KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

Venkatanathan Raghunandan

RIDE PERFORMANCE ANALYSIS OF A MOTORCYCLE WITH INTERCONNECTED SUSPENSIONS

Final project for Master degree

Supervisor
Assoc. Prof. Dr. KESTUTIS PILKAUSKAS

KAUNAS, 2015

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Supervisor
Assoc. Prof. Dr. KESTUTIS PILKAUSKAS

Reviewer
Assoc. Prof. Dr. VYTAUTAS DZERKELIS

Project made by
VENKATANATHAN RAGHUNANDAN

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN

(Faculty)

VENKATANATHAN RAGHUNANDAN

(Student's name, surname)

MASTERS IN MECHANICAL ENGINEERING AND ME M-3/2

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SANTRAUKA

Darbe pasiūlyta motociklo su tarpusavyje sujungtomis pakabomis koncepcija. Derinant tarpusavyje sujungtų pakabų darbą siekiama pagerinti motociklo stabilumą, , jam atliekant būdingus manevrus. Pasiūlyta dviejų svirčių – priekinės ir galinės motociklo principinė konstrukcija, kuri ženkliai skiriasi nuo tradicinės motociklo komponuotės, turinčios priekinio rato šakę ir galinio rato svirtį. Svirtis jungiančioje grandinėje esminius vaidmenis atlieka tamprus ir slopinantis elementai. Sudaryti dinaminis ir matematinis modeliai, aprašantys motociklo greitėjimo judesį. Matematinis modelis realizuotas blokine diagrama Simulink aplinkoje. Analizuojamas motociklo vertikalusis ir korpuso sukamasis judesiai įsibėgėjimo metu, šuoliškai pridėjus pastovaus dydžio traukos jėgą. Kadangi, esant priekinio rato svirtinė pakaba neleidžia panaudoti tradicinio vairo mechanizmo, pasiūlyta nauja principinė vairavimo mechanizmo konstrukcija. Gauti rezultatai rodo galimybę toliau vystyti pasiūlytos konstrukcijos motociklų pakabas.

ŽODŽIAI : Motociklas, Sujungtieji suspensija, Dinaminiu modeliavimu, Masės skirstinio, Vairo mechanizmo.

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SUMMARY

In this thesis, it can be seen in detail about the parameters affecting the stability of motorcycles and how they are going to be solved using the interconnection of the suspension systems. By doing this interconnection, establish the mathematical model for new design in interconnected suspension. As this primarily uses swing-arm, a new unconventional steering mechanism is also designed Even in today's most technically advanced motorcycle's suspensions are not able to provide the correct amount of weight transfer, according to the conditions of the speed at which the rider is trying to accelerate or brake. The most important thing is the constant amount of weight transfer at all conditions will put the motorcycle stability on a question mark. So here a new attempt is made to reduce the necessary weight transfer and the control of weight transfer through interconnections suspensions. All the motorcycles today have independent working of front and rear suspensions, but in this thesis they are coordinated towards each other for more efficient working and precision.

KEYWORDS: Motorcycle, Interconnected suspension, Dynamic modelling, Weight distribution, steering mechanism.

KAUNAS UN IVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of Mechanical Engineering Department

(Signature, date)

Vytautas Grigas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Ride Performance Analysis of a Motorcycle with Interconnected Suspensions

Approved by the Dean 2015 y. May m. 11 d. Order No. **ST17-F-11-2**

2. Aim of the project

To develop the concept of a motorcycle with interconnection of suspensions make analysis of its functionality and feasibility of its implementation in design solutions

3. Structure of the project

1. Analysis of the results in research and development of interconnected suspensions for four and two wheeled vehicles;
2. Proposal of the concept of a motorcycle with interconnection of front and rear wheel suspensions and definition of the problems in development of such vehicle;
3. Development of dynamical and mathematical models of the motorcycle with interconnected suspensions for acceleration braking analysis
4. Simulation of the vehicle performance in case of constant traction force accelerating and discussion on the results obtained.
5. Proposal of the steering system design concept
6. Conclusions

4. Requirements and conditions

Geometrical, mass and structural properties of the conceptual prototype should be in compliance with the corresponding properties of conventional high performance motorcycles.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student **Venkatanathan RAGHUNANDAN**

Task Assignment received **Venkatanathan RAGHUNANDAN** ______________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Assoc. Prof. Kęstutis Pilkauskas ______________________
(*Position, Name, Surname*) (*Signature, date*)

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KEYWORDS: Motorcycle, Interconnected suspension, Dynamic modelling, Weight distribution, steering mechanism.

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1. INTRODUCTION

The motorcycle is a tool to an individual, to assist what he loves to do. The job of an engineer is precisely, to sharpen the tool. As the specs of the motorcycle is increased, the optimization of the same is increased according to the characteristics of the rider and the extension of his body. So it becomes very important to optimize the motorcycle for optimum ride, enjoyment and safety through adrenaline. The most important parameter is the vehicle geometry and suspension which conventionally controls the geometry. If we take from a normal commuter based to grand prix motorcycles, suspension and vehicle geometry are primarily given more importance to ensure better aerodynamics, stability and comfort for the rider to take it through corners as fast and safe as possible. The proportionate fact about motorcycles is that, the technology of the same has always been in emerging trend while the skills of the humans who possess it, are not having the same emerging skills to handle those, except for a few. So it becomes a necessary point for every engineer involved in this, to have this fact in mind and concentrate on safety that can be through suspension and vehicle geometry character, although finally it is on the people who possess it. The design of vehicle suspension systems involves a compromise between ride comfort and vehicle handling. A softer suspension yields good ride performance with the expense of poor stability and directional control. Alternatively, a stiffer suspension enhances the chances of hard-braking maneuvers and trying to reduce additional amount of weight transfer towards the front, as it induces a lot more weight than the tire could withstand eventually ending up low side crash, here the ride comfort is compromised towards performance. Adversely what it really requires is the combination of a stiffer and softer one to make it through places very fast and safe, controlling the pitch. Each different rider has different opinion about their ride comfort as well as about their stability, but consolidating, all the possible configurations of adjusting them, a new design is tried in order to give the exact amount of weight transfer towards at very different situations.

AIM

To develop the concept of motorcycles with interconnection of suspensions and to make analysis of its functionality. The creation of mathematical model, a steering design is introduced, as normal steering mechanisms cannot be proposed for this model of suspensions. To carry out simulations using Simulink in order to check the system under the condition of acceleration.

TASKS

1) Analysis of research in results in interconnected suspensions development.
2) Develop a design concept of motorcycle with interconnected suspensions.
3) Dynamical model development.
4) Building mathematical model for interconnected suspension in accelerating maneuver.
5) Simulation and simulation result analysis.
6) Proposed design concept of steering mechanism for motorcycle with interconnected suspension.

2. PREVIEW OF PREVIOUS RESEARCH ATTEMPTED

Basically, suspensions are to deal with bumps in road surface and also to improve the overall leisure of ride. As a vehicle is riding over rough surface, coil springs are subjected to a load and by the time when they are subjected to a load, the function of spring is to take the load and release it without affecting the interior of the system. This action of taking the load is the main function of the springs and to absorb it. But, even though the springs have the quality, the nature of oscillations are liable to be produced. For this application, the process of damping is introduced into the suspension system, as they reduce these oscillations to a very significant level. In recent days, companies have been making a lot of research in damping characteristics in order to maximize, the control of oscillations. These oscillations have a specific limitations that, an ordinary human could withstand. It is in the limitation in between 1 and 1.5 Hz. If it is more than the specified limit, according to normal human behavior the intensity of load will be felt. Therefore ride quality is mostly controlled by the selection of suitable springs and dampers.

Gillespie stated that a suspension mechanism's primary function is to:

1. Eliminate the load taken by the chassis from the surface of the road, as well as to make the wheels follow the path;
2. Maintain the required wheel profile in relation to the surface of the road, such as steer and camber angles;
3. Transmit forces and moments produced by the tires on the vehicle;
4. Proper resistance to make the chassis roll;
5. Maintain tire and road to be in contact and to minimise ub-normal load variations.

Even in early stages in the dynamics of vehicles emphasized upon the purpose of suspension as a system to provide optimum ride comfort in lots of perspectives. This primarily means the separation of vehicle body from external forces. By early 50s, searching in great importance for performance in dynamic aspects of performance in handling as well as stability aspects were the prior perspective to optimize. In general, a vehicle with a relatively stiff suspension is likely to possess good handling stability but poor ride comfort, and vice versa.

One way of compromising the ride was done by the use of passive interconnected suspensions. This primarily means that, by the means of interconnecting in-between the individual wheel stations. Smith and Walker define a suspension system as interconnected when a displacement at one wheel station can produce forces at other wheel stations. Particularly in vehicles with two or four wheeled interconnections are done by the means of hydraulic or pneumatic components. Those effects in two wheeled interconnected suspensions, can be stated in two main methods. One of those methods is a type of anti synchronized interconnection in a stiffer one in motion in relation to the motion which is in out of phase, and another methodology is the non oppositional interconnected suspension to stiffen, the suspension which is in out of phase to relative motion.

Type of Interconnection	Same End (Front/Rear)	Type of Wheel Pairing (Right/Left)	Diagonally Opposite
Anti-synchronous (Z-bar or third string)	Stiffens, pitch & bounce	Stiffness, roll & warp	Stiffness, bounce & warp
Anti-oppositional (U-bar or T-bar)	Stiffness, roll & warp	Stiffness, pitch & warp	Stiffness, roll & warp

TABLE 1.1 Describing different types of interconnections with their impact on performance [8].

The most common advantage of interconnection of suspensions is that, the designing has more flexibility and even more control over the parameters that affects each and every mode of variation, instead to rely entirely upon the suspension at one particular corner of the vehicle. This gives a greater thinking perspective about the variations of modelling, in rather going in for conventional suspension mechanism. This thesis mainly focus on those variants, but at a smaller scale on some basic assumptions for introducing new concept of interconnection. In vehicles, the dynamics and its properties seems too similar to that of a motorcycle, but on a three dimensional basis, motorcycle dynamics is far complicated to analyze from its variants. With conventional suspensions these variants are not able to be analyzed and optimized for betterment of performance, but doing this interconnection, as it is stated above, the desining part has the ability to go beyond these parameters and also to optimize them.

There are four such modes for any vehicle which is subjected to constant roughness in road surface. The bounce mode and the pitch mode occurs particularly when the body of the vehicle having a rotational pitch or to be exact, it experiences a longitudinal type of oscillation and opposite to that motion is when the roll occurs due to the transverse oscillations. Particularly for the roll mode, the occurrence is characterized by bad weight distribution of the chassis in the transverse mode, pitch occurs when only wheels at one end (either front or rear) are subjected to load at equivalent rate, and twist (articulation or warp) occurs when only wheels diagonally opposed are subjected to surface roughness. Any oscillations occurring in vehicles can be classified as an umbrella term within these modes. In concept grand prix racing, these aspects should be eliminated at will, as they are solely built for the purpose of going very fast.

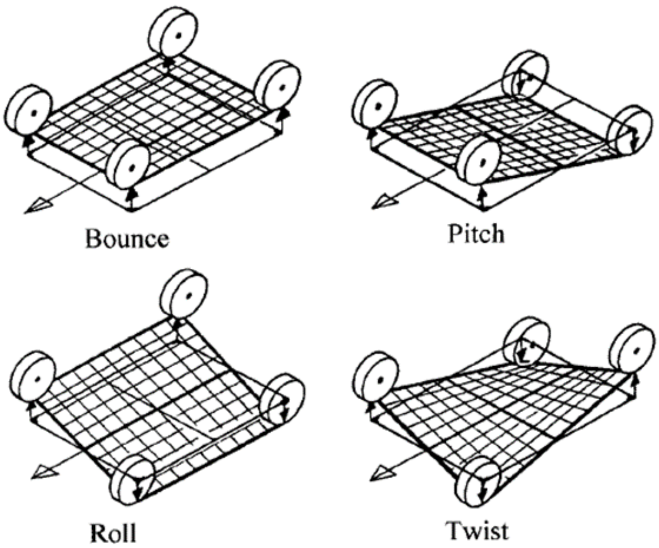


Fig 1.1 Depiction of different modes in vehicles [8].

A suspension system that is hard or stiff enough to withstand the changes that is infused to the ride through loads, particularly to the aerodynamic load. Also the suspension needs to resist changes of oscillation that infuses towards the pitch or roll oscillations, when subjected to the acceleration, traction, braking and cornering forces [8].

“THE BOUNCE-MODE - The bounce mode mainly occurs due to the aerodynamic down force acting on the vehicle. All the static load, vertical inertial loads, and the aerodynamic loads acts upon the system either when the system has more capacity for more speeds or the weak aerodynamic layout, also it can be due to poor weight distribution. For almost all types of vehicle, the bounce mode should have a rising rate, as shown by the solid line in Fig 1.1. This gives the vehicle a spring rate that rises in proportion to the load on the vehicle. When the vehicle is lightly loaded, it has a soft bounce-mode. When it is heavily loaded, the bounce-mode is much stiffer, and the vehicle is less likely to “bottom-out”.

THE PITCH-MODE - The pitch mode can be one of the modes to take on the loads acting on the system. The pitch mode that requires to resist in pitch attitude particularly for different parameter. Therefore for any racer, in pitch mode the spring rate that is highly non-linear is suitable. The rate of pitch should be stiffened up to yield when there is morer braking in the corners and accelerating more quickly. This type of arrangement can help any enthusiast to perform better in terms of performance. Here weight distribution is the main parameter that makes the change.

THE ROLL-MODE – Roll mode have the insecure mode in the four of the modes, it is just because of the fact that it could absorb only some sort of the bumps. The occurrence of situation for roll mode is very rare cause. When a normal vehicle making a turn have its load acts on the opposite sides of the wheel in the turn. The controlling of the roll mode occurs only when two wheels on the same faces a load acting on them at the same time or on the proportionate level

THE TWIST-MODE - This mode is the base for the design for interconnected suspension. Other conventional suspension mechanisms, have the challenge of controlling twist in a larger perspective. But when this mode is controlled in the larger scale then the suspension mechanism is flawless because only when the parameters of the system can be controlled. These parameters are for the vehicles with a commodity market, but the case scenario can also be in grand prix cars because, the scale of the twist is not that much high due to the surfave of the road.

The essential part to note that the perspective differs from other modes in a very two important aspects, if it is on the non-planar mode which allows the vehicle to do a transverse spatial surfaces, as it is controlled entirely by changing the geometry of the surface but considering with no inertial sprung mass components. Which means an excitation purely of the warp mode by the road surface would not result in any sprung mass motion (relative to the ground). Articulating stiffness do not contribute in direct to sprung mass stability but in rather influencing performance of the handling, getting through the effects on tire and road contact forces. Consequently, a soft warp mode is generally considered desirable. For typical passenger cars, a soft bounce mode is also typically sought, as it leads directly to improved ride comfort through reduced vertical acceleration levels in the cabin (sprung mass).

2.1 PROPOSED CONCEPTS OF INTERCONNECTED SUSPENSIONS IN CARS

By far the most easy and simple form of interconnected suspension arrangement in current use is the anti-roll on bar. [20] This anti-oppositional mechanism provides increased roll mode stiffness through a mechanical stiffness-only interconnection between left and right wheel pairs. This is particularly because of the fact that it can possibly reduce the stresses on the roll mode. This application is very important because of the fact that, cars in WRC can have lots of twist and roll modes and can often been seen with these anti-roll on bars. Anyways having these modes in a car is effective to give overall handling character, but with a compromise of the articulation stiffness, that concentrates to one single wheel. This can be disadvantageous in a lot of aspects.

The idea of interconnection is to make the suspensions along with the damping characteristics to co-ordinate with each other to distribute the loads in which they are subjected to. This cannot be possible in independent suspensions. That is why, even in the most modern study about interconnected suspensions can yield better in overall performance.

In early 20s, Hawley had an illustration possible interconnected suspension arrangements to control roll and pitch modes, which affect the performance in a large scale. He has also designed for four wheel interconnections, which diagonally represents the interconnected arrangements, as shown in Fig 1.2. Hawley's invention consisted of four double-acting cylinders interconnected hydraulically, wherein the interconnected pistons "move more or less in unison", implying that the fluid system transmission characteristics had not been considered in detail.

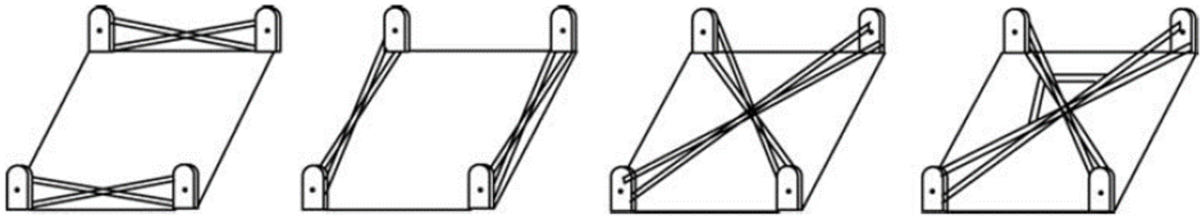


Fig 1.2 Hawley's interconnected suspension arrangements from the 1920s [20]

The first uses of interconnected suspensions in the automotive industry was on the pitch and the plane arrangements and it was then realized mechanically to the citreon 2cv. It used a hydro-pneumatically actuated in moulten's hydro elastic systems, which was studied widely in the later mid periods of 1900s. Fig 1.3 shows the schematic representation of the system.

The type of anti synchronous illustration, shown in Fig 1.3, served to increase the riding performance by controlling the pitch and other articulation modes in relation to the bounce and roll modes.

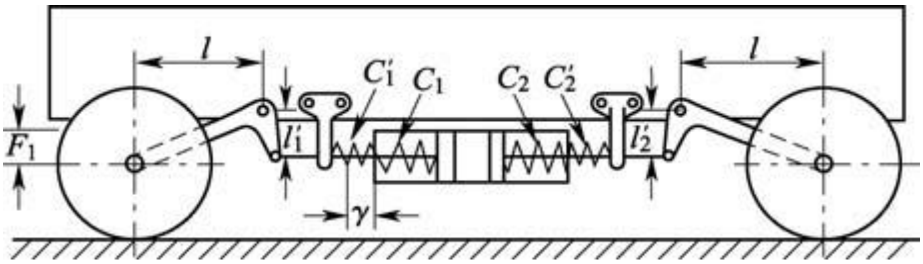


Fig 1.3 Schematic representation of the early Citroen 2CV suspension [20]

There was the need for the development of the Hydro gas system was importantly because of the more emerging trends to use shorter and more compact hatchback vehicles, but with higher pitch frequencies in the United States. Experimental part of the analysis proved that, there is increased ride performance and also in achieving objectives comparing over the conventional suspension mechanism at frequencies of 15 Hertz. These results which are greater than 15 Hertz, are in a mixed combination. In their study, simplified theoretical model was done and no simulation or validation of the model was done. Their theoretical model was supposed to have, had some linear viscous loss and also there fluid inertial effects, but they were neglected.

Many years after the primary concentration on the general dynamic vehicle aspects, emphasis shifted towards modes in the development of vehicle modes as discussed earlier in this chapter. The main motivation was to control the roll through hydro gas suspension which was arranged by the way of actively suspending mechanism. Later, there was still a demanded need for more simplified mathematical model for hydro gas model, in order to analyze the performance. They represented the mathematical model for both linear and bilinear presentation, for the stiffness and damping character. The terms of the matrices were determined empirically, and found that even the more advanced and sophisticated bilinear model had its limitations in the accurate manner in a frequency range of 1 to 8 Hertz.

In the late 80s and 90s companies like Nissan and Toyota attempted to develop a model on interconnected suspensions in order to improvise the overall ride comfort in the basis of pneumatic and hydraulic types of interconnections. However in both of the cases the focus of attention was on the development of fluid system modelling in the place of development of control system and the experimentation.

The consideration of the sensitivity analysis, as the effect of various several parameters, where some of them include flow loss coefficient, air spring volume to air ratio and the weight distribution of the vehicle in several perspectives. Although, there were limitations with the single line interconnection model as the model was simple and the omission of fluid component system and allow its effects to get associated more complex multi-line systems. In the late 90's Australian engineer [20] Chris Heyring invented kinetic suspension system, where the patent was acquired by a company by name Tenneco in the late 90s. The organization emphasized on the production development of the suspension technology. The adoption of the technology was on citreon C4 rally car, but the World Rally Championship banned the technology and the application of the technology also includes Lexus GX470. The utilization of gas and hydraulic pressure towards the improvement of ride comforts in active anti roll functionality. The technology has the ability to provide adaptive damping and therefore it is regarded as semi active suspension.

Four hydraulic cylinders are placed in the place of convention damping systems in which each of them contains a chamber for compression and a chamber for expansion. The concept of interconnection is introduced to the system by interconnecting the expansion chambers on one side and the compression chambers on the other and the right opposite again. The picture below should give you a clear idea Fig 1.4 (a). This interconnected mechanism has a large weightage in order for the establishment of better ride comfort. These mechanisms can be controlled and actuated to a large scenario in such a way that the systems have the ablity to control all the modes that is pitch, roll, bounce and twist in a wider aspect and the optimization of the system becomes important for the consideration for the better stability and ride performance issues.

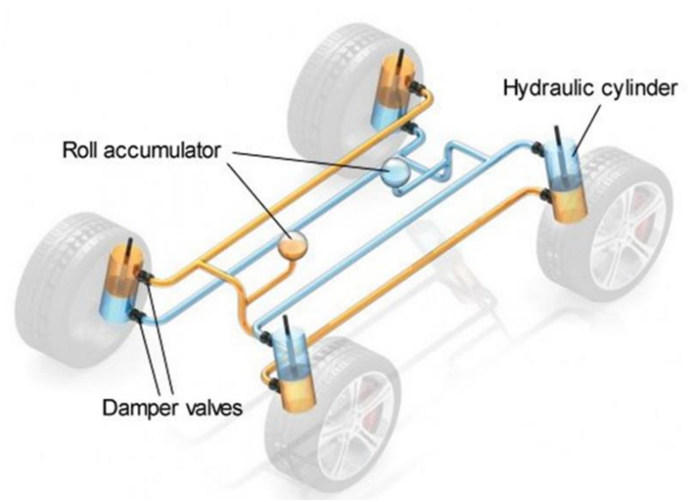
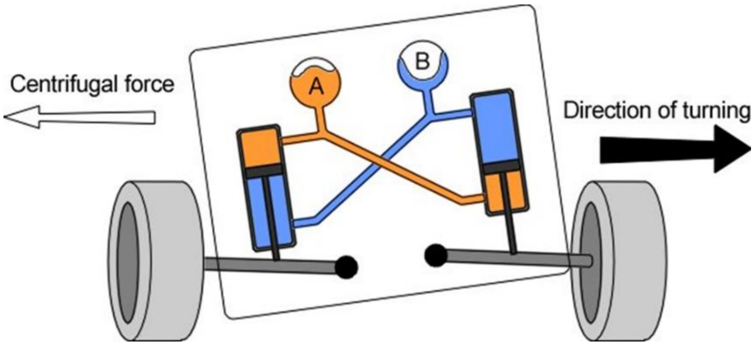


Fig 1.4 (a) Concept of Interconnection Proposed for lexus [20].

As it can be seen there are two roll accumulators that can be located in the hydraulic circuit. Accumulator contains oil and pressurized gas which is separated by the flexible membrane. The function of the electronic control unit is to vary the gas pressure. If the gas is pumped more in the accumulator, oil will be pushed backed to the circuit. If the gas pressure is released, the allowance for oil is allowed to flow inside the accumulator. The quantity of oil pressurized into accumulator depends on the intensity of the load.

When the steering mechanism is considered and explained, the main focus is on the roll mode. The constant actuation of the roll mode is controlled in this mechanism. When considering the case of steering the centrifugal force acts opposite to the side of turning, in the same way the load transfers itself to the opposite wheel. During this case in the system due to the difference in the pressures of the fluid, it gets compensated making the necessary transfer of fluids to make the damping as well as to distribute the loads in order to avoid too much of weight transfer towards one single side of the wheel. This mechanism implicates the properties that can be controlled through the interconnected suspensions. The behavior of vehicle when making a turn is one of the most important part of the vehicle dynamics, it is because, it is practically not possible to have straight line surface. So it becomes the most important part of the analysis to make the forces acting on the wheels when they make a turn.



(b) Half car model of the proposed design

A similar mechanical system can be designed for superbikes, where the front and the rear suspension are connected in such a way that the effect of pitching and weight transfer during braking can be used as an advantage to increase the stability and traction of the vehicle. But such type of interconnection needs, to be very specific in terms for motorcycles as there is space limitations. In this thesis a new type of interconnection is proposed, in order to reduce the disadvantages of the conventional suspension mechanism used in today's motorcycles.

2.2 STATE OF ART IN MOTORCYCLES

As far as the interconnection of suspensions in motorcycles is concerned, the concept was proposed by Moreno Ramirez, Gracia Fernandez, De Juan and Thomas Rodrigreuz,[23] in which they carried on the research on the emphasis of the dynamical response of the interconnected suspension system on a standard sport motorcycle. Their research contained a geometrical analysis of the motorcycle under the study of the suspension behavior on a rough road surface and a state space representation of the motorcycle was done through vehicle sim software.

The interconnection of suspensions in the field of motorcycles was not extended as in car industry, as it is limited to very less number of proposals. However, some proposals has been placed in the last years is the Creuat system one of the most significant examples. In all these cases, interconnection is presented as a way to uncouple the different modes involved in the suspension motion. Their main proposal was that, this attempted interconnection would significantly bring the scenario of adjusting stiffness and damping for pitch and bounce modes, which is what we are also precisely concentrating on this thesis too.

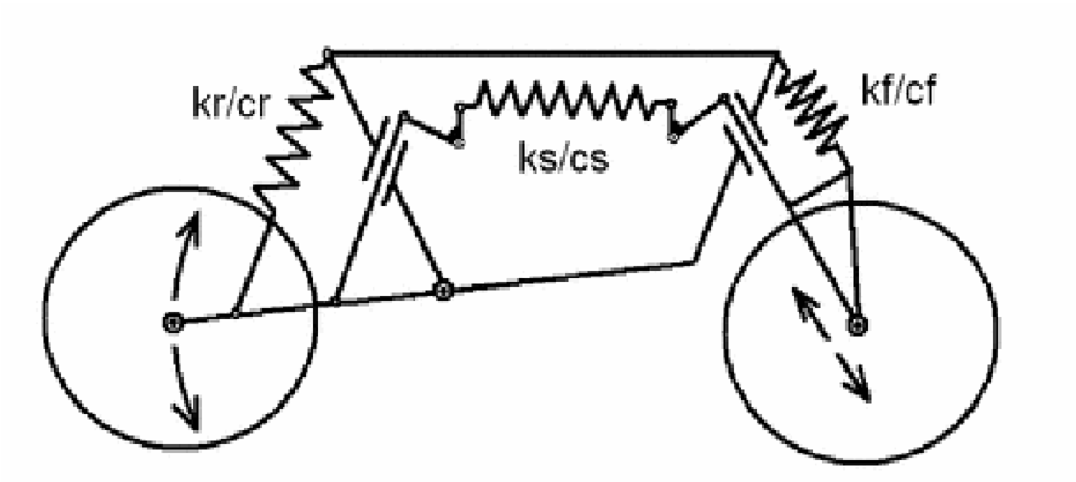


Fig 1.5 First interconnected suspension in motorcycle proposed [23].

The above figure shows about the interconnection of suspensions model that was proposed earlier. The above mechanism consists of a classical front and rear suspension system on a sport motorbike which are connected through a spring unit. In the scheme that was proposed, two levers systems were used to represent the physical connection between the central unit and the wheels. In their approach to the geometrical relation between the wheel displacements and the spring compression provided by these levers were considered constant. They represented the geometric relation between the fork compression and the front tip interconnected spring and the geometrical relation between rear swing arm arm rotation and the rear tip of the interconnected spring , the total force and the moment exerted by the spring system on each wheel is represented in the below equations. Both of these equations are dependent on the fork compression and swing arm angle.

$$F_s = -(kf + cdf^2 \cdot ks) \cdot Z - (cdf \cdot cdr \cdot ks) \cdot \theta$$

$$M_s = -(cdf \cdot cdr \cdot ks) \cdot Z - (kr + cdr^2 \cdot ks) \cdot \theta$$

This was the first practical attempt on the interconnection of suspensions in motorcycles whereas the previous investigations has been provided, as for the reference for the interconnection technological attempts in the automotive industry. As to proceed further, this literature tends to take even more detailed aspect, on the attempts made on the control of braking and weight distribution parameters on conventional motorcycles. These had to discussed here since, in this thesis we are going to concentrate not only to control pitching but also optimum braking performance. Tire characteristics are very important for this thesis, as the primary analysis does not involve a lot of tire characteristics, as the tractive force is made constant, but for further analysis, tire characteristics are mandatory to be analyzed for this arrangement proposed.

In an attempt Matteo cornoa, Sergio matteo savaresia, Mara tanellia, Luca fabbri in 2007 [21] analyzed about the optimum braking charecteristics on a motorcycle. Their starting point of the work was on the analysis of a typical hard-braking maneuver performed by a professional driver, where the measured front-wheel speed, front-brake pressure and suspensions elongation were analyzed (the measurements are made on the MY05 Aprilia RSV1000 Factory). During their braking maneuver, the rear brake was not used for the convinience for the research.The brake pressure had a ramp (of about 250 ms),and then it was followed by a small brake release, then the brake pressure is kept almost constant until the end of the braking maneuver. By inspecting the elongation of the front and rear suspensions, it is interesting to observe that the suspension hard-limit is reached in both cases; notice that this means that the rear-wheel is at the contact limit, apparently, this induced the driver to avoid turning the vehicle before the braking maneuver was ended.

Among riders and race engineers its a common opinion that the braking phase is the most critical and have to make sensitive maneuver too. [13] The ability of a rider to achieve an optimal braking can make a significant difference on the lap-time when they want to push themselves to the limit.

Even few milliseconds per braking hence can be very crucial. Due to this scenario it becomes very important to analyse the braking parameters of the motorcycle. Due to this , generally motorcycles for racing purpose have a harder setting for the front fork as they brake a lot deeper in the corners with minimized pitching towards the front.

Minimum pitch towards towards the front means, ability of the motorcycle to brake in with more stability is a proportionate fact about it. But the most important overall picture about the motorcycles is about the suspensions as a general term is independent. Motrcycles unlike vehicles have the space constraints and also dependency to control the weight transfer is there, particulerly for motorcycles with the coordination of the front and the rear suspension. But definite fact about the suspensions in motorcycles is that, when an interconnection can establish a relation between the front and the rear there can be optimization of more parameters than that of in the current conventional suspension mechanism.

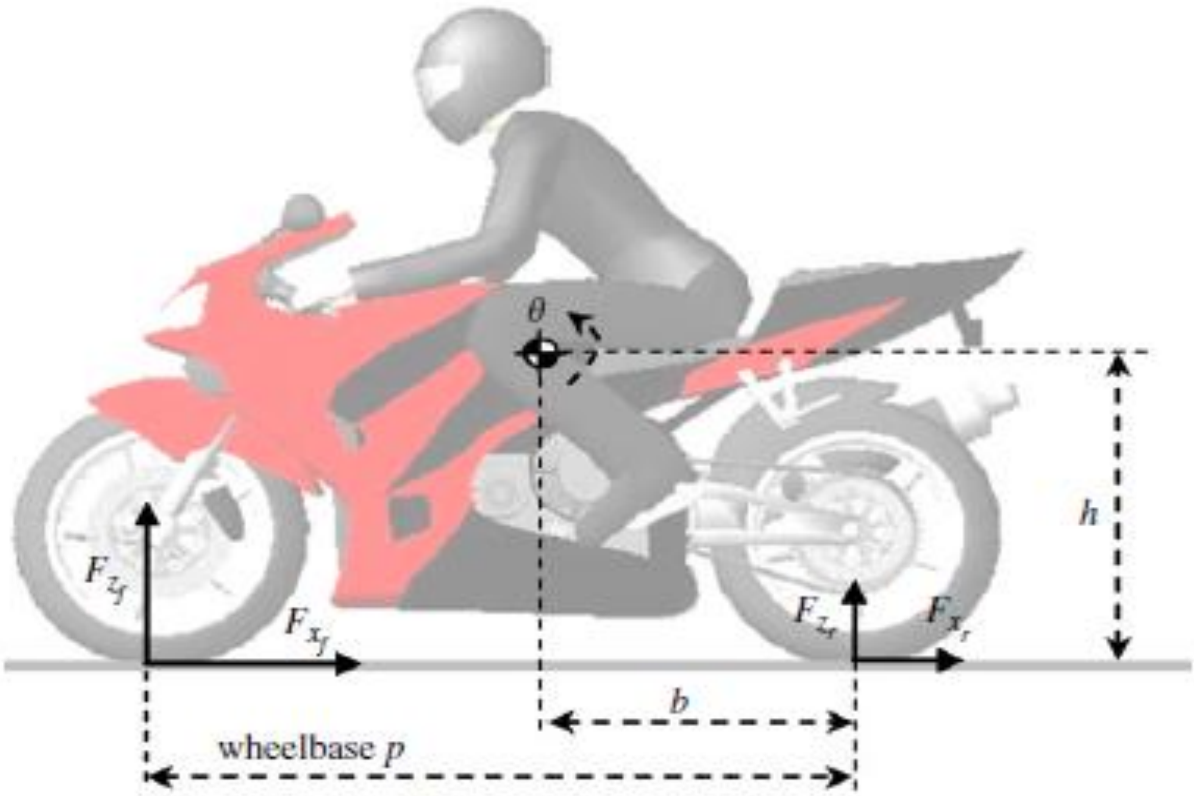


Fig 1.6 Advanced simulation in GUI of BIKESIM software[21].

The above figure shows about their analysis that was carried out in the GUI of the BIKESIM software and the analysis of the pitching, weight distribution and braking parameters were incurred. In their work the problem of high-performance braking was studied. There focus was on optimizing the braking performance, in terms of stopping time. All the main aspects of the problem were considered and the effect of aerodynamics on the loss of contact of the rear wheel,[13] the wheel-lock problem, the best torque modulation strategy at the beginning of the braking maneuver, and the role of the rear brake. Moreover, the sensitivity of the braking performance to fork damping was studied. Their results of analysis provided some useful insights on the problem of optimal braking. Moreover, their analysis showed the potential benefits of electronically assisted brakes and their benefits could be further exploited by joint design of braking control and semi-active suspension damping control, which is what the aim of this thesis and its work all about.

In the same view, Simos Evangelou, postulated about the concepts of stability analysis of motorcycles [22] where, the main mode of operation of a motorcycle is in free control, associated with the free steering system. Alternatively the rider can exercise fixed control, but under such circumstances the vehicle is unstable in roll at all speeds and therefore this method is not preferred. [22] There are many influences on the self-steering action, all of which can be observed and quantified when considering a vehicle under non-zero roll angle. Contributions are connected strongly to the design detail of the steering system and mainly arise from mass, inertia the tire force, tire moment and gyroscopic properties at the front of the vehicle, their relative importance being dependent on speed. It is also true that some have a stabilizing and others destabilizing nature, but in general the vehicle is able to self-stabilize without too much effort from the rider.

Nevertheless, [22] the self-steering capability of the motorcycle inevitably leads to oscillatory behavior, and it is a requirement that any motorcycle can self-stabilize effectively, without becoming too oscillatory under any circumstances. In straight running, the most obvious instability is the capsizing of the whole vehicle at low speeds, where it essentially behaves as an inverted pendulum about to fall over. Strictly speaking the instability is slightly more complicated than this, and it involves contributions both from the capsizing of the whole vehicle and the divergence of the steering system to the side.

In mathematical terms [9] these start as two real modes with positive eigenvalues at very low speeds that coalesce, when the speed is increased, to form a complex conjugate pair with a positive real part. At this point weave starts to form and at around 8 m/s is stabilized and has a frequency of about 0.7 Hz as shown in the left root-locus plot in figure listed below.

This mode involves movement of the whole vehicle-rider system with almost equal contributions from yaw and roll freedoms, and less from steer, with specific phase angle differences between them. With further speed increase the damping of the weave mode is increased until about 20 m/s and subsequently it begins to decrease, becoming lightly damped at high speeds. The frequency increases monotonically with speed reaching a value of about 3.5 Hz at high speeds. There are several parameters that could change the stability properties of this mode and these have been studied in the literature.

Under straight running conditions there is a possibility for another higher frequency lightly damped mode to appear, usually called wobble mode. It is mainly seen as relative motion between the fork assembly and the main frame of the motorcycle. The resonant frequency of this mode (6–9 Hz) is relatively unaffected by speed variations and is mainly set by the inertia of the steering assembly about the steer axis, the mechanical trail and the front tyre cornering stiffness.

The damping depends strongly on the torsional flexibility in the steering head region, with less stiff frames resulting in lightly damped conditions at moderate speeds. [13] The cornering situation is considerably more complicated. Steady state configurations require fixed values for forward speed, lateral acceleration, roll angle, yaw rate and tire side forces. These can be found by solving the non-linear algebraic equations of the equilibrium condition. The linear stability analysis involves small perturbations about the cornering trim condition, and the corresponding state variable values are required in the calculation of the linear analysis coefficients.

The in-plane and out-of-plane modes become coupled under cornering and this cross-coupling increases with roll angle. As a consequence, several modes were joined together to form combined modes with particular characteristics as shown in the right root-locus plot in the below figure.

Cornering weave is similar in frequency to straight running weave at high speeds, with decreasing damping as the lean angle increases, but now there is systematic involvement from the suspension system in the oscillations. [6] This has been observed experimentally and the influence of suspension damping on this mode has been demonstrated both analytically and experimentally.

Wobble possibly involves some suspension motions as well, and the previously speed independent suspension pitch and wheel hop modes now vary considerably with speed. A combination of front wheel hop with wobble could occur when the two modes are close enough to join, and this mode is possibly linked to patter, mainly known from anecdotal evidence at this point.

The coupling of the in-plane and out-of-plane motions also suggests that there is a possibility for road excitation signals to be transmitted into the lateral motions of the vehicle, causing steering oscillations by road profiling under cornering".

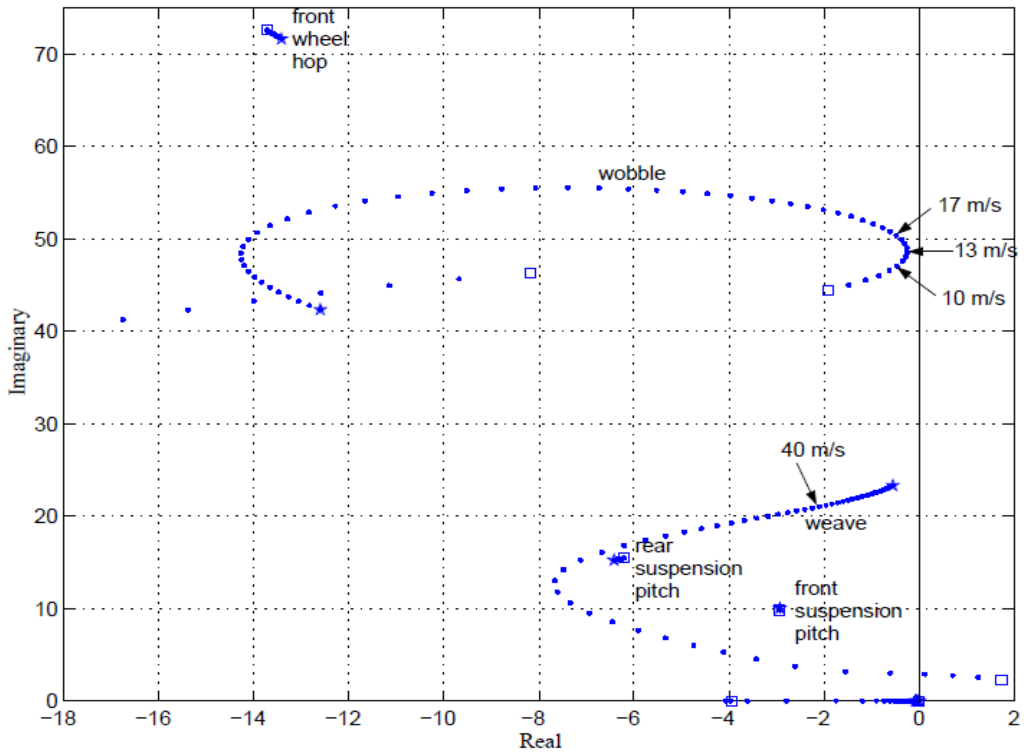


Fig 1.7 Comparison of pitching and wobbling characteristics with real and imaginary values in 2 Dimensions [22].

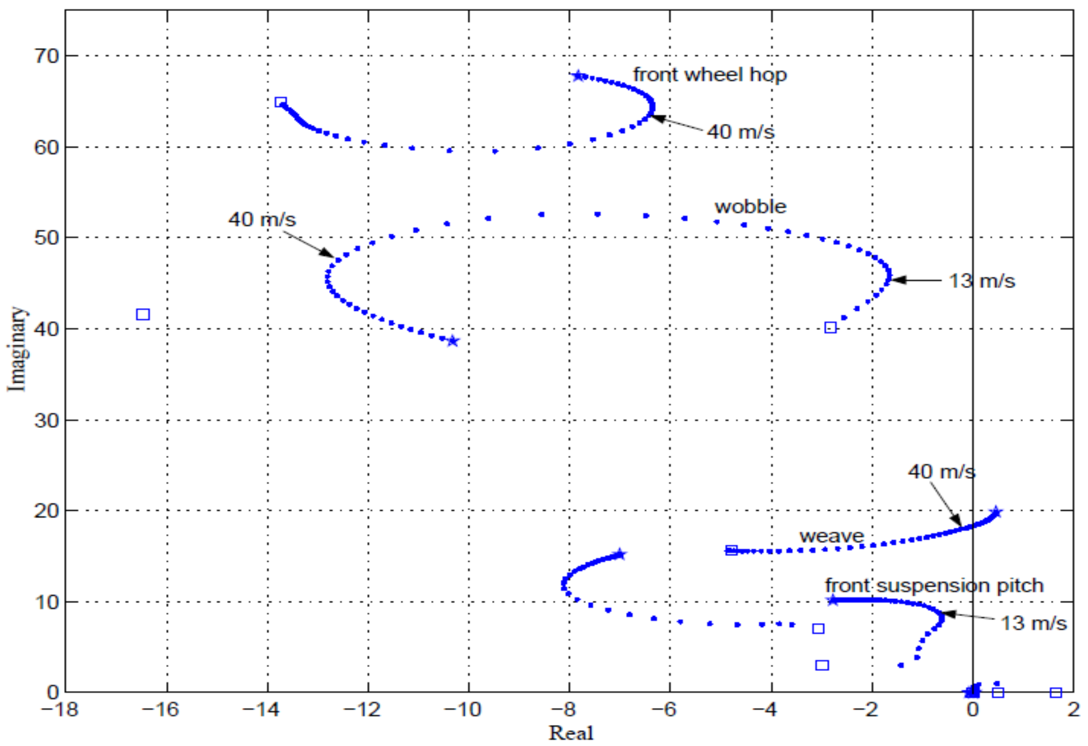


Fig 1.8 Comparison of pitching and wobbling characteristics in pitching and wobbling characteristics with real and imaginary values in 3 dimensions [22].

In 2005 Chih keng Chen, Thanh son Dao, Chih kai Yang, postulated about the dynamics of the vehicles in turning characteristics [5]. In their paper, a nine DOF dynamic model of two-wheeled vehicles was developed using Lagrange's equations for quasi-coordinates considering the contact relationship between the wheels and the ground surface, the constraint commons, including four holonomic and four non-holonomic constraints, were derived by combining the non-holonomic constraints and the velocity forms of holonomic constrains, the constraint Jacobin matrix was obtained with the developed equations of motion and constraints, the equilibrium of two-wheeled vehicles was fully investigated
The dynamic model of their study provided a fundamental understanding of the interesting dynamic behaviors of two wheeled vehicles. With their model, one can also Implement simulations, design controllers and do experiments.

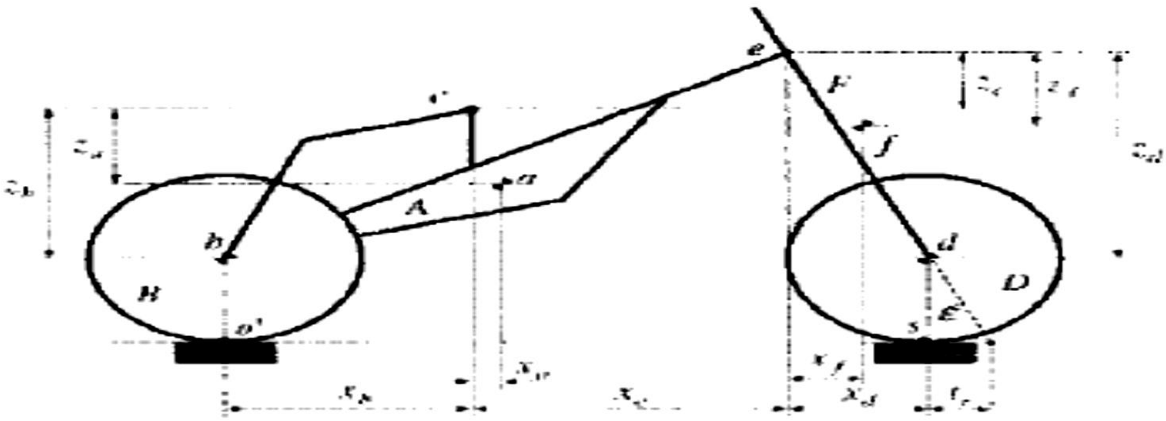


Fig 1.9 Two wheeled vehicle model converted form 3-D model [5].

In 2007 L.Wu and WJ. ZHANG proposed a step by step modelling of semi active suspension for motorcycles [4]. In their paper, a step by step modeling method was represented in order to frame different motorcycle model, compared to the old model with six degrees of freedoms system. Their control of the work were having a central control with two local controls and un-controllable parts. The front and the rear of the motorcycle are managed by the two independent 2 DOF systems. [4] “The driver and engine act as uncontrollable passive parts. The central control is composed of an algorithm made up of some dynamic equations that harmonize local relations”. The acceleration on the rotary pitch and the vertical displacement at the center of the suspension were treated as central control objects.. Linear Quadratic Gaussian (LQG) algorithms were adopted by two local controls, respectively, and Matlab software, their results of the simulation show that hierarchical modeling control requires less CPU time, reduces respond time and improves ride quality. The hierarchical framework is well explained with the fig 1.10.

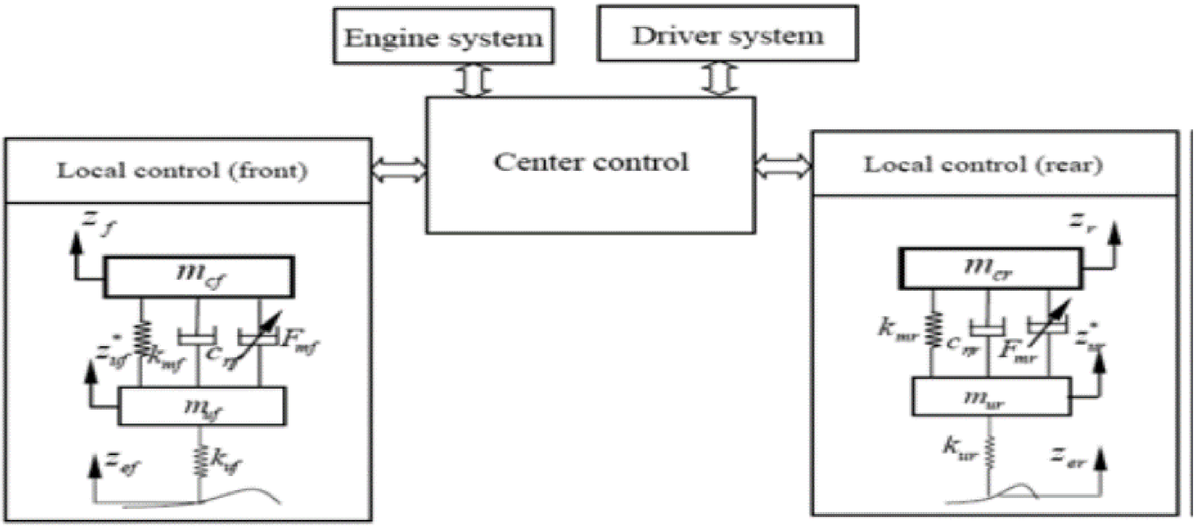


Fig 1.10 Proposed hierarchical modelling of control framework [4].

The total layout of the motorcycle suspensions could be treated as independent two DOF systems, according to the view of the control point Thus, some product of the matrix, which has four rows and columns, were required. Due to this reduction in a parallel aspect, the implication and the betterment of the hierarchical modeling control can probably be increasing and also with the level of detail, it could possibly emerge. Thus, it effectively shorten computing time, quicken response speed and increase sampling frequency, which indirectly improves the handling properties and ride comfort of a motorcycle. To realize the control mode, a continuous sprung-mass should be considered as two concentrated sprung-masses for the front and rear parts. Thus, an algorithm should be constructed so as to transform a motorcycle model with 6- DOF into two quarter suspensions with 2-DOF. Using this model, force analysis of the whole sprung-mass, separated from motorcycle model, must be executed first. Thus, two dynamic equilibrium equations for the force and moment of the sprung-mass center were written as follows

$$\text{“}M_c\ddot{x}_c = F_f + F_r - F_p - F_g$$

$$I_c\ddot{\theta}_c = -I_fF_f + I_rF_r - I_pF_p + I_gF_g\text{” [4]}$$

The analysis is used to transform the center motion into front and rear motions, so the relationship between the vertical motions of the sides of the sprung-mass and the center vertical motion was also taken into account.

$$“Z_{cf} = Z_c - I_f \theta_c$$

$$Z_{cr} = Z_c + I_r \theta_c” [4]$$

Fig 1.11 Force diagram of the sprung mass [4].

The purpose of their paper was to present a step by step modeling methodology in order to translate or convert a motorcycle suspension system with six DOF system into two quarter suspension systems without any special conditions. Decomposition and simplification of motorcycle suspension, resulted in the increased speed of control response, thereby decreasing the permitted sampling time. Thus, road excitation can be better described, and ride comfort of a semi-active motorcycle suspension can be improved. If the methodology can be adopted to the multi wheeled vehicles, the simplification of the model is easier and the complexity in working with more degrees of freedom can be avoided effectively. Therefore as they concluded that, step by step or hierarchical modeling technique is an effective technique for solving vehicle vibration problems.

In 2004 V. Cossalter, R. Lot and F. Maggio [1] did a model analysis of a motorcycle on a straight line and also on a curve. In the view of generalized vibrational modes in a motorcycle, the analysis was done with respect to several trim configurations. A 3 dimensional nonlinear mathematical model is developed and analyzed using natural coordinates approach. Proposal of a special procedure of evaluation of steady state solution for a motorcycle running in a straight and on curve was done. [1] Their paper presented about detailed modal analysis and results for production based sports motorcycle. In further reference, speed and lateral acceleration influence on stability, shape and coupling were presented. Finally, consistency between the first experimental tests and simulation results were shown in Fig 1.12.

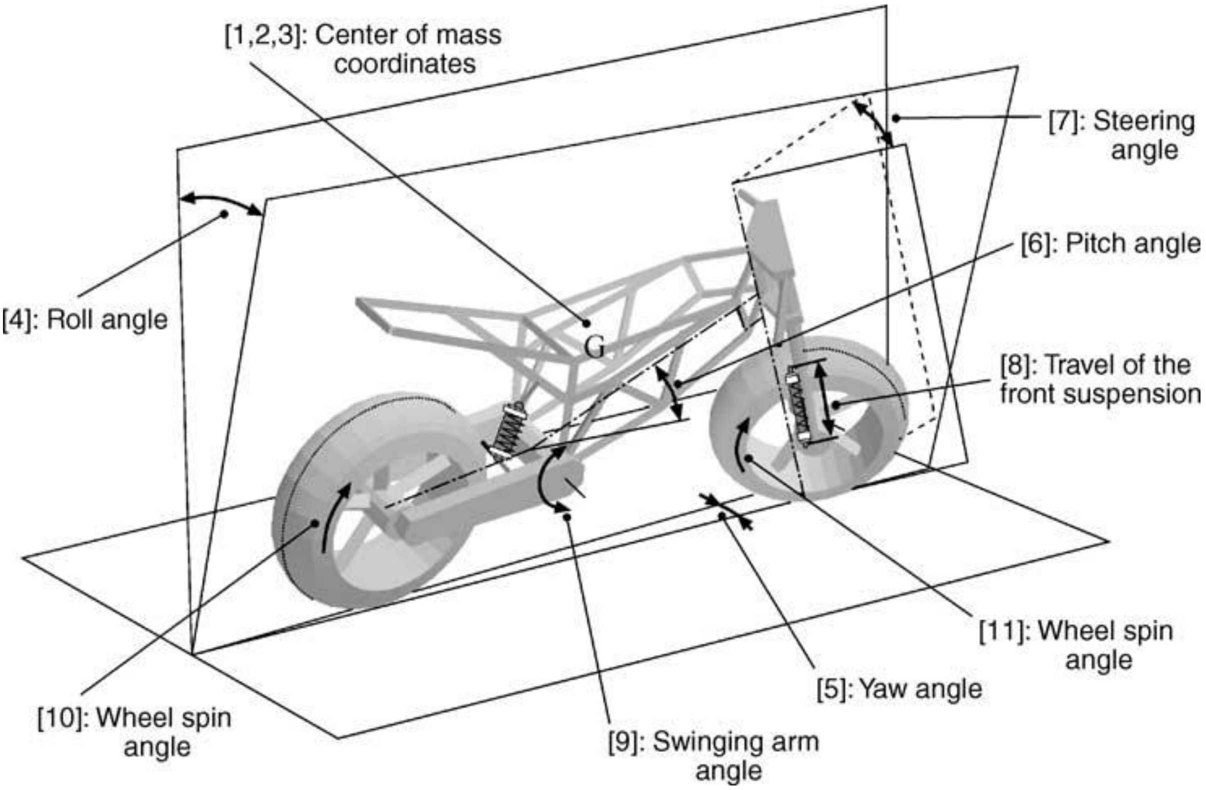


Fig 1.12 11- degrees of freedom motorcycle model [1].

The motorcycle with a multi body model is comprised of a six body system. The main consideration of the system are rear assembly, which variably includes chassis, engine and tank, while the consideration for the rider is the rigid body attached to the rear assembly. Another consideration was the front assembly that has the steering components, handlebars and the suspension. Here in further accordance they are more classified as the front unsrung mass which includes the part of fork which is not suspended and braking devices. The next is the rear unsprung mass which includes the swingarm and the rear braking device. Wheels are classified as last bodies. Their model was proposed with 11 degrees of freedom, as shown in the Fig 1.12. With reference to the figure there are 3 coordinates that define the entire rear assembly with orienting them spatially. In the other part to define the front assembly a 5 degree of freedom system has to considered as in the orientation it very much depends upon relative motion between the motorcycle parts, steering angle, pitch angle and the wheel spin angle. The motorcycle uses a front telescopic suspension and the rear has a swingarm type of suspension like a conventional motorcycle. The engine power is transmitted to the rear wheel through a chain drive system that is employed to ensure optimum power transmission at varying speeds. They also included the parameters like lift, drag and the lateral forces. The quantities that has to be input is the propulsion torque, steering torque and braking torque, but the leaning motion with the rider is avoided in their model. In their model the structures were considered to be rigid because of the fact that sport utility motorcycles will have very stiff frames and its structural flexibility has a very limited effect towards the stability.

The comparison is made between structural and motion modes which shows only a low interaction between them. The tire characteristics are the most important in the motorcycle modelling. The accuracy in the description of the geometry of the thread of the tire, which is very important in evaluating the fundamental tire behavioral characteristics at larger camber angles. Tire characteristics mainly affect the lateral stiffness of the motorcycle particularly when they are at higher lean angles. This complex analysis of the tire character needs to given prior attention and the consideration of the changing tractive effort due to various parameters must also be taken into account of it. The proportional tire character along with the stiffer front suspension can yield a better result when the consideration of the stability is taken into consideration for more better cornering character of the motorcycle. This will have large effect on the deformation of the tire.

The calculation of the external contact forces were calculated as a function of slip velocity and camber angle using the Pacejika formulas. The corresponding internal elastic reactions were calculated as a function of the tire deformations and camber angle. Their calculation of the model includes the position of the contact point, as function of the camber angle and tire deformations as can be seen in the Fig 1.13.

The tire forces that were applied to that point, which corresponds to the center patch contact. The torques in the tire consists of rolling resistance torque M_y and the yaw torque M_z. The overturning moment was not included in their case. Their model described the behavior of the tire in both steady state and in transient conditions. With further reference the tire character proves to be very important part of the dynamic aspects in motorcycles, since they can directly affect the system of the motorcycle in wider aspect with its rolling resistance and wheel spin, also when considering the geometry of the motorcycle with the tractive effort.

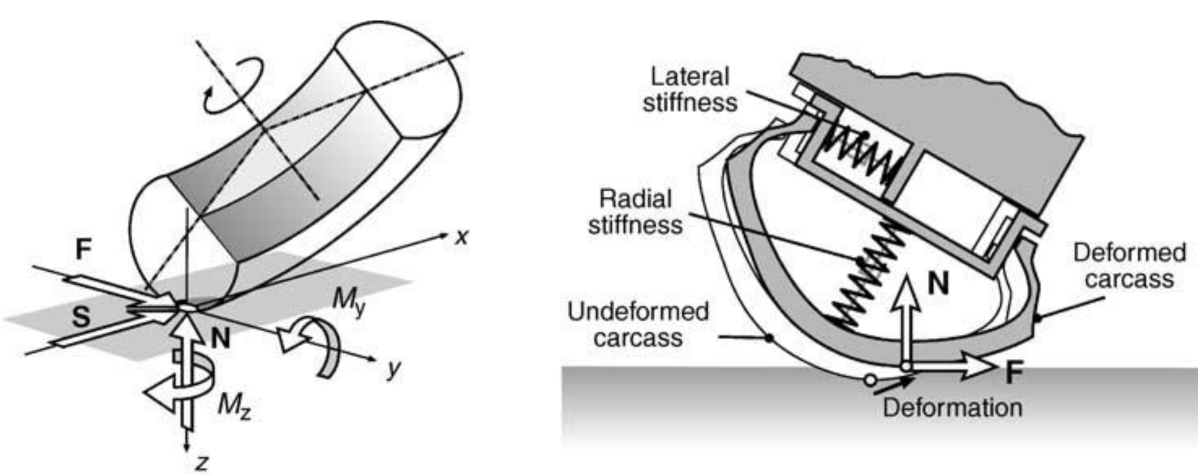


Fig 1.13 Elastic tire model [1].

The modal analysis was done and it was presented as a comparison between the motorcycle running on a straight and on a curved track. The numerical analysis of the mathematical model was based on the dependence of coordinates formulation. A new approach to procedural identification for the development of the equilibrium. The modes were calculated by linearization of the equations of motion and then dropping out the redundant coordinates. [9] Further modes show weak coupling. The modal shapes are described with the aid of vectorial graphs as shown below in Fig 1.14. In the experimental section of the paper, a safe and reliable procedure for the test has been described.

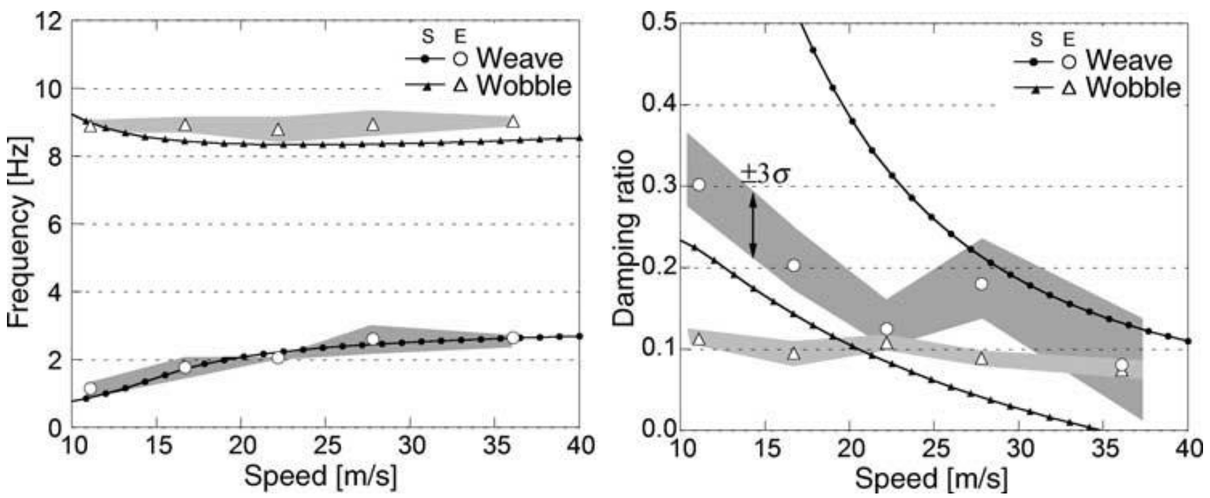


Fig 1.14 Modes in straight running, comparison between experimental and simulated data [1].

In a similar manner RS. Sharp, S. Evangelou and D.J.N. Limebeer,[2] experimented about the advances in modelling of motorcycle dynamics. To start from the existing dynamics of advanced motorcycle model, which permits the reasonably the simulation of general motions, stability and nodal response computations for small perturbations from any trim condition, improvements were described. [13] They can affect a lot of parameters like tire and road contact geometry, shear force of the tire and descriptions of the moment as a function of load, camber slip and tire relaxation properties through an analytic treatment of the monoshock rear suspension mechanism were given with sample results. These parameters were described for a high performance machine and the rider in a steady state equilibrium, power checking and steering control. In particular the Magic Formula motorcycle tire model was used for the sets of parameter values for tires were derived by identification methodology. The new model that was proposed is used for design parameter sensitivity, stability, steady state turning and response to the road forcing calculations.

Their results had a primary importance with the frame of the motorcycle as it is very important in dynamic aspect to change the characterization of the motorcycle in a lots ways. The observations of the behavior in the motorcycle in the field suggested that the frame flexibility remains the key area of analysis for the obtainment of better overall characterization of the stability behavior. This is certainly because, the frame is the interface of all the individual components of a motorcycle, where the effect of the frame can be realized in all areas of the motorcycle particularly in the high performance motorcycles. Most of the riders prefer to have the combination softer and harder flexibility of the frame.

[2] The workshop pamphlet for a motorcycle has the specific parameters for the motorcycles like dimensions, specifications of the electrical and electronics components used, maintenance procedures, solutions to general problems that may occur. They also include individual set of components that are listed in the appropriate manner so that when assembling or dismantling, to keep in checklist of the parts exists Also if we take they also describe the construction of frame swingarm, front fork spring and the rear suspension and also they include the mechanism of working of the same. A diagrammatically scaled representation of motorcycle is shown in Fig1.15, with the corresponding parameter values. In the representation point of front frame was measured to be given points p3 and p5. The point p4 is along the line of the lower front fork translation relative to the upper forks. The estimated location p2 is the elastic center of the rear frame with respect to a moment perpendicular to the steer axis. The total mass of the rider is considered as 72 kg and 62 percent of it has been associated to the upper body. The upper

body leaning towards the handle bars were considered to the part of the steering system itself. The variable parameters are gathered from the bio mechanical data of the system by analyzing the gesture of the seating posture in a motorcycle. The body mass centers are represented in the Fig 1.15 were in proportion with the masses concerned. These parameters were known through straight forward weighing.

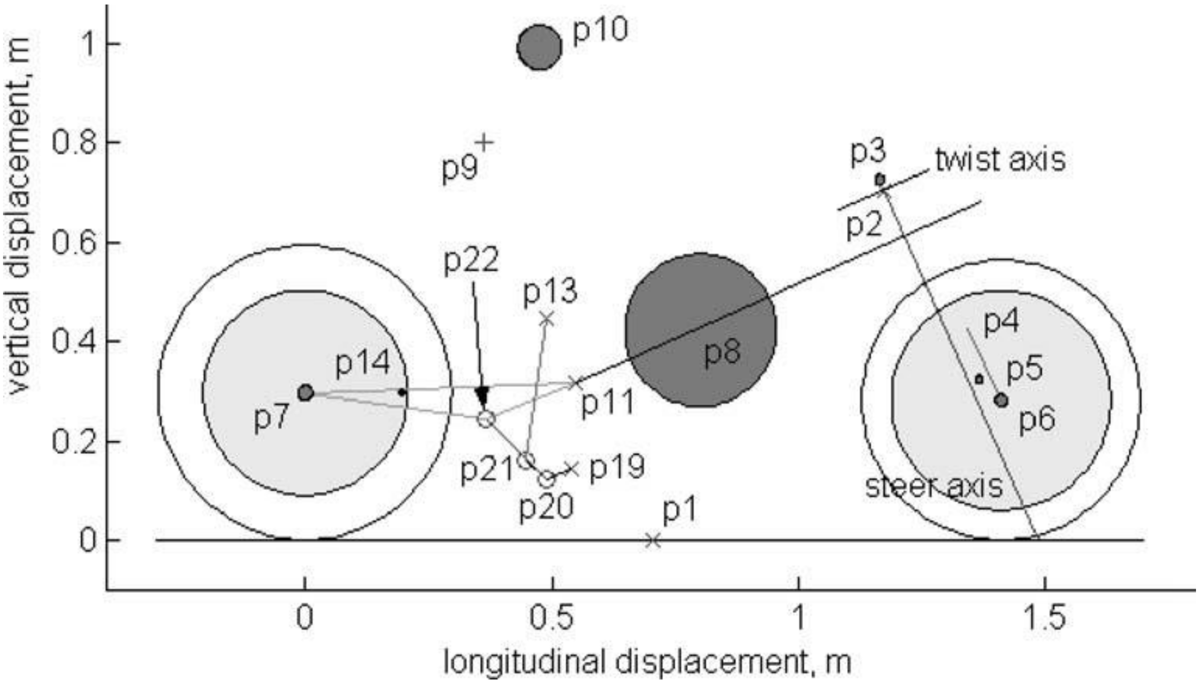


Fig 1.15 The diagrammatic representation of motorcycle geometry in 2 dimensional pattern [2].

The front tire and ground are in relative contact with each other and this part of motorcycle modelling was the complex part. So the machine behavior is also very important when the consideration is done. It was a common consideration to consider the tire as a thin disc as circumferentially migrating the contact point in the conditions of larger steer angles and camber angles, [2] but Dr.Cossalter made the pioneering idea of including the tire width in the descriptions. For overturning moment description, the disc model needs to be augmented. While in the case of wider tires, the automatic occurrence of the shifting of the contact point automatically occurs and the overturning moment is the consequence of the movement. A wide tire with a circular cross-section crown is now modelled. In addition to making the overturning moment automatic, longitudinal forces applied to the cambered tire will lead to realistic aligning moments appearing automatically. The test was conducted in order to check the comparison of the wider tire and the thin tire, which specifically gave similar results, when physically equivalent systems are being represented. This test has been applied, with some significant consequences. To define each tire/ground contact point the vertical and the wheel spindle directions are used in a vector (cross) product to describe the longitudinal direction, with respect to the wheel. Similarly, the wheel radial direction, OC in the below figure, comes from combining the longitudinal and wheel spindle directions. The vector OC is of fixed length and so is completely specified. G is vertically below C and the difference between the tyre crown radius and the distance CG defines the change in the tire carcass compression from the nominal state and hence the change of the wheel load from the nominal, via the tyre radial stiffness.[2] If the road is profiled, the road height is accounted for in working out the wheel load. The vector OG = OC + CG defines the contact point, which belongs to the wheel but moves within it. G remains at road surface height but the tire load cannot become negative. If the tire leaves the ground, the shear forces are zero, whatever the other conditions are. Tire forces are applied to the point G, in each case. The longitudinal slip is the rearward component of the material contact point velocity divided by the absolute value of the rolling velocity, the latter being the forward velocity of the contact point (or the crown center point, since these are the same). The contact point is defined by its coordinates in the parent body of the wheel and it is de-spun relative to the material contact point. Thus the longitudinal

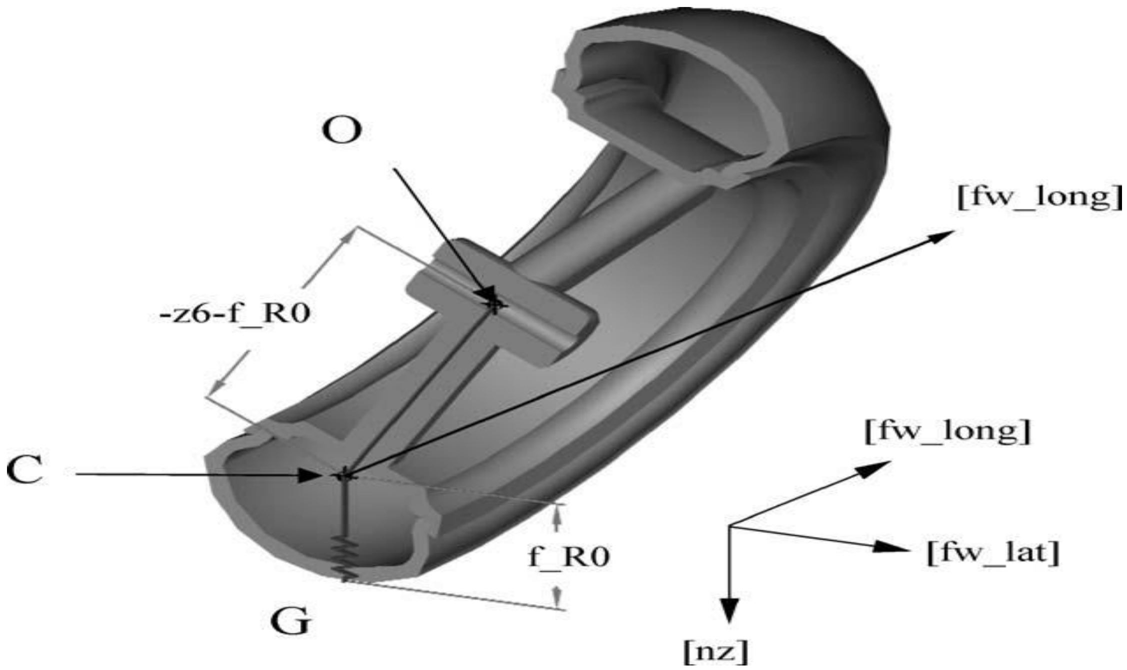


Fig 1.16 Diagrammatic representation of three- dimensional front wheel geometry [19].

[19] Slip is given by an expression of the form:

$\kappa = -$ (rolling velocity + spin component of longitudinal velocity)

/abs (rolling velocity)

The slip angle is the arctangent of the ratio of the (negative) lateral velocity of the

Tire contact center point to the absolute value of the rolling velocity. [19] In the development of the new model in modelling the wider tires for the inclusion in the overtuning moment from that of the thin disc given some subtle differences between the root locus predictions of the old and new versions were observed in circumstances which were at that stage thought physically equivalent. Such differences were found to be associated with the former description of the slip angles as deriving from the lateral velocity components of the disc tire contact points. When the wheel camber angle is changing, these points have a small lateral velocity component not connected with side slipping, since with the real tire, the contact point moves around the circular section sidewall of the tyre. The former model would have provided a more accurate description if it had used the crown center point velocities to derive the slip angles.

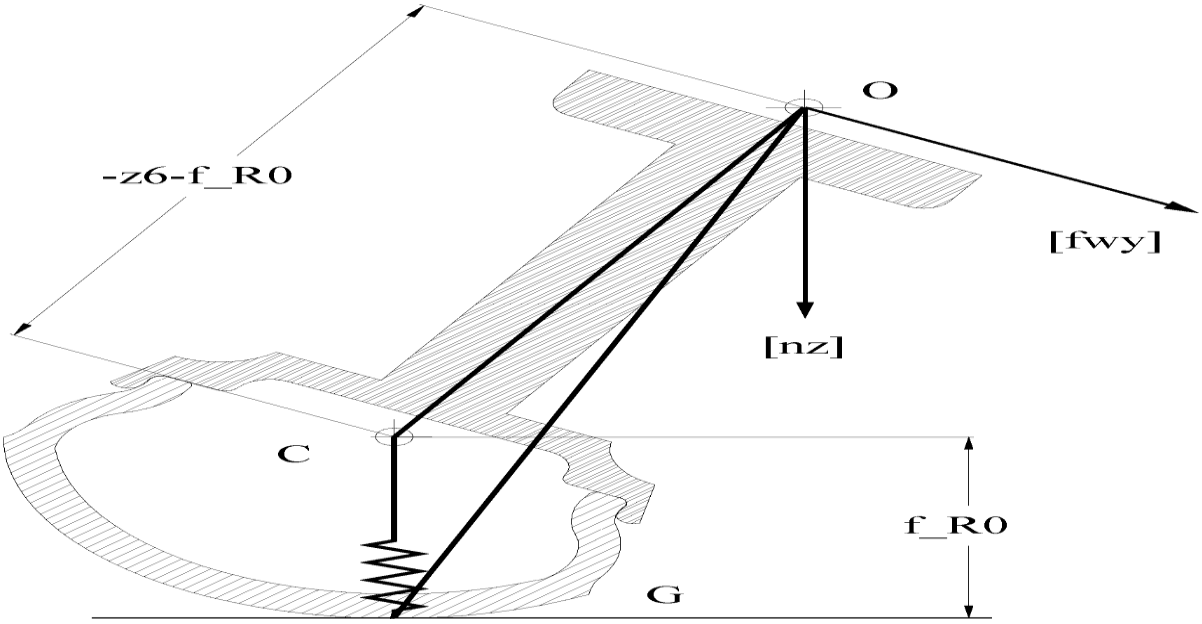


Fig 1.17 Diagrammatic representation of two- dimensional front wheel geometry[19].

[19] Substantial improvements to an advanced motorcycle dynamics model have been made, relating to tire and road contact geometry, the tire shear force and moment system, tire relaxation properties and the monoshock rear suspension mechanism.

In particular, parameters for the powerful Magic Formula method, representing the shear forces developed by modern, high performance motorcycle tires have been derived. [19] This provides a readily usable generic description of the steady-state force and moment system of such tires, with a very wide range of validity. Also, the geometric treatment of the monoshock suspension system is new and it contributes to computational efficiency. Steady-turning equilibrium force, moment and power checks have been refined and results of high precision shown testify to the model's accuracy of construction. Significant progress towards a complete parametric description of a contemporary, high performance motorcycle has been made, although a little further work is needed to finish the measurement campaign. The rider upper body structure has been represented as relatively compliant, in sympathy with the rig measurements of Nishimi.

Results obtained on this basis suggest that the rider upper body damping is significantly stabilizing to the wobble mode, accounting potentially for the observation that light riders are more at risk from oscillations than heavier ones. Steady turning equilibrium states, tire forces and steer torque requirements have been illustrated and the power dissipation through the speed range for steady turning at 45◦ lean angle has been shown for the first time. Straight running root locus plots, from a linearized version of the model, have suggested that, despite the relatively high torsional stiffness of many modern frames, it is still important to the stability and control and it needs including in analysis and design discussions.

Use of the model for the calculation of stability in cornering has been illustrated. Stability margins in cornering typically increase as compared with straight running, although complex patterns of behavior are possible.

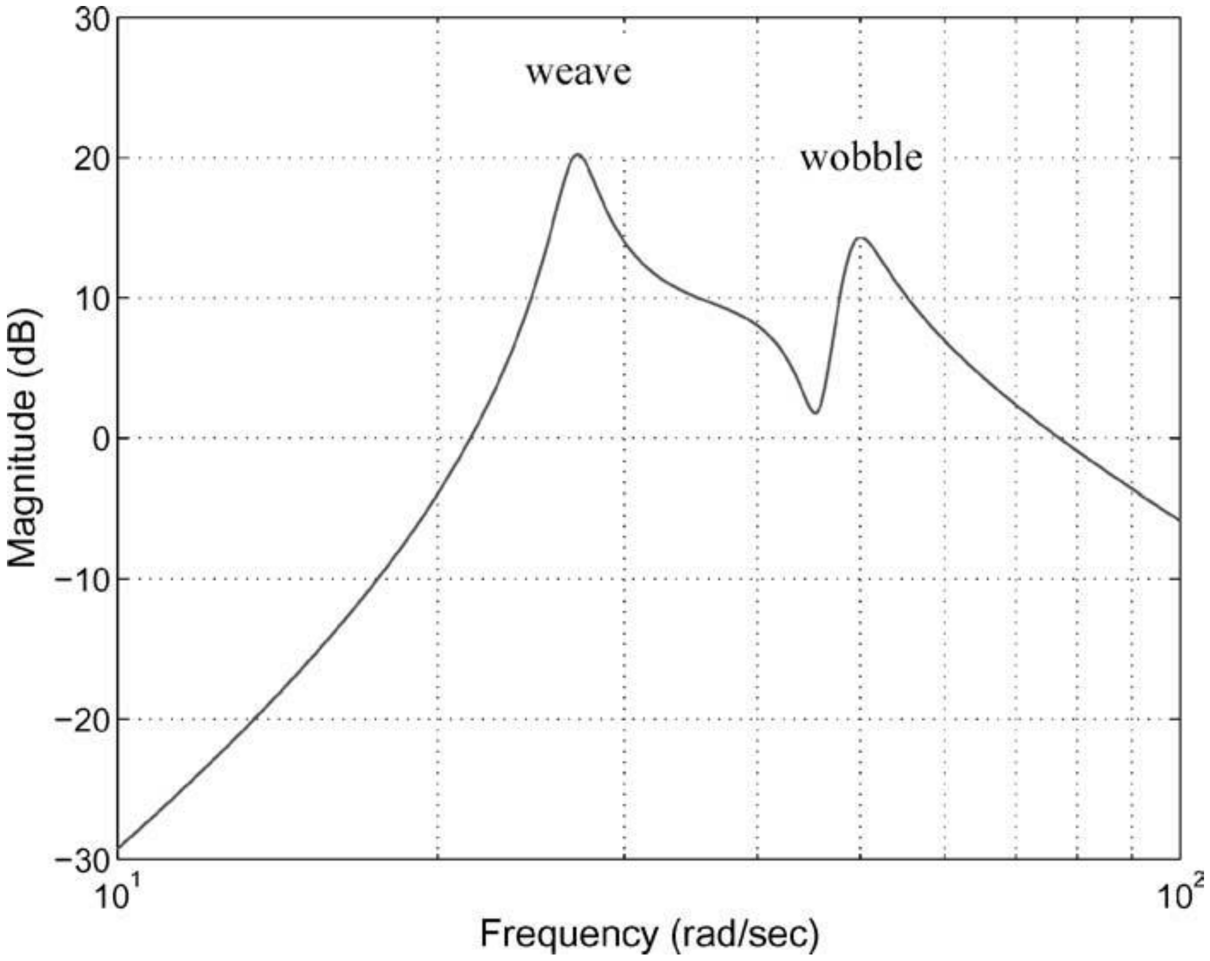


Fig 1.18 Steering angle response to road simulation at normal condition of lean angle [19].

The above literatures prove that there was a detailed investigation done for the analysis of the motorcycle models on various different parameters as well as settings, but we can always incur that there very less number of analysis carried out on the interconnection of suspensions. Nevertheless the above literatures have been a great deal of reference for the parameters that are going to be analyzed in this thesis and these literatures have significant reference for this research.

3. CONCEPT OF INTERCONNECTION IN MOTORCYCLE

Fig 2.1 Image of Ducati 1299 pannigale showing the conventional suspension mechanism [26].

The above Fig 2.1 shows the conventional steering mechanism that is used in today's motorcycles that is they use forks and swingarms. There has been lots of research to control this weight transfer towards the front and the rear in the conditions of acceleration and braking. The fact about motorcycles is that, the correct amount of weight transfer is required for different speeds of it. If there is too much of weight transfer towards the front, then rider has more possibilities of a low side crash, which is very common problem in race track in damped conditions. On the other hand there is another possibility that there more weight transferred towards the rear, then the motorcycle gets wheelie around the exit part even though having best precision anti wheelie sensors and actuators.

This primarily happens only because of the independent action of the suspensions in this arrangement. As discussed above that interconnection concept gives suspension a better form for performing the coordination, which is missing. The weight transfer also supports the tires to get more contact points, but those situations can be very rare, but on the contrary there are lot crashes due to weight transfer. This problem may be solved by using interconnection of suspensions in motorcycles with a swingarm. As interconnection primarily uses swingarms, conventional fork steering mechanism has to be designed too. In this thesis, a new concept of interconned suspensions for motorcycles and new concept of steering for interconnected suspensions is proposed to overcome the weight transfer difficulties.

The basic design is represented in the fig 2.2, as a basic part to start the analysis and understand about the behavior of this type of unconventional arrangement attempted for the first time. The fact of uniqueness of the design is about its suspension action that is going to take place in pitching, bouncing and bump modes. Fig 2.2 shows the proposed design of the interconnected suspension. In the below picture the proposed interconnection has the horizontal action in the case of vertical or inclined vertical action, that stands as the conventional design for the motorcycle suspension.

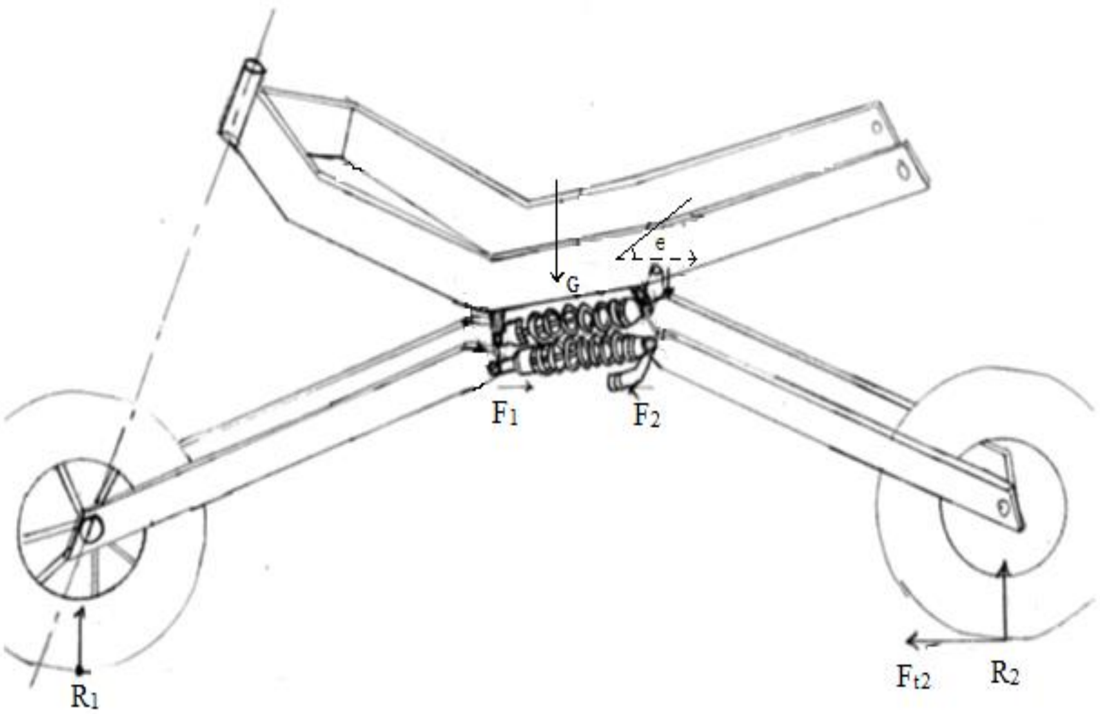


Fig 2.2 Graphical Representation for proposed concept of interconnected suspensions in motorcycle.

Fig 2.2 shows the graphically represented concept of the design that is attempted in this research. The chassis of the concept may be designed in future for further more analysis, but, as per the aim of this research is to reduce the pitching and bouncing action in the conditions of acceleration and braking. As of this design is concerned with, it can give the most important variation that is in need for any motorcycle for optimum handling, that is the change in wheel base. When the sprung mass is suspended and consider an additional force acts due to the condition of acceleration, we can clearly see from the picture, that wheel base extends to have a better acceleration and a good anti-wheelie system especially during acceleration. As this arrangement of suspension primarily uses swing arm, a new type of steering mechanism is also proposed with this thesis. The main benefit of this arrangement is to give better performance without compromising safety characteristics.

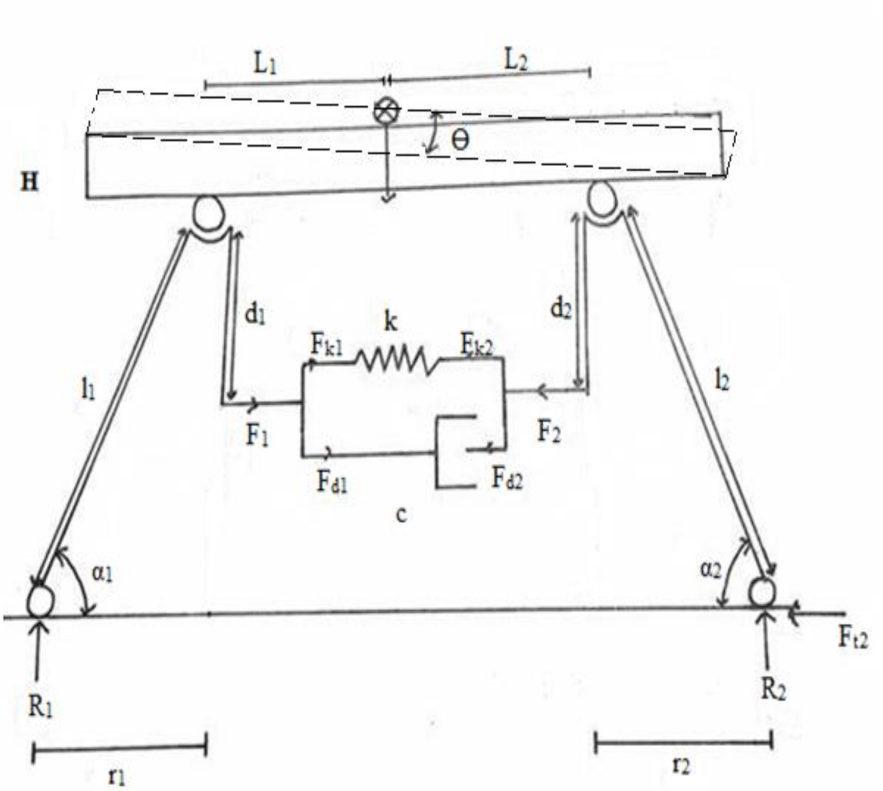


Fig 2.3 Dynamic representation of the proposed system.

The picture shows about the kinematical representation of forces acting on the design are depicted for the reference. The conditions considered is that, the motorcycle is moving in the straight as the initial part of the research and the forces shows when the concept design and the forces acting on it under the condition, when accelerating. Now a kinematic analysis can be proposed, to find the effect of variables affecting the performance during the condition of acceleration. Here the dynamic condition is applied in order to derive the relationship between the variables affecting the performance. We consider that the summation of the horizontal forces, vertical forces and the moments is equivalent to zero. The above consideration is done to find the relationship between non-linear parameters, so that when the analysis is carried out parameters are related in order to analyze interconnected suspensions.

4. MATHEMATICAL MODELLING

In this thesis linearization of the whole system is done in order to establish the interconnection. The main consideration for the linearization is about the swing arms used in the below kinematic representation has a very limited mass, as it is neglected when the whole system is considered.

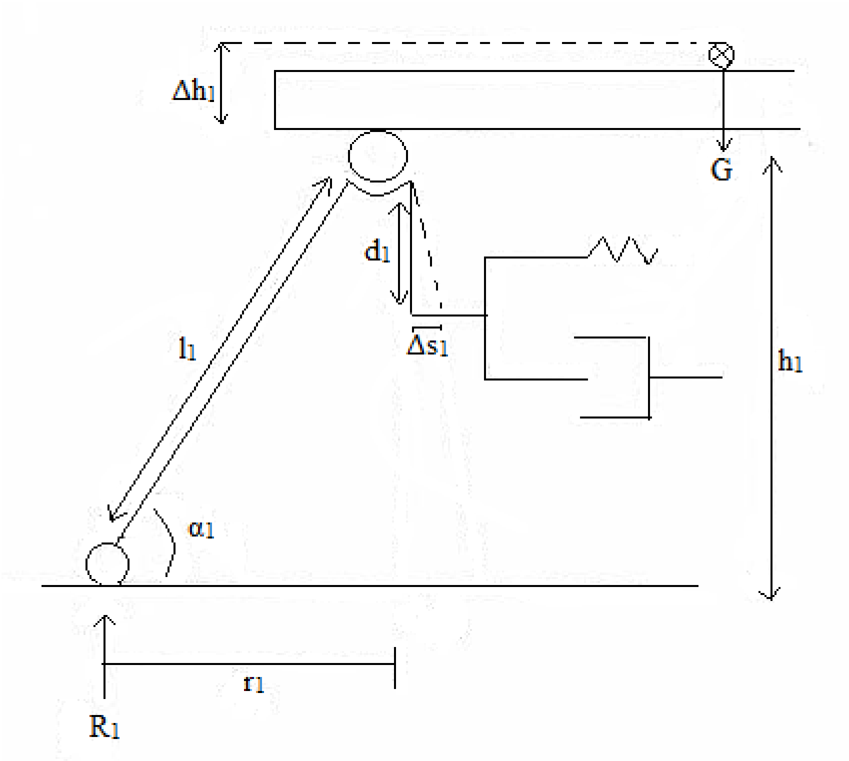


Fig 3.1 Diagram for linearization of the function $\Delta s_1 = f(\Delta h_1)$.

$$h_1(\alpha_1) = l_1 \sin \alpha_1 \tag{1}$$

Where:

h_1 = height from the point of reference.

l_1 = length of the swing arm.

Δh_1 = change in height at the specific condition of acceleration.

Δs_1 = change in horizontal displacement due to change in height.

R_1 = reaction in the front wheel.

r_1 = distance between the reaction at front wheel and the flexible hinge of the chassis.
α_1 = angle of inclination of the swing arm with respect to the surface of ground.
G = Gravitational force.

Now $h_1 + \Delta h_1$ can be expanded by taylor series as it can be represented as below, since the linear terms are considered while the higher order is neglected:

$$h_1 + \Delta h_1 = l_1 \sin \alpha_1 + l_1 \cos \alpha_1 (\alpha - \alpha_1) \tag{2}$$

Now comparing the equations 1 and 2 the term h_1 and $l_1 \sin \alpha_1$ will get cancelled and:

$$\Delta h_1 = l_1 \cos \alpha_1 \Delta \alpha_1$$

$$\Delta \alpha_1 = \Delta h_1 / l_1 \cos \alpha_1 \tag{3}$$

Now to establish the relation between the movement in horizontal and vertical direction we multiply both sides by d_1 on equation 3 we get:

$$\Delta \alpha_1 d_1 = (\Delta h_1 / l_1 \cos \alpha_1) d_1$$

$$\Delta s_1 = (\Delta h_1 / l_1 \cos \alpha_1) d_1 \tag{4}$$

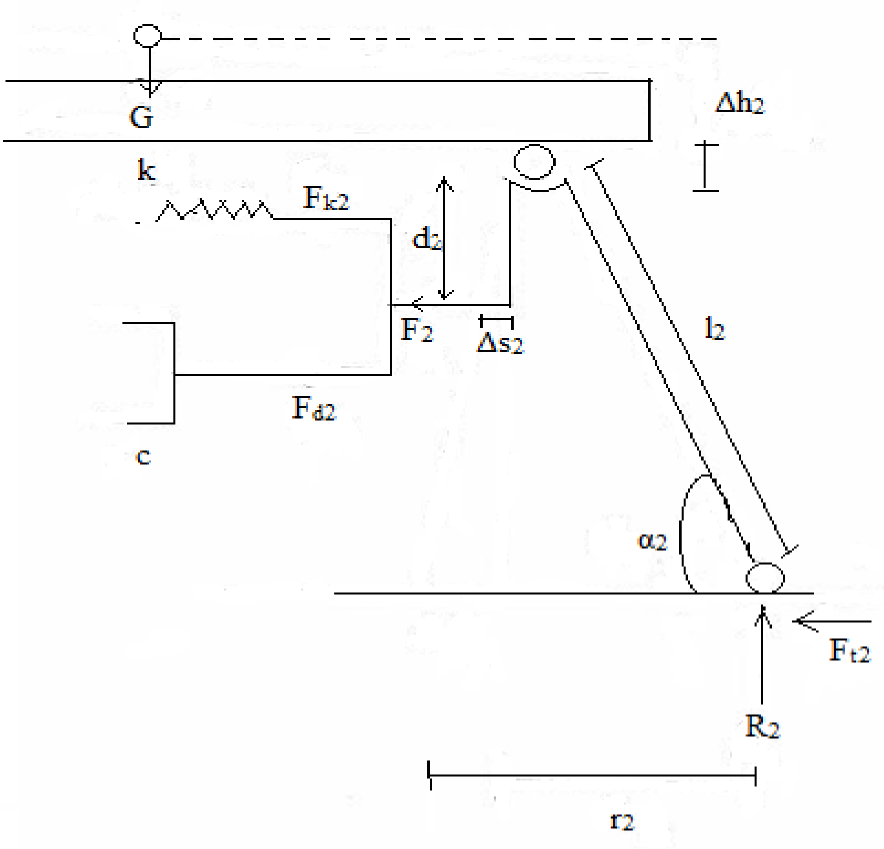


Fig 3.2 Diagram for linearization of the function $\Delta s_2 = f(\Delta h_2)$.

Now the other part of the system is considered with the same orientation of the variables:

Where:

F_{t2} = the tractive force of the tire induced to the system.

$$h_2(\alpha) = l_2 \sin\alpha_2 \tag{5}$$

Similarly like before expanding $h_2 + \Delta h_2$ again by taylor's series we get:

$$h_2 + \Delta h_2 = l_2 \sin\alpha_2 + l_2 \cos\alpha_2 (\alpha - \alpha_2)$$

$$\Delta h_2 = l_2 \cos\alpha_2 \Delta\alpha_2$$

$$\Delta\alpha_2 = \Delta h_2 / l_2 \cos\alpha_2 \tag{6}$$

Multiplying both sides by d_2 again we get:

$$\Delta\alpha_2\, d_2 = (\,\Delta h_2/l_2\ \cos\alpha_2)\, d_2$$

$$\Delta s_2 = (\Delta h_2/l_2\ \cos\alpha_2)\, d_2 \qquad (7)$$

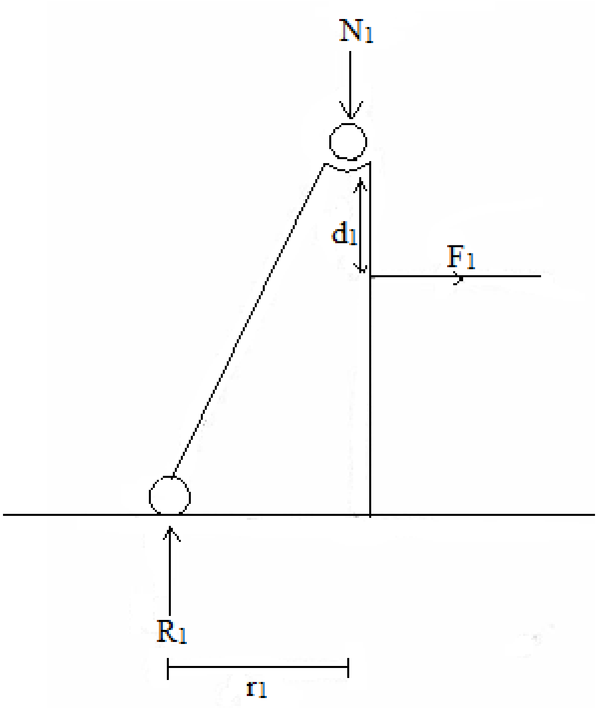


Fig 3.3 Free body diagram of the front swingarm.

Now the part of the system is considered for establishment of relation between the vertical reactions acting to one half part of the interconnected suspension.

The summation of vertical forces acting on the system considered is:

$$\sum F_{y1} = R_1 - N_1 = 0$$

Therefore: $R_1 = N_1$

(8)

Where:

N_1 = normal reaction at the joint.

F_1 = Total force acting on the spring and damper on this half part.

Now the total summation of the moment can be given by:

$$\sum M_o = (F_1 \times d_1) - (R_1 \times r_1) = 0$$

$$(\,F_1 \times d_1) = (R_1 \times r_1)$$

$$R_1 = {F_1 d_1}/{r_1}$$

(9)

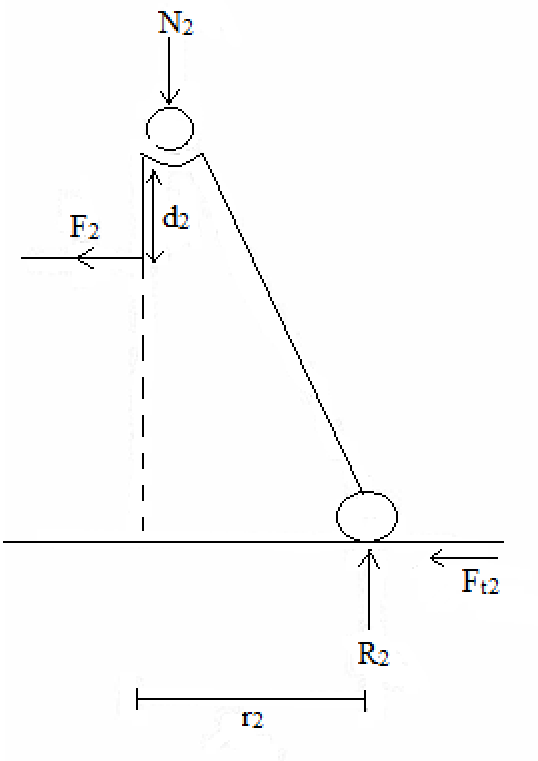


Fig 3.4 Free body diagram of the rear swing arm.

Similarly for the other part of the system we can obtain the summation of vertical forces:

$$\sum F_{y2} = N_2 - R_2 = 0$$

Therefore: $N_2 = R_2$

$$\sum M_{o2} = (R_2 \times r_2) - (F_2 \times d_2) - (F_{t2} \times h_2) = 0$$

$$(R_2 \times r_2) = (F_2 \times d_2) + (F_{t2} \times h_2)$$

$$R_2 = \frac{F_2 d_2}{r_2} + \frac{F_{t2} h_2}{r_2}$$

For the consideration of the spring stiffness and the force on the spring we make the necessary derivation to relate stiffness and damping to the equations:

$$F_{k1} = \Delta s_1 k \qquad (10)$$

$$F_{k2} = \Delta s_2 k \qquad (11)$$

$$F_{d1} = \Delta \dot{s_1} c \qquad (12)$$

$$F_{d2} = \Delta\dot{s_2}\, c \qquad (13)$$

Therefore the total force acting on the system is the sum of force on the damper and spring. Substituting the equations 10, 11, 12, 13 in respective forms in equations 14 and 15:

$$F_1 = F_{k1} + F_{d1} \qquad (14)$$

$$F_1 = \Delta s_1\, k + \Delta\dot{s_1}\, c$$

$$F_2 = F_{k2} + F_{d2} \qquad (15)$$

$$F_2 = \Delta s_2\, k + \Delta\dot{s_2}\, c$$

When the system is considered as a whole, then only total force on the spring as F is considered. This total spring force is sum of the forces on either side of the whole system, so therefore:

$$F_1 = F_2$$

$$F = [\Delta s_1 + \Delta s_2]\, k + [\Delta\dot{s_1} + \Delta\dot{s_2}]\, c$$

(16)

When the consideration of the whole system is done in order to do the linearization, the total spring force F is considered, the reactions at two wheels R_1 and R_2 are substituted with the total spring force:

$$R_1 = \frac{F\, d_1}{r_1}$$

(17)

$$R_2 = \frac{F\, d_2}{r_2} + \frac{F_{t2}\, h_2}{r_2}$$

(18)

Now substituting the equation 16, for the value of F, for the values of R_1 and R_2 we get:

$$R_1 = \frac{\{[\Delta s_1 + \Delta s_2]\, k + [\Delta\dot{s_1} + \Delta\dot{s_2}]\, c\}\, d_1}{r_1}$$

(19)

$$R_2 = \frac{\{[\Delta s_1 + \Delta s_2]\, k + [\Delta\dot{s_1} + \Delta\dot{s_2}]\, c\}\, d_2}{r_2} + \frac{F_{t2}\, h_2}{r_2}$$

(20)

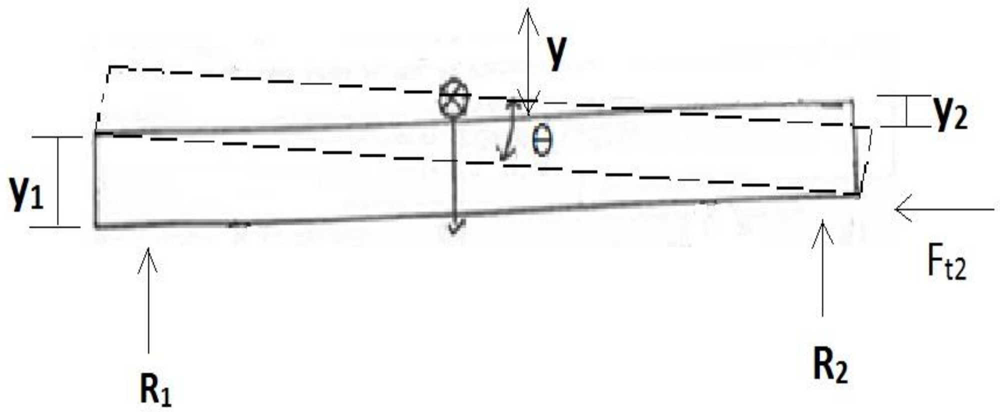


Fig 3.5 The whole system with parameters affecting the performance of the system.

Now when considering the total system the summation of vertical components in the system is:

$$m\ddot{y} \;=\; R_1 + \; R_2 - G$$

(21)

Substituting the values of R_1 and R_2 in the above equation:

$$m\ddot{y} = \frac{\{[\Delta s_1 + \; \Delta s_2]\; k + \; [\Delta\dot{s}_1 + \; \Delta\dot{s}_2]\; c\}\; d_1}{r_1} + \frac{\{[\Delta s_1 + \; \Delta s_2]\; k + \; [\Delta\dot{s}_1 + \; \Delta\dot{s}_2]\; c\}\; d_2}{r_2} + \frac{F_{t2}\; h_2}{r_2} - G$$

(22)

$$m\ddot{y} \;=\; \frac{[\Delta s_1 + \; \Delta s_2]\; k\; d_1}{r_1} + \frac{[\Delta\dot{s}_1 + \; \dot{\Delta s}_2]\; c\; d_1}{r_1} + \frac{[\Delta s_1 + \; \Delta s_2]\; k\; d_2}{r_2} + \frac{[\Delta\dot{s}_1 + \; \dot{\Delta s}_2]\; c\; d_2}{r_2} + \frac{F_{t2}\; h_2}{r_2} - G$$

(23)

$$m\ddot{y} = k\; [\Delta s_1 + \; \Delta s_2]\; \left\{\frac{d_1}{r_1} + \; \frac{d_2}{r_2}\right\} + c\; [\Delta\dot{s}_1 + \; \Delta\dot{s}_2] \left\{\frac{d_1}{r_1} + \; \frac{d_2}{r_2}\right\} + \frac{F_{t2}\; h_2}{r_2} - G$$

(24)

But as in equation 3 and 4 the value of Δs_1 and Δs_2 can be given as:

$$\Delta s_1 = \frac{\Delta h_1}{l_1 \cos \alpha_1} d_1$$

(25)

$$\Delta s_2 = \frac{\Delta h_2}{l_2 \cos \alpha_2} d_2$$

(26)

Therefore differentiating the displacement Δs_1 and Δs_2 with respect to time we get:

$$\Delta \dot{s}_1 = \frac{\Delta \dot{h}_1}{l_1 \cos \alpha_1} d_1$$

(27)

$$\Delta \dot{s}_2 = \frac{\Delta \dot{h}_2}{l_2 \cos \alpha_2} d_2$$

(28)

But the only varying parameter in the equation is Δh_1 and Δh_2 with respect and while the other values are considered constant.

Therefore now substituting the values of Δs_1 and Δs_2 in the equation of $m\ddot{y}$ and after some mathematical simplification the below equation is obtained:

$$m\ddot{y} = \frac{d_1}{l_1 \cos \alpha_1 r_1} \{k [\Delta h_1 + \Delta h_2] + c [\Delta \dot{h}_1 + \Delta \dot{h}_2]\} + \frac{d_2}{l_1 \cos \alpha_2 r_2} \{k [\Delta h_1 + \Delta h_2] + c [\Delta \dot{h}_1 + \Delta \dot{h}_2]\} + \frac{F_{t2} h_2}{r_2} - G$$

(29)

In the same way the summation of horizontal forces acting on the system is given by:

$$m\ddot{x} = F_{t2}$$

(30)

Now considering the total moment of the system:

$$y\ddot{\theta} = R_2 L_2 - R_1 L_1 - F_{t2} H$$

(31)

Substituting the values again for R_1 and R_2

$$y\ddot{\theta} = \left\{\frac{[\Delta s_1 + \Delta s_2]\, k + [\Delta\dot{s}_1 + \Delta\dot{s}_2]\, c}{r_2}\right\} d_2 L_2 - \left\{\frac{[\Delta s_1 + \Delta s_2]\, k + [\Delta\dot{s}_1 + \Delta\dot{s}_2]\, c}{r_1}\right\} d_1 L_1 - F_{t2}\, H + \frac{F_{t2}\, h_2\, L_2}{r_2}$$

$$y\ddot{\theta} = k\, [\Delta s_1 + \Delta s_2] \left\{\frac{L_2\, d_2}{r_2} - \frac{L_1\, d_1}{r_1}\right\} + c\, [\Delta\dot{s}_1 + \Delta\dot{s}_2] \left\{\frac{L_2\, d_2}{r_2} - \frac{L_1\, d_1}{r_1}\right\} + F_{t2} \left\{\frac{L_2\, h_2}{r_2} - H\right\}$$

Now substituting the values of Δs_1 and Δs_2 in the previous equation for $y\ddot{\theta}$ and some further simple mathematical simplifications the below equation is obtained:

$$y\ddot{\theta} = \frac{d_2}{l_2\, \cos\alpha_2\, r_2} \left\{\left\{k\, [\Delta h_1 + \Delta h_2] + c\, [\Delta\dot{h}_1 + \Delta\dot{h}_2]\right\} L_2\right\} - \frac{d_1}{l_1\, \cos\alpha_1\, r_1} \left\{\left\{k\, [\Delta h_1 + \Delta h_2] + c\, [\Delta\dot{h}_1 + \Delta\dot{h}_2]\right\} L_1\right\} + F_{t2} \left\{\frac{L_2\, h_2}{r_2} - H\right\} \quad (32)$$

Now the vertical displacement y due to the weight transfer in the acceleration. Now the plane of the mass center is displaced from a length of y_1 on one side and y_2 on the other, such that:

$$y_1 = y - L_1\theta \quad (33)$$

$$y_2 = y + L_2\theta \quad (34)$$

$$\theta = \frac{y_2 - y_1}{L_1 + L_2}$$

(35)

$$y_1 = \Delta h_1$$

$$y_2 = \Delta h_2$$

$$\dot{y_1} = \Delta \dot{h}_1$$

$$\dot{y_2} = \Delta \dot{h}_2$$

Substituting these values to the equations of motion, we get:

$$m\ddot{y} = \frac{d_1}{l_1 \cos\alpha_1 r_1} \{k [y_1 + y_2] + c [\dot{y_1} + \dot{y_2}]\} + \frac{d_2}{l_1 \cos\alpha_2 r_2} \left\{k [y_1 + y_2] + c \left[\Delta\dot{h}_1 + \Delta\dot{h}_2\right]\right\} + \frac{F_{t2} h_2}{r_2} - G$$

(36)

$$y\ddot{\theta} = \frac{d_2}{l_2 \cos\alpha_2 r_2} \left\{\{k [y_1 + y_2] + c [\dot{y_1} + \dot{y_2}]\} L_2\right\} - \frac{d_1}{l_1 \cos\alpha_1 r_1} \left\{\{k [y_1 + y_2] + c [\dot{y_1} + \dot{y_2}]\} L_1\right\} + F_{t2} \left\{\frac{L_2 h_2}{r_2} - H\right\}$$

(37)

So now the theoretical model for the interconnection has been established in order to find the movement of the system towards back and front. With the above system of variables the parameters of the length can be brought from a very specific motorcycle and the analysis can be made in order to analyze the characteristics of the system behaving for specific situation. Although there is no limit for the number of cases that can be considered for the analysis, but as an ariel view of the situation the system can be analyzed towards the behavior of it and can be optimized to infinite level.

5. SIMULATION AND TESTING OF THE INTERCONNECTED SYSTEM

The system of interconnected suspensions is now simulated using Simulink. As the first step of the representation of the Simulink model is attempted.

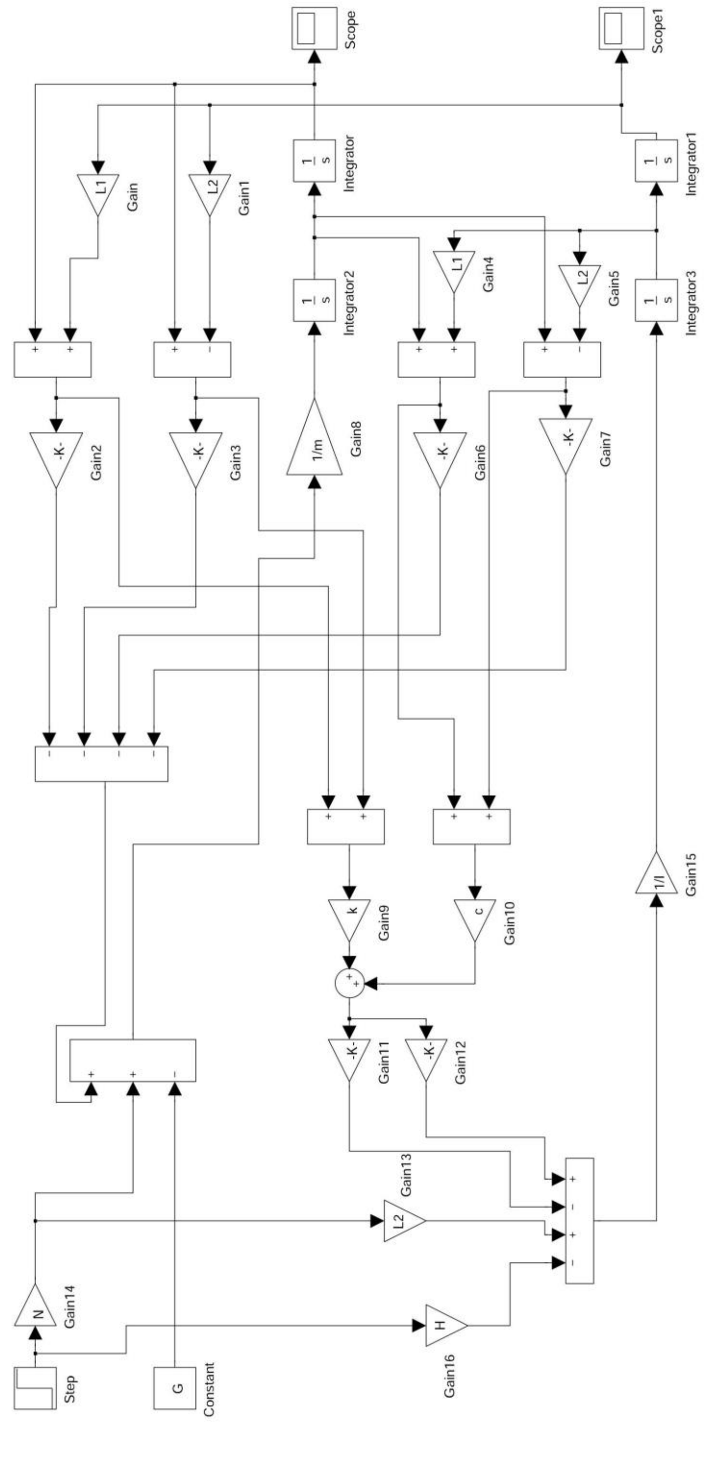


Fig 4.1 Simulink model of motorcycle with interconnected suspensions

With the above Simulink model Fig 4.1, a graphical representation is done in order to compare displacement of the chassis with respect to time at different intervals.

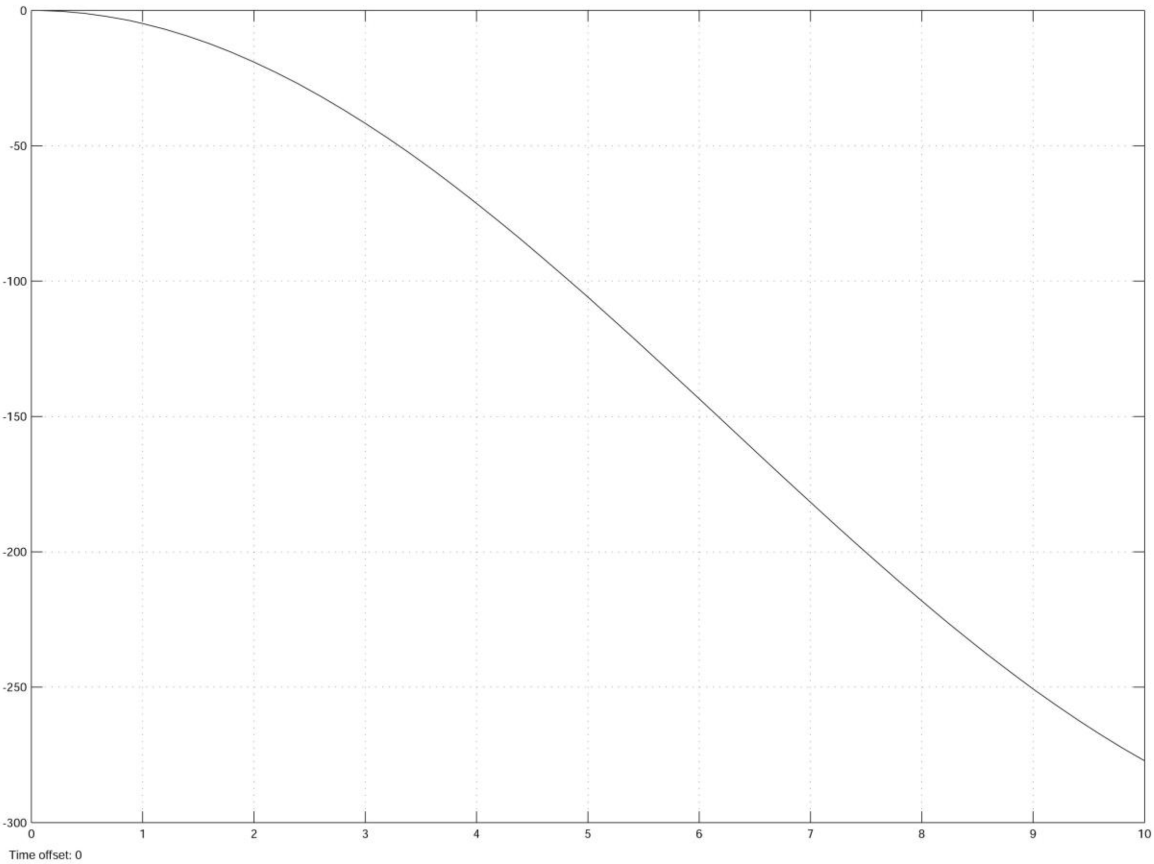


Fig 4.2 Graphical representation of displacement (mm) for t= 10sec

In the Fig 5.2 the displacement of the system is recorded as a function of different intervals of time. The system shows that the displacement of the whole system does not come to the position and the system seems to have displacement due to acceleration. Now again graphical representation is made for displacement with respect to more time interval i.e t = 20 sec.

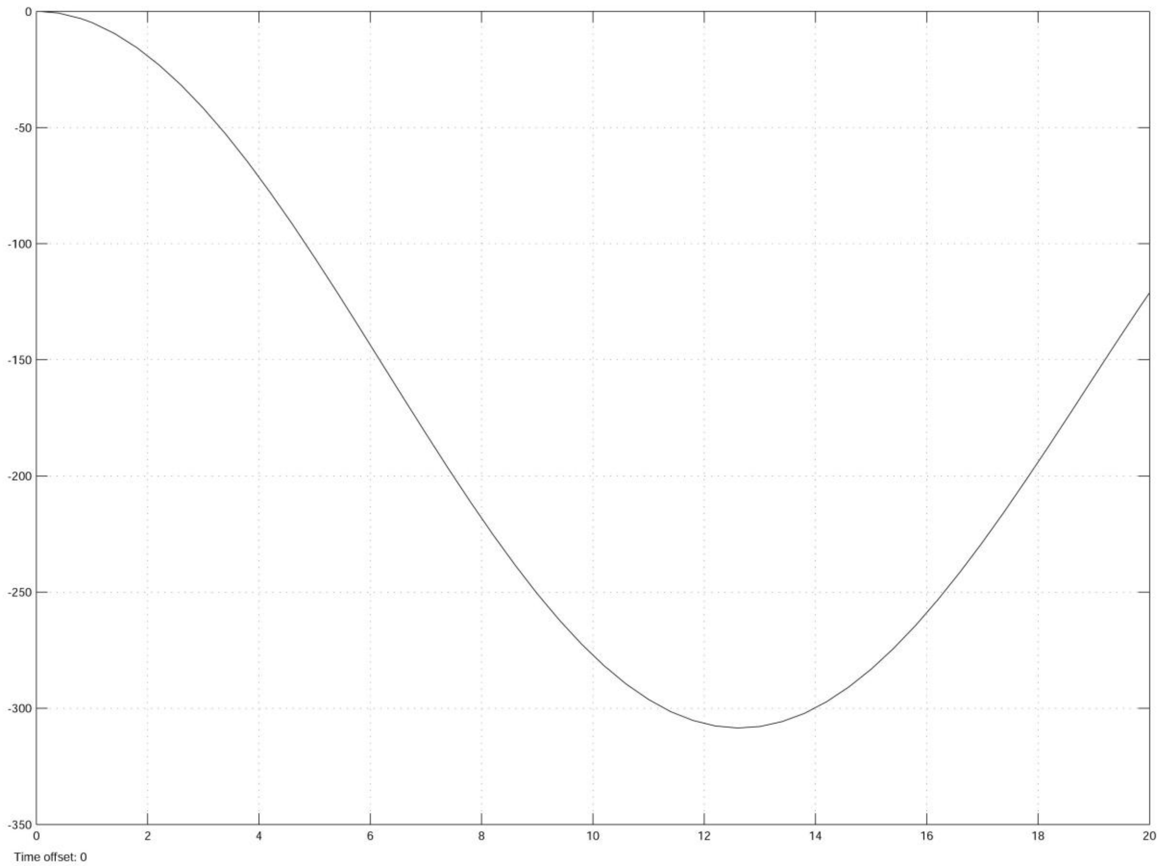


Fig 4.3 Graphical representation of displacement (mm) for time = 20 sec

When the system was simulated for displacement for a time interval of 20 sec as can be seen from Fig 5.3, the system now tends to get back from negative displacement due to acceleration. In further analysis to the simulation, a graphical representation was also done for pitching with respect to the time interval for 10 sec.

In Fig 5.4 the representation of the pitch in accordance to time interval. It can be seen from the graph that the system, does not have rotational pitch in the beginning, but as the time proceeds, the rotational pitch also proportionally increases.

The cause of this rotational pitch may be due to the damping co efficient that is introduced in the system may not be adequate to control the shock absorbed by the spring, as well as the stiffness value.

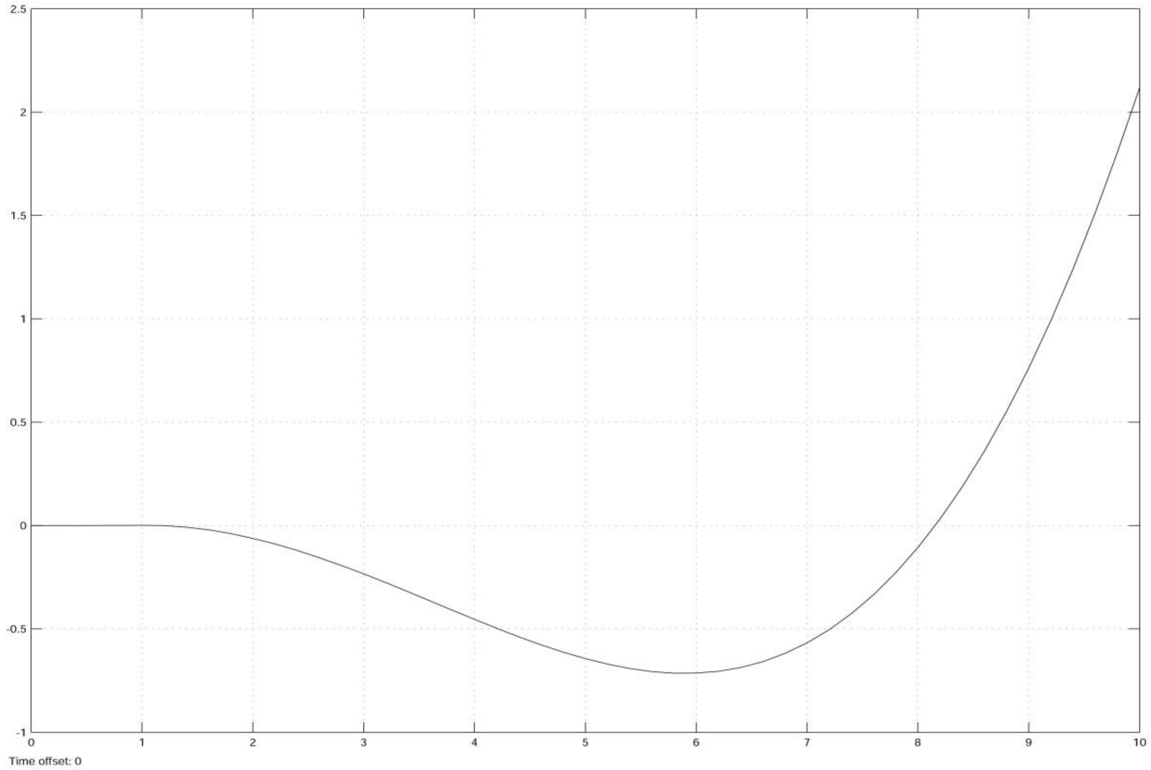


Fig 4.4 Graphical representation of pitch with respect time interval t = 10 sec

Now another graphical comparison is done in order to find the rotational pitch with respect to time for 20 sec as represented below Fig 5.5.

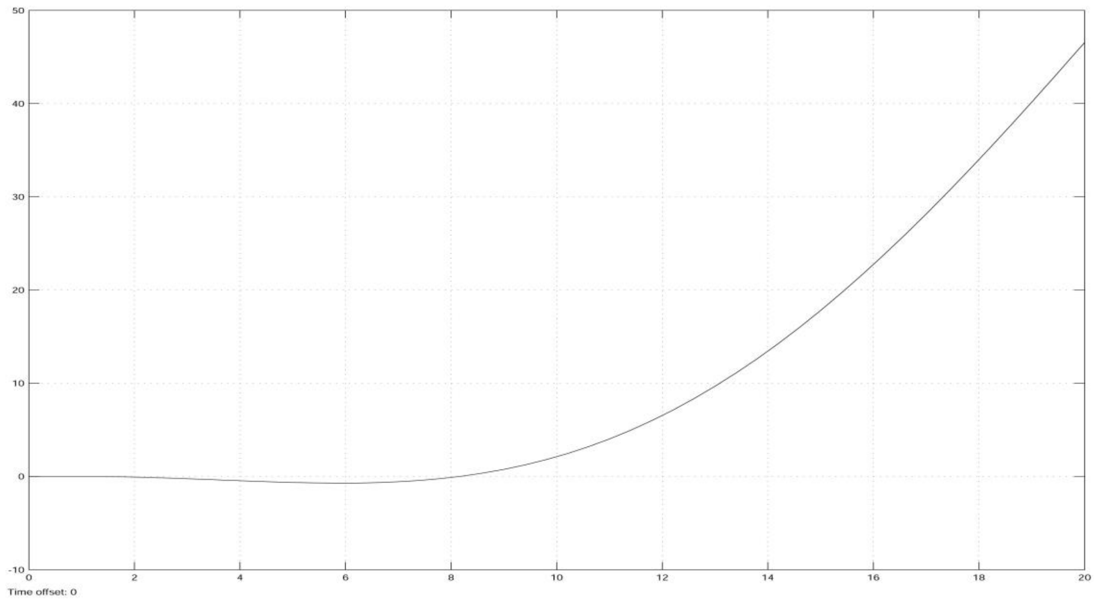


Fig 4.5 Graphical representation of pitch with respect to time t = 20sec.

In the Fig 4.5, the rotational pitch seems to be very low in the beginning intervals but it behaves in a similar manner that the previous comparison.

6. STEERING DESIGN FOR INTERCONNECTED SUSPENSIONS

As there is need for the steering mechanism that has to be designed for this unconventional steering mechanism. The usual steering mechanism cannot be a solution to steer this type of suspension arrangement as, the arrangement of the swing arms will affect the turning motion and the steering system cannot work and it will have a lot of constraints when turning. So it becomes very important to introduce the concept of design for the steering design that can be a solution to the turning of motorcycle. The concept of front swing arm was introduced to the commuter motorcycle market by BIMOTA by the model name TESI. The motorcycle has similar characteristics to this research as both has swing arms and conventional steering mechanism cannot be used to steer the motorcycle. The mechanism of working and the design of steering system is different from the motorcycle to this research, but the need for new design for steering system is very appropriate to convey the similarity. This concept of swing arm suspension and steering showed a very different dimension in selection of motorcycles.

The fact about this type of arrangement was to give better rideabilty in overall aspect in the general motorcycle market. This new concept that was introduced had a good welcome for the development of riding. The sophisticated modelling and development of these mechanisms, makes it expensive and in normal commuter based section it did not become very famous as it had different mechanisms. The concern for these designs, which had a question mark was about the maintenance.

Fig 5.1 BIMOTA TESI with ‘hub-center” steering mechanism introduced in 2011 [24].

The above image shows the new layout of the first front swing arm motorcycle introduced to the market by BIMOTA in 2011. Its steering mechanism is the famous “Hub-center steering” mechanism. The Fig 6.2 shows the layout of the mechanism with which it steers the front wheel according to the input. The main characteristics of the steering mechanism is about the steering arm and tie rod that is placed below the handlebar actuates the motion towards a joint, which is placed inside the wheel. The joint gives a rotational movement to the wheel as per the direction of the steering. This system had a very famous reputation for its one and only unconventional design for front swing arm suspension. The below figure shows the mechanism of Hub center steering in which there is the assembly unit inside the wheel. It can be seen clearly, that, m the too and fro motion of the tie rod is converted to rotary motion, by the component inside it.

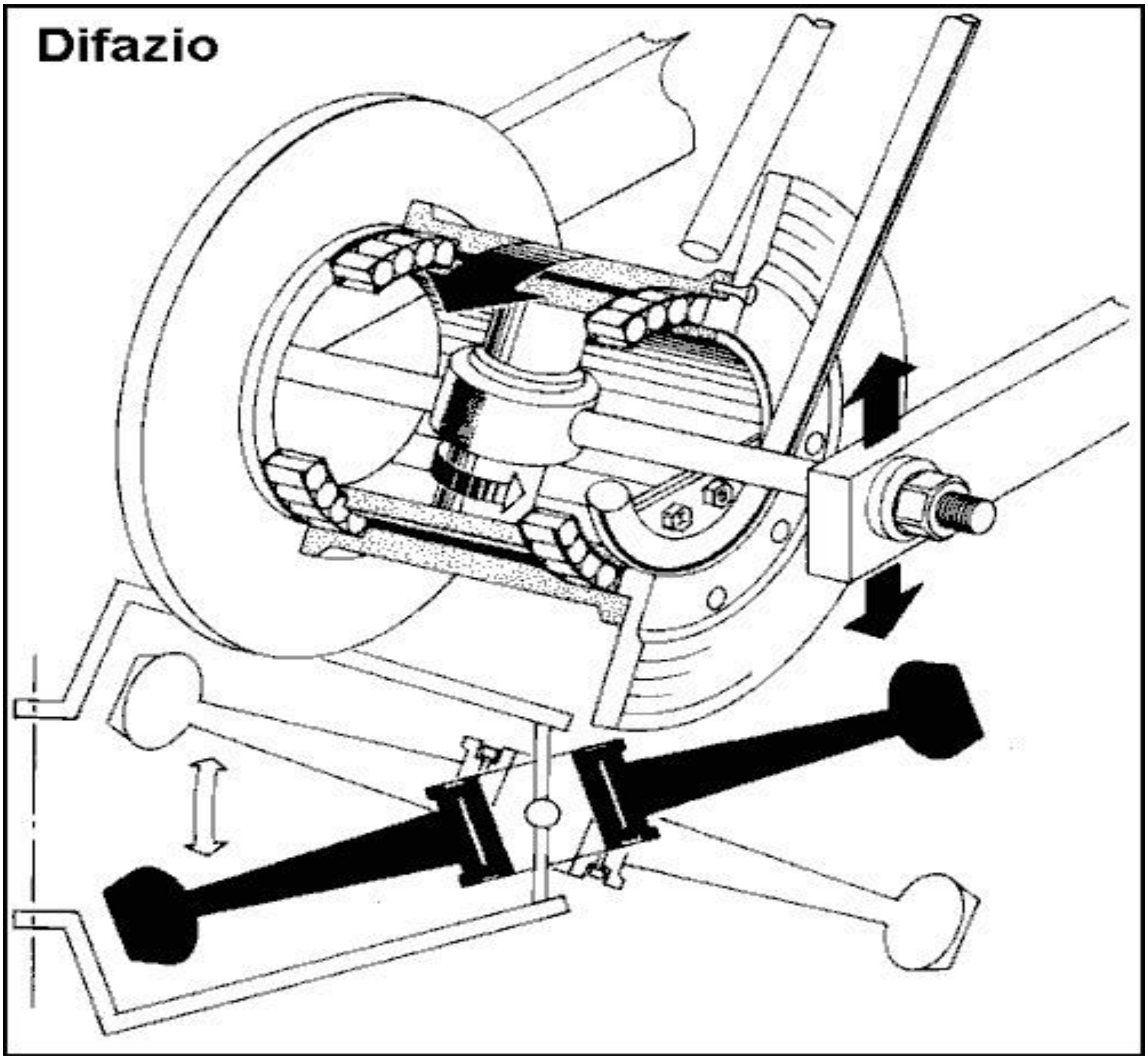


Fig 5.2 Diagrammatic representation of working in "Hub- center" steering mechanism [25].

BIMOTA and VYRUS are the only companies that have introduced commuter motorcycles with this exclusive mechanism, but the system has independent suspension system. In this thesis, a new steering design is proposed for both the motorcycle with interconnected suspension as well as for the swing arm type of arrangement. The main motivation for this kind of arrangement is for the fact that, the front swing arm type of suspension has the advantageous aspect that it provides a lot of steering ability in aspects of acceleration in corners. It improves the overall performance but the contradictory fact is that its name has not reached as it had a peculiar mechanisms and it not known for the commuters in a lot of basis expect for a few passionate who are really involved and interested about innovative technologies.

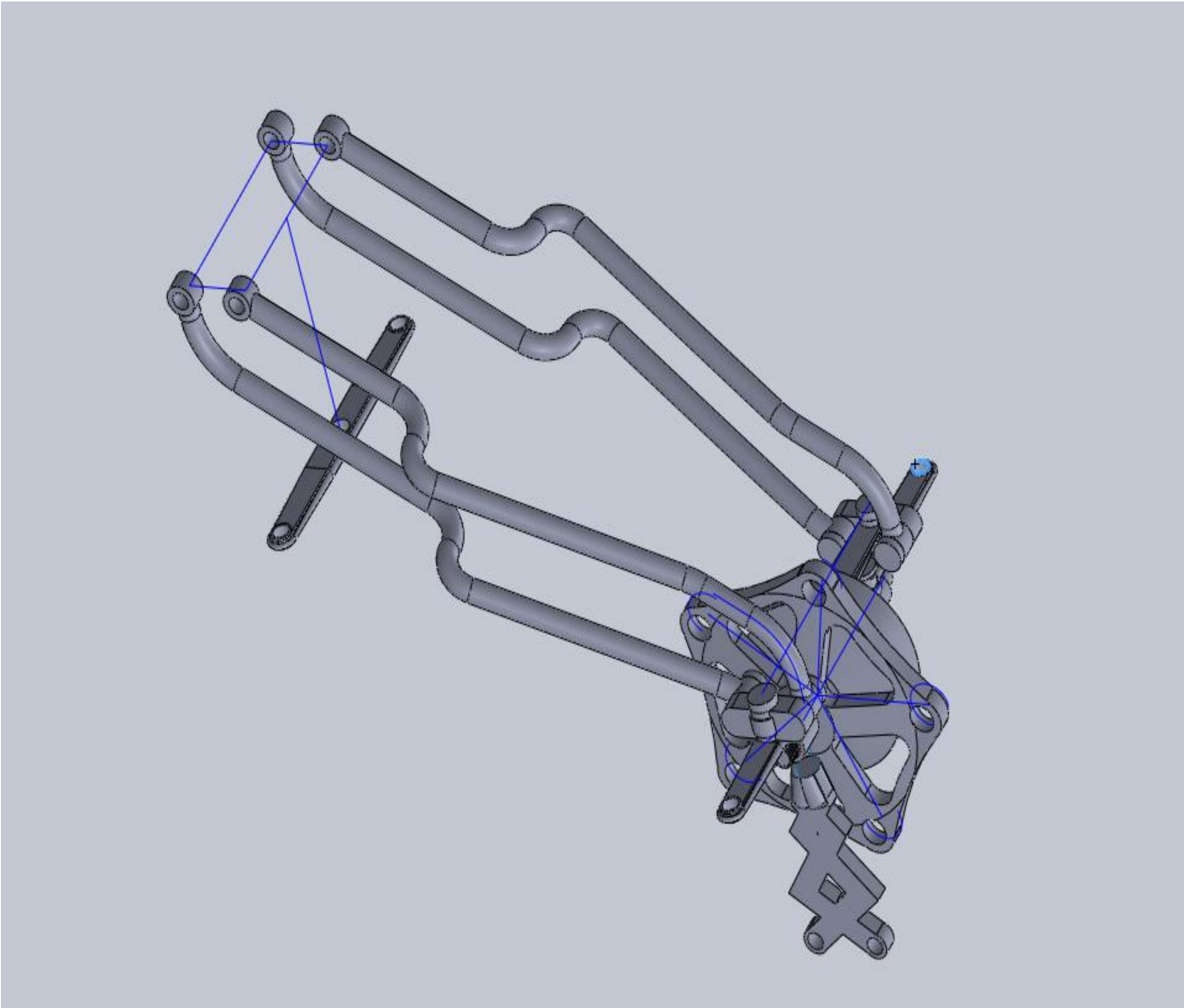


Fig 5.3 Proposed steering mechanism for interconnected suspensions in isometric view.

The above figure shows the isometric view of the proposed design for the steering system. This has four tie rods to ease the actions of the steering mechanism, as they push each other to turn the wheel right or left. The purpose of these two tie rods, is to give necessary action in order to give a very quick response in order to overcome the difficulty in the response in unconventional steering mechanisms that are designed to till date. Here these tie rods are actuated by the steering handlebar, where it directly pushes the bracket fitted to the swing arm. The bracket has constrained rotational motion providing the steering angle towards the purpose of design for ex: racing, off road, street or cruiser. All these purpose demands a very different characteristics in design of chassis and the suspensions. As the steering bracket can be actuated according to the movement of steering handlebar, it can be made compatible to any purpose of design for the motorcycle along with this arrangement of interconnection. This bracket turns the wheel hub which consists of both the alloy and the disc. The main constraint was about the caliper mount, as it shouldn't move. To facilitate the movement of caliper, splines are provided to the disc hub, even when it is turned, the whole disc unit has a free motion to move in direction of steering along with the caliper mounting as well as in contact with wheel hub to ensure optimum braking. This arrangement can be in a complicated perspective to understand the working of this steering mechanism and it needs a sophisticated manufacturing process too.

7. DISCUSSION OF RESULT

In this thesis, a new concept of motorcycle with interconnected suspensions is introduced, and the system shows that it can possibly work with more accurate dynamic modelling. The results here shows that this system primarily causes some problems, but the assumptions made here were the main reason to be worked on. One of the main reason is due to the constant tractive force, that was applied to the system at all conditions will definitely affect the stability. The main reason for inclusion of tire characteristics in the literature, is to show the importance of tire properties that can affect a new system like this in a very effective manner, although it was not gone in detail about it. The purpose of this paper was to propose a new interconnected suspension mechanism for motorcycle and new steering system to the same. With more sophisticated modelling and software, there is a need for time and research to optimize towards specific characteristics that it is designed for.

8. CONCLUSION

1. Analysis of research results in interconnected suspensions and its parameters is done.
2. Concept of motorcycle with interconnected suspensions is designed.
3. Dynamical model is developed.
4. Mathematical model for interconnected suspension in accelerating maneuver is built.
5. Process of simulation and simulation result analysis is done.
6. Design concept of unconventional steering mechanism for motorcycle with interconnected suspension is proposed.

9. FUTURE WORKS AND RECOMMENDATIONS

The design considerations can always be optimized to limitless extent, which it stays at the saturation point of almost perfect. Now a new concept of interconnection is proposed and the mathematical model is established. With more sophisticated multi body dynamics software like MSC Adams, AutoSIM and Bike SIM, the system can be established and the simulations can also be carried out in 3-D to obtain more detailed results. With these software, also the parameters affecting the system can also be changed and optimized for better functionality. The new proposed steering concept can also be optimized, in further with the basic design. A special type of chassis can also be modeled and analyzed for the proposed system of interconnection and the inclusion of electronics can have a greater impact on optimization of the system.

10. REFERENCES

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