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ABSTRACT

It is becoming a greater challenge to win a race as more and more technologies are put into use to enhance vehicle-handling characteristics. Vehicle handling during cornering and braking is one of the crucial performance characteristics that is continuously improved upon.   To help the driver achieve the best handling performance on the track, suspensions are tuned to optimize for the specific track and racing conditions. Typically 4-post test rigs are used to test for the heave, pitch, roll and torsional frequencies of the suspensions. However three more actuators (aeroload actuators) become necessary to tune the suspensions at the correct ride height by including the aerodynamic effects. By means of a 7-post testing system an optimization procedure is executed to improve handling performance. An instrumented vehicle is driven on the track. The response of the vehicle is then replicated on a 7-post system using Iterative Control System (ICS) software. Having identified the problems from the measurements and driver comments, the suspensions are fine-tuned and a better vehicle response is achieved for the same track and driving conditions. In this paper, a case study is presented for a 7-post system and more advanced technologies to improve the testing performance are discussed in detail.

INTRODUCTION

In today's racing, the winning teams are driven by more than horsepower. The premier teams and the winning vehicles are a combination of power, aerodynamics and handling. A great amount of effort and funding is spent in each of these areas. Dependant on the team size and budgets, some rely on engine development from outside sources to generate the required power. In some forms of racing, the engines are "sealed" and controlled by the engine manufacturer. Aerodynamics are developed by the manufacturers and, in some series, mandated by the race promoter through a tedious validation process. Some teams have multiple vehicles that run in a series and exchange data to maximize each vehicle's aerodynamics. Vehicle handling and dynamics is the remaining area that each team optimizes to achieve their goal of performance. The handling of a race vehicle is a complex matrix of variables that includes the characteristics of the chassis itself along with weight distribution, spring rates, damper setting and tire characteristics and how each of these affects the dynamics of the vehicle, while at speed. This paper focuses on the process of vehicle characterization and track simulation using a 7-post shaker rig, which provides teams an alternative to track testing, while enabling them to comprehend and optimize the vehicle's dynamics.

BACKGROUND

The 7-post shakers are in common use at the highest levels of motorsports, in fact it has become almost compulsory for an F1 team to have one at its disposal. The 7-post shaker rig at the Auto Research Center of Indianapolis, IN is available to race teams to characterize and optimize a vehicle for any racetrack. Aerodynamic loading and weight transfer during cornering and braking have a big effect on the suspension of Racecars and high performance cars. Traditional 4-post road simulators cannot reproduce the correct suspension loads under these conditions. In the 7-post shaker rig, the addition of three aeroload actuators, special fixtures, and software allow accurate reproduction of real track/road conditions.

The 7-post shaker enables the engineering staff of a race team to gain better understanding of the dynamics of the vehicle. They allow the users to study the frequency response of the cars using swept sine or random noise testing. The use of the frequency response of cars in order to tune its suspension is well developed; see for example Kowalczyk[1], or Kasprzak & Floyd[2].

Figure 1. A racecar being tested on a 7-poster rig

In racing it is imperative to extract the greatest amount of performance from the vehicle, thus, once the limits of the frequency domain analysis are reached, there is a need for further development of the racecar suspension. Using the ICS software it is possible to recreate the inputs that the car experiences on the racetrack. Using these inputs, the engineers can further tune the suspension in order to improve the handling of the racecar.

Ultimately, the response of the car is determined by how the tires generate lateral and longitudinal forces. The way in which the tire generates these forces is a complicated function of many parameters, including the normal force at each tire. It is generally accepted that minimizing the variation in normal load will result in improved handling due to the minimization in lateral and longitudinal forces. Playing back a track profile on a 7-post shaker allows the engineer to study the effects of damping changes on the normal load variation at each tire

METHOD

The process of generating a track profile is made simpler by the use of the ICS software that is part of the DCS2000 shaker rig controller. Oral[3] discusses the real-time capabilities of the DCS2000 in an active suspension system.

The method used to recreate the inputs is discussed briefly in this section.

SYSTEM CHARACTERIZATION

In order to recreate the road inputs, the characteristics of the vehicle must first be identified. This process is based on finding the frequency response function (FRF) or system matrix of the vehicle.

$$Y(f) = H(f) \, X(f) \qquad (1)$$

$Y(f)$ is the vehicle response vector, $H(f)$ is the system matrix, and $X(f)$ is the input vector. Equation 1 represents the linear multiple-input, multiple-output model in the frequency domain.

Equation 1 is the foundation of the ICS process. Through simple algebraic manipulation we can solve for any one the variables. Although in theory the solution for any variable can easily be found, in actuality many things conspire to make it more difficult, for example, noise in the measurements will affect the quality of the estimates. For a thorough discussion on the methods used see Fletcher[4].

The first step in the process is finding the system matrix of the vehicle. For this step a white noise drive file is used for $X(f)$, and the response $Y(f)$ is logged. Thus we can solve for the system matrix with equation 2.

$$H(f) = Y(f) \, / \, X(f) \qquad (2)$$

Once an acceptable estimate for the system matrix is achieved the first estimate of road input can be estimated with equation 3.

$$X_0 = H^{-1} \, Y \qquad (3)$$

Subsequent estimates are found by iterating using equation 4, where Y_a is the measured response, Y_d is the desired response and K is a user specified gain.

$$X_{n+1} = X_n + K * H^{-1}(Y_a - Y_d) \qquad (4)$$

Ultimately the quality of the estimated road input is based on the quality of the initial estimate of the system matrix as well as the validity of the assumption of linearity of the system matrix implicit in equation 1. It will be seen in the next section that very good results are achievable, easily achieving RMS errors of less than 20% and often substantially lower.

USING THE ICS SOFTWARE

The first step in the process occurs even before the car is installed on the rig. The data is collected at the racetrack using the onboard logging systems commonly found on the racecars. This data consists of 4 response channels as well as speed, lateral acceleration, inline acceleration, and vertical acceleration. The 4 response channels are the channels that the ICS software will attempt to match by varying the track profile, the other channels are used to calculate the appropriate loads that will be applied to the chassis in order to simulate down force and inertial loadings. Normally the response channels used are wheel hub accelerations, however, with open wheel cars it is also possible to use pushrod loads.

The next step in the process is to characterize the vehicle response to road inputs. This is done by first creating a white noise file and appropriately shaping it to excite the car. Once the noise file is played out to the car, the system matrix of the vehicle is computed. It is imperative that the system matrix calculation is of high quality, since the matrix will be used during all subsequent steps. The quality of the system matrix calculation is checked by examining the multiple coherence plots.

Multiple coherence is a measure of linear dependence between the input and the output. A multiple coherence is calculated for each response channel and will have a value between 0 and 1. If the result of a response channel is perfectly linearly related to all of the inputs, then the multiple coherence plot will show a value of 1 through the entire frequency. Any noise in the measurements will degrade the coherence. Also any non-linearity in the system will degrade the coherence. Thus the multiple coherence plots can be used as an indicator of the quality of our sensors as well as to validate the assumption of linearity of the system.

Once a good system matrix has been created, the subsequent steps are iterations until an acceptable track profile has been created. The ICS software plots the error after each iteration. The user can stop the process once a reasonable error is reached.
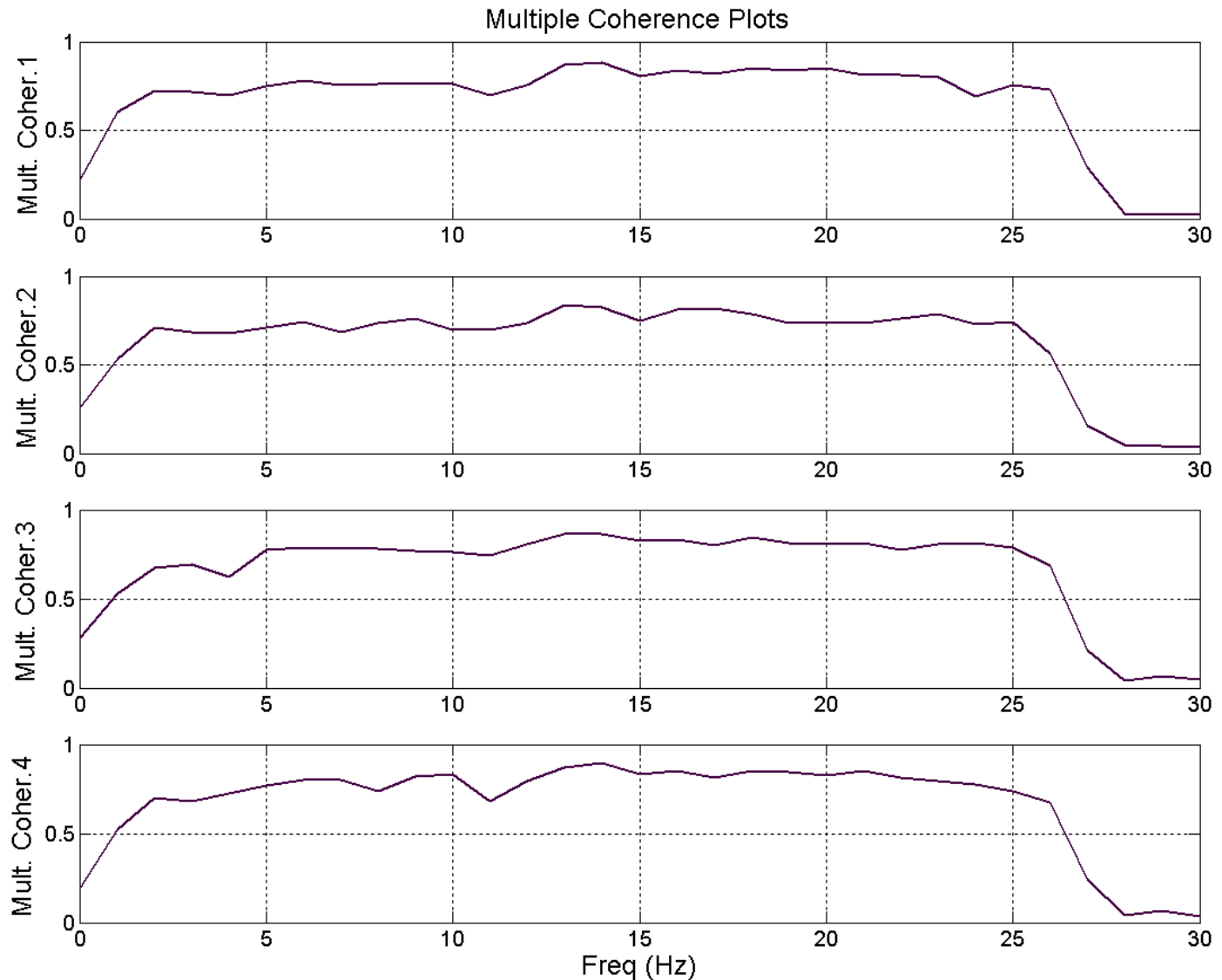
Multiple Coherence Plots

Figure 2. Multiple coherence plots in the operating range

RESULTS

For this track profile, hub accelerations were logged on a Champcar at Sebring. The accelerometer data was filtered through a bandpass filter of 1 to 25 Hz. It is the filtered signal that the ICS software attempts to reproduce. The same accelerometers are used when the car is on the shaker rig, and the same bandpass filter is applied to the data collected on the rig. Using the same sensors whenever possible is prudent, as this will eliminate any errors induced by small calibration errors or differences in the phase response of the different sensors.

Figure 2 shows the multiple coherence plots obtained from the calculation of the system matrix. These plots show very good coherence in the frequency of interest, which is up to 25 Hz. Note that the coherence quickly decays since the signals are filtered at 25 Hz.

Figures 3 shows the error obtained after eight iterations. The graphs show how quickly the software converges to a reasonable estimate for the track profile. The worst error is only 5%. The % RMS error for the entire lap is below 20% for all of the response channels. Although the % RMS error seems large, keep in mind that this is for the entire lap and includes areas that are unimportant to the handling of a racecar, for example the long straight sections of track. Examining the overlay of the desired vs. achieved response in the time domain in figure 4, shows that the responses are very close indeed.
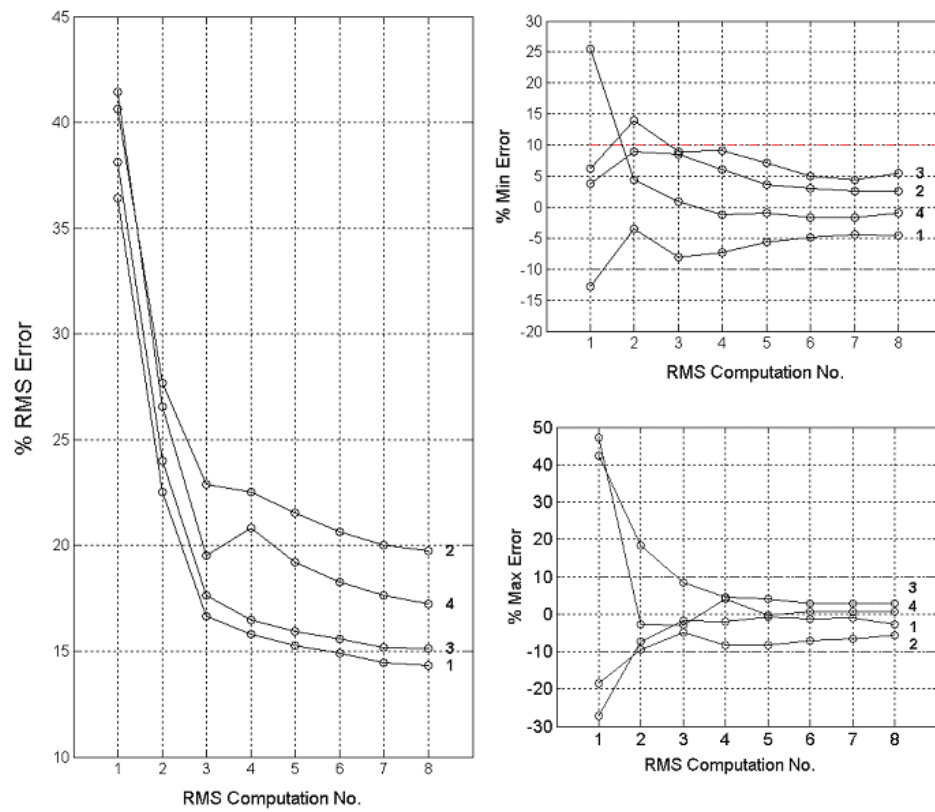
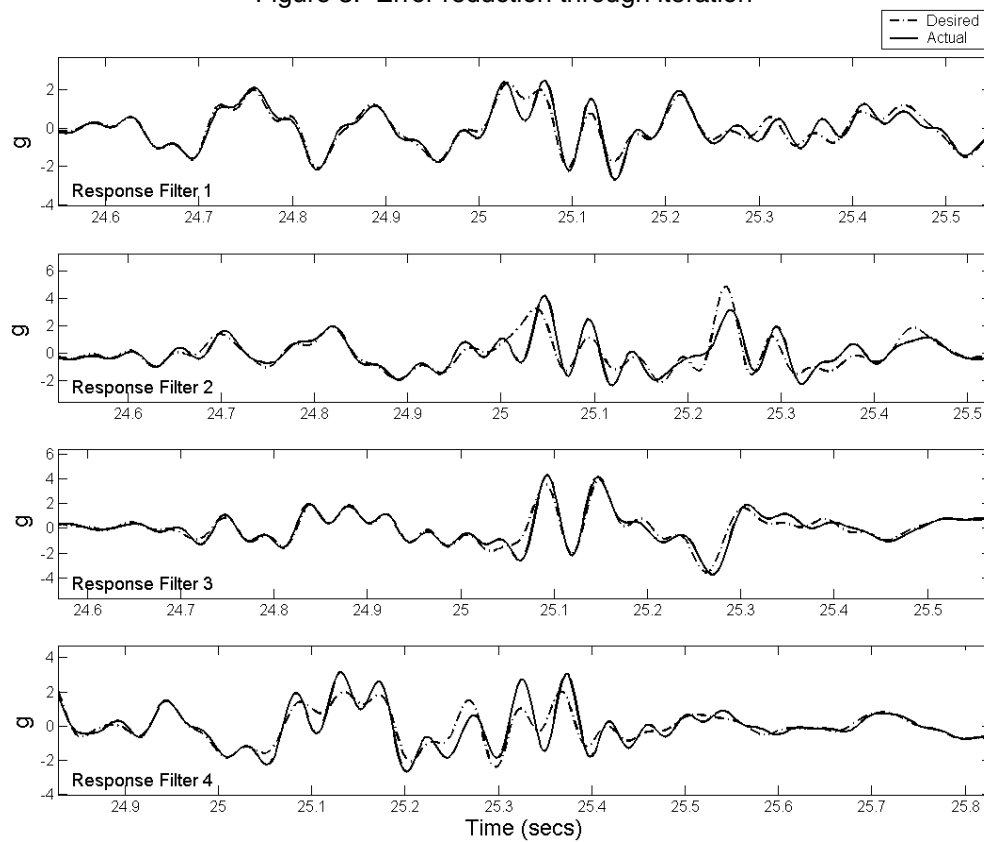Figure 3. Error reduction through iteration

Figure 4. The comparison between desired and actual acceleration signals

DISCUSSION AND CONCLUSION

A previous publication by Kowalczyk[1] discussed the use of swept sine testing to optimize damping levels. Swept sine testing allows the engineers to match the damping levels to the springs used. The use of track simulation takes this one step further by showing the exact effects of these optimizations at a particular track. This section shows the on-track effects of the optimized dampers. Here the term optimized refers to the methods discussed in the previous publication, namely an optimized set of dampers will result in a lower pitch response.

The following graphs show how the optimal dampers provide better dynamic ride height control. This is very important since the downforce generated by open wheel race cars is highly dependent on the ride height of the car.

Higher downforce is generated at lower ride heights. Therefore better ride height control will result in improved handling of the racecar.

Figure 5 shows that the optimized set of dampers minimizes the front ride height variation. The graph shows that the peak front ride height is lower by about 1 mm for the optimized setup when compared to the baseline. Therefore the optimized setup will produce more downforce in those portions of the track. Also it can be seen that the variation in ride height is less for the optimized setup.
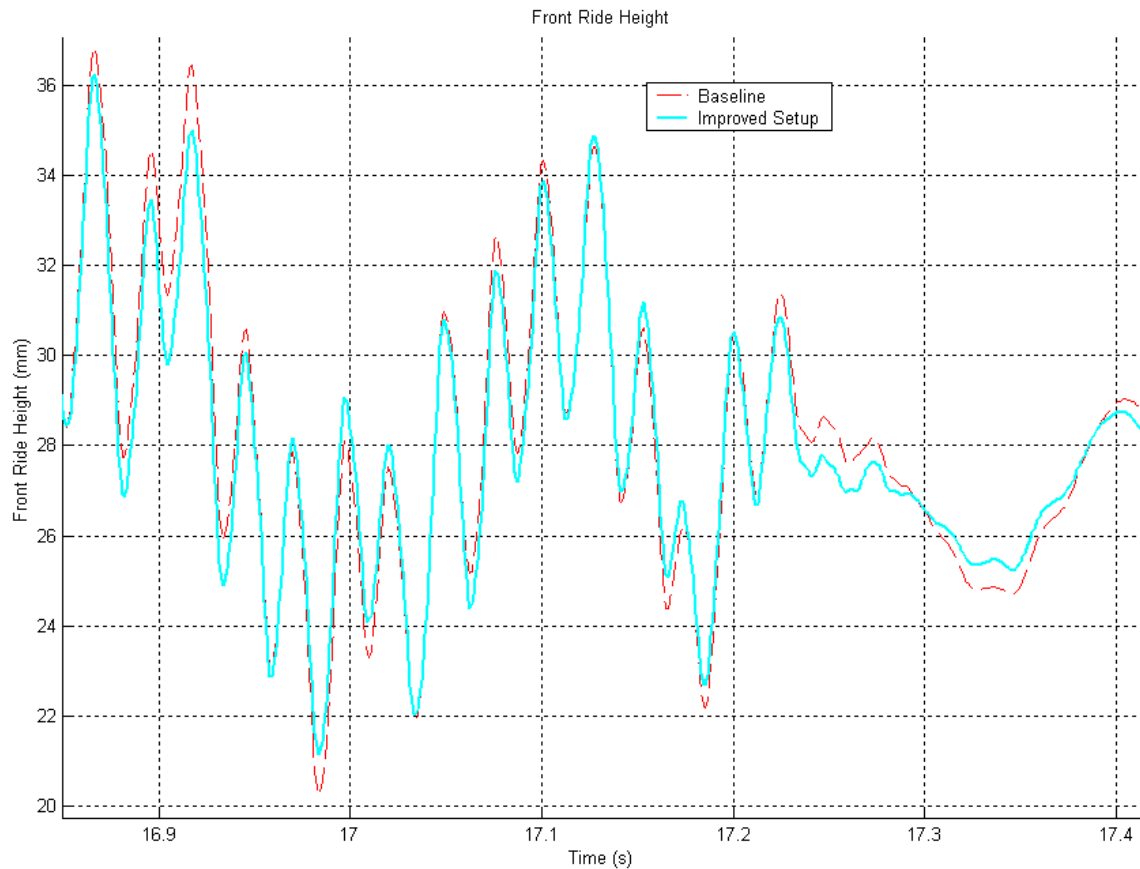

Figure 5: Front ride height comparison between baseline and optimized

Figure 6 shows the power spectral density of front ride height. This shows that there is less variation in front ride height with the optimized dampers. The fact that there is less variation in ride height means that there will be less variation in downforce, therefore giving the driver more confidence in the response of the car.

We have shown that the ICS method is very powerful in reproducing the actual time domain histories that are experienced by the racecar on the track.

The use of a realistic input to the car allows the engineers to better understand the dynamics of the car and make strategic setup decisions tailored to the needs of the racecar at a specific track. In today's racing environment any advantage that can be gained on the track must be exploited. With the current limits placed on testing, the use of 7-post shaker has become an important tool in improving the performance of a racecar.
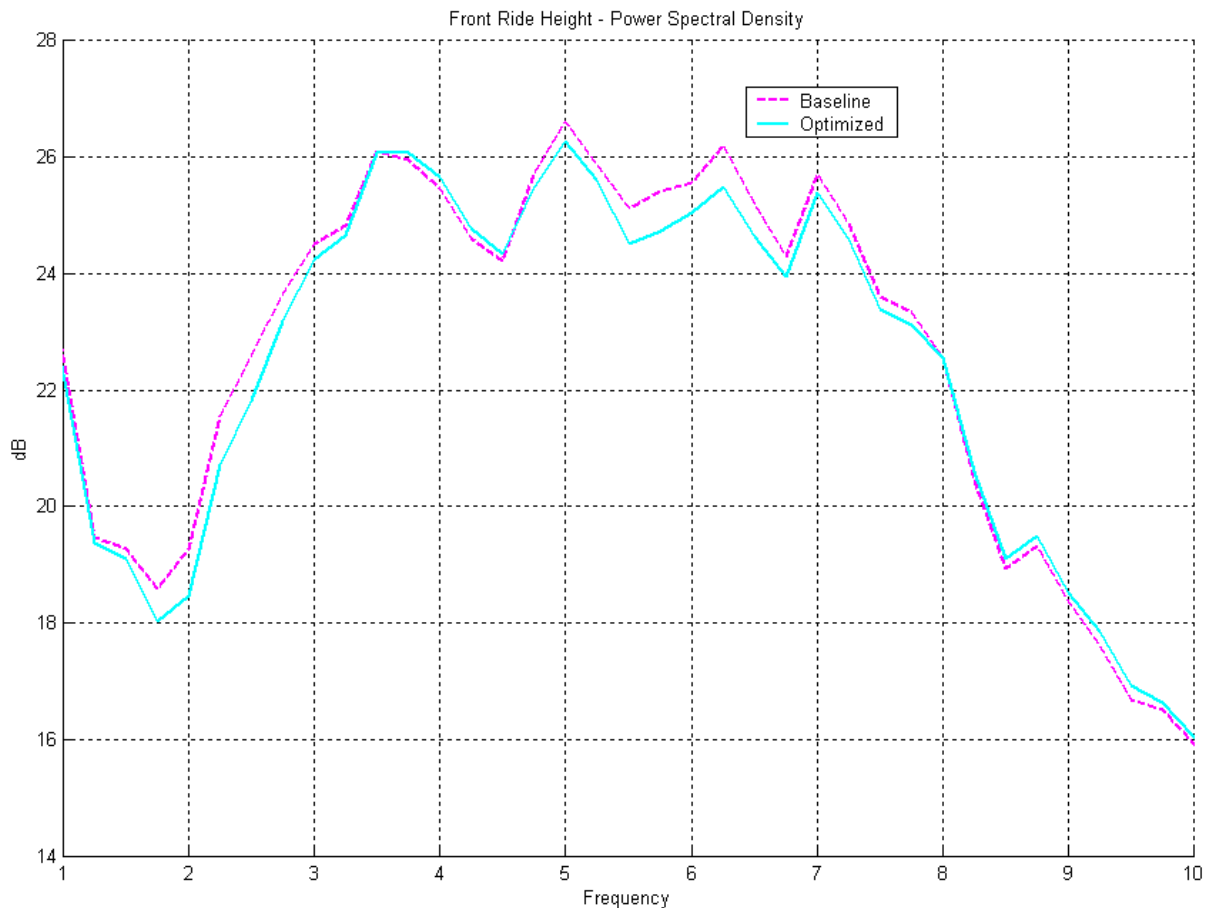

Figure 6 – Front Ride Height Power Spectral Density

ACKNOWLEDGMENTS

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