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WALES INSTITUTE OF SCIENCE AND ART



TRANSIENT RESPONSE MODELLING OF A VEHICLE

ADVANCED VEHICLE DYNAMIC BEHAVIOUR (ACEA7003)

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1.Abstract:

To measure the impact of all elements acting on the vehicle as a whole, including rolling forces, aerodynamic forces, and many more, on torque distribution and vehicle dynamics, the entire vehicle was examined under dynamic conditions. Mathematical models were created for two popular vehicle kinds, front and rear wheel drive, each with a particular type of tyre. The behaviour of a real car was replicated using both models, which were used to create comprehensive simulation software in the Matlab-Simulink environment. In this paper we are going to discuss about the Vehicle dynamic simulation methods and also given demonstration about the principles behind spring mass damper systems and how they are generated. Various Simulink that we have tested in Simulink software from 1DOF to 7DOF and we have taken the motec data to show the vehicle dynamic testing in Simulink software to find out the unknown variables. Finally analysed the validity of simplified modelling methods like the Simulink model approach as a means to simulate and test vehicle response under dynamic conditions.

2.Introduction:

Significant study has been conducted over the past 20 years on the static and dynamic properties of spring mass damper systems. Spong, Mark W., made one of the earliest important quantitative efforts in which he presented the Swing Up Control Problem for the Acrobot [Spong, 1995].

A vehicle's transient response describes how it responds to abrupt changes in speed or direction, such as those that occur when braking or turning. The vehicle's suspension system, tyres, and other dynamic components govern this behaviour. The weight distribution, suspension rigidity, and tyre grip are only a few examples of the variables that affect a vehicle's transient response. Engineers adjust a vehicle's transient reaction for better handling and safety through computer models and in-person testing.

A mechanical system with one degree of freedom (DOF) that consists of a single mass, one spring, and one damper connected in series is known as a spring-mass-damper system. The spring and damper are attached to the mass and a fixed point, and the mass is free to move in one dimension, such as along an x-axis. The damper opposes the mass's motion by providing a force corresponding to the mass's velocity while the spring provides a restoring force proportional to the mass's displacement from its equilibrium position.

A spring-mass-damper system with two degrees of freedom (DOF) contains two masses, each coupled to a separate spring and damper, and both connected to a fixed point. Including along the x and y axes, the two masses are free to travel in separate directions. Two separate sets of equations of motion, one for each mass, can be used to model this system.

Four masses attached to separate springs and dampers, each connected to a fixed point, make up a four-degree-of-freedom (4DOF) spring-mass-damper system. The four masses are free to move in a variety of directions, including the rotational axis, x, y, and z axes. There are four sets of motion equations that can be used to model this system, one for each mass.

Seven masses attached to individual springs and dampers, each connected to a fixed point, make up a seven-degree-of-freedom (7DOF) spring-mass-damper system. The seven masses are free to move in a variety of directions, including the rotating axis, the x, y, and z axes, roll, pitch, and yaw. There are seven sets of motion equations that can be used to model this system, one for each mass.

The complexity of a spring-mass-damper system rises with the number of degrees of freedom in the system. As the equations of motion grow more intricate, more complex mathematical methods are needed to solve them. With additional vibrational modes and resonance chances, the system's behaviour likewise gets more complex. These systems are typically utilised for mechanical systems that are more complicated, including those in robots, ships, and aeroplanes. It is vital to remember that the degree of freedom is a measurement of how many different directions the system can move in rather than necessarily indicating the complexity of the system.

3.Literature review:

3.1 Vehicle dynamic simulation methods:

A mathematical model of a dynamic system is defined as a collection of equations that reflects the system accurately or, at least, reasonably well dynamics of the system accurately or, at least, very effectively (Ogata, 2002). The process of modelling and simulating a vehicle's dynamic behaviour using computer software is known as vehicle dynamic simulation. This can include how the vehicle reacts to different inputs, also including steering, braking, and accelerating, as well as how the vehicle interacts with its surroundings, such as the state of the roads and wind resistance.

Vehicle dynamic simulation can be done using a variety of techniques, each of which has advantages and disadvantages. Typical techniques include:

Multibody dynamics (MBD) simulations: This technique simulates the total behaviour of a vehicle by using mathematical models of the various parts, such as the suspension, tyres, and powertrain.

Control-oriented modelling: This technique concentrates on the braking and steering systems of a vehicle to mimic how the vehicle will react to driver inputs.

Data-driven modelling: This technique builds a model of the behaviour of the test vehicle using real-world data, such as data gathered from sensors on the test vehicle.

Empirical modelling: This technique simulates the behaviour of the vehicle using experimental data.

Hybrid modelling: This technique combines many modelling techniques to provide a simulation that is more thorough.

New techniques and technologies are constantly being invented in this area of study to increase the precision and complexity of vehicle dynamic simulations. It is also critical to note that a thorough grasp of the behaviour and makeup of the vehicle is required for an effective simulation. The application of vehicle dynamic simulation in numerous disciplines, including testing and validation, design, control optimization, and more, is also important to note.

3.2 Principles behind spring mass damper systems:

A mechanical system that consisting of a mass, a spring, and a damper is known as a spring-mass-damper system. The spring attaches the mass to an immovable object and applies a restoring force proportionate to the mass's movement from its equilibrium position. A force proportional to the mass's velocity is provided by the damper, which is also coupled to the mass and the fixed point, to counteract the mass' motion. Together, the spring and damper govern how the mass moves. A spring-mass-damper system works on the fundamental tenet that the spring exerts a restoring force that tends to return the mass to its equilibrium position, while the damper exerts a damping force that resists the motion of the mass. These forces interact to affect how the system behaves, including the damping ratio, steady-state response to an external force, and natural frequency of oscillation. The system's mass and spring constant together establish the system's natural oscillation frequency. A lighter mass or a stiffer spring will produce a higher natural frequency, whereas a heavier mass or a softer spring will produce a lower natural frequency. The relationship between the damping force and the restoring force determines the system's damping ratio. When disturbed, a system with a higher damping ratio will quickly return to rest, whereas one with a lower damping ratio will oscillate for a longer amount of time. The amplitude and phase of the response in relation to the external force determine the steady-state response of the system to the force. The system's natural frequency, damping ratio, and external force's strength all affect the response's amplitude. The frequency of the external force in relation to the inherent frequency of the system determines the phase of the response. Many mechanical systems, such as cars, buildings, and bridges, as well as biological systems like human muscles and joints, can be modelled using a spring-mass-damper system. In conclusion, comprehending the concepts behind spring-mass-damper systems entails knowing how forces acting on the system, such as the spring force and the damping force, affect the mass's motion and how the system responds to various situations. Mathematical simulation and modelling, which may be used to examine and improve a system's behaviour, can be used to illustrate this understanding.

4.Methodology:

To simulate the dynamic behaviour of mechanical systems, SMD (Systems of Multi-Degrees of Freedom) models are utilised. These models might be as straightforward as single-DOF systems or as intricate as multiple-DOF systems. The following steps are commonly included in developing SMD models:

Modeling: The first stage is to create a mathematical model of the mechanical system. The usual method for doing this is to use Newton's laws or the Lagrange equations to derive the system's equations of motion.

Linearization: The motion equations must then be linearized, which is usually accomplished using small angle approximations. This enables the equations to be solved using less complex mathematical methods.

Solving: Then, using numerical techniques like the Runge-Kutta method or the matrix exponential approach, the linearized equations of motion are solved.

Validation: The model must then be validated by comparing the outcomes to experimental data. This can be accomplished by comparing the model's dynamic response under various operating conditions (such as pitch and roll) to published exemplars.

For 1DOF :

The mathematical equation for 1DOF:

$$-m\ddot{z} = k(z-y) + c(\dot{z}-\dot{y})$$

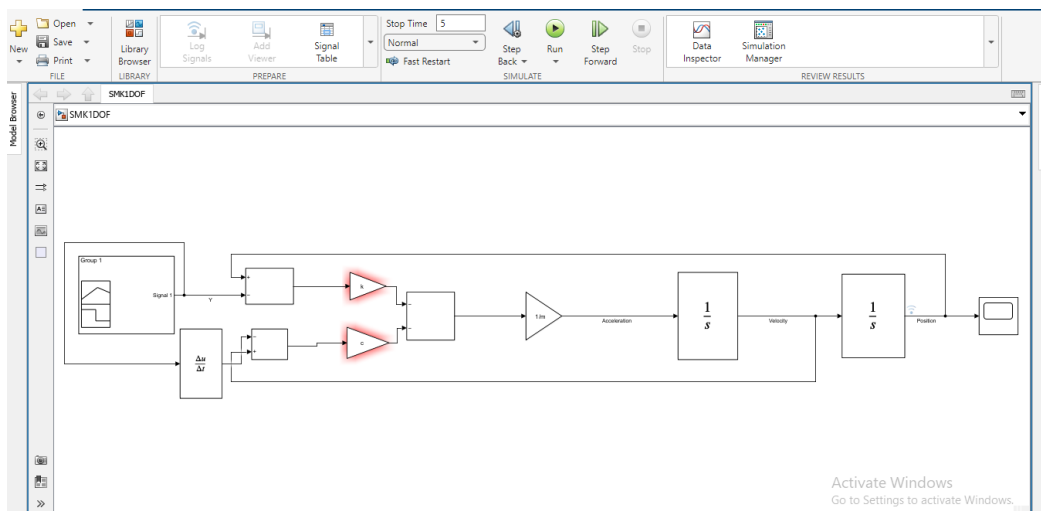


Figure 1: Simulink Program of 1DOF of Spring mass damper system

After deriving the Mathematical equation for the 1DOF, Open the Simulink software and start building the equation from the software. Double click the window and we get search option we need to select gain block which is used for multiplication

and double click on the gain block to get the parameters type $1/m$ from the equation and add acceleration and integrate to get the sprung mass that and add velocity and integrate that and it finally gives the position. From the equation add to negative inputs by adding sum block which goes to the gain block. And then add Damping and sprung mass inputs to the gain block of $1/m$. then we need to create a single builder to represent Y . Then add a differentiate block, to find velocity of Y we need to add derivative to find the damping coefficient to the input sum block which is coming out from the signal builder. Then add a Scope block and connect to the position line and the value shown in that scope is system response from the position data.

Write a MATLAB code for $1/m$, damping coefficient and sprung mass value and run the MATLAB code and then again run the Simulink model to get the Spring mass damper response.

For 2DOF:

The mathematical equation for 2DOF:

$$-m\ddot{Z} = \ddot{Z}(Z-Z_4) + (Z-Z_4)$$

$$-m\ddot{Z}_4 = K_4(Z_a - Y) + C_4(\dot{Z}_4 - \dot{Y}) - K_s(Z - Z_4) - C_4(\dot{Z} - \dot{Z}_4)$$

We can add a second degree of freedom to the equation, yielding two equations of motion, to create the model for a two-degree-of-freedom system. Specify any known beginning conditions or outside forces that are acting on the system, as well as the masses, spring constants, and damping coefficients of each degree of freedom. Analyse the system's reaction to external forces or changes in the system's characteristics after determining the position and speed of the masses (masses, spring constants, damping coefficients). This may entail computing the system's steady-state response, damping ratios, and natural frequencies. The process can be repeated to add more degrees of freedom by including additional equations of motion, each representing the motion of a single degree of freedom.

For 4DOF:

The mathematical equation for 4DOF without Pitch Torque:

$$-m\ddot{Z} = \ddot{Z}(Z - Z_2 - Z_3) + \ddot{Z}(Z - Z_2 + Z_3)$$

$$-m\ddot{Z}_2 = \ddot{Z}(Z - Z_2 + Z_3) - \ddot{Z}(Z - Z_2 - Z_3)$$

$$-m\ddot{Z}_3 = \ddot{Z}(Z_2 - Z_3) - \ddot{Z}(Z - Z_2 - Z_3)$$

$$-m\ddot{Z}_4 = \ddot{Z}(Z_2 - Z_3) - \ddot{Z}(Z - Z_2 + Z_3)$$

The mathematical equation for 4DOF with Pitch Torque:

$$-m\ddot{Z} = \ddot{Z}(Z - Z_2 + Z_3) - \ddot{Z}(Z - Z_2 - Z_3) + \ddot{Z}h$$

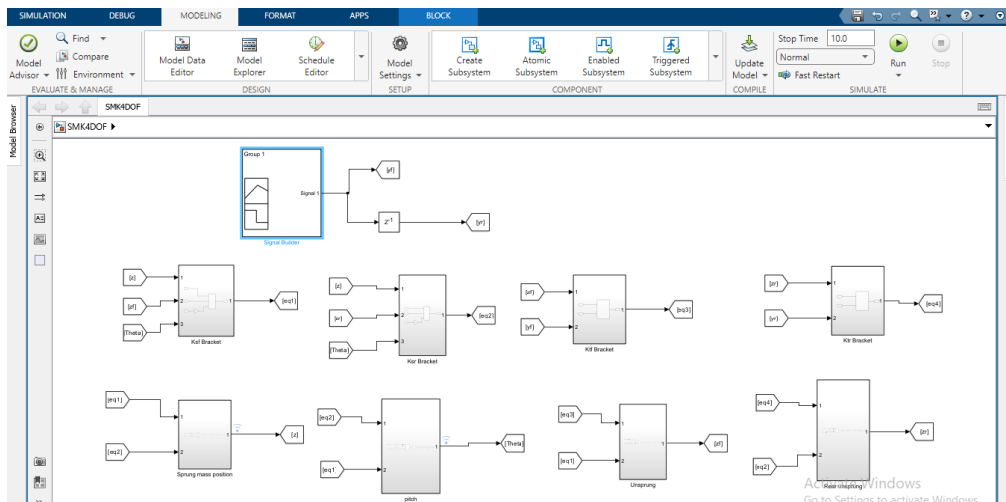


Figure 2: Simulink program of 4DOF of spring mass damper system

To represent the four degrees of freedom, add four "Mass" blocks to a fresh Simulink model. To establish a serial connection, join the inputs of one mass block to the outputs of the following mass block. Add four subsystems which are Sprung mass position, pitch, Front unsprung and Rear unsprung. Add sum blocks in each subsystems. Add two integer blocks for each sum block in each subsystem. Connect the output of each spring-damper block to the input of the corresponding integrator block. These blocks will simulate the displacement of each degree of freedom. Connect the input of the first mass block to the "Input" block you've added to the model. This will be utilised to put pressure on the system from outside. To examine the output of the system in terms of displacement and velocity of each degree of freedom, add "Scope" blocks to the model, one for each degree of freedom. In MATLAB, configure the parameters for each mass block (mass), spring-damper block (spring constant and damping coefficient), and execute the programme. Then, run the programme again in Simulink. Following the simulation's completion, check the graphs by clicking the log signals to see how the system responded by applying log signals to the subsystems' output.

For 7DOF:

The mathematical equation for 7DOF Including damping:

$$\begin{aligned}
 -Mz &= Kf1(Z-Zf1-\alpha) + Cf1(Z-Zf1-\alpha) \\
 &+ Kf2(Z-Zf2-\alpha) + Cf2(Z-Zf2-\alpha) \\
 &+ Kr1(Z-Zr1+b-\beta) + Cr1(Z-Zr1+b-\beta) \\
 &+ Kr2(Z-Zr2+b+\alpha) + Cr2(Z-Zr2+b+\alpha)
 \end{aligned}$$

Pitch

$$\begin{aligned}
-I_{xx}\ddot{\theta} = & b.Kr1(Z-Zr1+b\dot{\theta}-\beta\dot{\theta}) + b.Cr1(Z-Zr1+b\dot{\theta}-\beta\dot{\theta}) \\
& +b.Kr2(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta}) +b.Cr2(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta}) \\
& + a.Kf1(Z-Zf1-\ddot{\theta}-\beta\dot{\theta}) + a.Cf1(Z-Zf1-\ddot{\theta}-\beta\dot{\theta}) \\
& +a.Kf2(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta}) + a.Cf2(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta})
\end{aligned}$$

Roll

$$\begin{aligned}
-I_{yy}\ddot{\theta} = & +\alpha.Kf2(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta}) + \alpha.Cf2(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta}) \\
& +\alpha.Kr2(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta}) + \alpha.Cr2(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta}) \\
& +\beta.Kf1(Z-Zf1-\ddot{\theta}-\beta\dot{\theta}) + \beta.Cf1(Z-Zf1-\ddot{\theta}-\beta\dot{\theta}) \\
& +\beta.Kr1(Z-Zr1+b\dot{\theta}-\beta\dot{\theta}) + \beta.Cr1(Z-Zr1+b\dot{\theta}-\beta\dot{\theta})
\end{aligned}$$

Damping

$$\begin{aligned}
-mf_1z_{f1} = & K_{tf1}(Z_{f1}-Y_{f1})- K_{f1}(Z-Zf1-\ddot{\theta}-\beta\dot{\theta}) + C_{f1}(Z-Zf1-\ddot{\theta}-\beta\dot{\theta})+C_{tf1}(Z_{f1}-Y_{f1}) \\
-mf_2z_{f2} = & K_{tf2}(Z_{f2}-Y_{f2})- K_{f2}(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta}) + C_{f2}(Z-Zf2-\ddot{\theta}+\alpha\dot{\theta})+C_{tf2}(Z_{f2}-Y_{f2}) \\
-mr_1z_{r1} = & K_{tr1}(Z_{r1}-Y_{r1})- K_{r1}(Z-Zr1+b\dot{\theta}-\beta\dot{\theta}) + C_{r1}(Z-Zr1+b\dot{\theta}-\beta\dot{\theta})+C_{tr1}(Z_{r1}- \\
& Y_{r1}) \\
-mr_2z_{r2} = & K_{tr2}(Z_{r2}-Y_{r2})- K_{r2}(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta}) + C_{r2}(Z-Zr2+b\dot{\theta}+\alpha\dot{\theta})+ C_{tr2}(Z_{r2}- \\
& Y_{r2})
\end{aligned}$$

After deriving the Mathematical equation add subsystems in the Simulink window page which are unsprung mass, Pitch, roll, Front unsprung1, Front unsprung 2, Rear unsprung 1, Rear unsprung 2 according to the equation including damping equations. Add input blocks according to the equation and give the each subsystems output as equation numbers. Join the output of input blocks to the input of subsystems and output of subsystems to the input of the GOTO block in which we have given equation numbers. To create a full system, join the input, transfer function, and output blocks. To modify the values of mass, spring constant, and damping constant to correspond to the system you want to model, use the simulation parameters and write a cod in the MATLAB. Give log symbols for the variables we need to find form the Simulation. Run the simulation to see how the system reacts to the forces being applied.

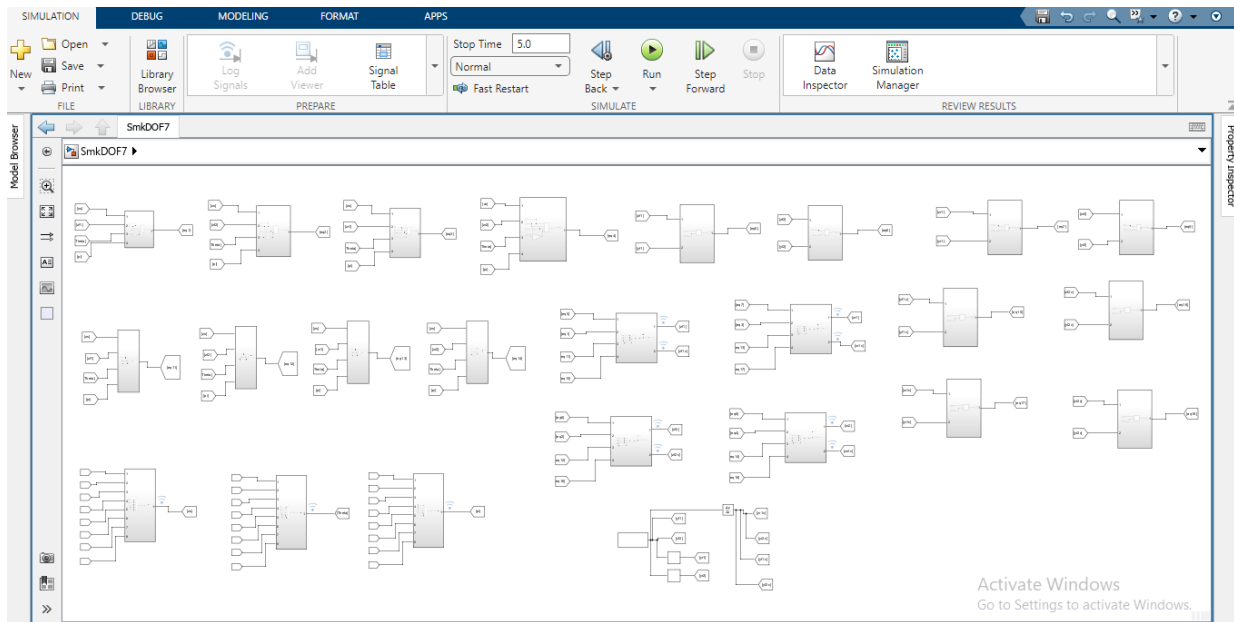


Figure 3: Simulink software of 7DOF of spring mass damper system

The complexity of a spring-mass-damper system rises with the number of degrees of freedom in the system. As the equations of motion grow more intricate, more complex mathematical methods are needed to solve them. With additional vibrational modes and resonance chances, the system's behaviour likewise gets more complex.

5.Simulation graphs:

Variable Pitch For Two line change for each setup

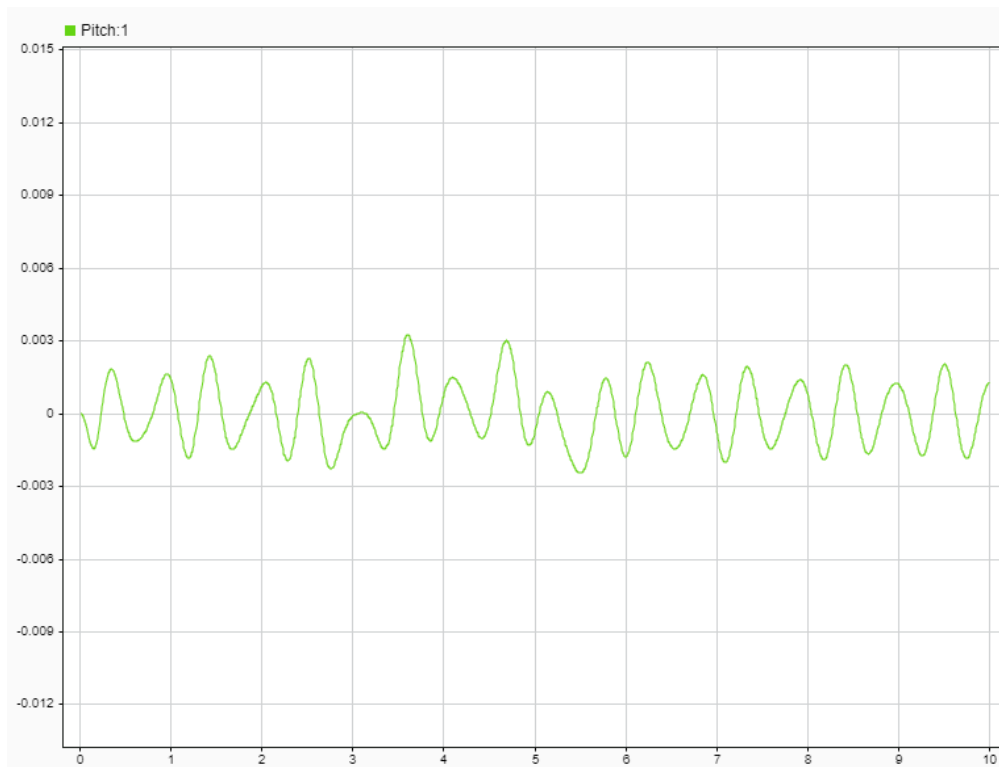


Figure 4: Pitch diagram for setup 1 for two lane change

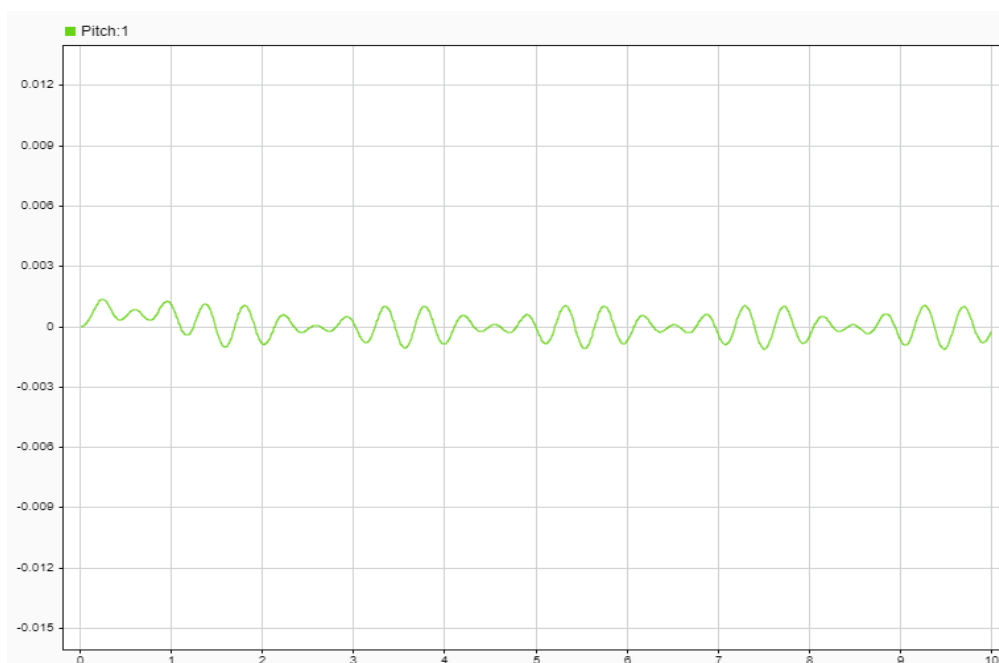


Figure 5: Pitch diagram for setup 2 for two lane change

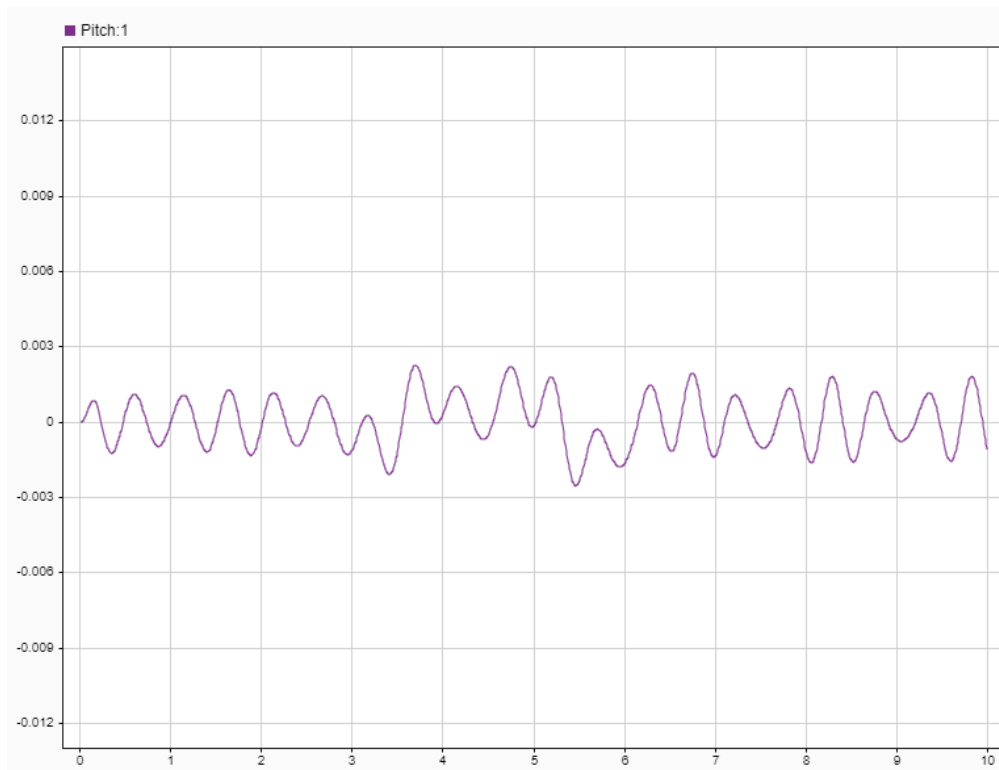


Figure 6: Pitch diagram for setup 3 for two lane change

Variable Roll for Two line change:

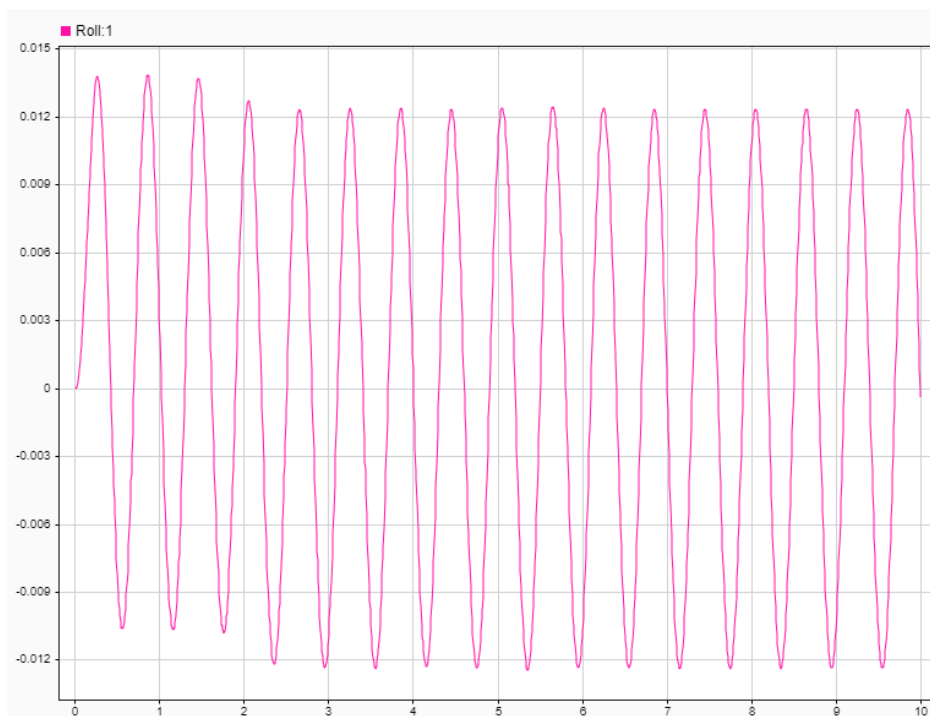


Figure 7: roll diagram for setup 1 for two lane change

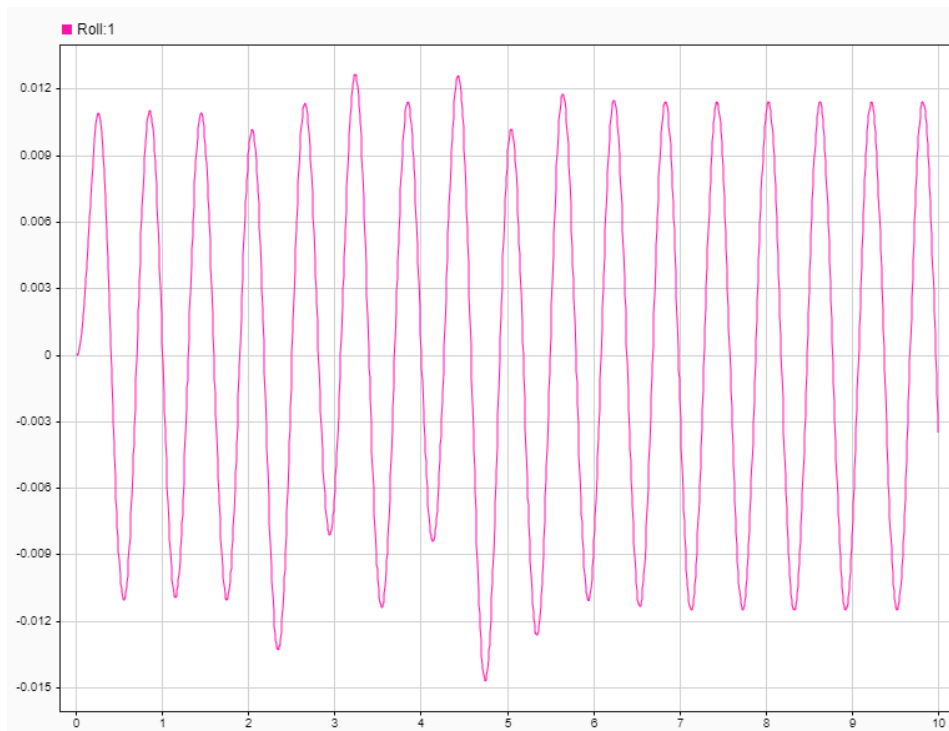


Figure 8: roll diagram for setup 2 for two lane change

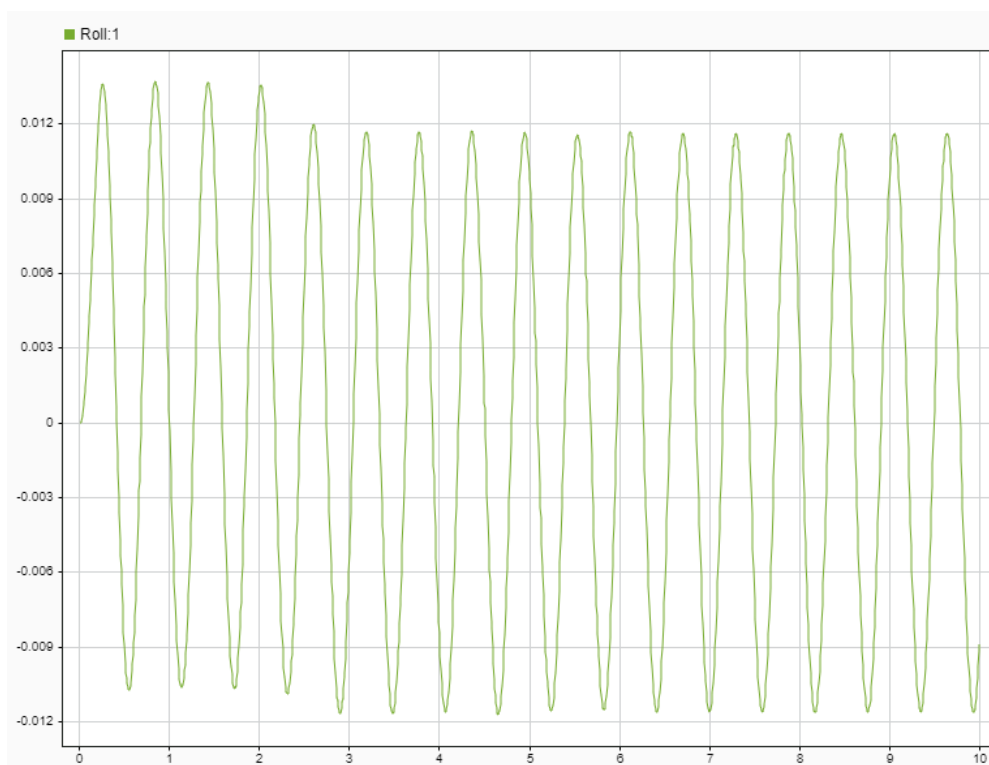


Figure 9: roll diagram for setup 3 for two lane change

Variable Sprung mass for two line change:

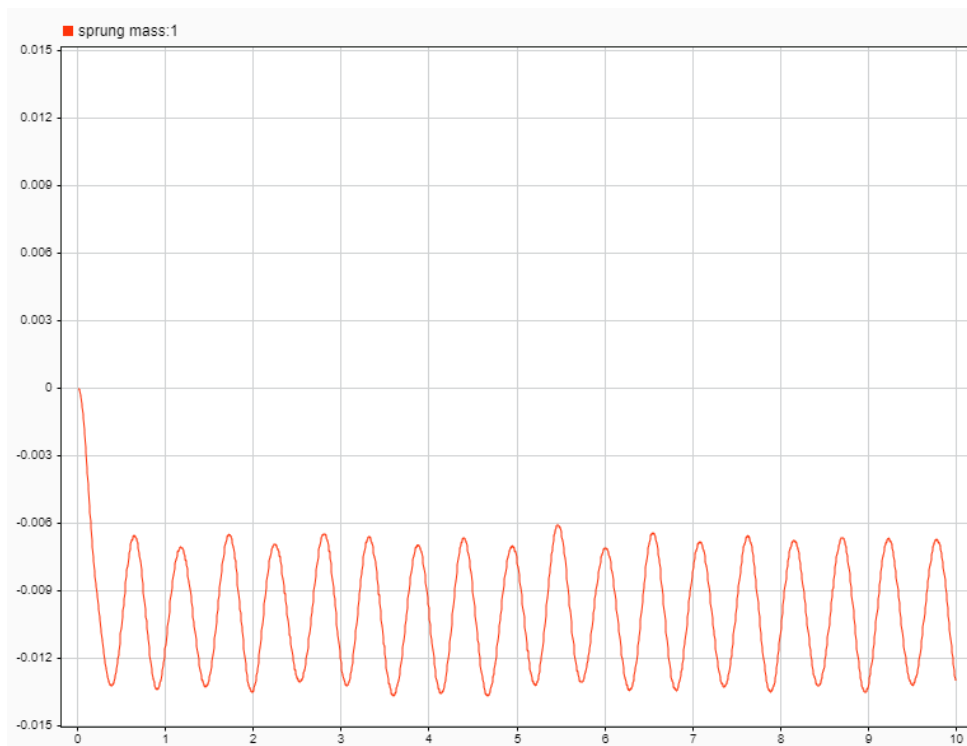


Figure 10: Sprung mass diagram for setup 1 for two lane change

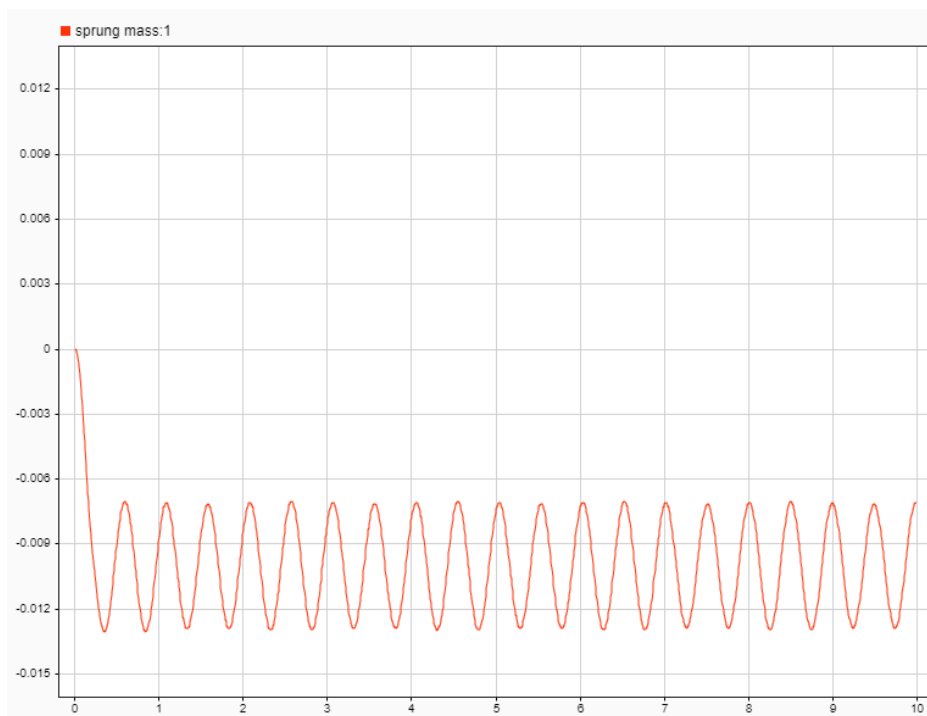


Figure 11: Sprung mass diagram for setup 2 for two lane change

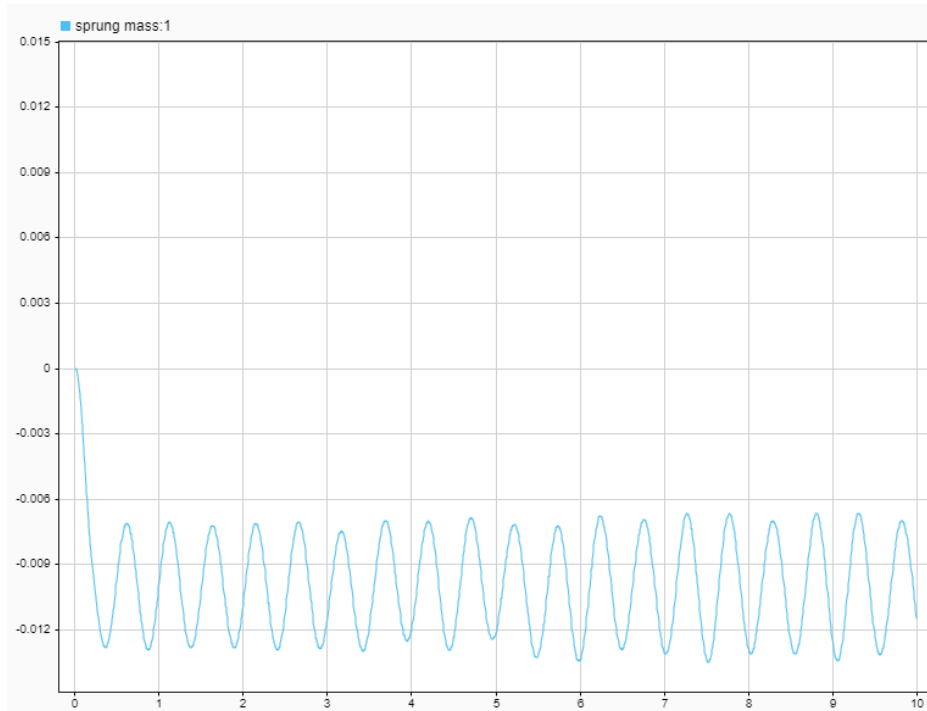


Figure 12: Sprung mass diagram for setup 3 for two lane change

Variable pitch for Slalom line change:

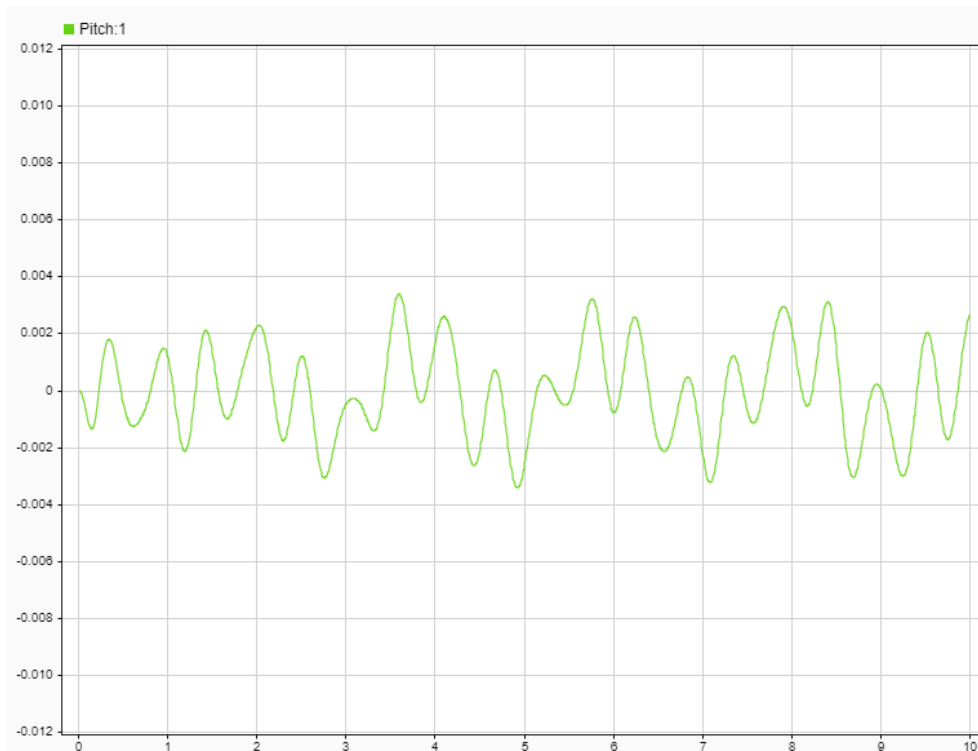


Figure 13: Pitch diagram for setup 1 for slalom line change

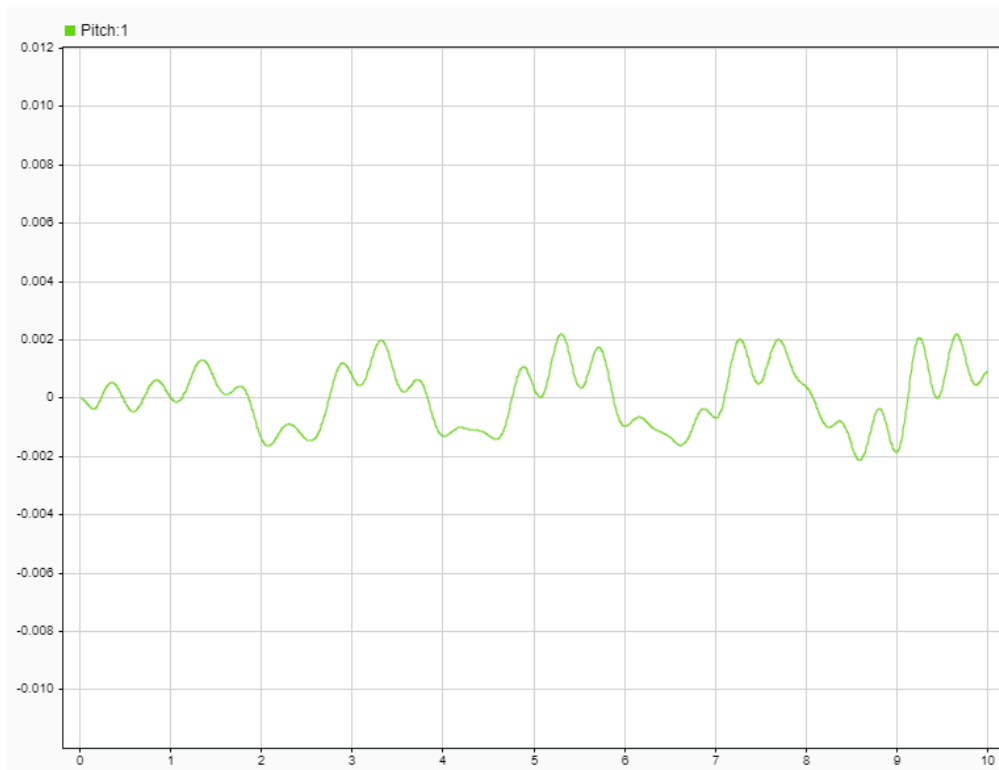


Figure 14: Pitch diagram for setup 2 for slalom line change

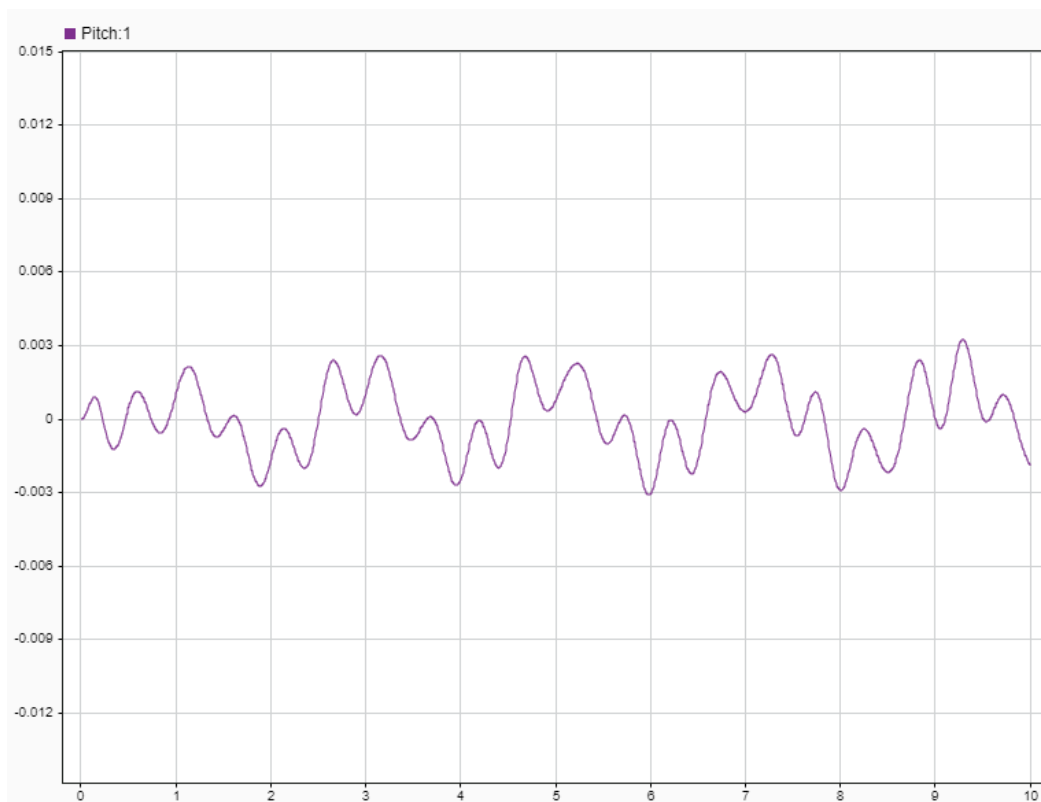


Figure 15: Pitch diagram for setup 3 for slalom line change

Variable roll for Slalom line change:

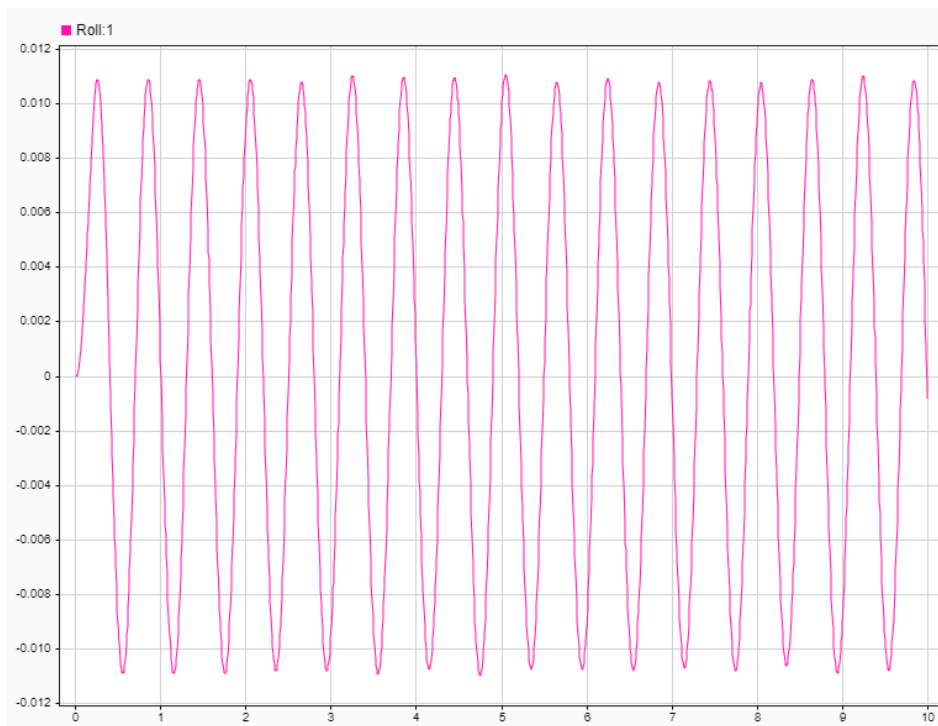


Figure 16: roll diagram for setup 1 for slalom line change

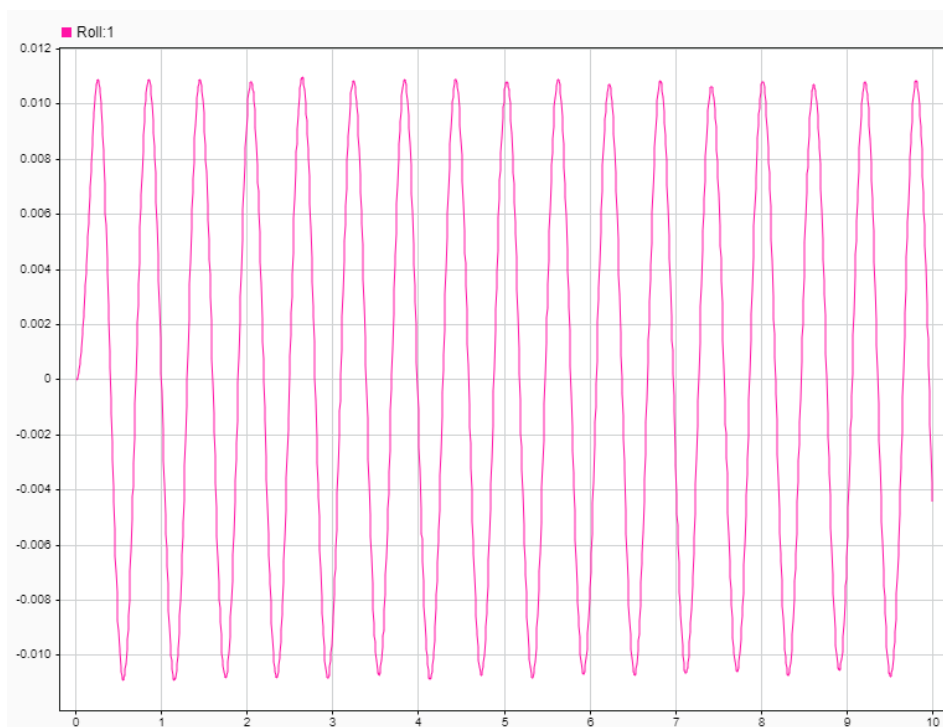


Figure 17: roll diagram for setup 2 for slalom line change

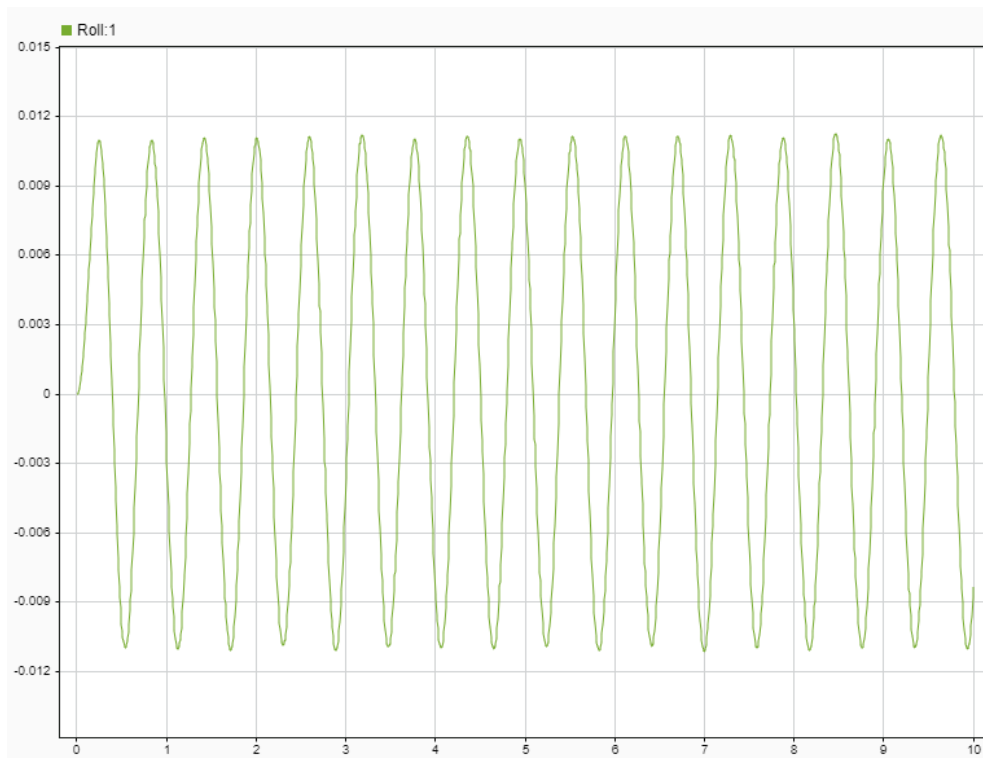


Figure 18: roll diagram for setup 3 for slalom line change

Variable sprung mass for Slalom Line change:

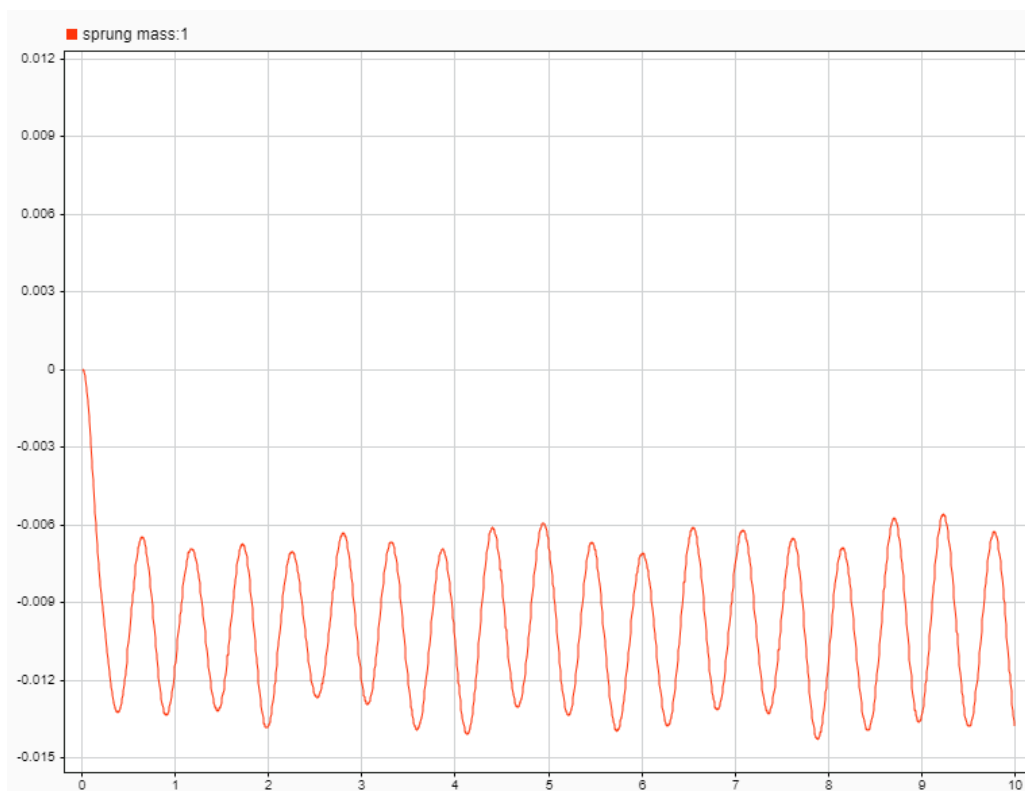


Figure 19: Sprung mass diagram for setup 1 for slalom line change

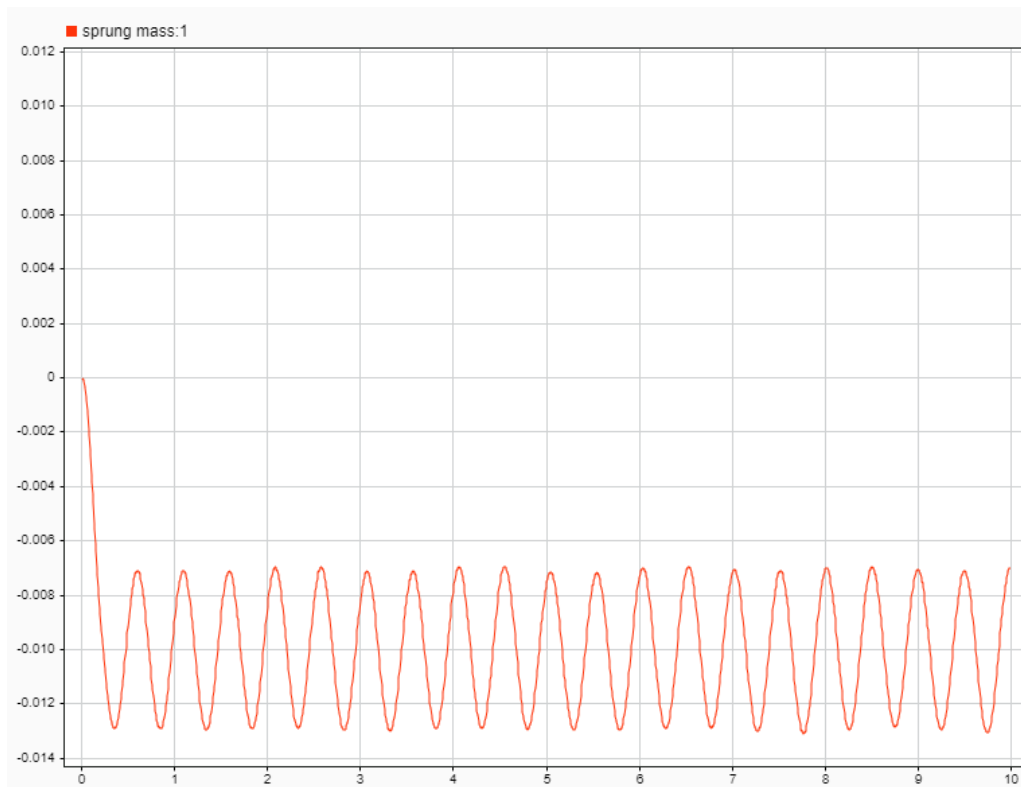


Figure 20: Sprung mass diagram for setup 2 for slalom line change

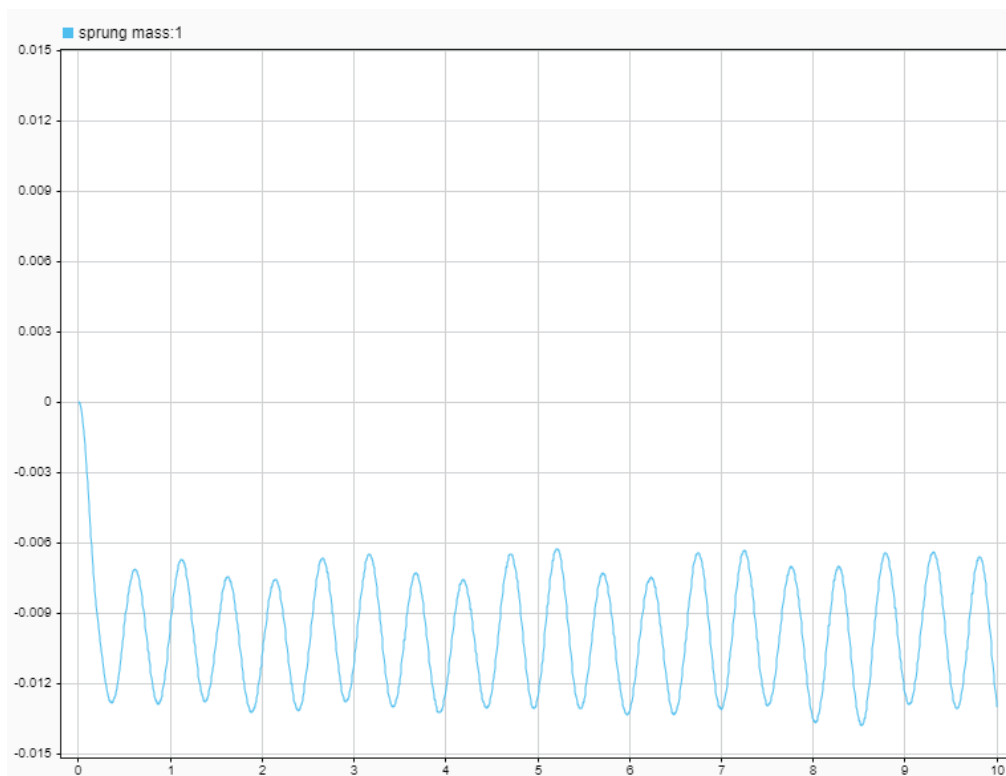


Figure 21: Sprung mass diagram for setup 3 for slalom line change

6.Results and Discussion:

Pitch angle, roll angle, and sprung mass are all significant variables that influence the dynamic response of a 7DOF spring-mass-damper system. The rotation of the vehicle about its longitudinal (x) axis is referred to as the pitch angle. It gauges how much the front and back of the car are inclined upward or downward. The suspension design, steering input, and road roughness are only a few examples of the variables that might affect the pitch angle. The rotation of the vehicle about its transverse (y) axis is referred to as roll angle. It gauges how far the car is tilting in one direction or the other. The suspension design, steering input, and road roughness are a few examples of variables that might affect roll angle. The mass of the vehicle that is supported by the suspension system is referred to as sprung mass. While the wheels and tyres are excluded, the mass of the body, chassis, and passengers is included. Because it impacts the forces sent through the suspension to the tyres and road surface, the sprung mass plays a significant role in defining the dynamic response of the suspension system.

Using the modelling program Simulink, a 7DOF model of the race car suspension system was created. This model incorporates the vehicle's pitch and roll angles as well as the suspension system's spring, damper, and mass properties. Enter the correct data into the model, such as the vehicle's mass, suspension stiffness, and damping coefficient. Run simulations to ascertain the system's dynamic reaction in pitch and roll under various operating circumstances, including variable speeds and road roughness. After entering all the data and simulating graphs by using MATLAB code and taking data from the MOTEC software to plot the graphs for variables like Pitch angle, Roll angle and sprung mass for the race car for two-lane change.

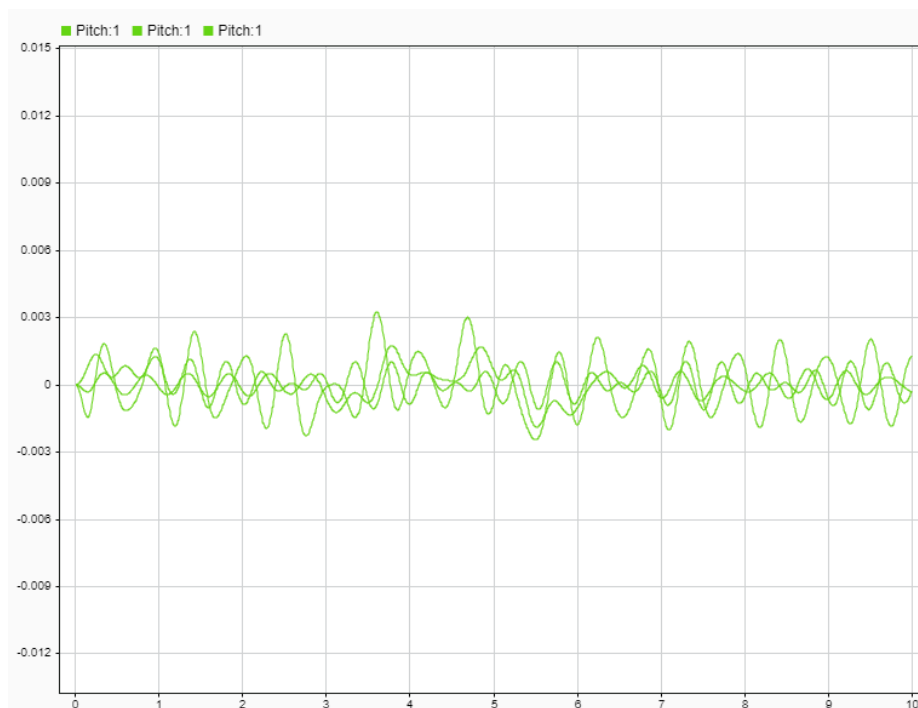


Figure 22: Pitch angle graph from 3 setups of two lane change

The pitch angle from the graphs for three setups the graph moves up and down such it went positive and negative angle this is because of the acceleration of the car during the line change. Pitch angle is the angle between the vertical axis and the line which connects mass damper. The system's properties, such as the spring constant, mass, and damping coefficient, as well as outside forces like gravity and external disturbances, have an impact on the pitch angle. There is a deflection when pitch angle of the two-lane change with the slalom line change because, A slight, oscillating motion around the lateral axis often characterises the pitch angle response in this movement. The vehicle mass, damping coefficient, and suspension stiffness all have an impact on the pitch angle oscillation's magnitude whereas in slalom line change a bigger and more noticeable oscillation along the lateral axis is often what characterises the pitch angle response in this movement. And also there is a deflection of graphs for three setups because of the changes in the Front and the Rear spring rates and also the amount of data that we are extracting from the MOTEC software.

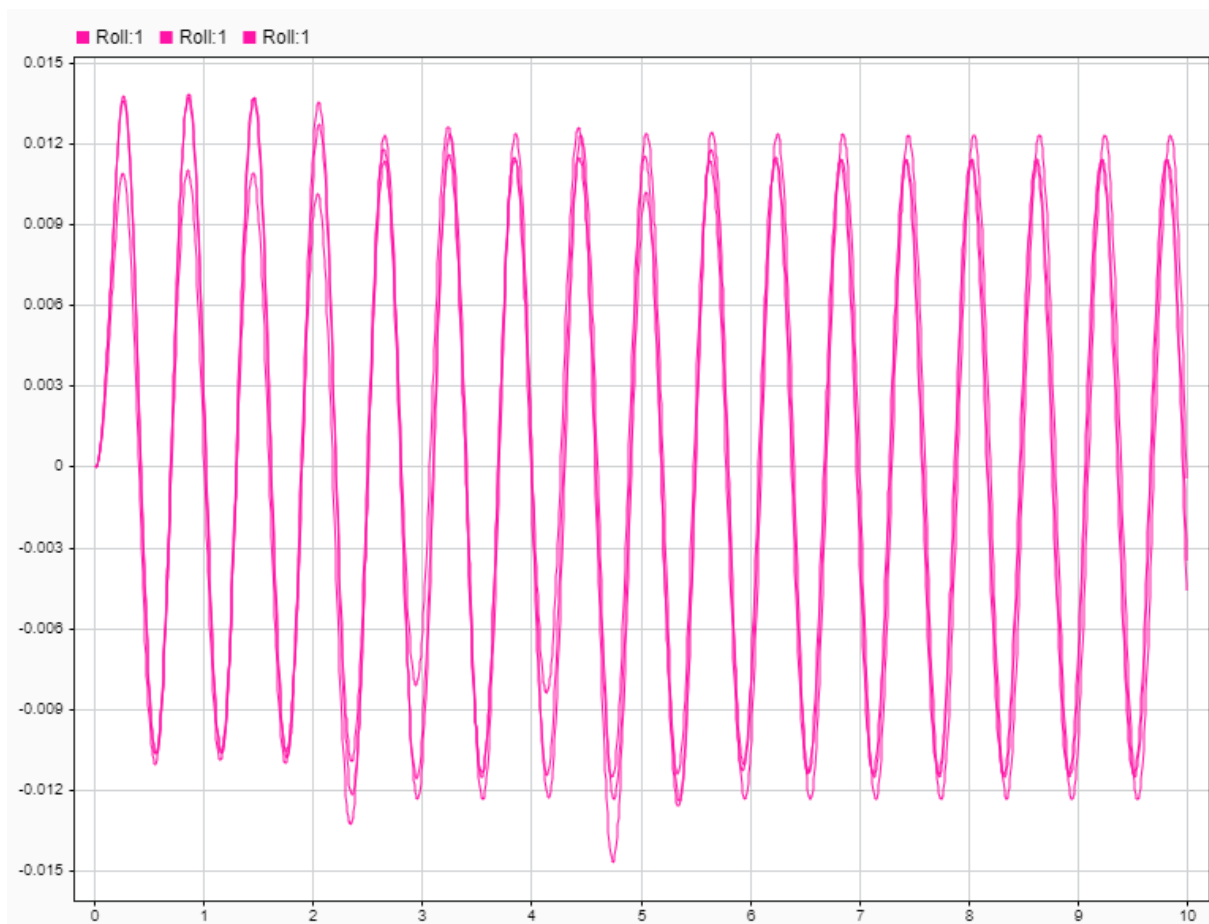


Figure 23: roll angle graph from 3 setups of two lane change

When a vehicle experiences a lane change or sharp turns, the roll angle graph from a 7DOF model displays the change in angle of the vehicle body along the longitudinal axis (y-axis). The roll angle, which impacts the vehicle's stability and

handling, is an important factor of vehicle dynamics. The roll angle response for this test can be simulated by inputting the lateral acceleration of the vehicle as it navigates through the cones and the roll angle of the vehicle can be observed from both Two line change and the Slalom line change. The roll angle may be effected by the tyre characteristics and drier inputs. There is small deflection between the graphs of two line change and slalom line change, because of the sudden changes in increasing or dropping of the acceleration. And also there is a deflection of graphs for three setups because of the changes in the Front and the Rear spring rates and also the amount of data that we are extracting from the MOTEC software.

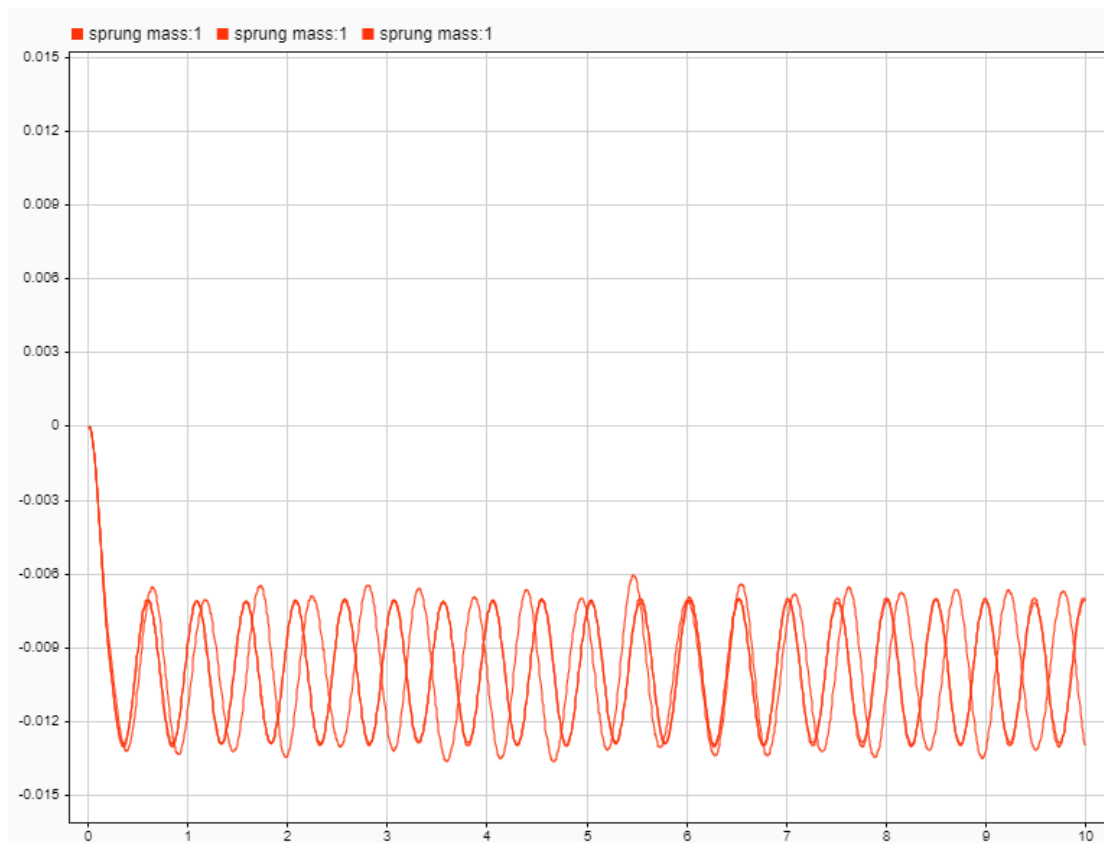


Figure 24: Sprung mass graph from 3 setups of two lane change

The car body's motion in reaction to a disturbance, such as a bump in the road, is represented by the sprung mass graph with damping from a 7DOF model of the vehicle suspension system. The graph, which represents the displacement of the sprung mass over time, can be used to analyze the ride quality and dynamic capabilities of the vehicle. The strength of the stimulation and the amount that the vehicle body moves in response both influence the amplitude of the sprung mass' displacement. A bigger displacement and more visible motion of the vehicle body are both indicated by a larger amplitude. The number of oscillations that take place during a specific time interval affects how frequently the sprung mass moves. More oscillations and faster bodily movements are indicated by a higher frequency. Because the motions are different, the sprung mass response will vary between the TWO line change and the slalom line

change. While the slalom line change will probably result in a larger amount of vertical displacement with a higher frequency and a lower damping ratio, the TWO line change will probably create a moderate amount with a reasonably low frequency and a moderate damping ratio. Because of the changes in the parameters of each setup the graphs has a slight change in it. The parameters include Front and rare damping rates and damping coefficients and also the data which we have taken from the MOTEC software

In a system with seven degrees of freedom (DOF), the model will have seven DOF, which will be divided into three DOF for longitudinal motion, two DOF for lateral motion, one DOF for vertical motion, and one DOF for yaw motion of the vehicle. These seven degrees of freedom are interrelated, and the movement of one DOF influences the motion of the others. For the model that assesses and forecasts the dynamic response of the 7DOF spring-mass-damper system, the pitch angle, roll angle, and sprung mass are crucial inputs.

7.Conclusion:

From the above graphs we conclude that the discussion of modelling methods in this paper and also discussion of Spring mass dampers systems. Discussion of how 7DOF including damping has been simulated from 1DOF. Plotted graphs for Double lane change as well as the slalom lane change and explained why there is deflection between those graphs from research. And also given demonstration of principles of Spring mass damper systems and also the vehicle dynamic simulation methods.

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