TSFS02 — Vehicle Dynamics and Control

Computer Exercise 5:
Vertical Dynamics (Ride Characteristics)

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1 Introduction

In this exercise you will study the vertical dynamics and, in particular, how the damping affects the ride characteristics in terms of comfort and handling. You will see how different passive-damping configurations perform compared to semi-active strategies.

For these evaluations you will be using a simplified vehicle model, often used for ride dynamics studies, known as the quarter-car model. All implementations and simulations is done with MATLAB.

1.1 Examination

To pass this exercise you should have fulfilled the following:

- Solved the preparation tasks.
- Solved all the computer exercise tasks.
- Answered all questions, with motivated and thoughtful answers.

The examination is done by presenting your results and answers to a course assistant at the scheduled exercise session. To speed up the examination process, it is recommended to present the tasks as you complete them, instead of saving them all to the end.

2 Preparation Tasks

The tasks in this section (i.e. Task 1–7) are preparation tasks that should be solved before starting with the computer exercise tasks in Section 3. Please verify with an assistant that you have solved these tasks correctly before starting with Task 8–10 (since your code implementations will be based on the equations you derive in the preparation tasks).

Task 1 – Quarter-car model (sketch)

Sketch a figure of the quarter-car model, with the following defined; sprung mass, unsprung mass, a spring, a damper, and a tire stiffness. In this figure, define all the parameters and variables you use in the following tasks.

Task 2 – Quarter-car model (equations)

Derive the equation of motion for the quarter-car model, using the vertical positions of the sprung and unsprung mass as states, and the road profile as input. Neglect damping in the tire.

Task 3 – Natural frequencies

Calculate the natural frequencies for the sprung and unsprung mass. Use the vehicle parameters in Table 1 (in the Appendix).

Task 4 – Performance indices

Define two performance indices; one for comfort measures, and one for handling. These indices should be scalars, describing the comfort and handling properties over a time interval. Formulate the equations to calculate the measures given measurements of your quarter-car model variables.

One option is to use the root-mean-square value of the sprung mass acceleration as a comfort measure, and the root-mean-square value of the tire deflection as a performance measure.

Task 5 – Nonlinear passive damper

For all of the passive dampers in this exercise, the damper force only depends on the damper velocity (i.e. the speed of which the damper is compressed or expanded with). For the linear dampers this

relation is linear. However, shock absorbers for vehicle suspensions are often designed to have nonlinear characteristics, for example as depicted in Figure 1 where the damping is different for low and high velocities.

In Task 8 you should implement a simple damper function (or script) that imitates the characteristics shown in Figure 1, where the velocity is input and the damper force is output. In the figure, the inclination of the graph is c_{max} for low velocities and c_{min} for high velocities.

Prepare for Task 8 by formulating the necessary equations for the passive nonlinear damper. Let the switching velocity (i.e. the velocity at which the inclination changes in Figure 1) be a parameter in your equations that you can easily change.

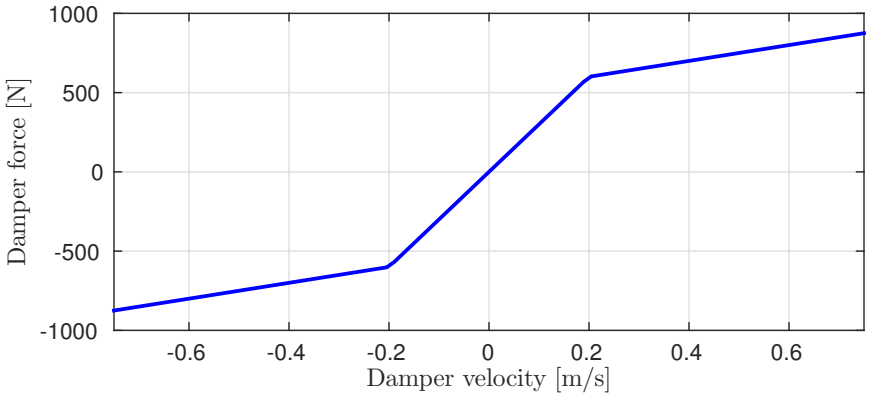

Figure 1 Force characteristics for a nonlinear passive damper.

Task 6 – Skyhook algorithm

You will also implement two versions of the skyhook control strategy in this exercise.

a) Formulate the simplified skyhook (switching between two constant damping coefficients) mathematically.

b) A slightly different variant of the skyhook is described by

$$c = \begin{cases} c_{min} & \text{if} \quad \dot{z}_1(\dot{z}_1 - \dot{z}_2) \leq 0 \\ \frac{1}{\dot{z}_1 - \dot{z}_2}(\alpha c_{max}(\dot{z}_1 - \dot{z}_2) + (1-\alpha)c_{max}\dot{z}_1) & \text{if} \quad \dot{z}_1(\dot{z}_1 - \dot{z}_2) > 0 \end{cases} \tag{1}$$

where c is the damping coefficient, c_{min} and c_{max} are maximum and minimum damping coefficients, z_1 and z_2 are the vertical displacement of the sprung and unsprung mass, and α a design parameter.

For which values of α is this skyhook algorithm the same as the one in a)?

To make it easier to refer to the two skyhook algorithms above, from here on we call the one in a) *Skyhook 1* and the one in b) *Skyhook 2*.

Task 7 – Amplitude gain

Describe the amplitude gains, for the sprung mass and the the tire deflection, as functions of the excitation frequency from the ground, when considering a system with linear passive damping. This analytic expression will be used in Task 10 to plot frequency response diagrams for the passive dampers.

3 Exercise Tasks

In the following tasks you will implement the quarter-car model with passive and active damping. The different damper implementations should be evaluated and compared using frequency response diagrams and simulations of driving over a bump.

Start by downloading the prepared MATLAB files from the homepage (TSFS02_Lab5_Vertical.zip).

Task 8 – Nonlinear passive damper

Implement the simple damper function from Task 5, either as a dedicated MATLAB-function or just a few rows of code. Verify your implementation by replicating the plot in Figure 1 and include it in the report. Ensure that your function support moving the switching velocity (the function should stay continuous).

Task 9 – Quarter-car model implementations

Implement the quarter-car model derived in Task 2 for the following damper configurations:

- Passive linear damping, nominal damping ($c = c_{nom}$); `qc_pl_nom.m`
- Passive linear damping, minimal damping ($c = c_{min}$); `qc_pl_min.m`
- Passive linear damping, maximum damping ($c = c_{max}$); `qc_pl_max.m`
- Passive nonlinear damping; `qc_pnl.m`
- Skyhook 1; `qc_sh1.m`
- Skyhook 2; `qc_sh2.m`

You are advised to use the corresponding MATLAB scripts as a base for your models. For the passive nonlinear damping, use your function (or script) from Task 8.

When implementing Skyhook 2, use a value of $\alpha = 0.5$ to start with. In Task 10 you will be elaborating with this slightly.

To verify that the implementations work, you are provided with the prepared script `VerifyQC.m` which simulates the quarter-car models. These simulations do not have to be included in the report.

Remember to include all your written or modified code in the report.

Task 10 – Frequency response

A frequency response diagram can provide interesting information about how a damper configuration performs for different excitation frequencies. In this task, you should investigate your damper models by creating frequency response diagrams for the sprung mass and the tire deflection, associated with the models implemented in Task 9. In `FreqResponsePlot.m` you will find code that can be used as a base for this task.

In Task 7 you derived analytic expressions of the amplitude gain for the linear models, that here will be used when creating the frequency response diagrams. The nonlinear models on the other hand, are not very pleasant to work with analytically. Instead you will use data from simulations to produce the frequency response diagrams for these. The simulations use a sinusoidal road excitation signal, with a specified excitation frequency. A new simulation is performed for each frequency of interest, and the simulation results are used for calculating the response at each frequency. However, this simulation script is already prepared in `FreqResponsePlot.m`.

The frequency response diagrams should be plotted over the frequency span of 0.5 to 20 Hz, with logarithmic scaling on both axes (you can use the `loglog` function in MATLAB when plotting).

a) Plot diagrams for the models with passive linear damping, using the expressions from Task 7.

b) Plot diagrams for all models using the simulation technique. Start with the linear damping models, to verify that the results in a) correlate with the resulting frequency response here.

c) Can you, just by looking at the diagrams, see where the natural frequencies appear? Do these observations coincide with the calculated frequencies in Task 3?

d) Try out a couple of different values for α in the Skyhook 2 model. How does this affect the frequency response? Settle for a value you find appropriate.

e) Generate figures that display the frequency response for all models (one figure for the sprung mass, and one for the tire deflection), and include them in the report. Use different colors distinguish the different damper configurations.

f) Consider the nonlinear passive damping. What happens with the frequency response if you change the road excitation amplitude (`Aroad`)? Why does it change? What happens if you change the switching velocity?

g) Describe the differences you see for your damper implementations. In which areas (of the frequency span) do they perform good or bad in terms of comfort and handling?

Task 11 – Single bump simulation

In this task you should analyze simulations of driving over a bump. The road profile starts with a single bump, after which the profile is flat. The bump have a sinusoidal shape, a height of 0.1 m, and a total length of 0.2 m.

In `SingleBumpSim.m` you can find prepared scripts for the simulations. Use this as basis for simulating and plotting the results for all of your implemented damper configurations.

a) Run simulations for velocities of $v = 30$ km/h and $v = 70$ km/h. Plot the results of all models together, to make comparisons easier, and include in the report.

b) Calculate the performance indices you defined in Task 4, and use them to evaluate the comfort and handling properties of the different models. (Include the calculated values of the performance indices in the report.)

c) Describe how the models differ in behavior. How do they perform in terms of comfort and handling? Discuss and highlight characteristics that agree with, or contradict, the characteristics seen in the frequency response diagrams.

   An important function of a suspension system is to support the vehicle weight, *i.e.*, by ensuring ground clearance and wheel clearance. The performance in this area can be measured in terms of minimizing the rattle space (suspension deflection). Include the rattle space in your discussion above.

A Quarter-Car Vehicle Parameters

Parameters for the quarter-car vehicle model is defined in Table 1.

Table 1 Vehicle parameters for the quarter-car model.

Parameter	Description	Value	Unit
m_s	Sprung mass	400	kg
m_{us}	Unsprung mass	40	kg
k_s	Spring stiffness	$30 \cdot 10^3$	N/m
k_t	Tire stiffness	$200 \cdot 10^3$	N/m
c_{nom}	Nominal damping	1500	Ns/m
c_{min}	Minimum damping	500	Ns/m
c_{max}	Maximum damping	3000	Ns/m