Co-simulation Study of Vehicle ESP System Based on ADAMS and MATLAB

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***Abstract*—ESP is an active safety system for road vehicles to control the dynamic vehicle motion in emergency, the composition and working principle of ESP were introduced in the paper, and the control technology of ESP was studied too. A virtual prototype model of a vehicle model was built in ADAMS/Car, and the yaw fuzzy control co-simulation model of vehicle was established in Matlab/Simulink, to study the stability of vehicle with ESP disabled and enabled under sine with dwell. Results showed that, the vehicle electronic stability program can make the handling performance under big steering wheel angle, and improve the vehicle stability.**

***Index Terms*—co-simulation; virtual prototype; ESP; stability**

I. INTRODUCTION

Electronic stability program (ESP) is an evolution of antilock brake technology designed to help drivers maintain handling control of their vehicles in high-speed or sudden maneuvers and on slippery roads. (Refs. [1], [2])Antilock brakes (ABS) have wheel speed sensors and the ability to apply brake pressure to individual wheels. ESP has additional sensors that monitor how well the vehicle is responding to a driver's steering input. If the sensors determine that the vehicle is straying from the chosen path, brake pressure will be automatically applied as necessary at individual wheels to bring the vehicle back to the direction that the driver is steering. In addition, in many cases engine power is reduced by means of an electronic throttle, thus slowing the vehicle down even more.

ESP is a vehicle control system comprising sensors, brakes, engine control modules, and a microcomputer that continuously monitors how well the vehicle responds to the driver's steering input. (Refs. [3])The computer compares a driver's commands to the actual behavior of the vehicle. In general, when the sensors indicate the vehicle is leaving the intended line of travel, ESP applies the brake pressure needed at each individual wheel to bring the vehicle back on track. In some cases ESP also reduces the force exerted by the engine. The way ESP systems are programmed to respond to the information from the sensors varies among vehicle models. Some systems intervene sooner and take away more driver control of speed than others.

ESP first appeared in Europe in the 1995 model year and in the U.S. market a few years later (Memmer, 2001). As is typical of new technologies, ESP initially was available as optional equipment on luxury cars. However, by model year 2001 it was standard on a number of high-selling vehicles and available as an option in many more. For the 2004 model year, ESP was on all cars and light trucks manufactured by Audi, BMW, and Mercedes, and on some models produced by just about every other automaker. The marketing names of ESP systems vary. For example, BMW refers to its system as Dynamic Stability Control (DSC), Mercedes calls it Electronic Stability Program (ESP), Toyota calls it Vehicle Stability Control (VSC), Ford calls it AdvanceTrac, and General Motors uses the names StabiliTrak, Active Handling, and Precision Control.

NHTSA estimates that the installation of ESP will reduce single vehicle crashes of passenger cars by 34 percent and single vehicle crashes of sport utility vehicles (SUVs) by 59 percent, with a much greater reduction of rollover crashes. (Refs. [4], [5])NHTSA estimates that ESP has the potential to prevent 71 percent of the passenger car rollovers and 84 percent of the SUV rollovers that would otherwise occur in single vehicle crashes.

Manufacturers first began equipping vehicles with ESP, introduced under many different names, in the mid-1990s in Europe, and the technology appeared in other markets several years later. As with many new technologies, ESP first appeared as an option on more expensive luxury vehicles but within a few years was being offered as standard equipment on these and other less expensive models. Although Europe and Japan initially led the way, ESP is now standard on many vehicles in the United States. In Europe, 5 million ESP are expected to produce annually by 2004, and in the U.S

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ESP is just catching on. On the other hand, in South Korea the demand of ESP is slowly rising.

A co-simulation model is established in the paper, based on yaw fuzzy control technology, the simulation results are studied, and used to study the vehicle handling and stability test method and rules.

II. SYSTEM COMPOSITION AND WORKING PRICINPLE OF ESP

The ESP system aims at helping the driver to maintain vehicle stability, its main design philosophy is that the system should help the driver to keep the vehicle controllable i.e. to avoid excessive vehicle side slip angles. (Refs. [6], [7], [8])This is achieved by using individual wheel brakes to control the vehicles yaw motion. A typical ESP system include traditional brake system, sensors (such as, wheel speed sensors, wheel steering angle sensor, later acceleration sensor, yaw sensor, and rake master cylinder pressure sensor), hydraulic modulator, stability electronic control unit (ECU), and other support system.

At the present, the control methods of most ESP system are differential braking control. Figure 1 shows the action of ESP using single wheel braking to correct the onset of oversteering or understeering, if the vehicle has entered a left curve that is extreme for the speed it is traveling. The rear of the vehicle begins to slide which would lead to a vehicle without ESP turning sideways unless the driver expertly countersteers. (Refs. [9]~[11]) In a vehicle equipped with ESP, the system immediately detects that the vehicle's heading is changing more quickly than appropriate for the driver's intended path, it momentarily applies the right front brake to turn the heading of the vehicle back to the correct path. (Refs. [12])In the situation of understeering, the ESP system rapidly detects that the vehicle's heading is changing less quickly than appropriate for the driver's intended path, it momentarily applies the left rear brake to turn the heading of the vehicle back to the correct path.

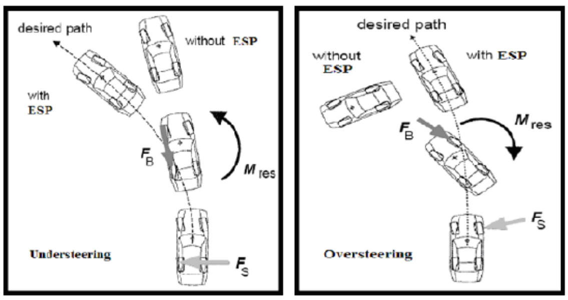

Figure 1 Note how the caption is centered in the column.

The agency proposes to adopt the ESP definition based on the Society of Automotive Engineers (SAE) Surface Vehicle Information Report J2564 (revised June 2004). The ESP is defined as a system that has all of the following attributes:

(a) Augments vehicle directional stability by applying and adjusting the vehicle brakes individually to induce correcting yaw torques to the vehicle.

(b) Is computer-controlled, which uses a close-loop algorithm to limit understeer and oversteer of the vehicle when appropriate.

(c) Has a means to determine vehicle yaw rate and to estimate its sideslip or the time derivative of sideslip.

(d) Has a means to monitor driver steering input.

(e) Has an algorithm to determine the need, and a means to modify engine torque, as necessary, to assist the driver in maintaining control of vehicle.

(f) Is operational over the full speed range of the vehicle (except below a low –speed threshold where loss of control is unlikely).

III. VEHICE MODEL

A. The ADAMS Model

An ADAMS model is established to study the ESP control system, based on the appropriate simplification of prototype vehicle.

The vehicle model is created in Adams, using the graphical user interface of Adams Car. (Refs. [13], [14]) The modeling process is structured to facilitate ease of modification later in the design, starting with creating hard points denoting the various key locations of the suspension system. This is followed by creating links using those hard points, and finally adding joints and constraints between the links to complete the geometry. The mass and inertia properties are then added to the components of the suspension system.

The suspension parts are created using the cylinder member in the Adams Car template tool box. The hard points already created mark the end points of each of the suspension links, these points are used to create the suspension geometry. Each suspension element is modeled as a separate part, connected to other parts through joints. The prototype vehicle employs a High Place Double A-arm suspension on front suspension. For each wheel a lower control arm, upper control arm and knuckle are modeled as parts. The upper and lower control arms are connected to the chassis with bushings and to the knuckles with spherical joints. The bushings are used to introduce some steering compliance and they are modeled to be extremely stiff in the vertical and longitudinal directions compared to the lateral direction. The prototype vehicle uses a rack and pinion steering system. The rack is connected to the chassis with a translational joint.

Figure 2 shows the front High Place Double A-arm suspension model in Adams Car, and figure 3 shows the rear Multi-links suspension model in Adams Car. The springs are modeled as nonlinear single component forces (S force in Adams) acting between two points which are the mounting points of the strut. The force is defined by a 2D curve with spring deflection on the x axis and force on the y axis. The shock absorbers are modeled as nonlinear single component forces acting between the same points as the strut. The force is defined by a 2D curve with deformation velocity along the x axis and force on the y axis.

Once the parts are created, their mass and inertia properties are defined. The data for the mass, inertia and joint locations were gained by the company. The graphics of the vehicle body are modeled, and the mass and inertia properties of the body are incorporated in the model.

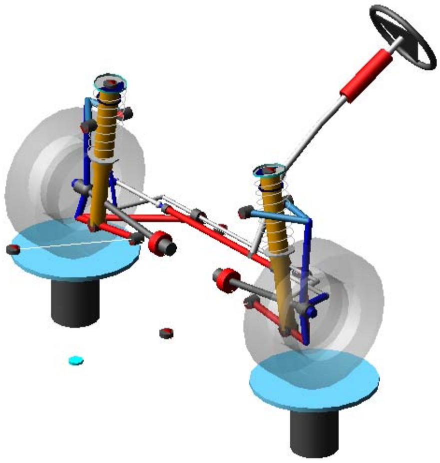

Figure 2 The front suspension model.

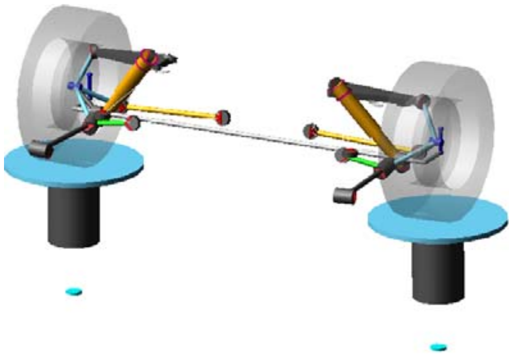

Figure 3 The rear Multi-links suspension model.

The tires and road are modeled using the Adams Tire module available in Adams Car. One of the default flat road profiles available in the Adams database is used for the road. The Pac2002 tire property file suitable for P205/55R16 tires was used. (Refs. [15])Road model documents are established by the road builder in the ADAMS/Car, and the parameters are setup. Figure 4 shows the vehicle ADAMS model.

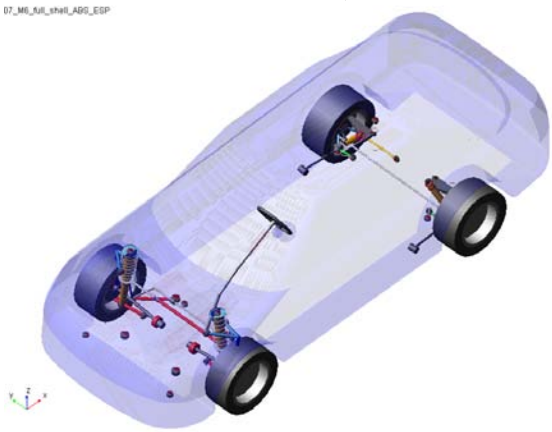

Figure 4 The ADAMS model of vehicle.

The vehicle model is run only in coast mode for testing the ESP systems, and for this reason a drive train is not incorporated in the model. Instead, forced motions are applied at the wheels to control the speed. The motions are then switched off using scripted controls to let the vehicle coast while the maneuver is performed. (Refs. [16]) Since the scripted controls cannot be used during co-simulation with Matlab, torqueses are used instead of the forced motions to control the vehicle speed when co-simulating with Matlab.

In any computer model, the accuracy of the simulation relies on the accuracy of the model and the vehicle parameters used to build the model. Hence the mode is checked against experimental data to ensure that the data matches to confirm the accuracy of the model.

In order to validate the ADAMS model, double lane change experiment and simulation are carried out, and the results are contrasted, shown in figure 5. Figure 6 shows the contrast of experiment and simulation under the Sine with Dwell maneuver, it can be seen that, the curves of simulation and experiment are in good agreement, so it is considered that, the ADAMS model can reflect the basic characteristics of vehicle, and can be used to simulate and analyze the vehicle stability and ESP control system.

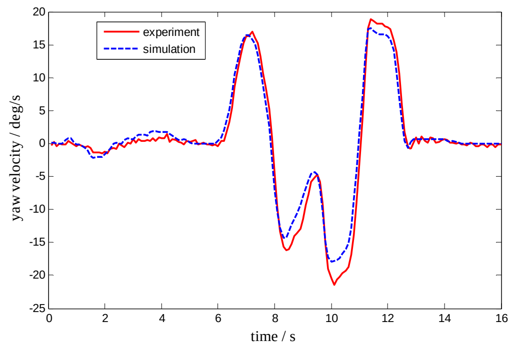

Figure 5 Contrast of simulation and experiment under Double Lane Change

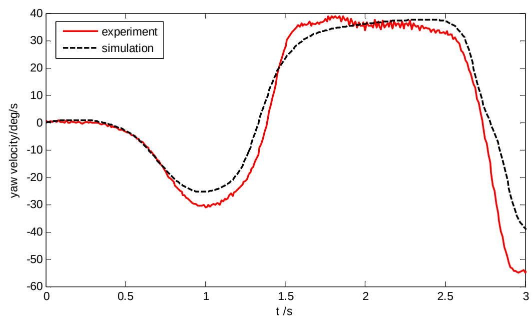

Figure 6 Contrast of simulation and experiment under Sine with Dwell

B. Co-simulation Control Model

In order to simulate the ESP control system, the ADAMS model should be translated into S-function in Matlab/Simulink. (Refs. [17], [18])Co-simulation is the process of simulating a system where two or more separate simulation programs are simultaneously used to model various aspects of the system and these simulation programs communicate during run-time, to simulate the whole system, thus affecting each other's output. In this case the vehicle is modeled in Adams-Car whereas the brake system is modeled in Simulink and a co-simulation is setup to run the vehicle model in Adams using the brake model in Simulink.

The various steps involved in setting up a co-simulation between Adams and Simulink are:

a. Loading Adams/Controls
b. Defining Input and Output Variables
c. Referencing Input Variables in the Adams Model
d. Exporting the Adams Block
e. Connecting the Adams Block and the CES Block in Simulink
f. Running the Co-simulation
g. Things to Remember

Figure 6 is the co-simulation principle of ESP, the yaw velocity and side slid angle of vehicle body are obtained from ADAMS model, and are contrasted with the same parameters which are calculated from the reference model, thus the stable state of vehicle can be estimated and intend to brake the wheel.

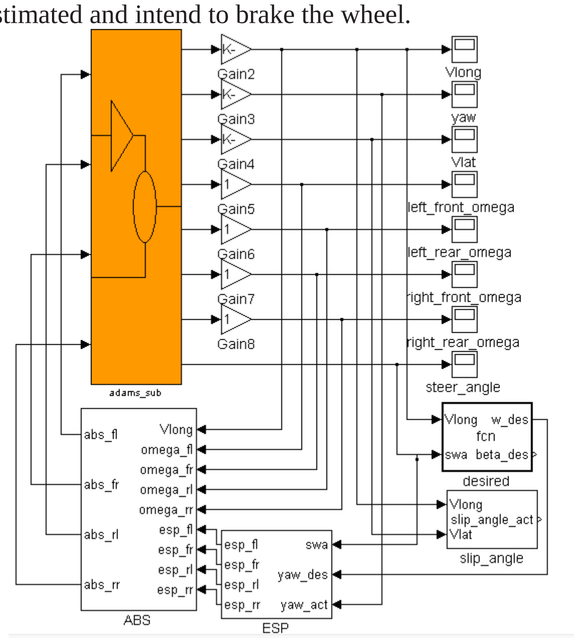

Figure 6 The co-simulation model of ESP system

The adams_sub module in figure 6 is the S-function obtained from ADAMS model, which includes the whole vehicle information. The input and output state variables have been defined while the sub-system being established, such as, the brake pressure of each wheel was defined as input state variable while the brake model being established, the later velocity, longitude velocity and yaw velocity were defined output state variables while vehicle body being established, and the steering wheel angle was defined as output state variable while steering system being established. Desired module is the linear two degrees of freedom vehicle model, used to calculate the desired state parameters of vehicle. ESP module is the core of co-simulation model, which can complete the estimation of vehicle stable state and active yaw control. The fuzzy control principle is adopted based on the yaw velocity in the paper, which is shown in figure 7.

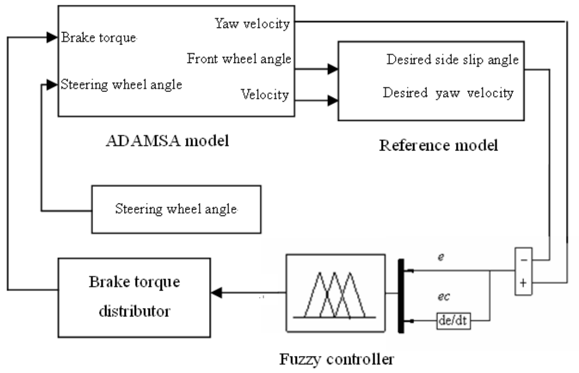

Figure 7 The fuzzy control principle based on yaw velocity

Once the system is setup, the simulation time is entered in the box on top of the screen and the play button is clicked to run the simulation. (Refs. [19]) Simulink invokes Adams and runs the model in Adams/Car while the damper forces are calculated in Simulink and fed into Adams while the simulation is running. Thus co-simulation is achieved.

IV. SIMULATION RESULTS

NHTSA has proposed a new Federal motor vehicle safety standard (FMVSS). FMVSS No. 126, Electronic Stability Control Systems, would require ESP systems on passenger cars, multipurpose passenger vehicles, trucks and buses with a gross vehicle weight rating of 4,536 Kg (10,000 pounds) or less.

As shown in Figure 8, the Sine with Dwell maneuver was based on a single cycle of sinusoidal steering input. A single cycle input is performed at a frequency of 0.7 Hz, with a 500 ms pause between completion of the third quarter cycle and initiation of the fourth quarter cycle.

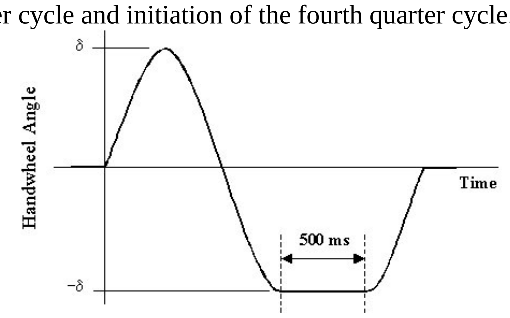

Figure 8 The Sine with Dwell maneuver

To begin the maneuver, the driver accelerates the vehicle to a speed of approximately 52 mph, at which point the throttle is released and a programmable steering controller is engaged. Since the maneuver entrance speed is always 50 mph, increasing the magnitude of the steering wheel angles is used to increase maneuver severity. This is accomplished by multiplying the steering wheel angle capable of producing a lateral acceleration of 0.3g during Slowly Increasing Steer testing (δ0.3g) by a series of scalars. The steering wheel angles nominally begin at 1.5*δ0.3g, and are increased in increments of 0.5*δ0.3g until the steering wheel angle of 6.5*δ0.3g or 270 degrees is used (whichever was greater). Sine with

Dwell tests are performed with left-right and right-left steering.

The proposed criterion performance limit establishes the displacement threshold to ensure that the ESP intervention used to achieve acceptable lateral ability dose not compromise the ability of the vehicle to response to the driver's input. The proposal would require that an ESP-equipped vehicle a gross vehicle weight rating of 3500Kg or less would have a lateral displacement of at least 1.83 meters at 1.07 seconds after the initiation of steering, and the ESP-equipped vehicle a gross vehicle weight rating of 3500 Kg above would have a lateral displacement of at least 1.52 meters at 1.07 seconds after the initiation of steering.

Based on consideration of all available test data, NHTSA ultimately decided a metric based on the YRR 1.0 seconds after completion of steer would meet the two requirements and effectively augment the later value, as indicated in Figure 9. Specifically, the yaw rate ratio of the vehicle are measured at 1.5 to 1.75 seconds after completion of steer, where the yaw rates of the vehicles equipped with fully enabled ESP systems had decayed to approximately zero while those associated with the fully disabled tests remained quite high.

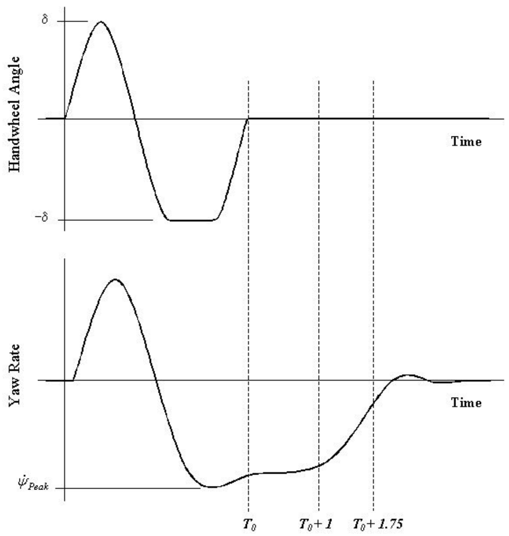

Figure 9 Steering wheel position and yaw rate information used to assess lateral stability

A formal definition of the lateral stability performance criteria is provided below.

$$\begin{cases} \dfrac{r_{T_0+1}}{r_{peak}} \times 100\% \le 35\% \\ \dfrac{r_{T_0+1.75}}{r_{peak}} \times 100\% \le 20\% \end{cases}$$

In both criterion, r_{peak} is the first local yaw rate peak produced after the second steering reversal, r_{T_0+x} yaw rate at x (x=1, 1.75) seconds after completion of a maneuver's dynamic steering inputs.

The sine with dwell maneuver simulation is carried out on the road with high attachment coefficient, according to FMVSS 126 sine with dwell standard, the results of vehicle with ESP disabled and enabled are shown in figure 10 and figure 11. As shown in Figure 10, when the steering amplitude is 80 and 120 degrees, following a smooth 0.7 Hz sinusoidal pattern, the absolute value of the yaw velocity increases with the absolute value of the steering angle, and then the vehicle changes to clockwise yaw velocity in response to right steering. At two seconds after the beginning of steering, the steering wheel has been turned back to straight ahead, and the yaw rate returns to zero after a fraction of a second response time. At that point, the vehicle is being steered straight ahead, and it is going straight ahead without any yaw rotation. The vehicle is responding closely to the steering input, and the driver is in control. However, when the steering amplitude is increased to 169 degrees, the vehicle spins out, exhibiting oversteer loss of control. This condition is identified in the yaw rate trace. When the steering is straight ahead at time = 2 seconds, the yaw rate for this run is still about 35 deg/sec. However, there is a time lag past the instant of steering to straight ahead even for the previous runs where there was no loss of control. What is different is that the yaw rate does not swiftly decline to zero as it does with a vehicle under control. At time = 3 seconds, the yaw rate is still the same, and it has actually increased at time =4 seconds in this example. The physical interpretation of this graph is that the driver has turned the wheels straight ahead and wants the vehicle to go straight, but the vehicle is spinning clockwise about a vertical axis through its center of gravity. It is out of control in a spinout. The driver's steering input is not causing the vehicle to take the desired path and heading, and the vehicle would depart the road surface sideways or even backward.

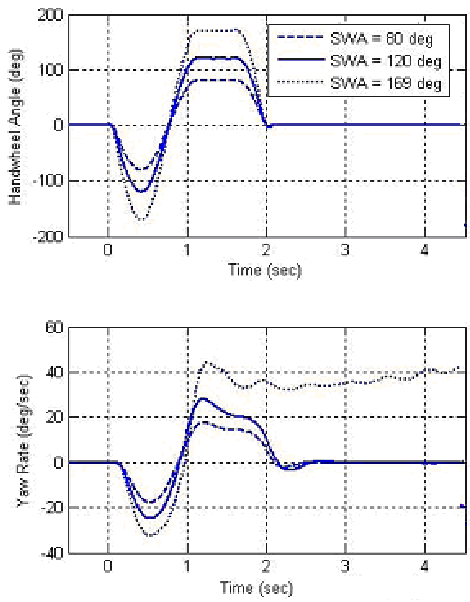

Figure 10 Sine with dell maneuver test of a vehicle without ESP

Figure 11 shows another series of tests of the same vehicle but with ESP enabled. The first two runs were at 80 and 120 degrees of steering angle, and the vehicle's yaw rate declined to zero in a fraction of a second after the steering command. This is the same good response to steering exhibited by the vehicle with ESP disabled in the previous figure. The third run was conducted at 180 degrees of steering angle. This is greater than the 169 degrees that caused a severe loss of control without ESP, but the yaw rate returned to zero with the steering angle just as quickly as in the runs with less steering. The final set of curves in Figure 11 represents a run conducted with 279 degrees of steering angle. This would be the left-right portion of the performance test proposed for the ESP system of this vehicle since 279 degrees is 6.5 times the steering angle that produces 0.3g steady state lateral acceleration for this example vehicle. In this case, the yaw rate did not return to zero nearly instantaneously as it had at lower steering angle. Instead, it steadily declined after the steering was turned to straight ahead, and the vehicle was completely stable and going straight in about 1.75 seconds. Clearly, the vehicle remained in control compared to its behavior without ESP (see Figure 10) in which turning the steering to straight ahead had no effect on the vehicle's heading. However, the ESP system required some time to cause the vehicle to stop turning in response to the driver's straight ahead steering command. It can be concluded that, ESP can make the handling and stability performance on big lateral acceleration and slip angle improved, and make the driver drive the vehicle normally.

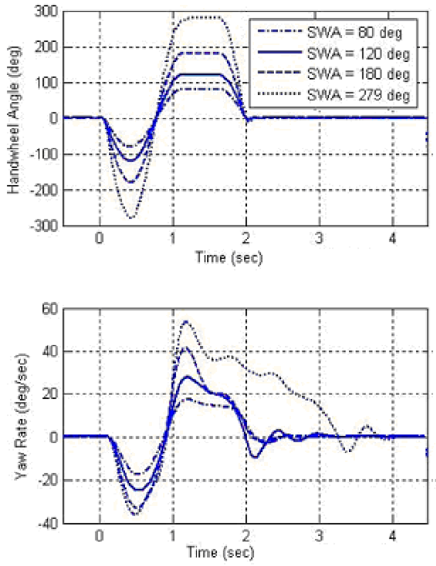

Figure 11 Sine with dell maneuver test of a vehicle with ESP

V. CONCLUSIONS

(1) The virtual prototype model of vehicle and co-simulation model of ESP control system based on the fuzzy control principle were established in ADAMS and Matlab, in order to simulate study the performance of ESP. From the simulation, the model was shown to give accurate results for the purposes of this study;

(2) The ESP model was developed in Matlab/Simulink and a co-simulation was set up to integrate the ESP model with the vehicle model. ESP fuzzy controller based on the yaw velocity can improve the controlling stability of the automotives by initiatively finishing the implementation of the wheel braking, thus the driver can help the driver to keep the vehicle controllable;

(3) The design cost can be decreased, and the development cycle can be shortened, by means of virtual prototype and co-simulation technology.

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