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ABSTRACT

Steer by Wire systems provide many benefits in terms of functionality, and at the same time present significant challenges too. Chief among them is to make sure that an acceptable steering feel is achieved. Various aspects of this subjective attribute will be defined mathematically. A control system that is architected specifically to meet these challenges is presented. Furthermore, the design is made such that it would be robust to tire and loading variations. Supporting vehicle data and model results are shown as needed.

INTRODUCTION

With advanced steering systems such as steer-by-wire, the mechanical link between the steering wheel and the road wheels is eliminated, as shown in Figure 1. In this particular architecture, the sensed road wheel (RW) force is used to command the hand wheel (HW) system to provide a resistive torque for the driver. Similarly, the steering wheel position is used to command the RW system to move the road wheels to the desired position. Thus, two control system loops are being closed: the HW force feedback loop and the RW position feedback loop. The commanding signals for both of these loops passes through and is modified within the Master Controller. While the discussions in this paper are affected by this architecture, similar issues would be faced with other architectural constructions.

The elimination of the mechanical link between the subsystems can result in abnormal steering system performance. In this paper, the authors have defined steering system performance by two important attributes, steering feel and steering response. An additional performance quality of a steering system that will be discussed is termed “free control”. Free control describes the steering system behavior for the case of the driver’s hands removed from the steering wheel. The coupled interaction of the HW and RW subsystems can greatly influence the nature of the free control response of a steer-by-wire system.

The term “steering feel” is commonly used as a catch-all phrase for describing the torque that the driver feels in relation to the position of the steering wheel and the motion of the vehicle. It refers to various conditions such as on-center (vehicle traveling nearly straight), off-center, and static steer (i.e. turning of the steering wheel with a stationary vehicle), where various kinds of inputs are applied to the steering wheel such as step, pulse, initial condition, or frequency response sweeps. An attempt to control the feel of a steer-by-wire and an electric power steering (EPS) system, respectively, are presented in [1,2]. Camuffo et al provides criteria for an acceptable steering feel [3]. There the focus on frequency response is interesting. A key aspect of frequency response that is important to steering feel is “input impedance”, which is the transfer function between handwheel position and hand wheel torque. This helps characterize the level of torque felt by the driver as a function of the steering wheel angle input. A very good methodology for on-center analysis (low frequency oscillations of the steering wheel about center) is discussed in [4]. This paper provides additional insights on improving steering feel through the examination of the input impedance characteristics of a steer-by-wire system.

Steering responsiveness for a steer-by-wire system presents unique challenges for roadwheel position control. Chief among those challenges is the significant variation of the steering loads experienced. This paper discusses a control design technique that reduces the influence of loading variation such that targets for steering response and control stability can be met.

In previous work, Bolourchi and Etienne presented the design of an algorithm for a good free control behavior in EPS applications [5]. A good free control response refers to a well damped return-to-center of steering wheel from an off-center release, or due to an impulsive (jerk& relase) excitation from on-center. We shall consider the performance of a steer-by-wire system due to the range of possible responses (and the tunability) in such a system. The final design will take into account all the above mentioned aspects of steering feel, responsiveness, and free control. Finally, some concluding remarks and references will be provided.

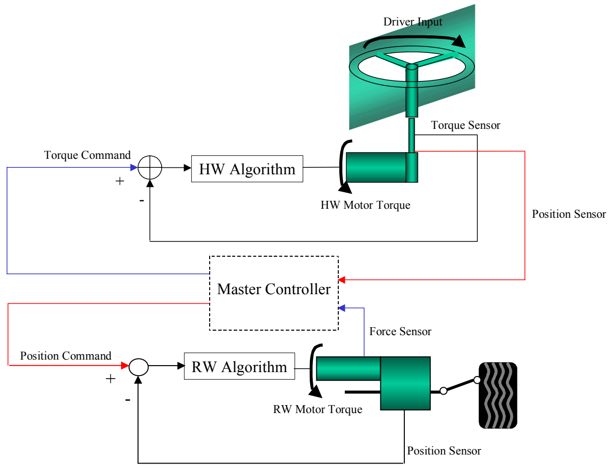

Figure 1: Functional Block Diagram of a Steer by Wire System

FREE CONTROL

As was mentioned before, the term Free Control, refers to the response of the wheel after an initial condition is given to the wheel. The subsequent response would be Free of driver inputs. For example, if the HW is released from a turned position, how the wheel comes back to center determines whether or not the Free Control behavior is good or bad. Or when the wheel is given a quick jerk (and release), the ensuing response is called the Free Control response. In either case a quick return to center with minimal overshoot is desired. Furthermore, and underdamped or sustained oscilations about the center is highly undesirable. To a large extent the Free Control response is determined by the magnitude of the returning forces developed in the steering rack going into and out of a turn [5]. Once this force is present then the steering system (be it hydraulic, EPS, etc.) reacts to it and the ultimate behavior is observede at the steering wheel. In the case of by-wire, the greatest degree of flexibility exist in that it is totally up to the designer as to how much of this (rack) force is commanded to the RW system (see Figure 1). As the magnitude of the desired (rective) torque (at the HW) goes up the chance for a poor Free Control response increases. This poor response starts once the driver removes his hands.

This is due to the fact that the torque provided by the motor to achieve the desired feel is being balanced (in off-center and steady state sense) with the driver's effort. Once the driver removes his hands, however, the torque provided by the motor accelerates the steering wheel to center and overshoots it, depending on the magnitude of the initial torque. As this overshooting action is taking place, the hand weel system sends the corresponding position signal to the road wheels, and the road wheels also return to center. However, due to lack of a driver resistance (and thus a hand wheel overshoot,) the road wheels overshoot, also. Therefore, the road wheel forces switch direction, and thus, the handwheel motor switches the direction of its torque (in response to the sensed road wheel forces). This causes the hand wheel to come back to center (from the opposite off-center position now), and an overshoot of center may take place, again.

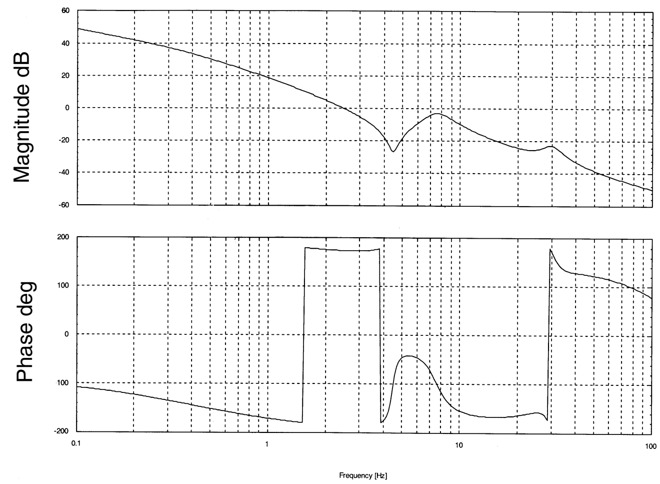

Figure 2: Free Control Bode Plot of the Steering System

Clearly, this behavior can be analyzed as a relative stabilty problem. If one opens the overlall closed loop system of Figure 1 at the point of the Torque Command, for example, a Bode plot similar to that of Figure 2 would be achieved. It is obvious that the amount of the (returning) forces being commanded scales the magnitude plot up or down. In this particular case, the -180° cross over is at 1.5 Hz, and with a high gains chosen here (multiplying the return forces), we have a Gain Margin of negative 10dB. In practice, though, this system would probably lead to limit cycling instead of an unbounded instability. This is due to the nonlinearities that exists in an actual vehicle (such as tire load saturation, friction, etc..). The above Bode plot is generated with the tires represented by a spring and the rest of the model being free of any nonlinearities (friction, lash, etc..). Also, it is important to note that driver is not holding the wheel in this model. With a driver in the loop, the system stabalizes itself, as was explained previuosly.

Traditionally, Free Control response has been resolved by adding damping (in the case of EPS) or friction (in the case of hydraulic steering) to the system [5]. The steer-by-wire system would also benefit from an additional damping. The damping torque at the HW subsystem, for example, would be providing the reactive torque that the driver was providing.

STEERING FEEL

As mentioned previously, input impedance is an important characteristic of good steering feel. Input impedance measures the transfer function from the steering input angle from the driver to the feedback torque that is felt by the driver, see Figure 3 below. One major issue with the elimination of the mechanical connection is that the phase relationship between the driver's steering wheel angle input and the torque felt by the driver can change significantly. This change in phase relationship can cause the system to have poor steering feel and can also have a destabilizing effect on the system. In addition, there may also be issues with the magnitude of the torque felt by the driver over the frequency range of operation.

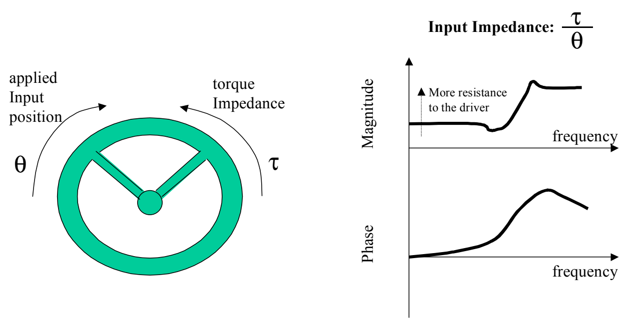

Figure 3: Input Impedance Transfer Function of a Steering System

As discussed previously, a typical steer-by-wire system uses steering wheel position information in order to control the position of the road wheels. Then the forces at the road wheels are measured and used to provide the feedback torque to the driver. This approach results in driver steering wheel position and the resulting torque felt by the driver being largely decoupled. From a steering feel perspective, there is a desirable phase relationship between steering wheel angle and steering wheel torque. This phase relationship is not guaranteed and actually may not even be possible using only feedback of the forces from the road wheels to determine steering wheel torque. There is also a desirable torque magnitude felt by the driver (as a function of input frequency).

The approach described here addresses these issues by using information about steering wheel position to directly influence the torque felt by the driver. Figure 4 shows a simplified view of this approach. As can be seen, handwheel position information is fed through an appropriate transfer function and is used to directly influence the torque felt by the driver. Figure 5 shows a comparison between a baseline steer-by-wire system and the same system with handwheel position information fed into the torque command using a simple gain. As can be seen, the dip in handwheel torque is pushed to a higher frequency and is reduced in magnitude. There is also a significant impact on the phase relationship. This example uses a simple gain, but a tunable transfer function provides greater benefit.

By using a properly shaped transfer function, the feel of the steering system can be changed over a wide range to get the desired feel. By including steering wheel position in determining torque felt by the driver, the desirable coupling between steering wheel position and steering wheel torque can be provided. However, beyond the fixed coupling that the mechanical connection provides, this approach can provide a tunable coupling which can be adjusted based upon preferences or operating conditions to get the desired steering feel for the vehicle.

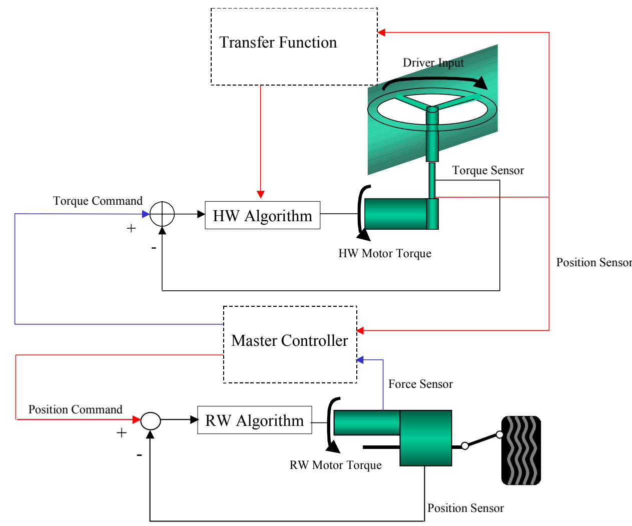

Figure 4: Feeding HW Position Signal back in the Torque Loop

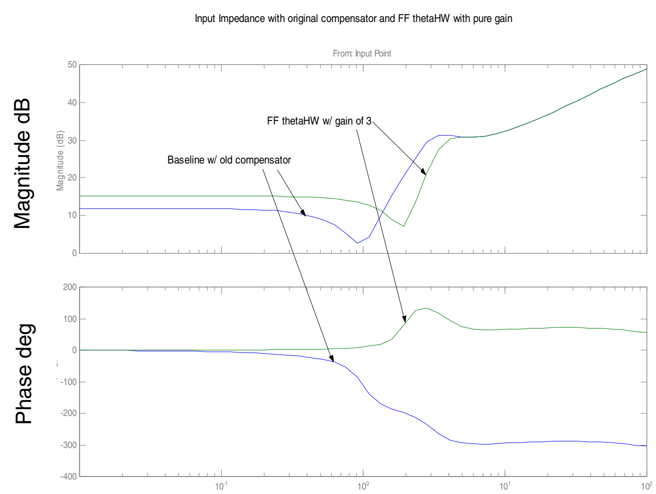

Figure 5: Input Impedance Comparison

In essence, the approach involves feeding handwheel position information directly into the handwheel motor command through an appropriate transfer function. The handwheel motor command determines the handwheel torque felt by the driver. This results in a direct relationship between handwheel position and handwheel torque, which can be tuned to get the desired steering feel. Selecting the proper transfer function is crucial to the performance. This approach allows a level of tunability not currently available in steer-by-wire systems and beyond that addresses some shortcomings of the current steer-by-wire system. Without this approach, it may not be possible to get the desired steering feel from a steer-by-wire system. Alternatively, this approach may allow cost reduction in the steer-by-wire system by providing acceptable performance while using lower bandwidth actuators.

It is desirable to influence the input impedance for particular frequencies while not impacting the steady state torque felt by the driver. Figure 6 shows the ability to do this by using different transfer functions to get the desired performance. As can be seen, this gives the ability to modify the dip in handwheel torque magnitude to the point of completely removing it and also allows the transition in phase angle to be modified.

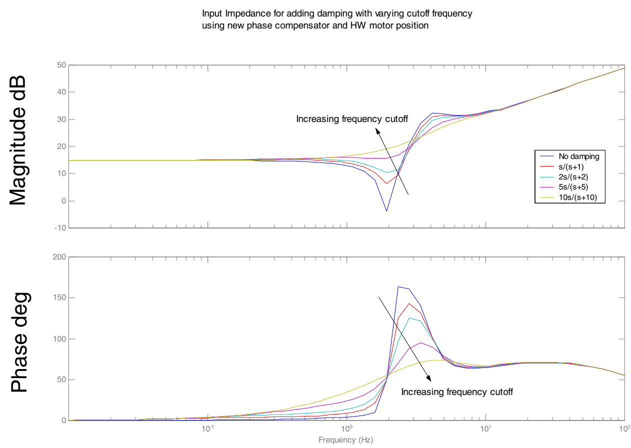

Figure 6: Input Impedance Comparisons

Beyond improving input impedance, this approach also has benefits in the overall stability of the system (free control) and in rejecting disturbances (from road and motor). Figures 7, 8, and 9 show these impacts. As can be seen, the overall stability of the system is improved in Figure 8. In addition, disturbances coming from the road (Figure 8) and from the motor (Figure 9) at higher frequencies are reduced. This is all significant in that improvements in one area most often result in compromises in other areas, but here there appear to be improvements in all areas.

The end result is that each of the measures of system performance can be improved by using handwheel position information to influence the handwheel torque. The results show that there is some flexibility in the exact way in which this gets implemented. The final evaluation of this approach will be in-vehicle tuning and optimization. Given the flexibility in the implementation, a desirable feel could be achieved in the vehicle. Beyond achieving acceptable feel, using this approach may actually result in greater tuning flexibility that allows for better steering feel than is possible without it.

A final item to note is that although the results were not discussed here in any detail, increasing the bandwidth of the handwheel and roadwheel actuators also is beneficial to input impedance.

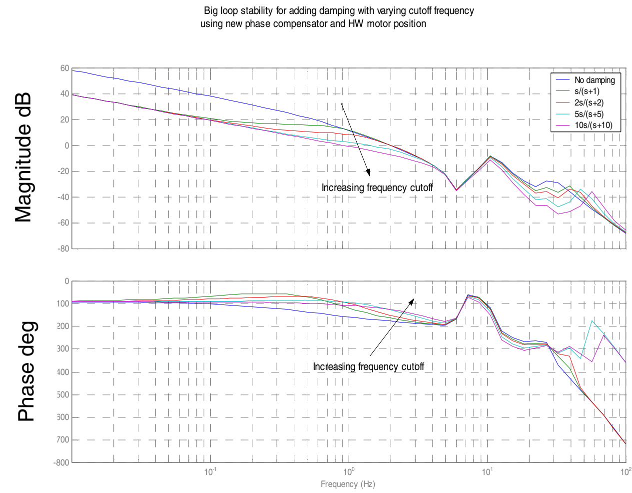

Figure 7: Free Control Comparisons

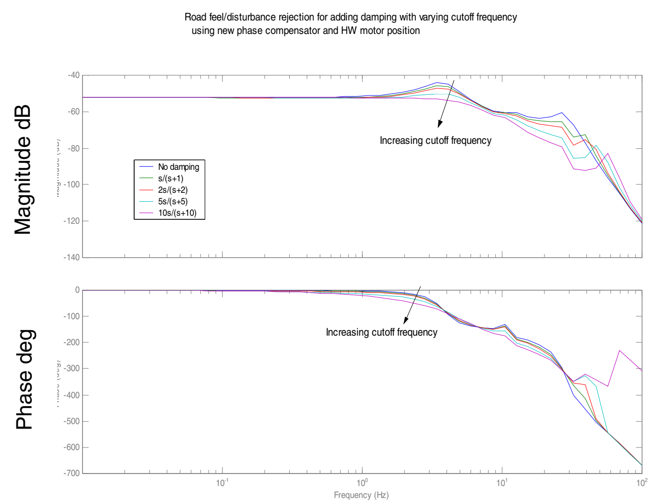

Figure 8: Road Disturbances Comparisons

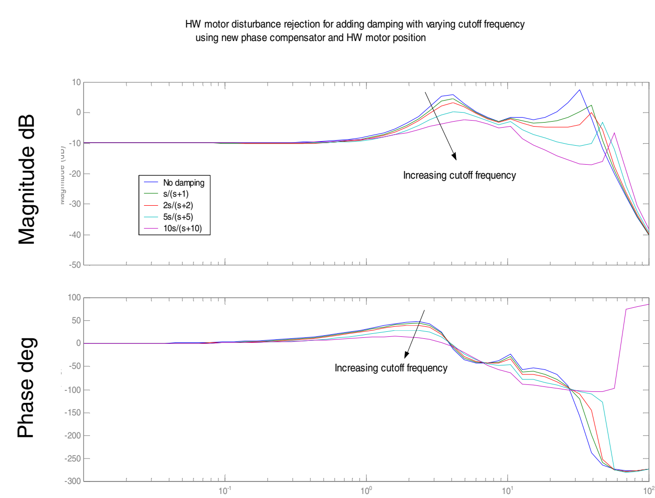

Figure 9: Motor Disturbance Comparisons

STEERING RESPONSE AND ROBUSTNESS

Despite the warnings by classical texts [6] that feedback should be used for its insensitivity attributes, typical position control systems utilize feedback to (only) track to a desired position. The control law may be a proportional, integrative, or derivative gain on the tracking error or may be a more sophisticated higher-order dynamic. In either case the feedback measurement is the actual position and in some cases it's derivatives.

This approach is sufficient for most applications where the load on the system has a predictable relationship to the system position (rotational or translational). In control system terms this could be predicted by the location of the poles and zeros of the system or frequency response. A conventional control system could then be designed based on these dynamics.

However in many systems, the load varies based on operating conditions even with the position and its derivatives kept the same. In automotive applications, the load on the steering system changes as a function of the road surface, operation (lateral acceleration, vehicle speed etc) and tire properties. In such cases, the conventional control design is optimal for a given operating condition, but has reduced performance as the conditions change.

These position control laws can be enhanced using an adaptive scheme. The adaptive scheme includes a measurement of load acting on the system as a feedback signal. In a steering application this would be forces acting on the steering rack, their estimates or equivalents. The feedback term effectively negates the variance in the system dynamics due to operating conditions. This allows a conventional control to then be implemented with optimal performance for all conditions. Performance is improved in the areas of system tracking, disturbance rejection and stability. A simple schematic of this control is shown in Figure 10. In this case the conventional control law (RW comp) is used to control the RW position of the system (RW plant). The control is augmented by the adaptive component (Force comp), which is based on the load experienced by the plant. The benefit of this added element is seen in the road feedback plot shown in Figure 11. The desire is to match the target vehicle behavior. An undesired mode is seen at 3 Hz if only conventional control is used. With the adaptive component, the undesired mode, which would have resulted in loss of feedback to the driver is eliminated.

Another benefit is that the adaptive component has a stabilizing effect on the system. An example of this is shown in Figure 12. This is a frequency response of the open loop system showing the effect of the adaptive control. The conventional control is not added to either case. An improvement can be seen in the phase margin which is an indication of relative stability. The reason is that the load feedback has a dampening effect on the system. The desired gain margin can then be achieved via a conventional control law. This allows the conventional control law to focus on providing optimal performance under varying conditions.

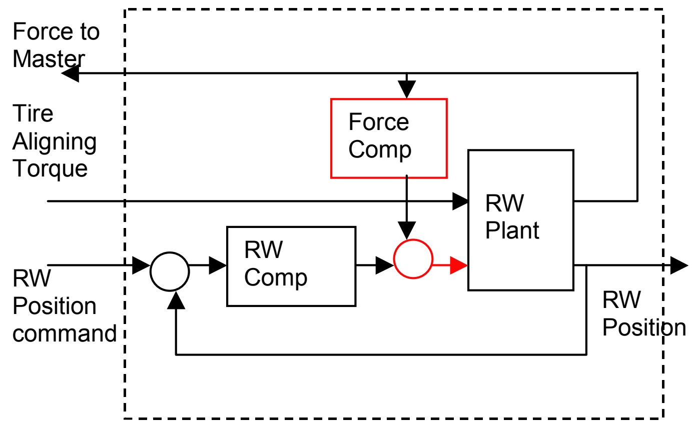

Figure 10: Feeding RW Force Signal back in the Position Loop

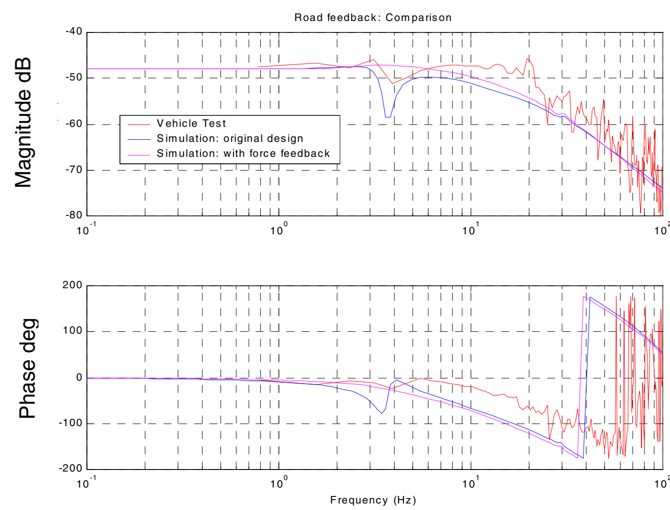

Figure 11: Road Feedback (disturbance rejection) Comparison

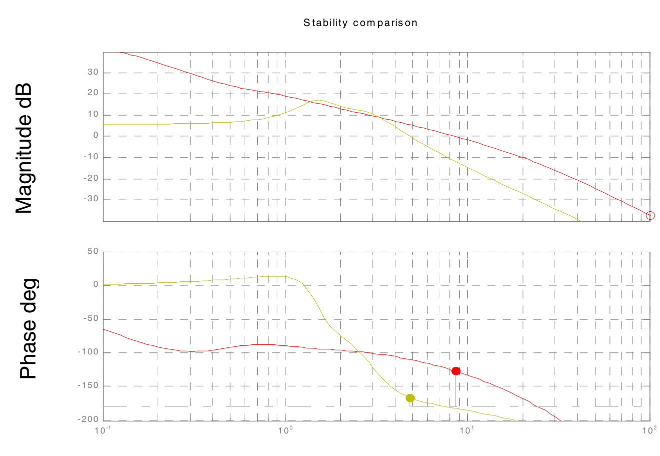

Figure 12: Open loop stability comparison for Free Control

A way of measuring stability is improvement in free control oscillations. A more stable system would damp out such oscillations more quickly. This is seen in Figure 13.

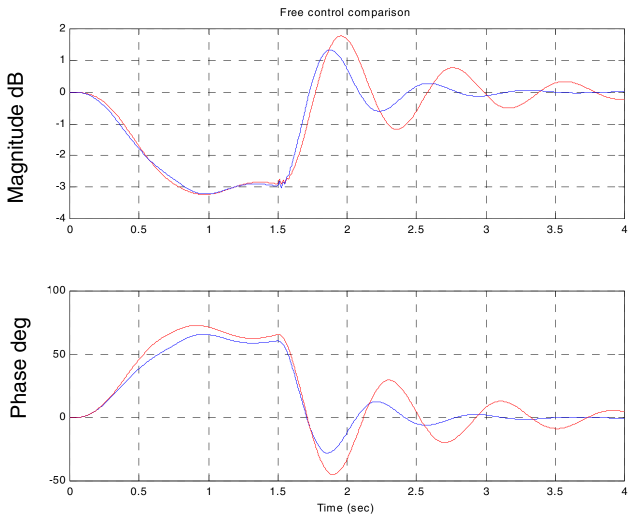

Figure 13: Free Control Oscillation Comparison

Also this feedback does not negatively impact the system bandwidth as significantly as a pure rate based damping. This is important because it has been observed in computer simulation and vehicle tests that the system bandwidth has a significant impact on the steering feel of an automobile. A higher bandwidth position system will be able to keep up with the driver applied input and as a result generate the expected effort (steering mechanism load) as feedback. Input impedence is a way of characterizing feel and the improvement can be seen in Figure 14.

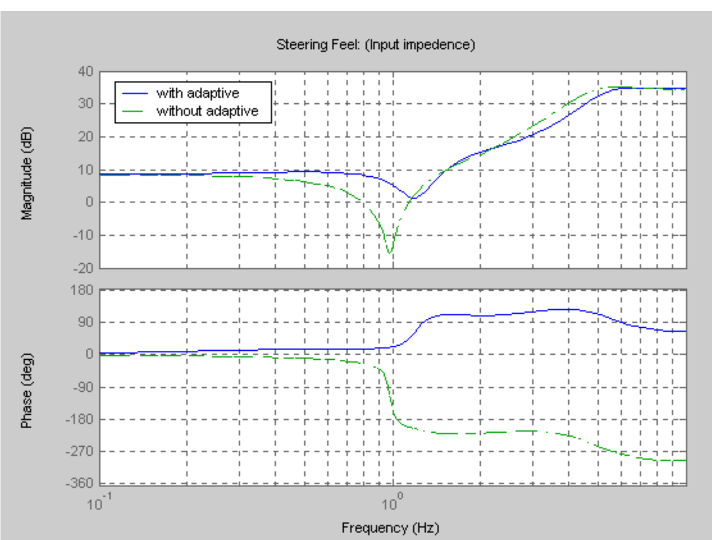

Figure 14: Input Impedance Comparison

CONCLUSION

The performance of the steer-by-wire system has been improved with respect to feel, responsiveness, and stability. The methods demonstrated and their results include:

- The use of handwheel position directly within the handwheel feedback subsystem has been shown to positively influence the input impedance characteristics of the steer-by-wire system. An increased level of system tune-ability can be achieved, especially at targeted frequency ranges without negative trade-offs on steady state feedback torque to the driver. Also, the possibility of reducing the required bandwidth of the HW feedback is an additional benefit obtained.

- The steering responsiveness has been improved through the use of steering road force within the RW position control design. A key advantage is that conventional position control design can be maintained and still obtains optimal position tracking performance especially under the presence of load variations. The dampening influence of using steering forces helps to improve the system stability margin and therefore can provide a better solution for reducing free control oscillations.

- Both control techniques have been shown to be capable of providing improved system stability. The combination of both provides the best tailoring of the steer-by-wire's free control response characteristics while avoiding compromises upon other performance criteria.

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