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Spectrum Analysis with VehicleSim Models

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The equations of motion for VehicleSim (VS) vehicle math models are not linear. They contain nonlinear force equations, nonlinear motions involving trigonometric functions of angles, friction and other hysteresis, lock conditions, and many other physically realistic characteristics that are nonlinear.

At least two methods are available analyze the frequency response of the VS model, both involving external math tools such as MATLAB from The Math Works. One option is to use the VS `LINEARIZE` command to linearize the model, and then analyze the linearized system in MATLAB. This method is described in a separate technical memo: Linear Analysis in VehicleSim Models. The other approach, described in this memo, is to export time-domain simulation results into MATLAB, and then use frequency transform tools in MATLAB to generate plots of power spectral density (PSD) and other frequency response functions.

As with other applications of VS Simulation tools, the method is nearly the same as would be done with physical testing:

Run a simulated test.

Transfer the time-domain results to MATLAB.

Use MATLAB functions to transform the time series to the frequency domain, and then view plots defined from those frequency-domain arrays.

This document presents the steps used to transform the simulation data from the nonlinear vehicle models to the frequency domain through the *Fast Fourier Transform* (FFT). This memo assumes that you are familiar with the basic use of your VS product and with MATLAB. At a minimum, you should have gone through the Quick Start Guide.

> **Note** Prior to 2014, VS Simulation tools included a frequency analysis tool called Spectrum, developed in the 1980s. Spectrum did not have a GUI and had serious memory limits. It has been retired.

Example: Sine Sweep Steer Test

Frequency response plots are widely used for characterizing electro-mechanical system behavior, including vehicle systems. Here, a CarSim example is tested to see the frequency response to steering input from the driver. The simulation run is named **Sine Sweep Steer Test** in the category **Steering Tests** of the **CarSim Run Control** screen (Figure 1).

Note: TruckSim 9.0 includes the same example but uses different vehicle.

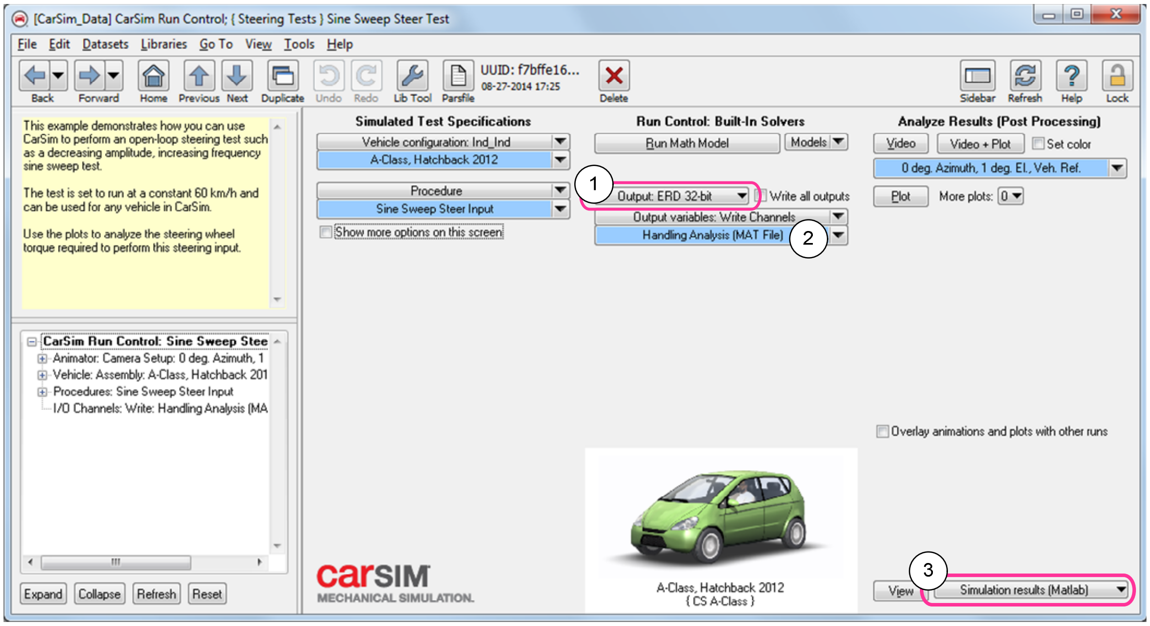


Figure 1. Run Control screen for Sine Sweep Steer Test.

A small A-Class vehicle is set up to run on a flat surface with a constant speed of 60 km/h. A sinusoidal steering angle input is defined that provides significant contents over a broad range of frequency. Steering starts with low frequency and increases to high frequency over a time of 110 s (Figure 2). Outputs of interest are yaw rate and lateral acceleration, also shown in the figure.

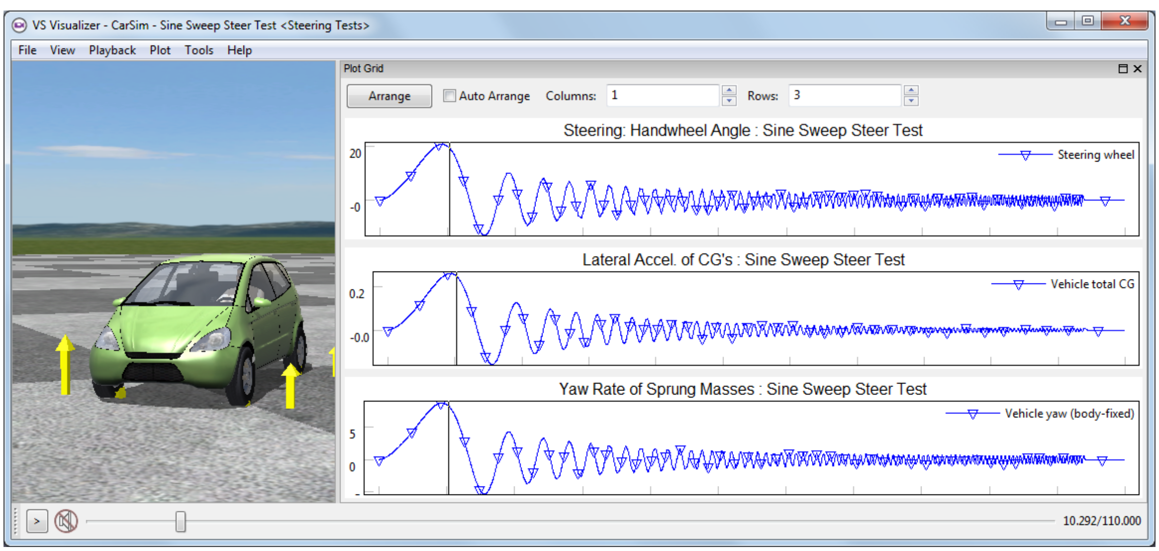


Figure 2. Vehicle response with a sinusoidal-sweep steer input (from low to high frequency).

In order to feed the time history data shown in Figure 2 into MATLAB, the simulation results are written in ERD format and converted to MAT format with the ERD converter tool. In Figure 1, output data format is set as **ERD 32-bit** ① and ERD converter is specified in a separate link ②. The ERD converter has already been configured to convert the time, steer angle, yaw rate, and lateral acceleration in this example. For details of ERD converter setting, please see the ERD File Converter Reference Manual.

> **Note** CarSim 9.0 supports three options for output: 32-bit ERD, 32-bit VS, and 64-bit VS. At the time this memo was written, the ERD converter does not support the VS format file, so it is necessary to generate outputs with the ERD option.

Spectrum Analysis with MATLAB

After the simulation, choose the drop-down menu item **Simulation results (Matlab)** ③ (Figure 1) and click the adjacent **View** button. This launches MATLAB with the output variables from CarSim available in the MATLAB workspace (Figure 3).

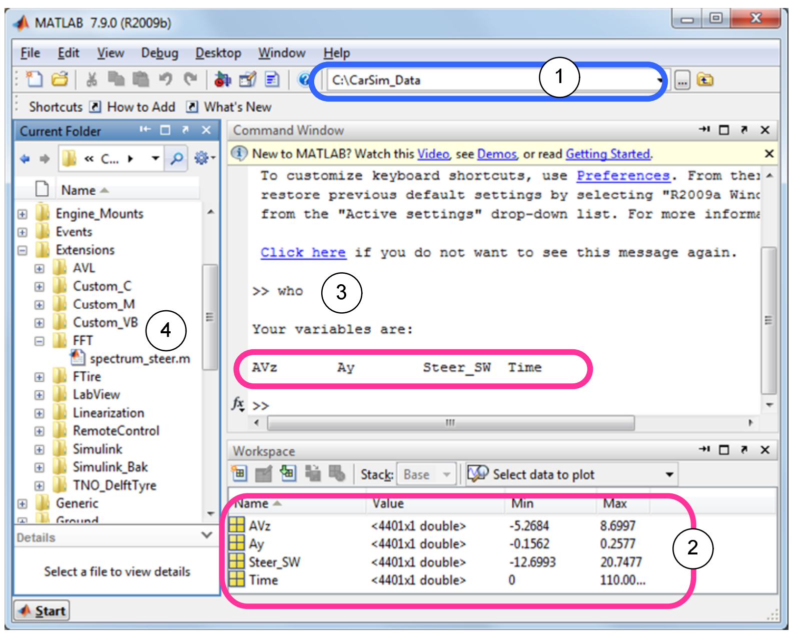
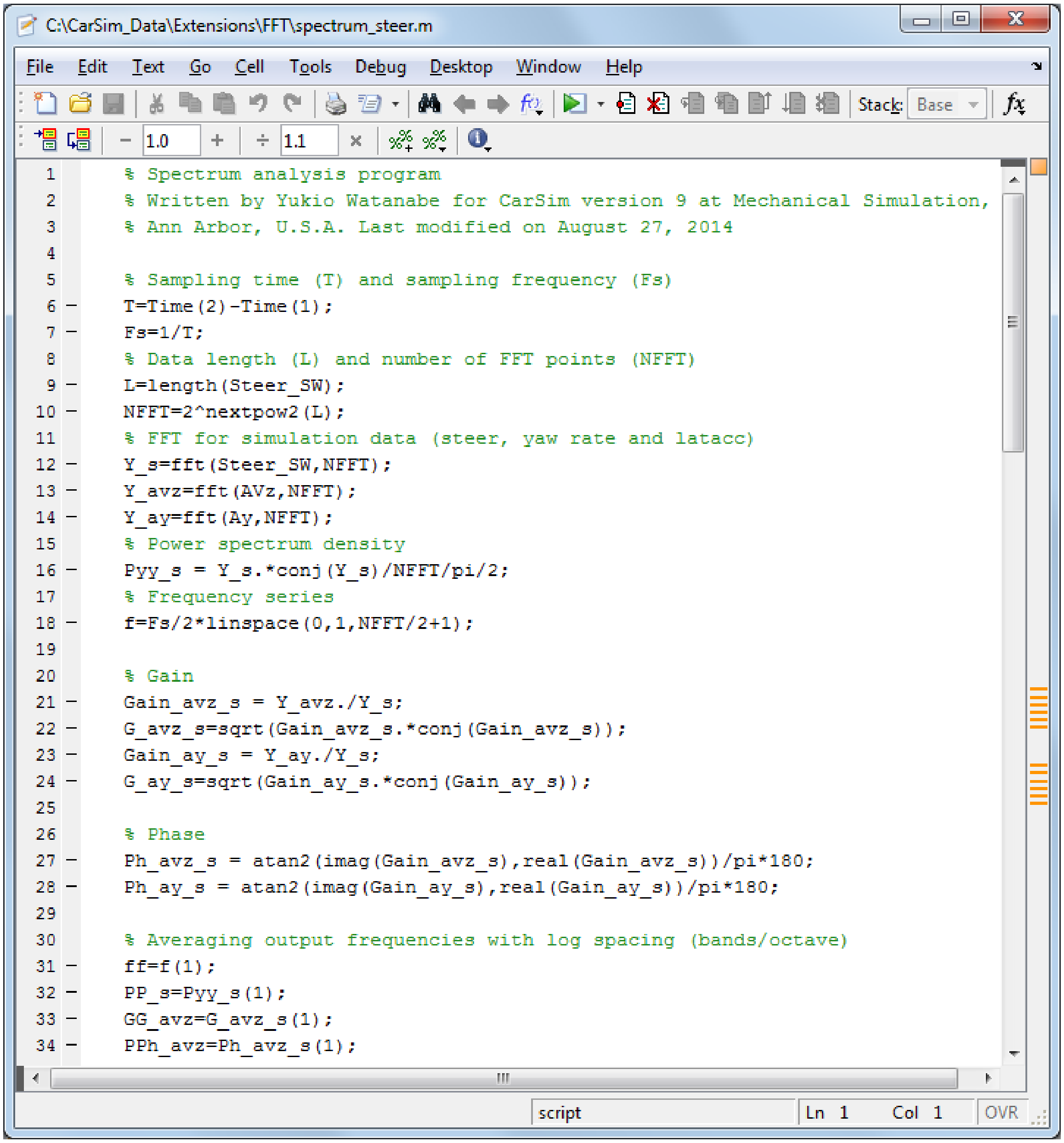


Figure 3. MATLAB command window with VS output variables in workspace.

The current working directly should be the CarSim database folder ① (e.g. `CarSim_Data\`) and the MATLAB workspace ② should include the output variables from the VS model; in this example, the variables are time, steering angle, yaw rate, and lateral acceleration. If you don't see the workspace window (depending on your MATLAB command window setting), you can type `who` on the command line ③ and press the return key to display the variables.

An FFT and bode plot program (`spectrum_steer.m`) already exists for this particular example in the `FFT` folder under `Extensions`. Find the `FFT` folder in the file browser window ④ and double-click it to move the current directory to this local folder. Double-click on the file named `spectrum_steer.m` to view the contents of the program (Figure 4).




```
% Spectrum analysis program
% Written by Yukio Watanabe for CarSim version 9 at Mechanical Simulation,
% Ann Arbor, U.S.A. Last modified on August 27, 2014

% Sampling time (T) and sampling frequency (Fs)
T=Time(2)-Time(1);
Fs=1/T;
% Data length (L) and number of FFT points (NFFT)
L=length(Steer_SW);
NFFT=2^nextpow2(L);
% FFT for simulation data (steer, yaw rate and latacc)
Y_s=fft(Steer_SW,NFFT);
Y_avz=fft(AVz,NFFT);
Y_ay=fft(Ay,NFFT);
% Power spectrum density
Pyy_s = Y_s.*conj(Y_s)/NFFT/pi/2;
% Frequency series
f=Fs/2*linspace(0,1,NFFT/2+1);

% Gain
Gain_avz_s = Y_avz./Y_s;
G_avz_s=sqrt(Gain_avz_s.*conj(Gain_avz_s));
Gain_ay_s = Y_ay./Y_s;
G_ay_s=sqrt(Gain_ay_s.*conj(Gain_ay_s));

% Phase
Ph_avz_s = atan2(imag(Gain_avz_s),real(Gain_avz_s))/pi*180;
Ph_ay_s = atan2(imag(Gain_ay_s),real(Gain_ay_s))/pi*180;

% Averaging output frequencies with log spacing (bands/octave)
ff=f(1);
PP_s=Pyy_s(1);
GG_avz=G_avz_s(1);
PPh_avz=Ph_avz_s(1);
```

Figure 4. FFT and bode plotting script (MATLAB M-File).

Run the file `spectrum_steer` by typing the name in the command window and pressing the Enter key. This will display the bode plot (Figure 5) showing the power spectrum density (PSD) of steering angle input, and gain and phase of yaw rate and lateral acceleration with respect to the steering input.

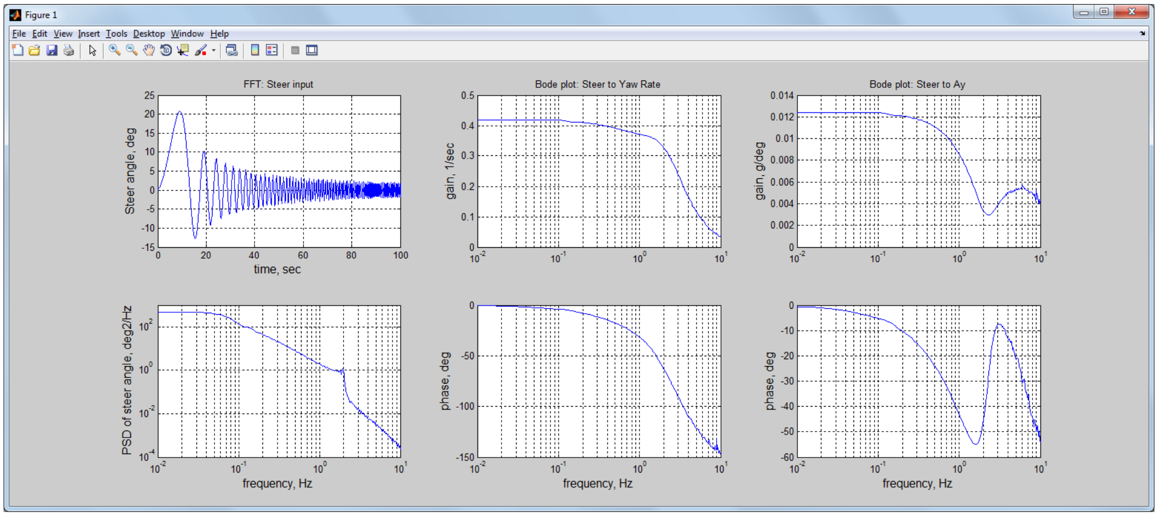


Figure 5. PSD of steer input and frequency responses for yaw rate and lateral acceleration.

Comparison with Linear Analysis

As noted earlier, the vibration frequencies of a linear system can be calculated in MATLAB given A, B, C and D matrices. VehicleSim products have commands to linearize the model at any time during the simulation. The CarSim database has an example linearization involving the same vehicle (A-Class, Hatchback). The simulation is named **Bode Analysis (Steer to Yaw Rate and Ay)** in the category **Linearization**. Run this example, and observe the plot and animation (Figure 6).

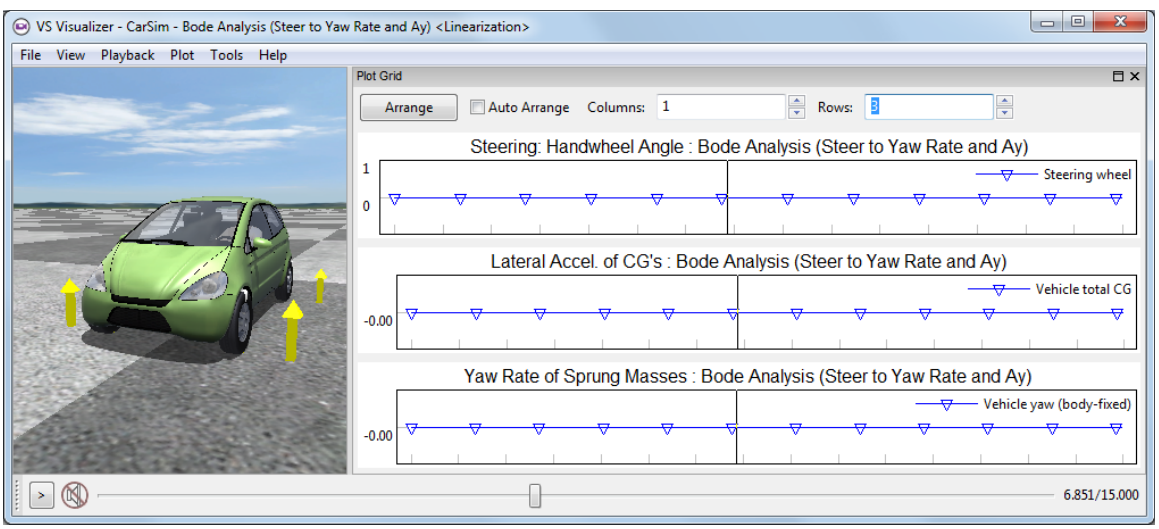


Figure 6. Steady-state vehicle maneuver for linearization.

You may notice that the car runs on a flat surface with a constant speed of 60 km/h with no steer input. However, this example inlcuded linearization of the vehicle model at a steady-state vehicle maneuver in the middle of simulation run. The calculated linear matrices are written in a MATLAB M-File (`Linear_steer_input.m`) under `Extensions\Linearization` folder.

Note This document does not describe the details of linearization; these are provided in the tech memo: Linear Analysis in VehicleSim Models.

A bode plot program for linearized model (`bdp_steer.m`) exists for this particular example in the `Linearization` folder under `Extensions`. Move the cursor over the `Linearization` folder in the file browser window (4 in Figure 3) and double-click it to move the current directory to this local folder.

Run the file `bdp_steer` by typing the name in the command window and pressing the Enter key. This will display the bode plot (Figure 7) showing the gain and phase of yaw rate and lateral acceleration with respect to the steering input.

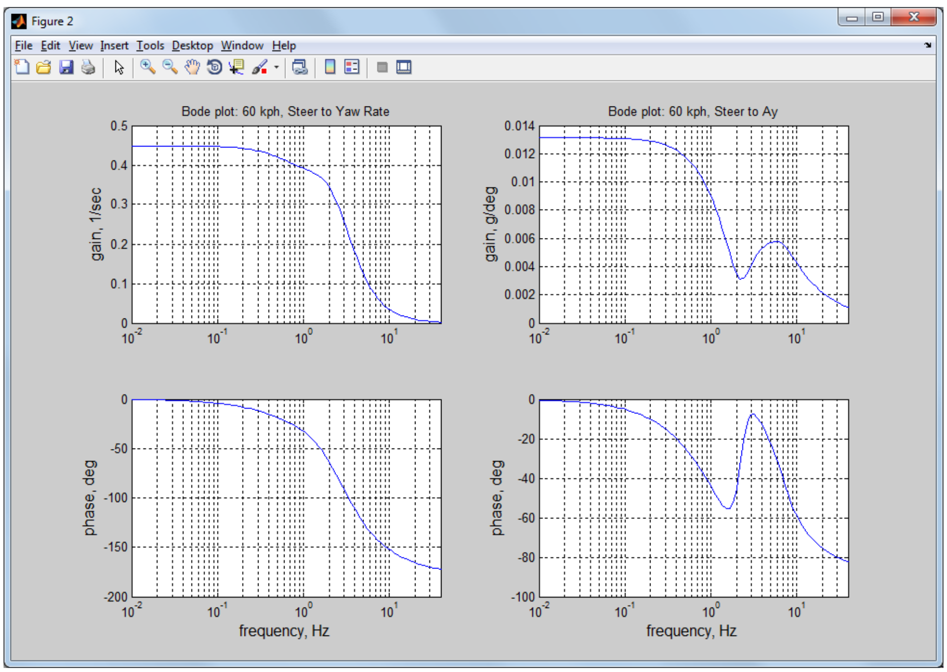


Figure 7. Bode plot based on the linear model

Note The bode plot program (`bdp_steer.m`) uses the MATLAB *bode* command, which requires a *Control System Toolbox* license.

You can see the correlation between the bode plot based on the FFT with time history output data from the nonlinear vehicle model (Figure 5) and bode plot with other method based on the linear model (Figure 7).

References

1. Bendat, J. S. and Piersol, A. G., “Engineering Applications of Correlation and Spectral Analysis”, Wiley-Interscience, New York, 1980, ISBN 0-471-05887-4.