Indian Institute of Technology Madras

Engineering Design Department

ED 5220 – Vehicle Dynamics

Jan - May 2024

End Semester

Date: Fri, 10 May 2024	**Due Date**: Sat, 11 May 2024 9.00 am

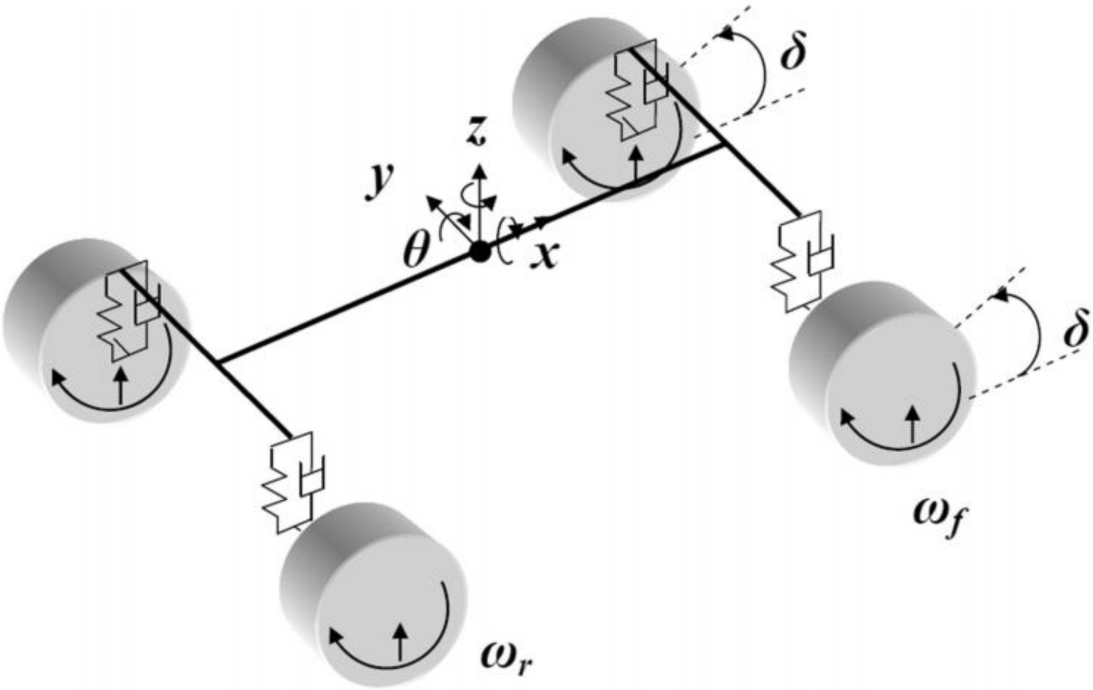
Instructions:

- *MATLAB/Simulink inbuilt vehicle model or vehicle component models cannot be used for the exam.*
- *Report should be submitted in pdf format. Along with report submit your codes/Simulink model, zipped together as a single file*
- *Report should include clearly labelled figures, relevant assumptions & explanations, references (wherever required). Handwritten scanned copies are accepted.*
- *Zip file should be named with roll numbers. Ex. <Sem_Ed24b001.zip>.*

Question

Your classmate has established a startup of manufacturing autonomous cars as direct competition to Tesla. Trusting your knowledge acquired from VD course, he has hired you for a handsome package as a Senior Manager to design and evaluate vehicle dynamics. The first task assigned is to design and evaluate performance of a conventional FWD passenger car. Please help our friend to

You are required to do a vehicle level modelling and analyze its performance based on standard tests.



<table>
<tr>
<td>Passenger vehicle
15 DOF</td>
<td>Vehicle DOFs
6
<table>
<tr><th>Translational</th><th>Rotational</th></tr>
<tr><td>Longitudinal</td><td>Pitch</td></tr>
<tr><td>Lateral</td><td>Roll</td></tr>
<tr><td>Vertical</td><td>Yaw</td></tr>
</table>
</td>
<td>Wheel DOFs
2 per wheel – total 8
<table>
<tr><th>Translational</th><th>Rotational</th></tr>
<tr><td>vertical</td><td>rolling</td></tr>
</table>
1 front steering</td>
</tr>
</table>

The vehicle needs to be maneuvered as per driver signals. These form input to the vehicle system.

All other signals needs generated by the vehicle are the outputs. Vehicle outputs should be global coordinates.

<table>
<tr><th>Inputs</th><td rowspan="8">
FL – Front Left
FR – Front Right
RL – Rear Left
RR – Rear Right</td><th>Outputs</th></tr>
<tr><td rowspan="2">Gas, brake</td><td>Global coord - (X, Y, Z)</td></tr>
<tr><td>V_x, V_y, V_z</td></tr>
<tr><td rowspan="2">Steering</td><td>a_x, a_y, a_z</td></tr>
<tr><td>Global coord - θ, ϕ, ψ</td></tr>
<tr><td rowspan="3">Road excitation</td><td>$\dot{\theta}, \dot{\phi}, \dot{\psi}$</td></tr>
<tr><td>$\ddot{\theta}, \ddot{\phi}, \ddot{\psi}$</td></tr>
<tr><td>$\lambda_{FL}, \lambda_{FR}, \lambda_{RL}, \lambda_{RR}$
Tire forces and Moments $(F_x, F_y, F_z, M_x, M_y, M_z)_{FL,FR,RL,RR}$</td></tr>
</table>

Some of vehicle parameters are given

Class	Parameter	Value
Physical	Mass	1200 Kg
	Distance from CG to – Front-axle Rear-axle	 1.0 m 1.6 m
	Ixx Iyy Izz	500 Kg*m^2 1600 Kg*m^2 1800 Kg*m^2
Suspension	Spring stiffness – FL,FR RL,RR	 To be calculated N/m To be calculated N/m
	Damper – FL, FR RL, RR	 1600 N*s/m 1600 N*s/m
	Antiroll bar stiffness Front Rear	 15000 N/m 15000 N/m
Tires	Full Magic Formula	Example tire in simscape multibody toolbox
steering	Steering ratio : driver hand to wheel	15:1

```
TirFilename = 'sm_car_heave_roll_tire_245_60_R16.tir';
TireParameters = simscape.multibody.tirread(TirFilename);
% Wheel mass and inertia
WheelMass    = 20;    % kg
WheelInertia = [1 2 1]; % kg*m^2
```

Tasks

- Derive equations for the 14 DOF vertical dynamics vehicle model (including antiroll bar). Given natural frequencies of vertical vibrations for front and rear as 0.9Hz and 1.5Hz, calculate suspension stiffnesses and plot mode shapes. [10 marks]
- Build a full 15 DOF simulation model (including steering). [15 marks]
- Performance analysis. [15 marks]
  - Perform step steer test and compute response metrics (see Appendix for test details) with and without antiroll bar.
  - Perform impulse steer test with and without antiroll bar and plot mimuro figure (see Appendix for test details). Also plot simulated and transfer function estimated responses (aY and yaw rate).
  - What test would you perform to compute understeer gradient? Can you simulate, compute and explain with resultant graphs. What vehicle parameters affect understeer gradient?
  - [Hint]: Antiroll bars are used to minimize roll and stabilize vehicle by improving tire contact with ground. A simple way to implement antiroll bar simulation is to compute difference in suspension deflection between left and right sides, multiply with antiroll stiffness and apply the resultant force in opposite direction to left and right wheels.
- Based on the metrics obtained, can you improve performance of the vehicle? Explain in detail with necessary equations/simulations and resultant graphs [10 marks]

Appendix

1. Step Steer Test [ISO 7401 : 2003 (E)]

Input and Output

- steering wheel angle - δ_H
- lateral acceleration - a_Y
- yaw rate - $\dot{\psi}$
- longitudinal velocity - v_X
- lateral velocity - v_Y

Important time and frequency domain characteristics

- Time lags between input - δ_H and responses - a_Y and $\dot{\psi}$.
- Response times of a_Y and $\dot{\psi}$.
- a_Y and $\dot{\psi}$ gains
- a_Y and $\dot{\psi}$ overshoot
- a_Y and $\dot{\psi}$ phase delays wrt to δ_H

Test procedure

- Test vehicle be run at $v_X = 60\,kmph$ with 3s – 5s neutral steering
- Determine the δ_H amplitude by steady – state driving on a circle radius of which gives the preselected steady – state a_Y. The standard steady – state $a_Y = 4m/s^2$
- Time between *10%* and *90%* steering wheel input should be maximum 0.15s

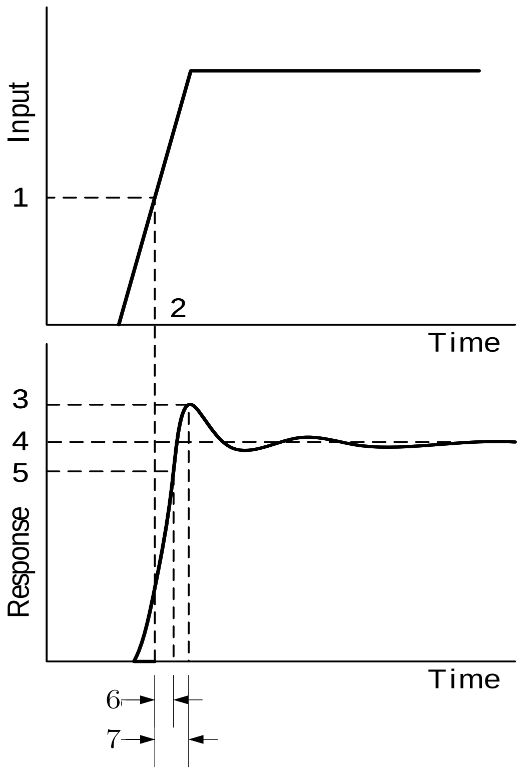


Figure: Step Response

Data analysis

1 *50%* steering wheel input

2 time for (1)

3 peak response

4 steady state response

5 *90%* steady state response

6 response time

7 peak response time

Table: Step input - response data

Parameter	Symbol	Iteration 1	Iteration 2	Iteration 3	...
Comments		________	________	________	________
Lat accl response time	T_{aY}	________	________	________	________
Lat accl peak response time	$T_{aY,max}$	________	________	________	________
Lat accl steady state gain	$\left(\frac{a_Y}{\delta_H}\right)_{ss}$	________	________	________	________
Lat accl overshoot	U_{aY}	________	________	________	________
Yaw rate response time	$T_{\dot{\psi}}$	________	________	________	________
Yaw rate peak response time	$T_{\dot{\psi},max}$	________	________	________	________
Yaw rate steady state gain	$\left(\frac{\dot{\psi}}{\delta_H}\right)_{ss}$	________	________	________	________
Yaw rate overshoot	$U_{\dot{\psi}}$	________	________	________	________
Roll angle response time	T_{ϕ}	________	________	________	________
Roll angle peak response time	$T_{\phi,max}$	________	________	________	________
Roll angle steady state gain	$\left(\frac{\phi}{\delta_H}\right)_{ss}$	________	________	________	________
Roll angle overshoot	U_{ϕ}	________	________	________	________

2. Pulse Steer Test [ISO 7401 : 2003 (E)] extended to Mimuro plot

Input and Output

- steering wheel angle - δ_H
- lateral acceleration - a_Y
- yaw rate - $\dot{\psi}$
- longitudinal velocity - v_X
- lateral velocity - v_Y

Important time and frequency domain characteristics

- Time lags between input - δ_H and responses - a_Y and $\dot{\psi}$.
- Response times of a_Y and $\dot{\psi}$.
- a_Y and $\dot{\psi}$ gains
- a_Y and $\dot{\psi}$ overshoot
- a_Y and $\dot{\psi}$ phase delays wrt to δ_H

Test procedure

- Test vehicle be run at desired $v_X = 60kmph$ with 3s – 5s neutral steering
- Pulse steering amplitude is found such that peak $a_Y = 4m/s^2$
- Steering pulse width to within 0.3s – 0.5s

Data analysis

- Post-process of data to produce both transfer function

$$\left(\frac{a_Y(s)}{\delta_H(s)}\right) = a_1 \frac{1 + b_1 s + b_2 s^2}{1 + 2\zeta \frac{s}{\omega_n} + \frac{s^2}{\omega_n^2}}$$

$$\left(\frac{\dot{\psi}(s)}{\delta_H(s)}\right) = a_2 \frac{1 + b_3 s}{1 + 2\zeta \frac{s}{\omega_n} + \frac{s^2}{\omega_n^2}}$$

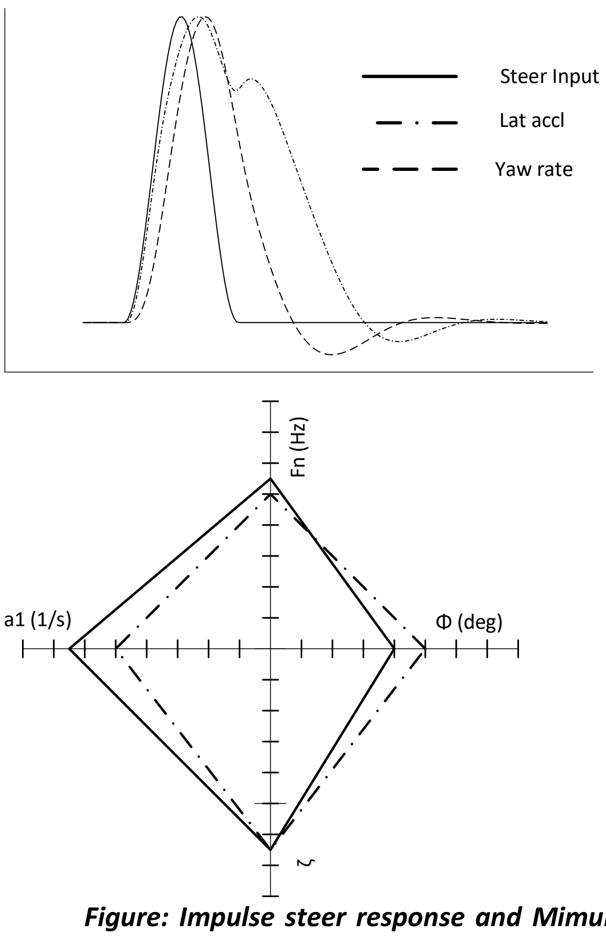


Figure: Impulse steer response and Mimuro plot

- Following 4 parameters are thus deduced
  - a_1: steady state gain of yaw rate response
  - f_n: natural frequency of yaw rate response
  - ζ: damping of yaw velocity response
  - ϕ: phase delay at 1Hz of lateral acceleration

Table: pulse steer response data

Parameter	Symbol	Iteration 1	Iteration 2	Iteration 3	...
Comments		________	________	________	________
steady state gain of yaw rate response	a_1	________	________	________	________
natural frequency of yaw rate response	f_n	________	________	________	________
damping of yaw velocity response	ζ	________	________	________	________
phase delay at 1Hz of lateral acceleration	ϕ	________	________	________	________