

Development of multi-body suspension for a single seat formula car

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Introduction:

Among all the different critical parts in a vehicle, the most important system is the drive mechanism of the vehicle starting from its primary drive train unit to its transmission unit. After considering the drive train unit if we talk about another most important part of a vehicle, that will be nothing but the suspension unit of a vehicle. Now one may think about the need for a suspension unit of a vehicle, and a very basic answer will be comforted. In this paper, we are discussing all about the need of the suspension unit within a vehicle especially for a single-seat formula racing vehicle as well as the construction details with all of its design criteria.

In the previous days, the model of the suspension system was quite conventional therefore the comfort level, as well as the driving experiences, was not that much efficient in previous days of the development. In recent days in the automobile industry, each and individual company are running behind technological advancement in their vehicles. In the case of a racing scenario, things becoming really advance in these days because the concepts of the active suspension system are now very common in high-profile cars also. So, the designing and the working criteria of the suspension unit are becoming very much critical therefore it is really very necessary to evaluate the performance of a suspension system along with the design criteria using a different virtual model and their analysis using different software.

This is the only reason why we are considering this topic and for that, the technological developing feature of the suspension system of a single-seat racing vehicle and the design of the entire unit is getting more and more focus in this paper. Along with the physical model design, we are also concerned about the performance of the suspension system because the vehicle considered here is a racing one. So very conventional suspension features will not be there in this model as well as the performance will be a little different in this case. Now as per the requirement we are using the CATIA V5R20 software tool to prepare the design of the suspension system and using MATLAB we are preparing the Simulink model of the suspension unit. For better performance in the bouncing scenario due to different road conditions in the further parts of the paper, we are also considering the design approach of an active suspension unit along with the conventional design. It will help the vehicle not to jerk more in bad road conditions so that the driver will become confident enough while driving. An active suspension unit is a sensor-based approach within the mechanical work that will allow the lower body of the vehicle to jerk without making any vertical displacement on the upper body, using this technology now so many companies like Nissan, Chevrolet, Hyundai, Honda are making their top-end vehicles very comfortable in term of jerking and driving experience also. Considering the sprung and un-sprung mass of a vehicle the simulations are done in Matlab Simulink and also for the design aspects individual components were prepared and they have been assembled in a single suspension unit that is shown throughout the paper. Using the design criteria and materials used in the design all the spring constant, spring-mass, un-sprung mass are used so that all the graphs plotted in the Simulink will show the behavior of the suspension unit.

Aim and objective:

Before we start presenting any thesis it is required to set a goal and its corresponding objectives so that we can match all the requirements stated in the assignment brief. For this particular research and development approach below are the aims and their corresponding objectives,

Aims of this research are,

- The first and foremost need is to design the entire suspension unit in such a way that the design will not get more complexity. The reason behind it is a complex suspension may get so many difficulties in events so a complete robust mechanical unit will be the best solution. Along with that we can say in actual the suspension will be different in terms of the design but for better understanding and analysis we made this in a simpler way.
- Secondly, the performance evaluation is one of the most important needs of this presentation. It will ensure us the behavior of the suspension unit as well whether it is good for the current application or not that can be determined through the performance evaluation.
- Finally implementing the feature of an active suspension system along with the conventional suspension unit is another aim of this report.

Based on these aims the corresponding objectives are,

- For the design perspective of the suspension system first, we need to use a 3d modeling software and the design criteria with all the features and measurements are needed to be done in properly using different research articles. Also, formula racing cars data handbooks can be used for gathering design data.
- The usage of Matlab simulation using the module named Simulink is very important and for it, we need to take so many research articles into consideration so that the Simulink model can be generated which will be similar to the single-seat formula racing cars.
- For the performance optimization, we can check the vertical displacement of the wheel hub and the vehicle so that we can get some concluding statements based on the model we are developing.
- Finally using the Simulink modeling or direct Matlab programming we can check with the performance of the suspension system when it is connected to the active suspension system. As well for comparative study, we can also compare the performance of the suspension system with or without an active suspension system so that in the final stage of development we can choose the correct option.

This is all about the aim and its corresponding objectives in the development of a suspension system of the vehicle for a single-seat formula racing car. Along with all these, we should always keep concerned about the nature of the vehicle. We should never think about the suspension system in a conventional car because the suspension in a racing vehicle is more on the stiffer side

because of lesser comfort and dynamic driving. For the racing purpose, the racing vehicle should be stiff enough so that the terms like roll center, center of gravity, slip, bounce each and everything will become suitable during the time of its performance.

Research questions:

Question 1:

How do suspensions differ from conventional vehicles and racing vehicles?

Answer:

In general, the suspensions are having similar types of work in every application. Reduction of a jerk, vibration, and vertical to and fro movement of the vehicle is controlled using a suspension system. In this scenario, the combined structure of a spring and a damper is can be seen in different static types of machinery for absorbing the sudden impacts. Similarly, if we can compare the implementation and application of a suspension system in conventional vehicles and racing vehicles most of the working is similar. But it differs in the usage with their requirement.

The suspension system in a conventional vehicle is focused on the comfort of the passengers. So the suspension is on a softer side. On the other hand the in a racing vehicle the comfort is not a concern, we should always think about the performance of the vehicle without any accidents. So the suspension in a racing vehicle is not more complex with so many sensors and also it is more on the stiffer side. This is how the suspension differs from conventional vehicles to racing vehicles.

Question 2:

What are the main factors needed to be considered in the suspension system of a racing vehicle?

Answer:

Two main factors are needed to be concerned in the design and performance evaluation of the suspension system in a racing vehicle-like performance and the complexity in the design. The performance of the vehicle should be such that there might not have any problem while driving the car. As well as the complexity of the suspension should be minimal. In the complexity of the suspension system, the design of the entire assembly should not have any difficulty designing as well as the working nature of the unit should not have any other working complexity.

Therefore, so many research articles are needed to be followed before we go for any concrete solution and design approach. As the vehicle model is not generated in our hand, therefore, the sprung and un-sprung mass should be taken from any other research article, and using that we can simulate the Simulink model to obtain the plotting based on different quantities.

Question 3:

How we can improve the performance of the suspension unit of the racing vehicle:

Answer:

The performance can be evaluated using the software-based simulation using Matlab Simulink modeling. Now the improvement can be done on the basis of the performance of the suspension system. As we can see the construction feature of the suspension units cannot be changed with the different dimensional features because of so many design limitations in the racing authorities. So it is very crucial to maintain a higher performance of the suspension. At this stage we can do some of the changes in the spring and the damper coefficients of the suspension as well we can also add the concept of active suspension in the physical model.

The dimensional feature of the suspension like 'A' arm's length, turning radius, camber, caster these things are having lots of limitations therefore we need to maintain them as much as near to the regulations provided by the racing organizing authority.

Considering such types of research questions we can easily prepare a set of research questions that will be merged with the research goals and in the further steps it will helping us out for making the best performing suspension system in a higher speed and stiff corners.

Literature review:

The literature review is the part of a research paper where we can create a model of the development using the approaches taken by other researchers in their paper. For this time also we have used so many papers from research gate, Elsevier, and other reputed publishing authorities and gathered so many research papers to get the knowledge about the approaches that should be taken in the paper presentation.

The best option for presenting such type of design evaluation paper based on a physical model of a suspension system the first thing we need is the physical model preparation. Now the physical model preparation does not signify the prototype development. It is all about making a 3d model of the suspension system. It is proven as one of the best approaches by different researchers the reason behind it is, it will ensure an effective set of knowledge from the very ground level of development. Similarly, the design skills using different software tools can be emphasized using this approach. The nature of designing the physical model of the suspension system also shows the maintaining nature of the regulations. Any design software like CATIA, Solidworks, Ansys can be used to prepare the model so one can use any of the software according to his/her expertise. For this case, I have used CATIA V5R20 software and simulated it in the performance in the Matlab Simulink modeling tool. It is also reviewed by s many research works that the complexity in the design should be very little therefore the design is also taken very simple so that the chances of getting an error can be reduced to a higher extend.

Along with the performance evaluation we also need to ensure the overall capability of the designed model for this finite element analysis is the right way by which we can create a stress and deformation simulation to check whether the model is good enough to sustain continuous and sudden loading on it during the operational condition.

Now the focus of presenting this research paper is not all about the design, it is more about the performance of the complete unit. For its performance, we will be using Matlab programming specifically for the active suspension system and Simulink for the spring and damper modeling. In this case, the vertical movements of the vehicle's sprung and un-sprung mass is taken into consideration. Using step signals as an input we will be carrying out the performance evaluation. All these things will be given in the further chapters of the paper. Along with all these getting general information regarding different types of conventional suspension systems is needed because it can help us to get a brief knowledge about the research and development in suspension from a long ago. These things will also be discussed in further chapters.

Chapter: 1 (Brief study of suspension system)

1.1. Different types of suspension systems:

According to the construction and the working principle of a suspension system it can be classified into three different types, those are dependent suspension system, independent suspension system, and finally the semi-independent suspension. Among all these three different types we cannot make anyone superior over others because each of them is having their perfect usage as per the application in the automobile sector. It is obvious, the suspension of a two-wheeler, four-wheeler, racing vehicle, and goods carrier will be similar in construction and working. So, different types of suspensions are used in different applications. But to choose the correct option for our application is very important and for this reason only if we can learn all the advantages and disadvantages of different types of suspension it will be better to find out the best solution.

1.1.1. Dependent suspension system:

A dependent suspension system is a kind of suspension in which the vertical travel of a wheel is captured by the entire transmission system and the other will also achieve the travel. In practical terms, we can say in this suspension system if a single wheel moves over a bump or hump another wheel connected to a similar axis will also get distorted by that movement. So the movement of a single wheel is directly dependent on the movement of another wheel that is why it is known as a dependant suspension system.

The advantages of this type of suspension system are,

1. It can sustain higher loads compared to any other type of suspension system.

2. The mechanical complexity of this type of suspension is totally flawless therefore chances of getting error in it is negligible and also the failure is very rare.

Even with these advantages, there are few disadvantages, those are,

1. Any vertical movement in a single wheel in such suspension is transferred to the other wheels attached to the same axis.
2. Such type of suspension system is heavy and its sizes are really very bulky so they can only be used in commercial goods carrier.
3. In a stiff corner, the chances of getting tilt are very common therefore the vehicles with this suspension system should maintain certain driving skills otherwise accident is very common in it.

1.1.2. Independent suspension system:

An independent suspension system is more or less an advanced design compared to the dependent suspension system because of its performance. In this category the vertical movement of a single wheel is not transferred to any other wheel of a vehicle. Therefore, different wheels are having their own suspension system. Single wishbone arm suspension, double-wishbone arm suspensions are the two very commonly used independent suspensions. Though this type of suspension is used in private cars and small vehicles in earlier days but in recent days for better driving quality some of the commercial vehicles are also equipped with an independent suspension system with some of the advanced features.

The advantages of an independent suspension system are,

1. The vertical to and fro motion of a single wheel never transferred to any other wheel.
2. It can maintain the vehicle body always horizontal without tilting, therefore, under stiff cornering, it can reduce the chances of getting tilted with the respect to the road surface.
3. The overall driving quality is superior in this type of suspension. Also, the mechanical complexity and chances of failure are very rare.

Along with these advantages, there are few disadvantages, those are,

1. Instead of superior driving quality, it is not made for heavy multiple axle vehicles which is one of the most important limitations.
2. The mechanical complexity in this type of suspension system is a little bit complex compared to the dependent suspension.
3. There are so many small and high-performance parts are attached to this type of suspension therefore the cost is higher compared to any other suspension system but it is improving day by day with lots of research and development.

1.1.3. Semi-independent suspension system:

The semi-independent suspension system is nothing but a combination of the independent and dependent suspension systems. Therefore, the performance of this type of unit is not like very hard as dependent ones, and also it is not too soft like independent suspensions. Still in some of the front-wheel-drive vehicles if we have a dummy axle in the rear then we may have this type of suspension. The twisting nature of the linkage rods will be giving the damping nature of the vehicle but an excessive loading on a vehicle having semi-independent suspension may cause a failure in the entire system.

The advantages of using this type of suspension are,

1. The load-carrying capacity is higher than that of the independent suspension incorporated vehicle.
2. Using the twisted bar-based suspension model it acts like an independent suspension unit therefore it has a satisfying comfort level.
3. The design complexity is negligible as well as failure is rare in it.

Along with all these advantages the disadvantages are,

1. Compared to the independent suspension system it is not having that much comfort.
2. After the permissible limit of carrying capacity, the chances of getting failure are very common in it.
3. This can be mostly used in the front-wheel-drive vehicle. incorporating it in a rear-wheel-drive vehicle is not a feasible option.

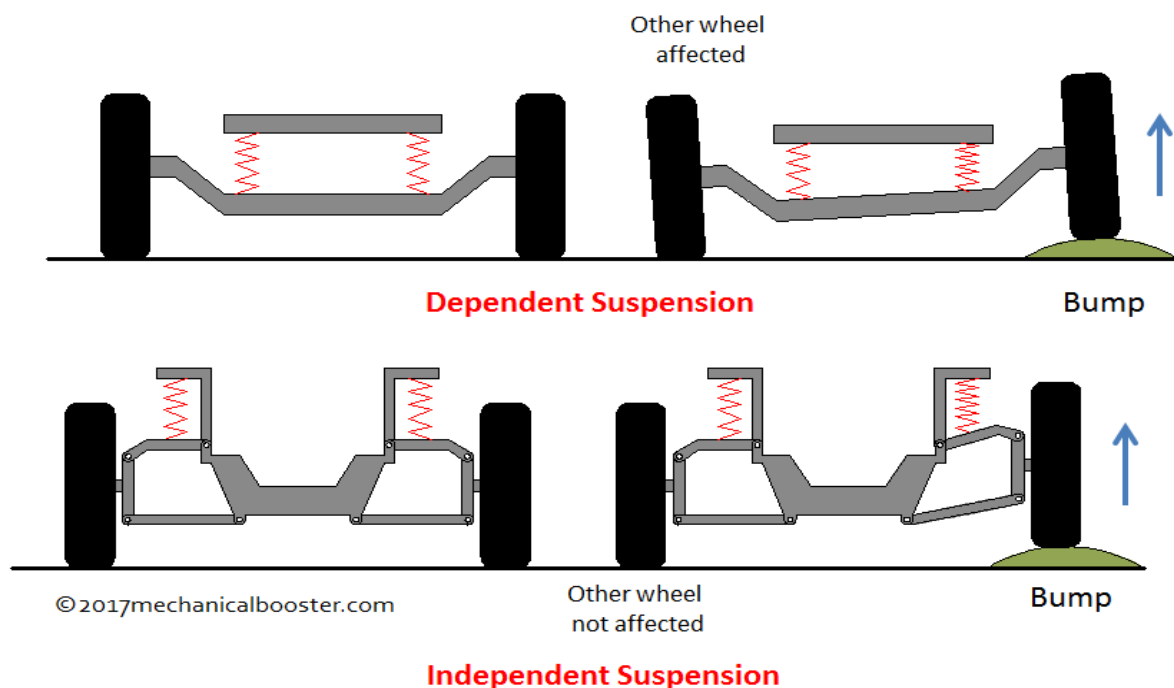


Figure 1: The basic difference between the dependent and independent suspension system

If we can observe the above figure the things become clear to us whatever is discussed above. In the first scenario, we can see the dependent suspension system is tilting the entire axle but on the other hand in an independent suspension system, the only wheel is getting an extended position maintaining the horizontal condition of the vehicle body.

1.2. Active suspension system implementation:

The implementation of an active suspension system is now becoming a very common factor for all the high segment cars as well as for a racing vehicle where we may have a higher risk factor the implementation of an active suspension system is necessary.

An active suspension system is not advancement on the mechanical components of the suspension system rather it is basically the implementation of an electromechanical device that will be using in the damper assembly so that the internal pressure of the fluid in the damper can be controlled. In a bad road condition, the bouncing nature of the suspension system cannot be controlled by any type of mechanical advancement. But the bouncing nature can be controlled if we can control the pressure of the internal fluid in the damper then it will become easier for us to control the vehicle's vertical movement.

In general, we can see in a stiff corner the vehicle's body tilts which is very uncomfortable for the occupants. In that situation, if there is an electromechanical sensor-based pumping unit that can increase or decrease the pressure then we can easily control the tilting scenario of the vehicle body. It is the only reason why most of the higher segment vehicles are using completely electronic sensor-based active suspension systems. Similarly, when we are considering a formula racing car then the traction is very important; therefore, if there is a huge gap between the tire and the road surface then the active suspension system can work properly to maintain the gap at an instance. A detailed discussion and the Matlab simulations will be given in the further parts of this paper.

1.3. Feasibility of different types of suspension:

Considering different types of suspension systems choosing the best solution as per the requirement is very much important because in a racing scenario there we have to concern about the performance as well as the safety. In the design criteria of a racing vehicle suspension system to reduce the mechanical complexity the attaching the transmission unit to the rear wheel is the best option because the rear wheel is always the fixed one without any steering controlling mechanism.

Similarly, if we can attach the entire steering controlling unit to the front wheels then it will be free from any transmission complexity. At this condition considering the research and development, we can keep our focus on the suspension unit for a long time. After lots of research through different published research papers, the independent suspension system is becoming one of the most useful options for formula racing vehicles because of its higher stability. As well in

this type of system can easily be implemented in either wheel along with the suspension damper. For this application we can use the spring and damper assembly in a single unit and the damper unit can be attached to the active suspension sensor. For the physical modeling or designing, we cannot show its implementation but in the analysis of the performance, we can directly use the concept in our analysis module.

1.4. Suspension components:

Before going towards the designing approach if we discuss a little about the different components available in the entire suspension unit it will become easier to understand. Let us show all these components and their general descriptions below,

- **Suspension 'A' arm:** This part is nothing but the entire holding assembly of the suspension unit. Sometimes it is known as the suspension 'A' arm and sometimes it is also known as the wishbone arm as per the suitability and design approach. The suspension assembly, steering unit, and drive train are attached to this part. The structure just looks like 'A' that is why it is known as suspension A-arm. The two legs of the arm are attached to the vehicle chassis and the wheel knuckle is attached at the vertex of the A-arm.

Using this arm the suspension is also attached between the wheel and the mainframe at a certain distance so that the angle can be maintained as per the design criteria. The two chassis attaching ends are always fixed with bushes for obtaining a free movement about their axis and at the vertex, there is a right angle ball joint arm attached which will be used in the holding assembly of the wheel hub and knuckle. These similar types of two identical components are attached to a single suspension unit but sometimes in advance designing we can see single-armed suspension but it is a rare scenario of racing cars because safety matters a lot.

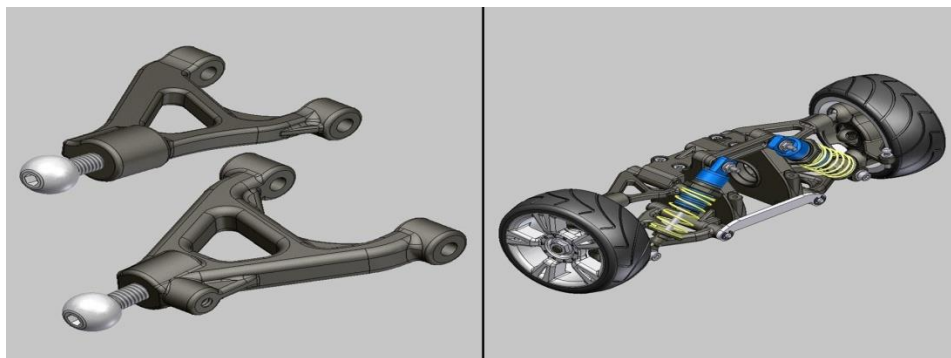


Figure 2: Suspension 'A' arm

- **Right angle ball joint:** The right angle ball joint is nothing but the attachment situated at the vertex end of the A-arm. It is used to hold the wheel hub and knuckle assembly.

As well as the steering system will be making the axis of the wheel hub different at different steering angles therefore using the ball joint we can have a free rotational movement of the wheel hub. Along with that, the camber and caster adjustment is only possible by making the arms of the ball joint larger and smaller as per the requirement.

In this part there we have two different arms that are situated right-angled to each other and they are always threaded to a long length so that the length adjustment can be done in an effective manner.



Figure 3: Right-angled ball joint

- **Knuckle joint and wheel hub:** The wheel hub is the end part of the suspension unit because it is carrying all the rotator parts like bush and bearing joints and finally the wheel assembly. The wheel hub is finally coupled with the transmission system either from the engine or an electric motor. Sometimes, wheel hub motors are also placed in them for better performance and lesser complexity.

The knuckle joint is the bearing holding part which is helped to attach the wheel hub with the suspension arm. The upper and the lower portions of the knuckle joints are attached to the ball joints placed at the end of the 'A' arms. The extended arm at the knuckle joint is used to attach the steering arms so for angular displacement of the wheel axle.

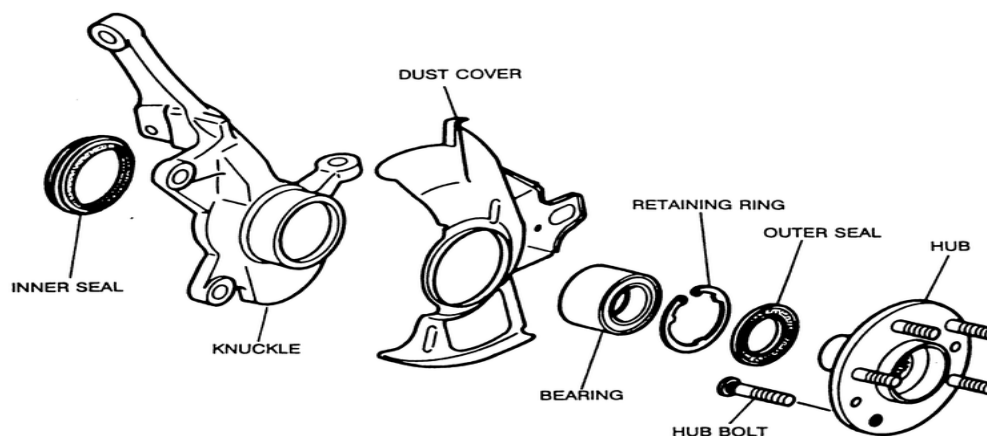


Figure 4: Knuckle and wheel hub assembly

- **Spring and damper assembly:** During sudden bumps and bad road conditions a sudden wave can be captured by the wheel hub assembly therefore it is needed to be absorbed in such a way that the comfort and the driving quality will not distort. The springs are used as a shock absorber and the damper will be managing the bounce and re-bouncing.

In most cases the spring and the damper are attached separately and but if we are having a compact design approach with less space then we can use assembled spring and damper altogether. For a heavily loaded vehicle, the springs are having a higher diameter, as well as the coil springs, are having a higher cross-sectional area. Similarly, for a heavily loaded vehicle, the damper will also be higher in cross-section. a shorter journey is necessary for the racing vehicles because the road conditions are generally good with a slight amount of bounce therefore we will be using a short-sized shock absorber in the design.

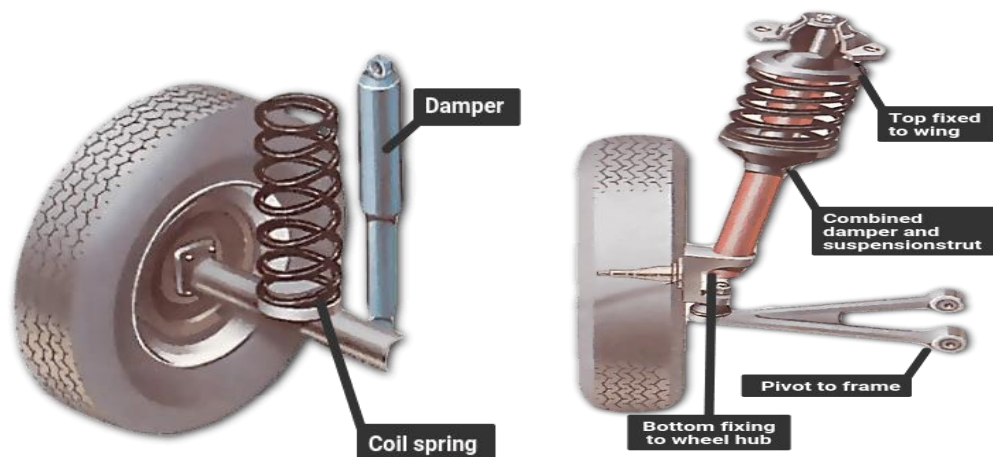


Figure 5: Individual spring & damper and combined spring-damper assembly

Along with these main mechanical components we need to incorporate three more components like acceleration sensor, displacement sensor, and steering wheel positioning sensor. The acceleration sensor is used to calculate the real-time acceleration of the vehicle on the other hand the steering wheel positioning sensor is used to check what the angle of displacement of the wheel axle is so that the acceleration and the active suspension system pressure monitoring system controlled with its own methodology. Similarly, the displacement sensor is attached to the suspension system to measure the vertical displacement of the wheel hub so that the pump attached to the damper can increase or decrease the internal fluid pressure.

Chapter: 2 (Design critique and the numerical analysis)

In this chapter, we are presenting the designed model of the suspension system we are intending to use in the prototype. Though it is very simple but its implementation will give the most robustness and failure-free characteristics for a long time. Before we go through the actual design approach it is necessary to choose the dimensional feature and based on it we will be finding out the basic performance of individual components and finally using the design criteria and dimensional feature we will be initiating the design approach using 3d design software.

2.1. Design methodology:

The design methodology is totally based on the usage of the software tool and preparing different small parts along with their assembly to create the final model of the suspension system. Using the non-parametric software we are tries to prepare the model of the suspension system. The usage of the parametric software is mentioned here because the methodology is signifying a trial and error method of the design approach. The reason behind it is, we may have different kinds of difficulties while designing the entire model, therefore, we need to change the dimensioning of different parts, therefore, using non-parametric software will be the best option for our case study.

Even along with the physical model creation if we will think in detail about the performance of the suspension system then we can say not only the comfort and driving qualities are the significant factors of the performance of a suspension because the sustainability of the designed model matters a lot. For this reason, the finite element analysis is also taken into consideration in our development so that the load-bearing capacities are understood. Numerically finding out the stress concentration and the deformation of the structure under continuous and sudden loading is a tough job but using a software tool if we perform finite element analysis then we can easily come up with the factors related to sustainability which is also one of the most important factors in the performance evaluation. The actual motive is to present the short-term and long-term performance of the suspension system considering its behavior in operation and structural strength.

2.2. Numerical analysis:

A design cannot be placed until of unless we are have prepared the conceptual design. Now the conceptual design should have different dimensional parameters so that the actual design will become feasible for the application. Now one may think about the selection of dimensions as arbitrary in this context it is very important that the dimensioning is allowing the system to sustain all kinds of load under different conditions. Therefore, in this part of the paper, it is tried to present the numerical analysis for different parts so that in the further portions the design can be portrayed,

- **Spring design calculation:**

The actual design parameters of the designed vehicle are not present in our hands therefore calculating the dimensional feature of the spring is not possible at all. But using some of the assumptions and some pre-defined data from the feature handbook we can collect the loading scenario by which we can easily calculate the dimensional feature of the springs.

$$P_m = \frac{1}{2}(P_{\max} + P_{\min})$$

$$P_a = \frac{1}{2}(P_{\max} - P_{\min})$$

Considering the material used in the spring is hardened steel and the jounce and re-bounce are 25.4 mm or 1 inch.

$$\tau_m = K_s \left(\frac{8P_m D}{\pi d^3} \right)$$

$$\tau_a = K \left(\frac{8P_a D}{\pi d^3} \right)$$

$$C = D / d$$

$$K_s = 1 + 0.5 / C$$

$$K = \frac{4C - 1}{4C - 4} + \frac{0.615}{C}$$

In this expression, the different symbols are having their own significance. K and K_s are the spring constant, D and d are the outer and inner diameter of the spring. Now the sustainability of the spring in different unwanted situations can be expressed as,

$$S_{se} = 0.225S_{ut}, S_{sy} = 0.45S_{ut}$$

$$\frac{\tau_a}{\frac{S_{sy}}{f_s} - \tau_m} = \frac{S_{se}}{2S_{sy} - S_{se}}$$

In this expression, the f_s is known as the factor of safety of the spring on the other hand by using the design handbook data from different research articles we can say the factors of safety should be greater than 2 and lesser than 3. Finally, using all these data and different design calculations we can calculate the number of turns in the spring and that can be further expressed as,

$$N = \frac{Gd^4}{8D^3K_f}$$

- **Suspension ‘A’ arm design calculation:**

This is basically the main structural part of the suspension system therefore we need to be very much careful while designing the suspension ‘A’ arm because the entire load will be transferred through the ‘A’ arm only. Considering the total weight of the vehicle is 600 kg, therefore, each wheel of the vehicle will be carrying a load of 150 kg or 1500 N if we take acceleration due to gravity is 10m/s^2 .

If we just think of the suspension arm as a cantilever beam and the load application is upward at the end then we can easily calculate the deflection of the arm assembly considering restricted free rotation with respect to the chassis axis.

$$\Delta_{\max} = \frac{PL^3}{3EI}$$

$$P = 1500\text{N}$$

$$L = 400\text{mm} = 0.4\text{m (Approx)}$$

$$E = 2 \times 10^{11} \text{ N / m}^2 \text{ (Assumption as per the grade of steel)}$$

$$I = 226530000\text{mm}^4 = 0.00022653\text{m}^4$$

Therefore deflection will be,

$$\Delta = \frac{1500 \times 0.4^3}{3 \times 2 \times 10^{11} \times 0.00022653} = 1.76 \times 10^{-6} \text{ m}$$

Which is not even 0.5 mm therefore the structural sustainability of the swing arm of the suspension 'A' arm is adequate enough for our application. Now the detailed finite element analysis-based results can give us the exact results regarding the deformation and stress failure on the structure.

2.3.Other design approaches:

Along with all these basic design criteria there, we should always have detailed design parameters because the performance of the suspension system differs a lot with a simple change in the system. So, while preparing the virtual 3d model we can use these features stated below,

1. There should have a minimum of 1-inch travel in the suspension system but it can be a maximum of 4 inches for the vehicle. As we all know the race track will be smooth still the bounce effect should be absorbed by the suspension module so we need to go for a higher amount of suspension travel.
2. A very stiff and a very soft suspension should not be there because both will create different types of errors while driving on a race track. A stiff suspension will not allow the driver to get confidence in corners similarly a too soft suspension will be harmful because of traction loss on the successive bounce.

3. Along with these two important points, the suspension springs and the damper should have the ability to carry the un-sprung mass of the vehicle. It should not travel to the highest range on the vehicle's self-weight.
4. There should have adjustable rings in the suspension so that the softness and the hardness can be changed manually because the road conditions are not pre-defined.

If we can go with all these crucial parameters then undoubtedly the suspension will become one of the most effective ones for student-developed formula cars. As we can see there are ball joints at the ends of the suspension 'A' arms, therefore, we do not think much about the caster, camber, and toe angle, all these things can be changed as per the requirement.

2.4. Design:

Below are the designed parts of the suspension system we are preparing for the formula race car,

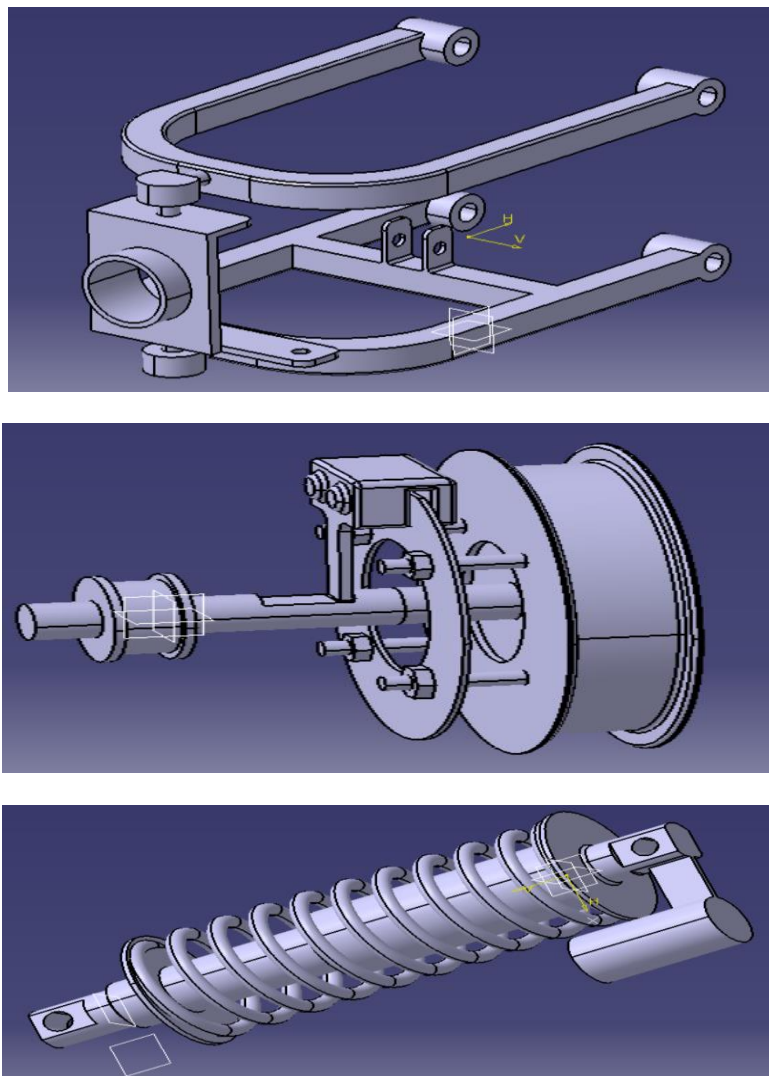


Figure 6: Different designed parts of the suspension system

After getting done with the design approach we have been prepared different components of the suspension system so that we can finally assemble them to get the entire suspension unit. Now the suspension unit can be prepared using two different approaches like double wishbone arm suspension and double-wishbone arm suspension with the pushrod. Both of these two suspensions are quite effective but the pushrod may make the suspension a little complex compared to the other one but we can choose it because of higher efficiency under the worst road condition.

Below are the two different types of suspension we can have for the application,

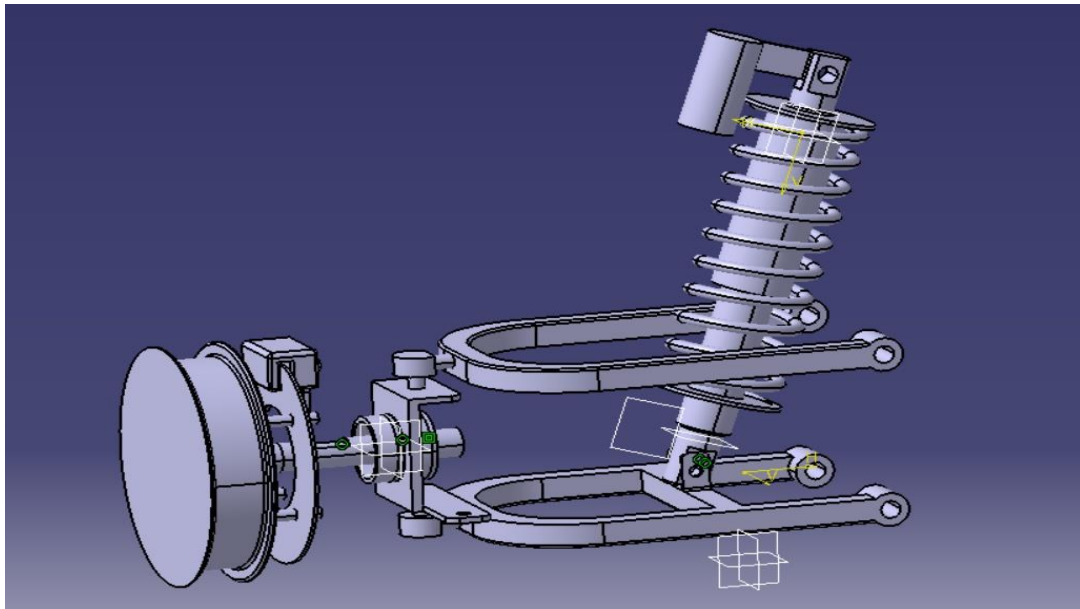


Figure 7: Double wishbone arm suspension

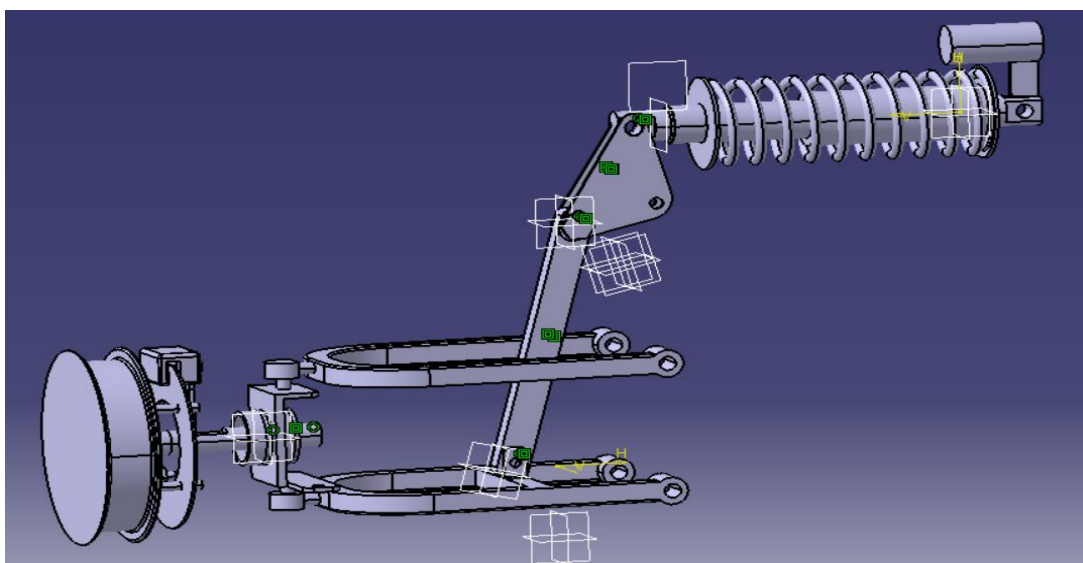


Figure 8: Double wishbone arm suspension with pushrod mechanism

2.5. Presentation methodology:

For both the design approach and performance evaluation we need to think about the presentation of the paper from the initiation to the ending. Three different stages are contributing their individual significance in the paper presentation. The first chapter representing the theoretical base of the intended suspension system, chapter 2 is representing the design methodologies and the design approaches along with the exact physical model prepared and in the third chapter, we will be doing the performance evaluation of the proposed suspension system using Matlab Simulink module. To achieve all requirements from initiation to the ending we can follow few steps, like,

1. Critical thinking about the exact problem statement. In this stage using different requirement parameters and research articles, we need to understand the actual requirement, and based on that a virtual model is to be generated in the mind so that it can be portrayed in the first design approach.
2. In the further step, we need to make the first stage of design. It might have so many errors at the starting of the design but with repetitive modification in the non-parametric software, we will be able to change the design specifications along with the dimensional features.
3. Theoretical base creation is the next step where we can prepare a write-up so that the visualization of the actual problem becomes superior. As well as the technical parameters will become more and more significant to the study.
4. If the storytelling and the theoretical base are ready then individual team members can have a conversation with each other with multiple solutions to find out the best possible solution.
5. Comparing all the solutions given by different team members' decision-making will be the further step because choosing the best solution is a tough job. So, for this approach we may need to consult with experts or tutors as well there are so many research articles are available on reviews of different available technologies so we can use them too for decision making.
6. When the decision-making is done, then we are good to go with the best approach and for this, we need to validate the approach through several team meetings and consultation with the tutors. If the proposed methodology and the design approach are approved then they can be adopted.
7. Finally using the best possible solution to make a sketch and converting the sketch into the virtual 3d model is the further step. In this step also we can try iteration so that the best result is obtained from development. Using different prototype model and their performance evaluation we can prepare the final paper.

Exactly the same approach is taken into consideration for our case study. Therefore the chances of getting errors in the design and performance evaluation are negligible.

Chapter: 3 (Design and performance evaluation)

In this chapter of the paper, we are focusing on the performance evaluation of the vehicle suspension system considering the design aspects as well as the performance at operational conditions.

In this condition, it will be better for us if we can evaluate the mechanical performance of the designed suspension. Now, what does it mean by the mechanical performance that should be clear to us. The mechanical performance signifies the overall structural sustainability under different working conditions. The reason behind it is, the structural failure in a suspension system will also be considered as a general failure if it happens under operational conditions. To check these things we can use the finite element analysis using numerical approach or software approaches. As we are using the CATIA software tool in the design then it will be better to use that software only for FEA analysis to detect the failure modes in the structure.

So, along with the Simulink modeling of the performance, we are also attaching the finite element analysis in this part of the paper considering the structural failure as a performance obligation in a system.

3.1. Finite element analysis:

In this section using the software tool, we have designed different components and the finite element analysis is performed for each of the parts. For this, the load actuation in different parts is needed to be understood. To obtain the load application we have just used the assumed weight of the vehicle and at any jerk, we are assuming the load will be double. Therefore, if we will be using the double weight as a load actuation on those parts then if those parts will show us very good structural sustainability then the so-called mechanical performance will be good to go. Two different parameters are shown in this analysis the first one is the von-mises stress and the second one is its deformation under the loaded condition.

The selection of the material is also an important thing because the material property plays an important role in their sustainability. the metals like steel, aluminum, copper all are having different structural strengths therefore they are used in different applications, so choosing the perfect solution in terms of material is very important. For our case, we are selecting steel as a material. The material properties are stated below,

Table 1: Material properties

Material	Steel
Young's modulus	2e+011N_m2
Poisson's ratio	0.266
Density	7860kg_m3

Coefficient of thermal expansion	1.17e-005_Kdeg
Yield strength	2.5e+008N_m2

3.1.1. Selection of boundary conditions:

The selection of the boundary conditions is very important because they will help us to get the exact results in terms of stress concentration and deformation. Any error or misunderstanding will give faulty results. In the boundary condition, we just need to apply the load at the certain position which will be experiencing the load and the support will also be needed to be applied to the portion which will be attached to the vehicle body.

For our case, the suspension A-arm will be experiencing a load like a cantilever beam because the rotational movement will be restricted while analyzing. Similarly, the suspension spring will be experiencing a compressive force and the wheel hub will be experiencing a fixed torsion and a cantilever beam-like loading. Using this particular approach we will be using the entire FEA analysis.

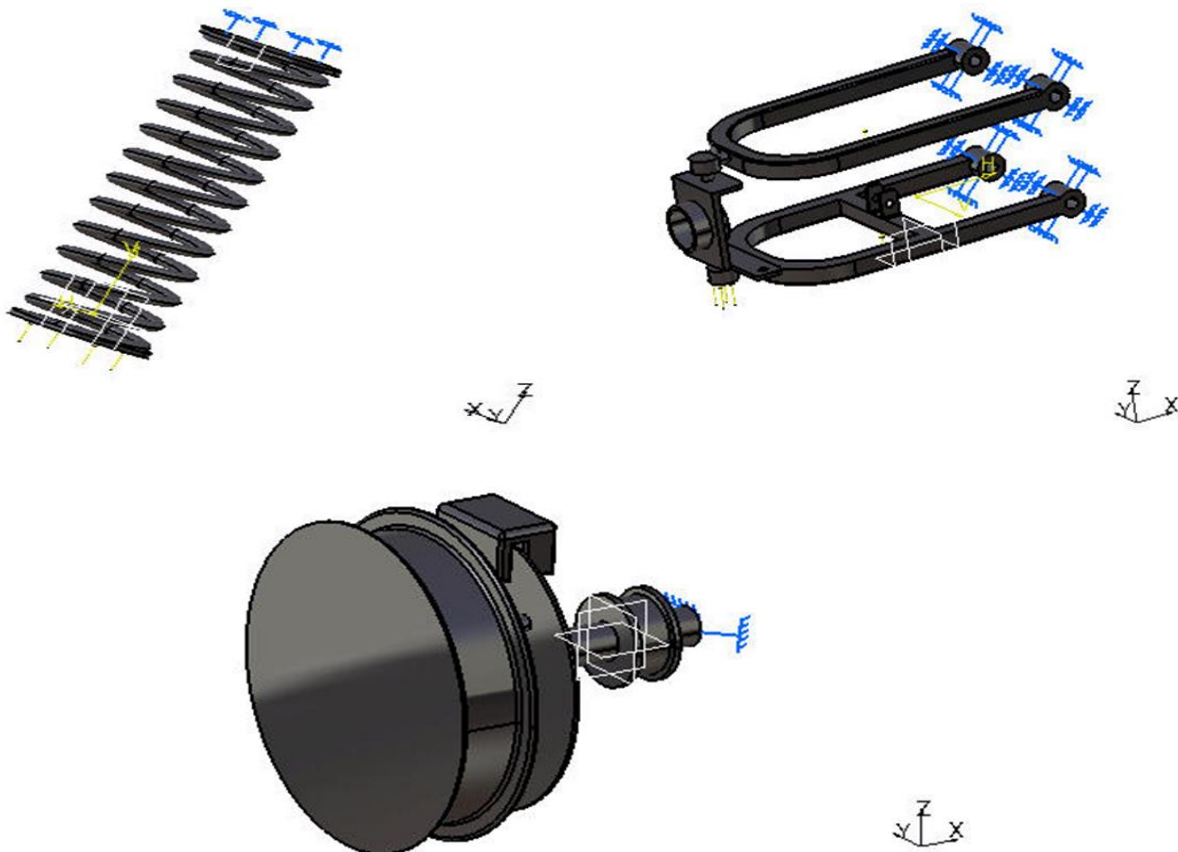


Figure 9: Boundary condition application

3.1.2. Von-mises stress:

The yield failure in the structure is one of the worst failures that occurred in the suspension system that leads to certain failure and undoubtedly it can only be controlled if we are having predefined structural analysis. Obtaining general stress concentration is possible by mathematical analysis but if we need to find out the local stress concentrations in different regions then we can easily obtain it using the finite element analysis approach.

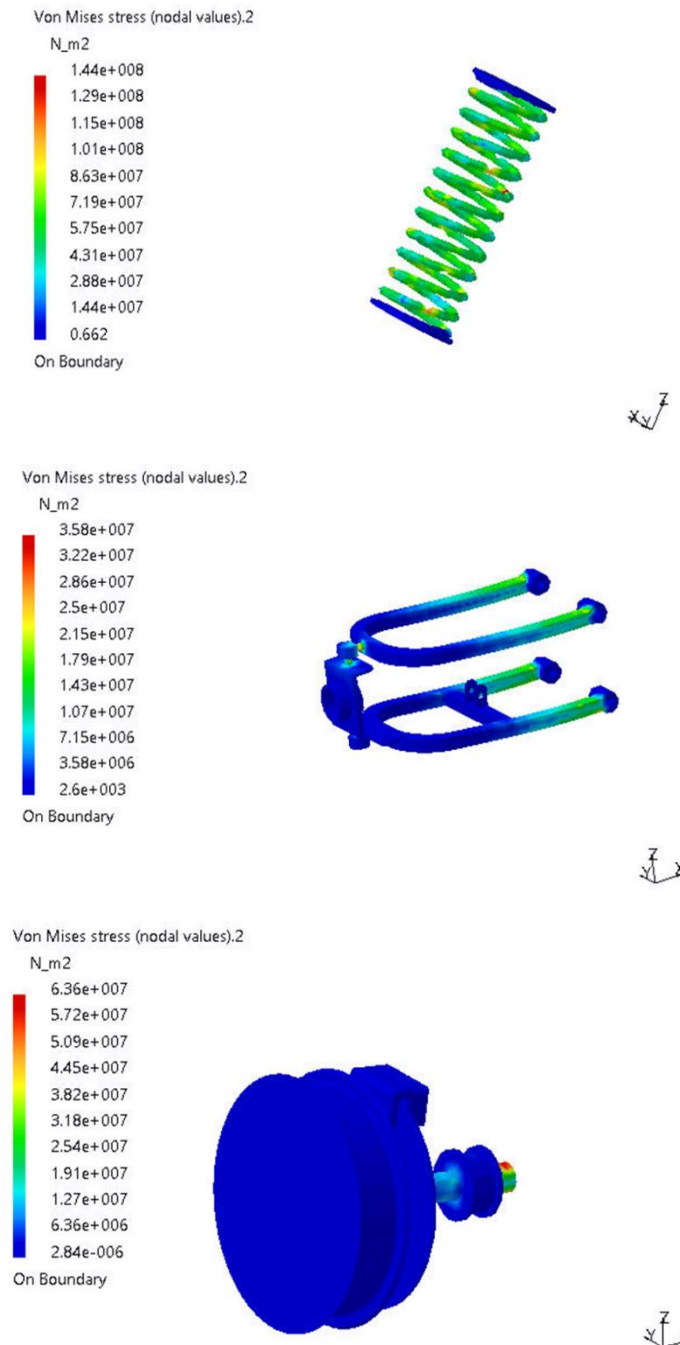


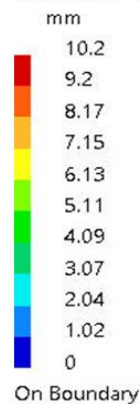
Figure 10: Von-mises stress concentration in different parts

3.1.3. Translational displacement:

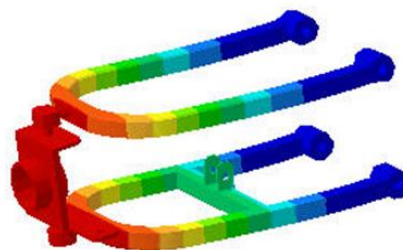
Translational displacement is nothing but the deformation of the structure under loading conditions. When we are applying load on the structure then due to the internal stress after a certain level it deforms. This deformation is known as translational displacement. Finding out the general deformation of the structure is very easy but the concept of translational displacement is something different because using finite element analysis we can find out the deformation at any position of the structure.

In the translational displacement result, we are showing the color-coded figures that show the deformation from the very small amount to the higher range of deformations. For the static components, the maximum deformation is less than 0.5 mm therefore the structures are strong enough to sustain the experiencing load on them. As the spring is not a static component and is attached to sustain the compressive force, therefore, it is showing deformation of 10.2 mm.

Translational displacement magnitude.1



Translational displacement magnitude.1



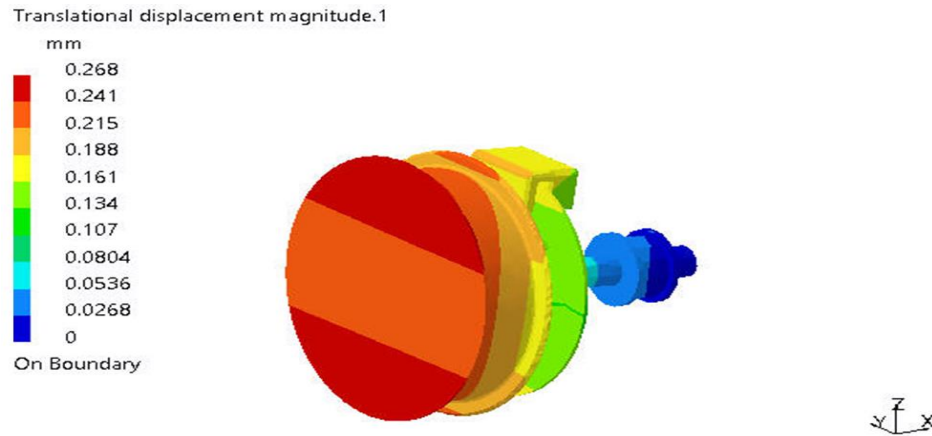


Figure 11: Translational displacements of different components in the suspension system

These types of performance analysis are not the main focus of the research therefore we are focusing a little bit on this part. This is the only way by which we can easily obtain the performance of the mechanical components which is also very important whenever we are considering the operational condition of the suspension system.

3.2. Performance evaluation:

For presenting the performance evaluation of the suspension system we can go through different phases of development. In the initial phase, we are just showing the damping scenario of a single spring-mass system so that the wave and its damping will become understandable. But in this step as we are going through the very basic Simulink model, therefore, we cannot separate the sprung and un-sprung mass damping scenario.

Before we go through the performance evaluation we need to assume some parameters like,

1. The wheels are always rigid and there is no bouncing nature in the wheels.
2. The spring is linear in nature.
3. There is no variable loading applied to the vehicle.

For the damping nature in the vertical movement of the wheel body, we can obtain the damping equations like this,

$$y_{road} = x$$

$$y_{car} = y$$

$$K_s = K(\text{Spring constant})$$

$$K_d = C(\text{Damper constant})$$

From equation of motion we can determine the final solution will be something like this

$$m\ddot{x} + K(x - y) + C(\dot{x} - \dot{y}) = 0$$

$$m\ddot{x} = K(y - x) + C(\dot{y} - \dot{x})$$

$$\ddot{x} = \frac{K(y - x) + C(\dot{y} - \dot{x})}{m}$$

Therefore,

$x = \text{Output}$, $y = \text{Input}$

For m , K and C we can use any demo values as per the vehicle input characteristics

Considering the above expressions we can derive it in the Simulink modelling following some steps like this,

1. In this evaluation, we can use Y as input and X as the output.
2. Now for getting $(Y-X)$ and $(Y\dot{}-X\dot{})$ we can easily use differentiation and use subtract feedback.
3. Then we can use different types of feedback systems and loops so that the final expressions can be obtained using those algebraic methods.

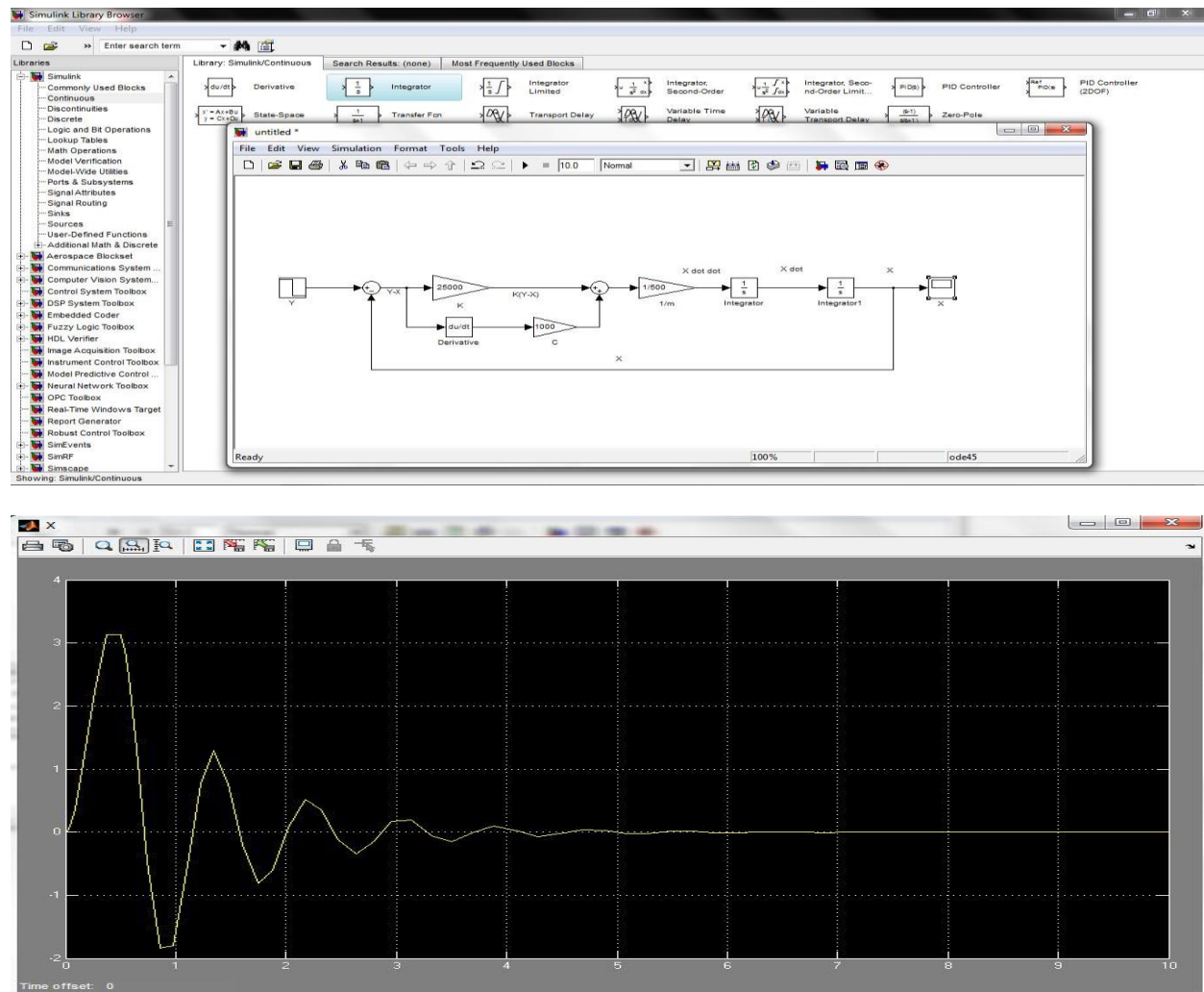


Figure 12: General damping scenario of a sprig mass system

Now the same thing can be modified with few extensions in the mathematical expressions. Let us have a look at the expressions we can use in the detailed performance evaluation. In this approach, the bounce of the car body and the bounce of the wheel can be defined as,

$$M_s \ddot{X}_s + C_s(\dot{X}_s - \dot{X}_u) + K_s(X_s - X_u) = 0 \dots \dots \dots (1)$$

and,

$$M_u \ddot{X}_u + C_s(\dot{X}_u - \dot{X}_s) + C_z(\dot{X}_r - \dot{X}_u) + K_t(X_u - X_r) + K_s(X_u - X_s) = 0 \dots \dots \dots (2)$$

In these two expressions, the symbols are having their individual significance, like,

M_s = Sprung mass

M_u = Un-sprung mass

X_r = Road displacement

K_t = Tire stiffness coefficient

C_s = Damping coefficient

K_s = Stiffness coefficient

Now to reduce the complexity we can express the rest of the equations like this,

We all know

$$\sum F = \sum ma$$

If we consider the sprung mass first then,

$$\begin{aligned} \sum F &= -F_d - F_{s2} = M_s \ddot{X}_s \\ &= -C_s(\dot{X}_s - \dot{X}_u) - K_s(X_s - X_u) \end{aligned}$$

Re arranging this equation we get,

$$M_s \ddot{X}_s + C_s(\dot{X}_s - \dot{X}_u) + K_s(X_s - X_u) \dots \dots \dots (3)$$

If we consider unsprung mass

$$\begin{aligned} \sum F &= F_d + F_{s2} - F_{s1} \\ &= C_s(\dot{X}_s - \dot{X}_u) + K_s((X_s - X_u) - K_t(X_u - X_r)) = M_u \ddot{X}_u \end{aligned}$$

$$M_u \ddot{X}_u + K_t(X_u - X_r) - K_s((X_s - X_u) - C_s(\dot{X}_s - \dot{X}_u)) = 0 \dots \dots \dots (4)$$

From equation (3)

$$\ddot{X}_s = \frac{1}{M_s} [C_s(\dot{X}_u - \dot{X}_s) + K_s(X_u - X_s)] \dots \dots \dots (5)$$

From equation (4)

$$\ddot{X}_u = \frac{1}{M_u} [K_t(X_r - X_u) + K_s((X_s - X_u) + C_s(\dot{X}_s - \dot{X}_u))] \dots \dots \dots (6)$$

Now if we can portray the equations in the Simulink interface then the sprung and the un-sprung mass can be evaluated with the damping scenario. Below are the steps we can follow.

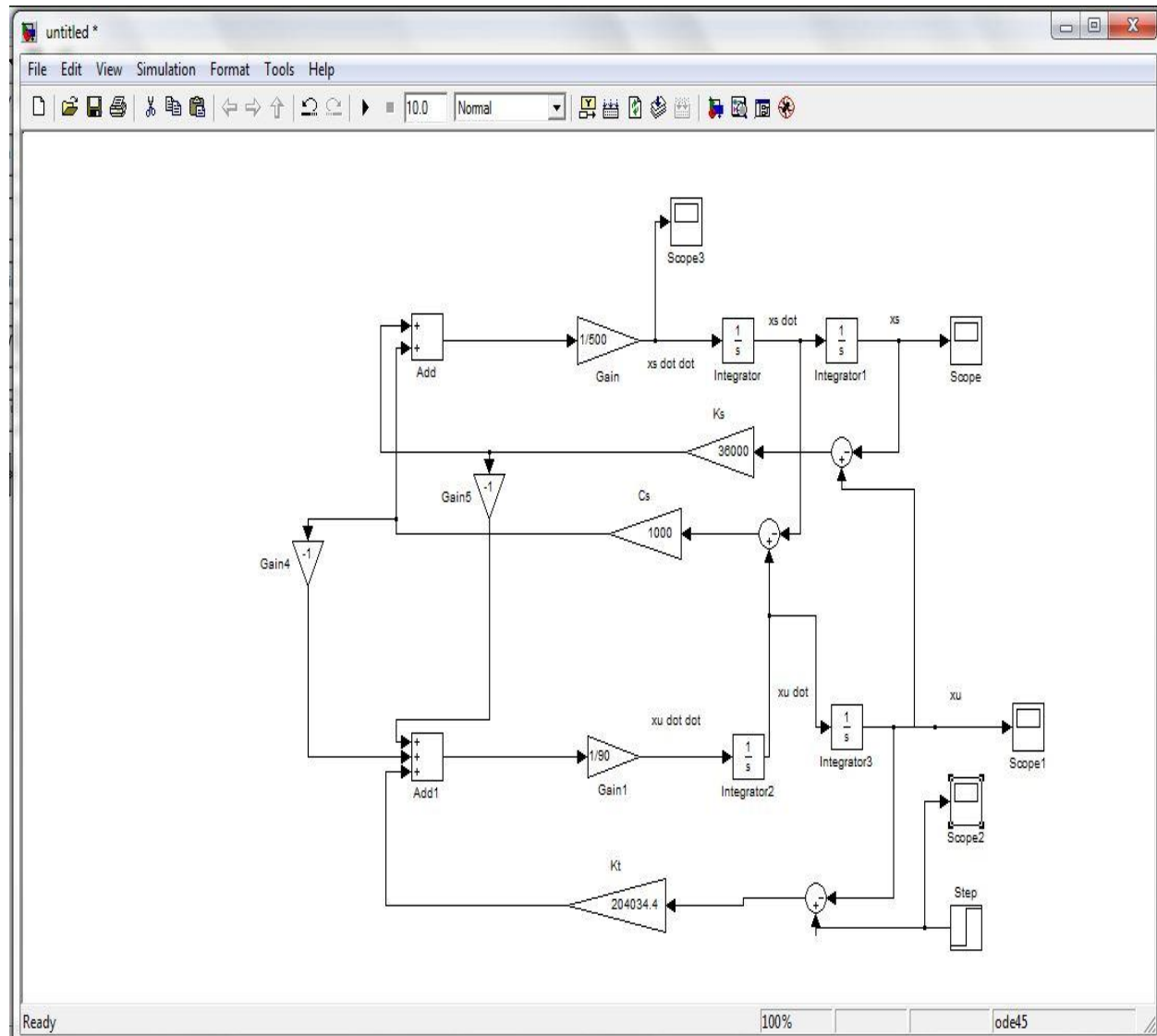


Figure 13: Final performance evaluation Simulink model

Now the Simulink model is described below,

- For the sprung mass and its damping, we should consider the spring as well as the damper therefore the adder is used at the left-most so that they can be added together that will be providing the consecutive displacement parameters.
- As we need to consider three different parameters like the spring, damper, and tire coefficients, therefore, the three adders are used on the left-hand side of the model. It will be providing us the damping nature of the un-sprung mass of the vehicle.

- Along with these two adders the gains are used in the Simulink model so that we can have the multiple coefficients in the equations previously addressed. For the positive gain, we will be using positive multiple gains, and for negative gain, we will be using negative multiplication gain in the model.
- Along with the general gains where we are having $1/m$ as gain there we are just using the simple gains and making their values equals to $1/m$. The values of $1/m$ are selected as per the mass of the spring and the vehicle.
- When we have done with the general addition and the differentiation then we should multiply the coefficients with the added and subtracted quantities as per the requirement. Just by using the gains, we are applying the values of the coefficients like spring constant, damper constant, and tire constant.
- The integrators are used to make the differentiation into general quantities so that the final expressions are obtained in the output terminal. Here we can say the X dot dot can be transferred to X using double integration.
- Finally, at the rightmost portion of the Simulink model, the scopes are just used to see the output after simulating the entire model.

As we have already presented the Simulink model, therefore, we are now presenting the output results and describing them so that the performance can become clear to us.

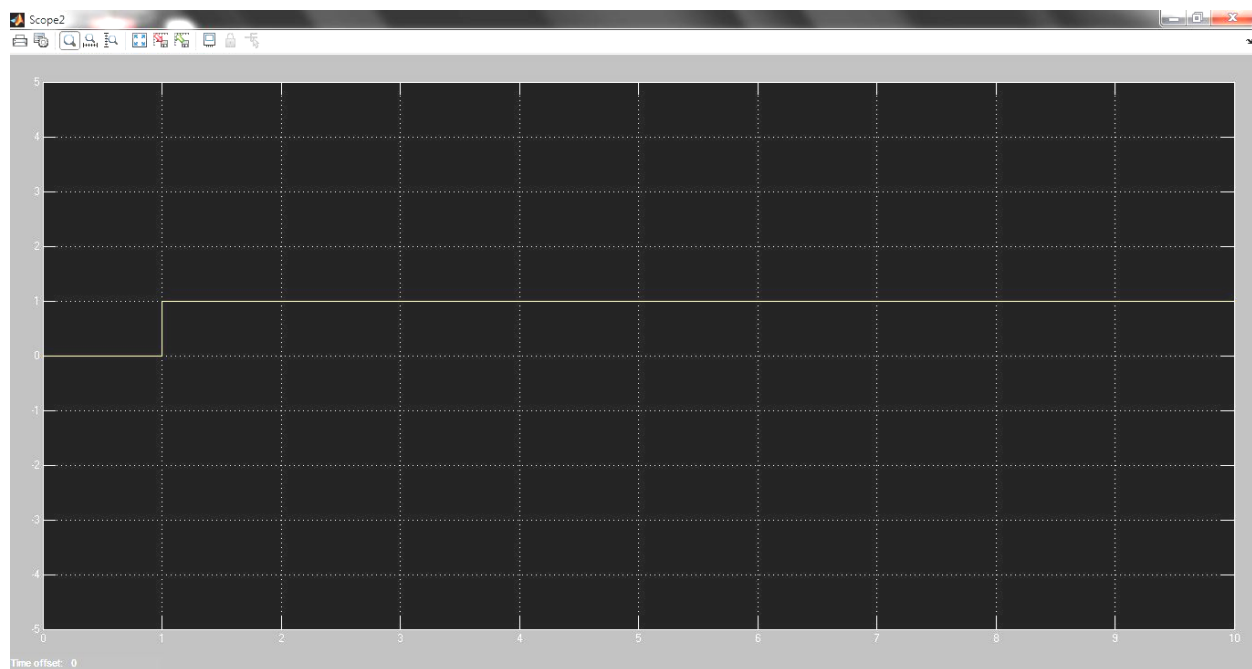


Figure 14: Input signal used as a bump on the roadway

The sudden jerk in the vehicle can only be obtained if there is a bump on the road therefore if we will be getting this bump in the signaling atmosphere then we can use any type of step input.

Similarly, in this problem, we are using a positive step signal to check whether the jerk is damping by the suspension system or not.



Figure 15: General damping due to the suspension system

Now, for the step signal that is used as a bump under the wheel, we can have a damping scenario like this. Now we might have a question, why the first peak in the damping wave is higher than that of the step input signal? For this question, we can say the step signal is nothing but an input parameter that is physically presented under the vehicle wheels therefore it will be working as a physical parameter and the first jerk produced by that signal on the vehicle will be something like that, which is shown as the highest peak in the damping graph.

Now the damping nature of the sprung mass is kind of different compared to the damping natures of the un-sprung mass and general damping of the full vehicle. The sprung mass is nothing but the upper portion of the vehicle therefore the damping nature of the sprung mass is more important than anything else because the driver or the passengers will be there in the cabin. If we can clearly observe the damping waveform of the sprung mass then we can see there is a positive peak and a significant negative peak after that the damping is very basic in nature. The positive peak is observed when the vehicle just hit the bump and the negative peak is that when the vehicle is just cross the bump and that time the vehicle will always experience a sudden downward jerk. In the positive and the negative peaks we can see there are few fluctuations are available, those are nothing but the bounce and re-bouncing nature of the spring. As soon as the damper observes the jerk it will suddenly control it without making the fluctuations any more for the further damping scenario. Below is the sprung mass damping waveform.

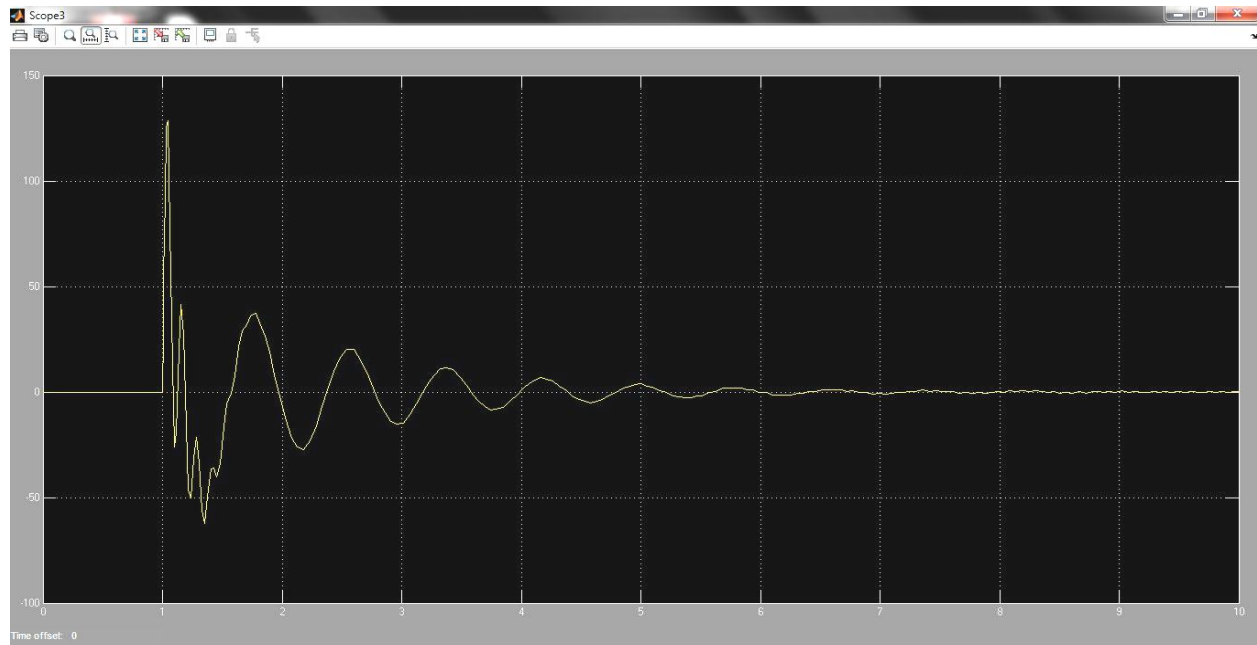


Figure 16: Sprung mass damping in a designed suspension system

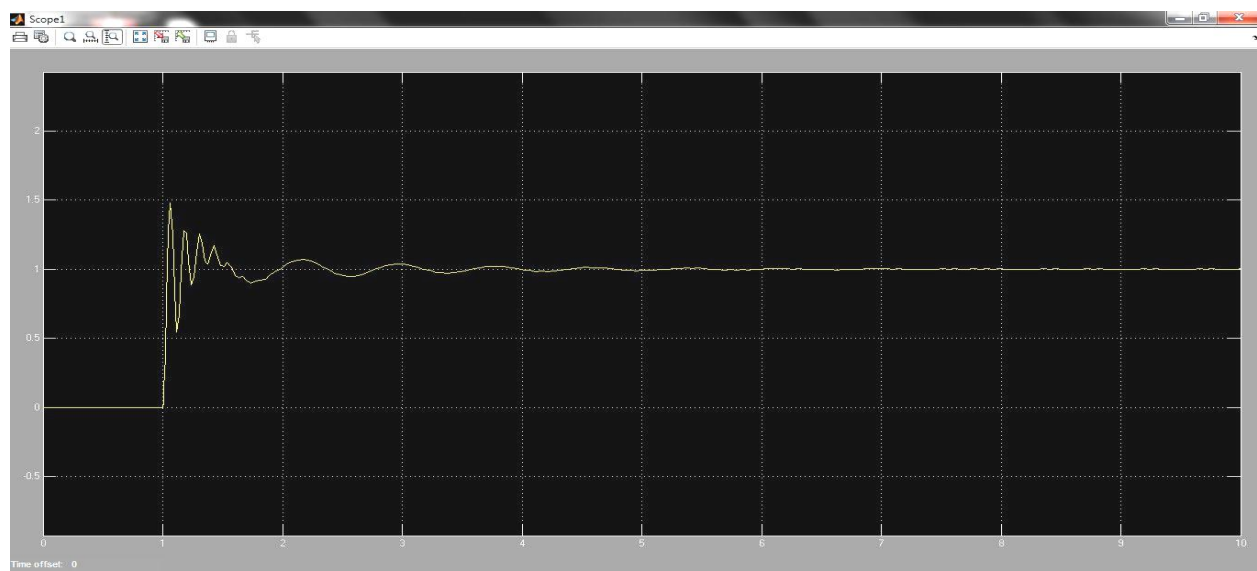


Figure 17: Un-Sprung mass damping using the modeled suspension

The un-sprung mass is the mass of the vehicle that is situated under the vehicle chassis. Therefore it is the mass of the entire suspension assembly only. After getting a bump under the vehicle along with the entire vehicle body the whole suspension assembly will also experience a sudden jerk and for that reason, the suspension assembly will also experience a vertical movement. This movement also needed to be dumped in a while otherwise there will be a chance of getting a loss of attachment from the ground surface.

The damping waveform of the un-sprung mass is also shown in the figure above. Here we can see the waveform is quite different than the others because it will just capture the sudden upward movement due to the bump, as well it will experience the displacement it will get the linearity in a while and continues to maintain the linear line till the end of the smooth road.

3.3. Active suspension:

It is not necessary to have an active suspension unit in the main suspension but as we are researching and developing the suspension unit of a formula racing car so if we will implement it in the main system there is nothing wrong even it will enhance the overall performance of the vehicle. Using different electric controlling units and sensors the active suspension system can work within a conventional suspension system. Basically, some of the parameters like wheel speed; braking condition, vertical acceleration, lateral acceleration, steering positioning, and make more things are related to the working of the active suspension system.

The working of the active suspension unit in a vehicle can be demonstrated as,

1. When a vehicle passes through a bump then it the vertical travel of the vehicle will be measured by the sensors attached to the active suspension components. All the displacement data from different parts will be then transferred to the ECU.
2. Basically, the ECU works as a CPU in a computer. It will then calculate all the possible pressure requirements in the damper. When the pressure requirements are calculated then it will give feedback to the actuators so that it can control the travel of the suspension in a very short period.
3. As per the feedback received from the ECU, the actuators can initiate the pumping of the working fluid in the damper to increase or decrease the pressure.

To have the programming related to the active suspension and the performance criteria of the active suspension system we are using Matlab programming that is attached below. But before we go through the programming we should know the base of the programming. Basically, H infinity controller design is the best approach to understand an active suspension system.

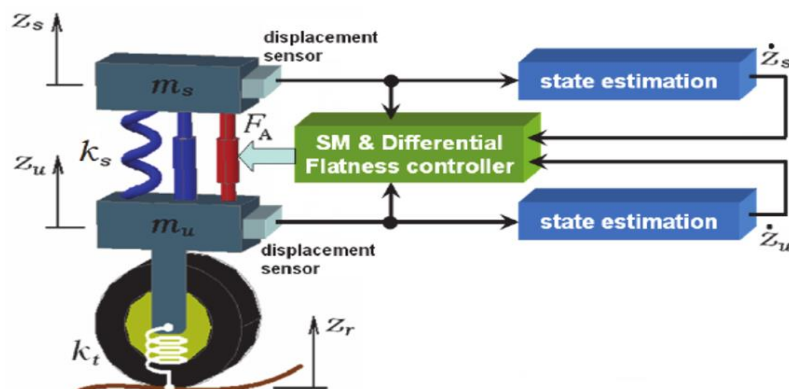


Figure 18: Active suspension system block diagram

The programming can be followed by this; the only difference is that we can easily vary the programming results just by varying the quantities.

Clear

% Physical parameters

```
mb = 500; % kg
mw = 90; % kg
bs = 1000; % N/m/s
ks = 36000; % N/m
kt = 204034.4; % N/m
```

% State matrices

```
A = [ 0 1 0 0; [-ks -bs ks bs]/mb ; 0 0 0 1; [ks bs -ks-kt -bs]/mw];
B = [ 0 0; 0 1e3/mb ; 0 0; [kt -1e3]/mw];
C = [1 0 0 0; 1 0 -1 0; A(2,:);
D = (0 0; 0 0; B(2,:));
qcar = ss(A,B,C,D);
qcar.StateName = {'body travel (m)'; 'body vel (m/s); 'wheel travel (m)'; 'wheel vel (m/s)'}
qcar.InputName = {'r'; 'fs'};
qcar.OutputName = {'xb'; 'sd'; 'ab'};
```

% Nominal Actuator Model

```
ActNom= tf(1,[1/60 1];
ActNom. InputName = 'u';
ActNom. OutputName = 'fs';
```

% Weights

```
Wroad = ss[0.07]; Wroad, u = 'd'; Wroad.y = 'r';
Wact = 0.8*tf([1 50],[1 500]);
Wact.u = 'u'; Wact.y = 'e1';
HandlingTarget = 0.04* tf([1/8 1],[1/80 1]);
ComfortTarget = 0.4* tf([1/0.45 1],[1/150 1]);
```

% Three design points

```

beta = reshape([0.01 0.5 0.99],[1 1 3]);
Wsd = beta / HandlingTarget;
Wsd.u= 'sd'; Wsd.y= 'e3';
Wab= (1-beta) / ComfortTarget;
Wab.u = 'ab';
Wab.y = 'e2';
sdmeas = sumblk('y1 = sd');
abmeas = sumblk('y2 = ab');
lCinputs = {'d';'u'};
lCoutputs = {'e1';'e2';'e3';'y1';'y2'};
qcaric = connect(qcar(2:3,:),ActNom,Wroad,Wact,Wab,Wsd, sdmeas,abmeas,lCinputs,lCoutputs);
ncont = 1; % one control signal, u
nmeas = 2; % two measurement signals, sd and ab
K = ss(zeros(ncont,nmeas,3));
gamma = zeros(3,1);
for i=1:3
    [K(:,i),~,gamma(i)] = hinfsyn(qcaric(:,i),nmeas,ncont);
end
K.u = {'sd','ab'};
K.y = 'u';
CL = connect(qcar,ActNom,K,'r',{'xb';'sd';'ab'});

```

%Road disturbance

```

t= 0:0.0025:1;
roaddist = zeros(size (t));
roaddist = (1:101)/101-0.025*(1-cos*8pi*t(1:101));

```

% Simulate

```

P1= lsim(qcar(:,1),roaddist,t); %Open loop
Y1= lsim(CL(1:3,1,1),roaddist,t); %Comfort
Y2= lsim(CL(1:3,1,2),roaddist,t); %Balanced
Y3= lsim(CL(1:3,1,3),roaddist,t); %Handling

```

% Plot results

```

plot (t,p1(:,1),'b',t,y1(:,1),'r',t,y2(:,1),'m',t,y3(:,1),'k',t,roaddist,'g')
title ('body travel'), ylabel ('x_b (m)')

```

legend('open-loop','comfort','balanced','handling','road disturbance','location','northeast')

Now considering the results we are obtaining from this programming we can say the comfort level, as well as the driving quality, will be enhanced to a higher extend. The below-given figure showing the enhancement in the comfort and the driving quality, as well as the safety, will become superior after using the concept of active suspension.

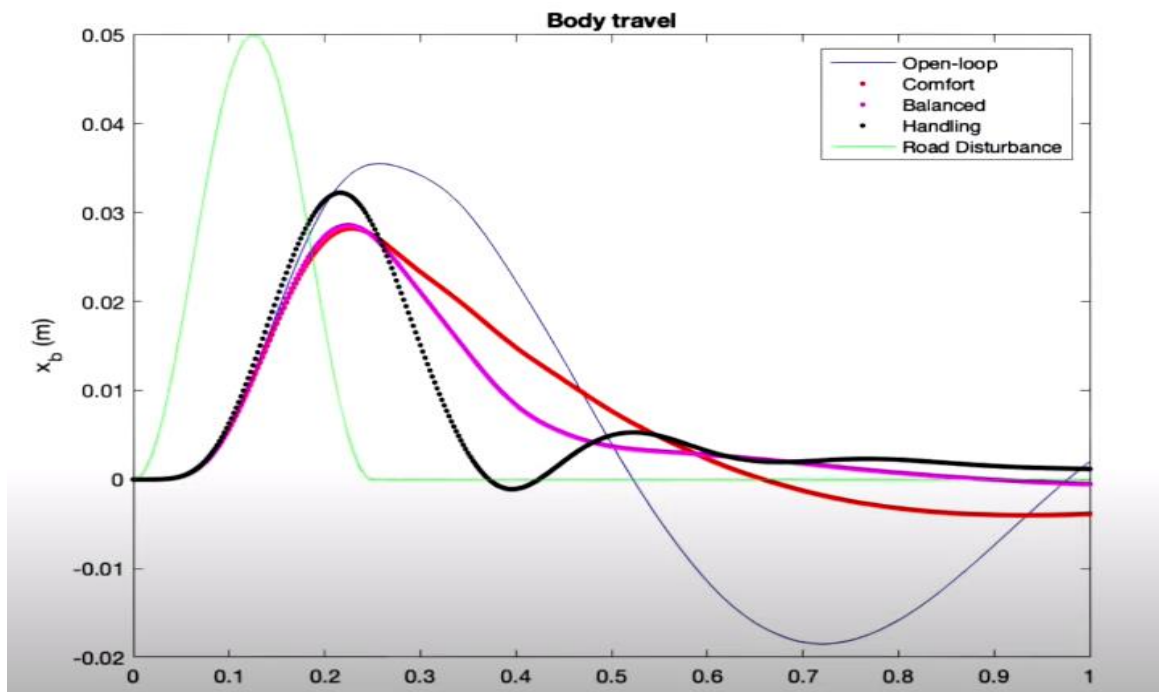


Figure 19: Output in the different parameters after application of active suspension

Chapter: 4 (Final implementation)

This is the chapter where we will be concluding the entire things we have done on it. As well as for the successful completion and the physical implementation how to plan it and what are the things needed to be concerned are discussed more. The project planning Gantt chart and the bill of material along with the pricing are given in this part of the paper.

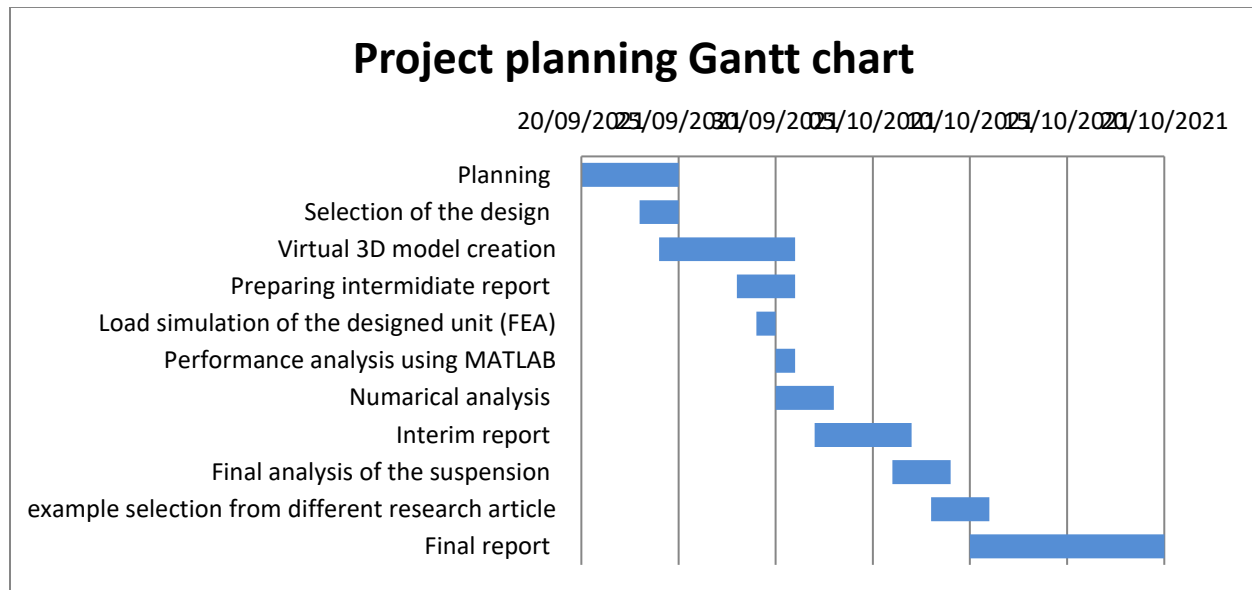


Figure 20: Project planning Gantt chart

Table 2: BOM and costing of different parts will be using in the development

Sl no	Item	Specs	Quantity	Unit price	Total price
1	Steel shaft	1. Dia 30mm, length 207 mm	1 Nos	1.4 \$	1.4 \$
		2. Dia 70mm, length 36mm	1 Nos	1.5 \$	1.5 \$
2	Steel plate	1. OD 250mm, Thickness 4mm	2 Nos	1.8 \$	3.6 \$
		2. OD 220mm, ID 120mm, Thickness 3mm	1 Nos	1.8 \$	1.8 \$
3	Nylock nuts and bolts	Length 63 mm, Dia 12mm	4 Nos	1 \$/ Piece	4 \$
4	CHS	OD 40mm, ID 18mm, Length 80mm	80 mm	5 \$/ 304 mm	1.31 \$
5	Rectangular hollow section	25*25*2.5	1650 mm	5 \$/ 304 mm	27.1 \$
6	Bushings	OD 70mm, ID 60mm, Thickness 50mm	1 Nos	10 \$/ 304 mm	1.64

7	Steel plate for knuckle	119.52*100*10	1 Nos	3.5 \$	3.5 \$
8	Steering holding bracket	70*70*6	1 Nos	1.2 \$	1.2 \$
9	Additional nut and bolts	1. Dia 12mm, Length 50mm	1 Nos	1.3 \$	1.3 \$
		2. Dia 12mm, Length 50mm	4 Nos	1.2 \$	4.8 \$
10	Angular ball joints	Dia 40mm, Stud length 40mm, stud dia 15mm	2 Nos	5.3 \$	10.6 \$
11	Suspension spring	1. Length 311.6mm, Dia 120mm, Coil dia 10.39mm	1 Nos	16 \$	16 \$
		2. Circular plate Dia 120mm, Thickness 5mm	2 Nos	1.3 \$	1.3 \$
12	Damper	Length 380mm, C_OD 70mm, P_OD 49mm	1 Nos	18 \$	18 \$
13	Steering position sensor		1	100 \$	100 \$
14	Acceleration sensor		1	56 \$	56 \$
15	Displacement sensor		1	45 \$	45 \$
Total expenditure					300.05 \$

Using such type of very basic project planning Gantt chart and the costing we can further proceed to the final implementation of the suspension model.

Conclusion:

As it is not a case study therefore it will not be that much feasible for us to conclude any statement against it but whatever we have done throughout the research and development can be portrayed in some small sentence in the conclusion.

Throughout the entire research process we are just finding out the best solutions from different types of research papers and based on them we have prepared some virtual models of the suspension system used in formula racing cars. Though the real-life development will be somehow different from that of the virtual model, the overall development process may follow

all the steps discussed in this paper. In terms of the performance evaluation, the designed model can withstand almost double the weight of the vehicle under sudden loading conditions as well as the operational performance proved very suitable for a vehicle that will be running on a race track. All these technical things will become clearer if we can carefully go through the whole paper.

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