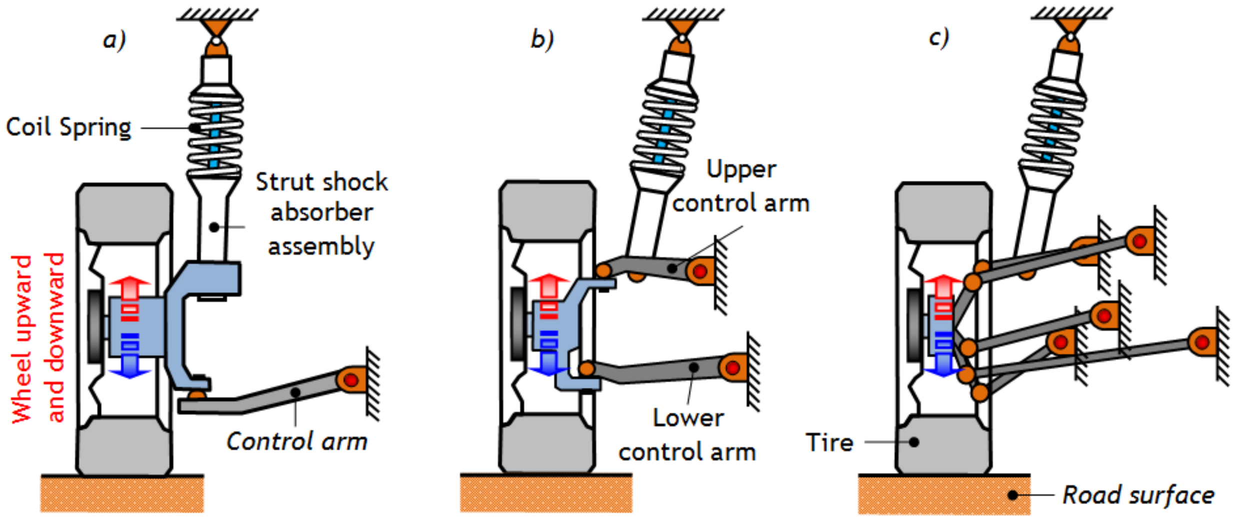

Figure 4 – The independent suspension system;
a) MacPherson strut, b) double wishbone and c) multi-link suspension system

McPherson strut, a clever compromise that permits reasonable performance compare by low cost, but never match the performance or adjustability such as double wishbones or multi-link suspension system. Furthermore, this type of suspension requires sufficient vertical space and a strong top mount.

*The **double wishbone** suspension system in the USA often is called "A-arms" and "Double Wishbones" in UK. The double wishbone suspensions system are applied to luxury sedans and sports cars because their design of elastic – kinematic parts allow to provide an optimum compromise between handling and comfort [5]. The double wishbone used two lateral control arms to hold the wheel from tilting with suspension action (Figure 4). The upper and lower control arms usually are with unequal length where the acronym SLA (short-long arm) gets its name. During design of this type of suspension, it is required careful refinement of suspension geometry in order to get good performance [3, 6].*

There are a few advantages of the double wishbone suspension system, e.g. the primary benefit is increase negative camber as a result of the vertical motion of the upper and lower arms. This justify to stability performance for the vehicle as the tires on the outside maintain better contact with the road surface during cornering. Disadvantages of the double wishbone compared with MacPherson strut suspension system, becomes in the complexity of the design, production cost, increased number of parts such as joints and bearing which have negative consequences on the tire wear due consumption of bushing rubber.

*The **multi-link** suspension system belongs to the group of the independent system. It is used on both the front and rear axles and is derived by refinement of the double wishbone. Use three or more lateral arms and one or more longitudinal arms, which do not require to being with equal length [7] (Figure 4.c).*

Recently, the multi-link suspension system seems to be the best independent system for vehicle, because offers the best compromises between comfort, stability and manoeuvrability [7]. Moreover, such suspension system allows vehicles to get better performance compared with other types. Probably, would be good solutions to equip a terrain vehicle, with such system. The multi-link suspension system has advantageous for the designer who enable to change one parameter without influencing the entire assembly. This is a major difference compared to a double wishbone suspension. By taking into consideration all of good things, the multi-link suspension system is more complex to design and has higher manufactures cost. To get better performance of the vehicle, the suspension geometry should to be checked carefully by adequate software.

As disadvantage of the already described suspension systems, is considered basically fact that they not allow enough the vertical movement of wheels in order to get good performance and characteristics of the terrain vehicles. It requires to be developed such suspension system.

GEOMETRY OF THE INDEPENDENT SUSPENSION SYSTEM

Nowadays, as well as in the past, the development process for suspension systems of the vehicle has shown great interest by designers and manufacturers of the vehicles. During development process should be considered design constraints and requirements provided in the check list (Table 1), conceptual design, analyses different aspects of the suspension kinematics, behaviour of structures of mechanical systems, etc. All these investigations relation to the suspension system will be exploited to obtain the optimal suspension geometry in order to equip a terrain vehicle with suitable suspension system.

The suspension geometry

The suspension geometry is important factor during design process, which helps us to identify the vertical wheel motion and how is position of the wheel in such motion. The suspension geometry not only dictates the path of the wheel, but also controls the forces that are transmitted between sprung and un-sprung mass.

The design of the suspension mechanism for a terrain vehicle will be same for the front and rear axle which in an advanced model of the double wishbone. This model is ranking in the multi-link suspension system and is discussed previously. During design should be paid attention for that suspension mechanism to allow sufficient vertical wheel motion in order the vehicle to negotiate with roughness terrain. In case, when a tire contact a bump and the suspension mechanism does not allow sufficient vertical motion, the tire will continue to move upward, taking the frame with same high velocity and result on causing large acceleration in driver. The terrain vehicle will be equipped with an operational suspension system which allows vertical wheel motion to be least 500 mm, where + 250 mm bound and – 250 mm rebound (Figure 5).

Figure 5, present case when the wheel moves in the vertical direction and get maximum values in bound (upward) and rebound (downward). The important parameters which involved in suspension geometry are classified as: camber angle, kingpin inclination angle, kingpin offset, etc.

The Camber angle, *γ - is angle between the vertical axis of the wheel and the vertical axis of the vehicle viewed from the front or rear site. When vehicle operate during different road, wheels will move upward and downward and vertical wheel center will be changed. This change is known as the camber angle (γ). According to the configuration of the suspension mechanism, camber angle has three possible positions such as positive camber, zero camber and negative camber (Figure 6.a).*

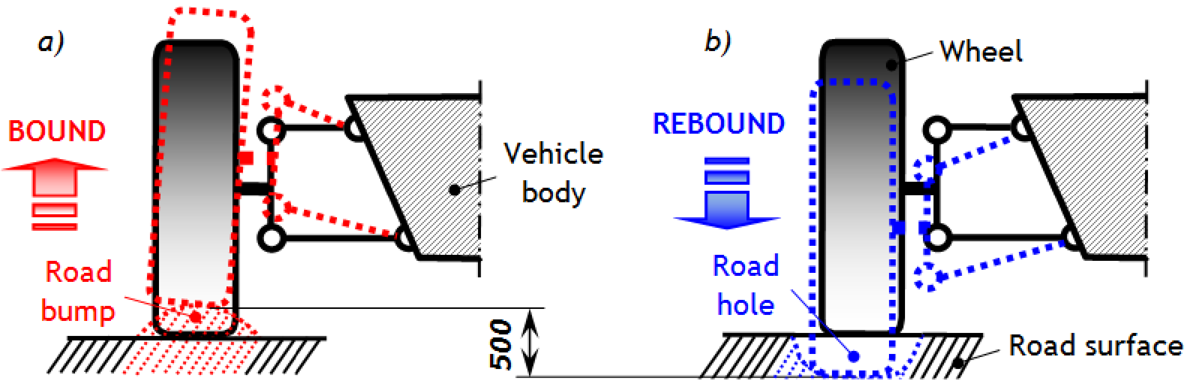

Figure 5 - Suspension motions; a) upward and b) downward

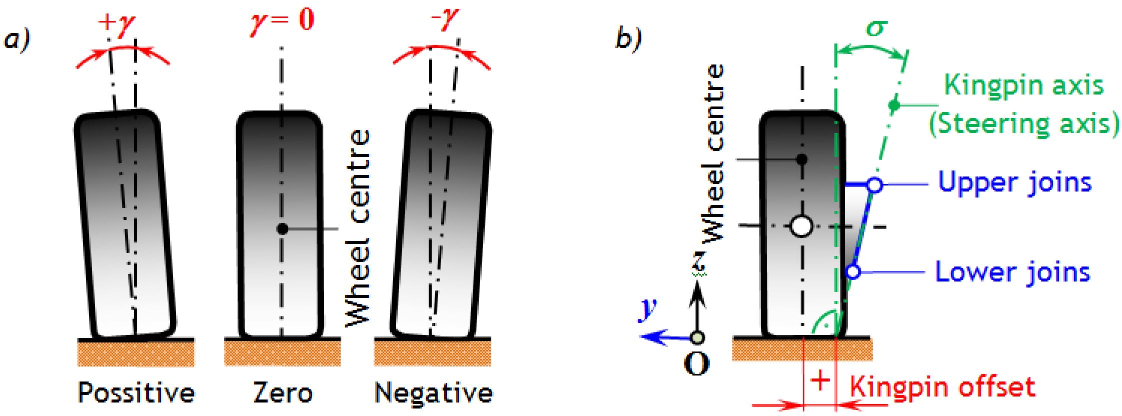

Figure 6 - Suspension geometry;
a) camber angle (front view) and b) kingpin inclination angle and kingpin offset (front view)

The camber angle is termed positive camber (+γ), if the top of the wheel is further out than the bottom. Is called negative camber (-γ), when the bottom of the wheel is further out than the top. While is known as zero camber (γ = 0), if the top and the bottom of the wheel is in same centreline with vehicle. By increasing camber angle, the stability and traction of the vehicle will be reduced as a result of a small contact of the tire with road surface. Derived expression for calculation of camber angle (γ) in function of input angle (θ_3 = 335.18 to 378.22 deg) according to Figure 7, is written as follow:

$$\gamma(\theta_3) = a\tan\left[\frac{Y_M(\theta_3) - Y_N(\theta_3)}{Z_M(\theta_3) - Z_N(\theta_3)}\right] \quad (1)$$

Simulation results realising in MATLAB environment shown that camber angle during all motion of the wheel (bound and rebound) are nearly to zero $\gamma(\theta_3) \sim 0$ deg.

The Kingpin inclination angle, σ *- is the angle which is arises between the kingpin axis and a vertical axis to the ground, viewed from the front of the vehicle (Figure 6.b). It is also known as steering axis inclination and usually is 0 … 20 deg [3]. The inclination angle helps to give space for fitting the vehicle brakes and is important design features in vehicle suspension geometry. It determines the steering feeling of drivers, the handling performance and the steering stability of a vehicle. By determines the right kingpin inclination will be reduces the steering effort and will provide the driver with a good "road feel". If the kingpin inclination angle is zero, is called centreline steering. The kingpin inclination axis usually is not vertical or centred on the tire contact patch for reasonable issues of the steering stability of the vehicle. Expression for calculation of kingpin inclination angle (σ) of the multi-link suspension system (Figure 7) is given, as follow:*

$$\sigma = a\tan\left[\frac{(y_K - y_I) - (y_J - y_H)}{(z_I - z_H)}\right] \quad (2)$$

By substitution of known values given in Table 2, kingpin inclination angle is σ = 12.28 deg.

The kingpin offset *is the horizontal distance measured from steering axis to the intersection point with ground and wheel centre contacted with ground (Figure 6.b). Kingpin offset it is also known as scrub radius. Kingpin offset can be positive, negative and zero offset. It is positive when the contact centre of wheel is outside of the steering axis intersection point on the ground. Negative kingpin offset is case when the contact centre of wheel is inner of the steering axis intersection point* *on the ground. Zero offset is called when contact centre of wheel are in same point of steering axis intersection on the road. Larger kingpin inclination angles result with a smaller or negative kingpin offset. Derived expression for calculation of kingpin offset of the multi-link suspension system (Figure 7) is written, as follow:*

$$Kingpin\ offset = \left[y_M - y_K + (z_M - z_K - r_d) \cdot \tan\sigma \right] \qquad (3)$$

By substitution of known values given in Table 2 and equation (2), kingpin offset is 0.9 mm.

DESIGN OF THE SUSPENSION MECHANISM

The state-of-the-art for design of the suspension system of the terrain vehicle is based on three fundamental principles:

- *To design simplest and robust,*
- *By using the best proven performance that offered reviewed suspension system and*
- *Continuing refining the design until it is optimized to fulfil submitted requirement.*

Actually, by advent and using personal computer has made possible to analyse suspension geometry without needs to cut and weld its structures. By applying the available knowledge for using of computer simulations, it is possible to get predefined requirements. The only thing what is required to do is to decide what the suspension system to behave and then activate the computer to precede the design variables and to get desired design.

The design of the suspension system is based on analyzing of the performance that provide double wishbone with longer equal control arm. This type of suspension allows a relatively large vertical motion of wheel which corresponding by small change in angular movement of the control arm. This configuration facilitates the suspension geometry. Developed suspension system it is categorised as multi-link suspension system (Figure 7).

For further developing process it is focused that lateral motion of the tire and camber angel to have smaller values in boundary positions during vertical wheel motion caused on bound or rebound motion.

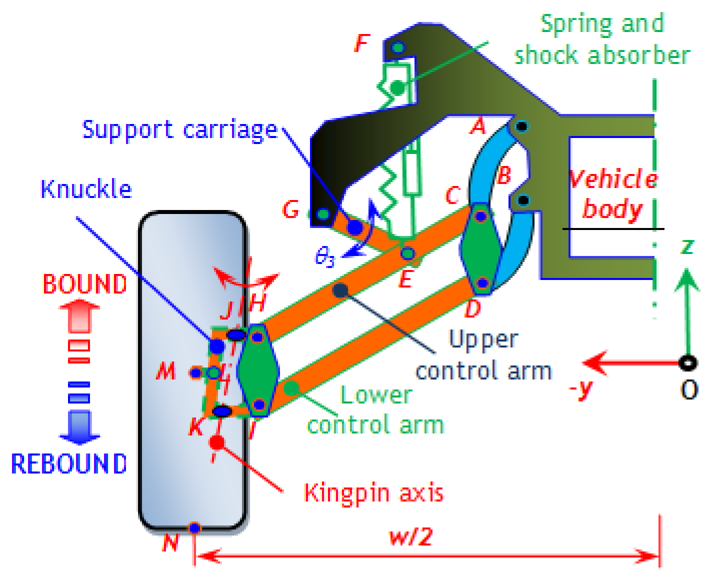

Figure 7 - Quarter of multi-link suspension system in 2D

Point O is centre of coordinative system -yOz with coordinates O (0, 0). Axis -yO go through centre of the wheel (rest position), while Oz is centres of vehicle – front view. For evaluation of the performance that provides this suspension system is required to make geometric modelling. Joint points and necessary data for geometry modelling are given in Table 2. Modelling of multi-link suspension system in Working Model 2D environments is done. Results from simulation are presented in following diagrams. All simulations are make under assumption the vehicle body is fixed and motion parts are considering wheel with its devices which usually is called un-sprung mass.

Table 2 - Joint points and main lengths of multi-link suspension system (Figure 7)

Axis	Joint points and lengths of links (mm)											
	A	B	C	D	E	F	G	H	$\overline{AC}$	$\overline{BD}$	$\overline{AB}$	$\overline{CD}$
y_i	-273	-273	-351	-351	-517	-554	-708	-876	220	220	170	170
z_i	317	147	111	-59	19	501	107	-181				

Axis	I	J	K	L	M	N	$\overline{CE}$	$\overline{EH}$	$\overline{GE}$	$\overline{DI}$	$\overline{HI}$	$\overline{ML}$
y_i	-876	-913	-950	-930	-1017.5	-1017.5	190	410	210	600	170	325
z_i	-351	-176	-344	-250	-250	-650						

Many authors in his research have analyses only the quarter vehicle suspension system. Therefore, it is seems to be enough sufficient to analyse only the quarter vehicle suspension. This justification is a reason that terrain vehicle is equipped with same suspension mechanism in all wheels.

Figure 8 shown wheel trajectories of the double wishbone with longer equal control arm and developed multi-link suspension system.

When wheel moved from its rest position to downward (rebound: 0 ... – 250 mm), multi - link suspension system (green line, Figure 8) provides 45% less displacement of wheel in lateral motion. When wheel move upward (bound: 0 ... 250 mm) situation is better and produce 72.6% less displacement of wheel compare with double wishbone suspension system (red line, Figure 8).

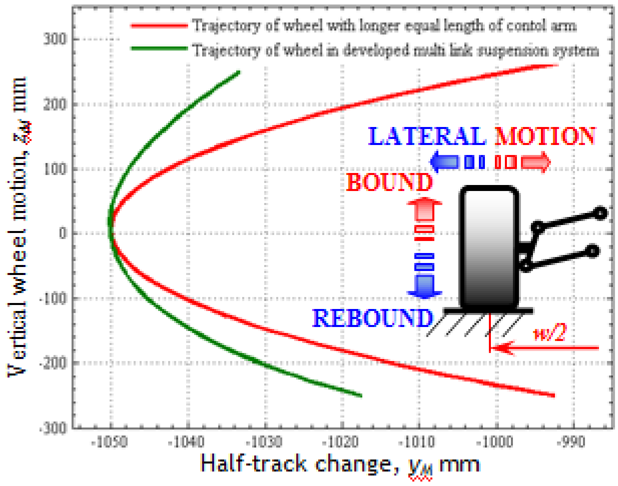

Figure 8 – Comparison of wheel trajectories between double wishbone and multi-link suspension system

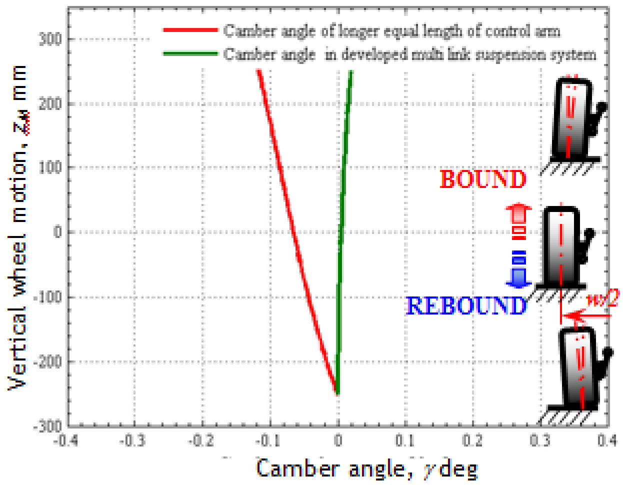

Figure 9 – Comparison of camber angle between double wishbones and multi-link suspension system

Investigations have shown the vehicle suspension system, most of time operates upward from rest position as result of road excitation caused by road bump. In this case, suspension system provides a relatively small amount of displacement of the wheel in lateral direction. Such displacements in other systems are considered to be relatively large. Therefore, such suspension system provides good performance and directly affects in improvement of life expectance of tire, reducing the addition load in suspension mechanism and improves stability of vehicle during driving in various terrain.

Changes of camber angle between double wishbone with longer equal length of control arm (red line) and multi-link suspension system (green line) in function of vertical wheel motion (bound or rebound) is shown in Figure 9. From this diagram is seen the change of camber angel in multi-link suspension system provides a relatively small values nearly to zero, which means offers better contact between tire and road surface. This improving in contact are a result that suspension mechanism allow wheel respectively tyre to acts perpendicular in road surface. This improve, has influence to improve vehicle stability when vehicle operate in the roughness terrain, cornering, acceleration as well as during braking process.

CONCLUSIONS

This paper present design of the suspension mechanism intended to use in a terrain vehicle with four wheels steer and four wheels drives. The main aims are concentrated to design an independent suspension system to provide better contact of tire with road surface and less lateral displacement of the tire. Following are derived some important conclusions, such as:

- *Designed suspension system provides 45% less displacement of the wheel in lateral motion. When wheel is pushed upward situation is better and provides 72.6% less displacement compared with same double wishbone suspension system,*
- *Designed suspension system provides relatively small values of camber angel nearly to zero which influence to have better contact of the tire with road surface. This improve, is a result that suspension mechanism allow wheel respectively tyre to acts perpendicular in road surface.*

The large vertical motion of the wheels (- 250 ... 250 mm) will be caused a lot of problems in steering mechanism. The large vertical motion should be not influence on the contra torque on the steering wheel, but have ability to rotate the wheel around the kingpin axes for minor angle thus causing the vehicle to decrease stability. To avoid this problem completely new design of steering mechanism should be done. Achieved results that are presented here in general will help the designer of vehicles to equip his vehicle with such suspension system, especially terrain vehicles.

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