Study on Torque Vectoring Differential for Vehicle Stability Control via Hardware-in-Loop Simulation

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***Abstract*—A Torque Vectoring Differential (TVD) system base on vehicle stability control is proposed to achieve additional torque steering for improving vehicle steerability and stability. Firstly, a four-wheel-drive vehicle model is set up by veDYNA. Furthermore base on fuzzy logic control structure, the virtual controller including the yaw moment controller and TVD model are designed by Simulink. The yaw moment calculated by yaw moment controller is realized by TVD model with distributing vectoring torque from left to right wheel. In the end, a hardware-in-loop simulation (HILS) system simulating the rear wheel and axle equipped with TVD is introduced to combine with the vehicle model, the virtual controller, virtual instrument by LabVIEW and the experiment platform for transmission. The HILS results show that TVD system compared with Electronic Stability Program (ESP) can restrain the sideslip angle and yaw rate within their desired value without the deterioration of the longitudinal performance. Moreover, the effectiveness of TVD system for enhance vehicle cornering performance by vectoring torque is also guaranteed in simulation validation.**

Keywords-torque vectoring differential; vehicle stability control; electronic stability program; hardware-in-loop simulation

I. INTRODUCTION

Vehicle stability control systems are being increasingly used as standard equipment in many vehicles. Most vehicle stability control systems such as Electronic Stability Program (ESP) in the market are brake-based, which generate yaw moment for a vehicle utilizing the longitudinal braking force difference. Thus, it results in the decrease in vehicle longitudinal speed and the large energy loss caused by braking, which is suitable only for improving vehicle driving stability during deceleration cornering or a critical cornering situation and not suitable especially in situations where the driver desires to accelerate the vehicle [1].

To overcome the limitations of ESP, some researchers have proposed a different mechanism system called Torque Vectoring Differential (TVD) for generating a direct yaw moment [2][3]. This system provides vehicle stability control regardless of whether the vehicle is accelerating or decelerating by transmitting differential driving torque (also called vectoring torque) between the left and right wheels without deteriorating the longitudinal performance of the vehicle [4]. Therefore, the widely use of TVD based stability control in four-wheel-drive (4WD) vehicle is proposed. Recent developments in vehicle yaw control using TVD include Honda SH-AWD [5], and Mitsubishi AYC [6]to enhance cornering performance and stability.

However, in the process of TVD system design, development and validation, traditional real car test method did poor in cost, time and flexibility, and it is difficult to test the control effect in extreme conditions. In the past decades, the Hardware-In-Loop Simulation (HILS) technology has been investigated and introduced by the automotive engineers as a powerful tool in developing the electronic control system of automotive [6]. HILS makes the sensors and actuators of the certain hardware run synchronously with the simulation software, communicating by PC I/Os, and verifies the control algorithm in the lab, which will fundamentally reduce the development cost and time [7].

In this paper, therefore, an HILS method for TVD based on virtual integrated technology is introduced, which combines virtual vehicle dynamic model by veDYNA, virtual controller by Simulink and LabVIEW platform, takes full advantages of each of the three in different fields of virtual technology, and realizes the predominance of HILS technology in the development process of TVD.

II. TORQUE VECTORING DIFFERENTIAL SYSTEM

TVD system consists of slipping multi-plate wet clutches and planetary gears that are controlled by electrical, electromechanical or electrohydraulic control systems. Four-wheel-drive (4WD) vehicle equipped with TVD in both front and rear axle can vectored engine torque to each wheel. In other words, while TVD system monitors vehicle speed, wheel speed, steering angle, yaw rate and other inputs, it splits engine's torque from front to back and distributed it from side to side on a given axle.

Take a rear-wheel-drive vehicle with TVD applied to only the rear axle as an example. According to Fig.1, when the vehicle is turning left with understeer, TVD automatically transmits the input torque T_d of the driveshaft from left rear wheel to right rear wheel with vectoring torque T_v by engaging clutches. Thus, it results in additional driving force T_v / R acting on right rear wheel and extra braking force $-T_v / R$ acting on left rear wheel. Finally, the differential longitudinal driving force ΔF between the right and left wheel is produced, which generates yaw moment M helping the vehicle bend into the corner more sharply. When the vehicle is driving straight, TVD behaves like an ordinary open differential with the input torque T_d

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equally distributed to the left and right rear wheels, which means $T_v = 0$. The maximum of vectoring torque T_v is decided by the structural properties and friction characteristics of wet clutches, as in (1).

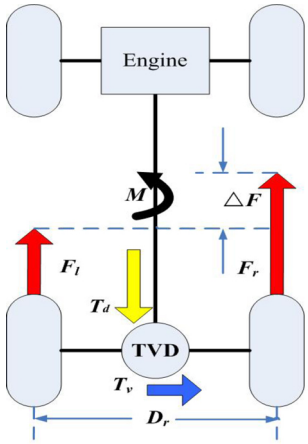

Figure 1. Definition of torque vectoring differential.

$$
\begin{aligned}
F_l &= (T_d / 2 - T_v) / r \\
F_r &= (T_d / 2 + T_v) / r \\
\Delta F &= F_r - F_l = 2T_v / r \\
M &= \Delta F \times \frac{D_r}{2} \\
T_v &= n \cdot f \cdot F_h \cdot r_f
\end{aligned}
\tag{1}
$$

Where r is tire radius, F_l and F_r are longitudinal driving force of the left and right rear wheel respectively, D_r is the track width, n is the number of the friction component surface of clutches , f is the friction coefficient of friction component, F_h is the axial pressure on the friction components due to the clutch actuator movements; r_f is the equivalent friction radius coupled to the friction component.

Compared with ESP system, the TVD system is capable, by means of torque vectoring, of controlling yaw moment at any time even when engine torque is fluctuating and/or the vehicle is decelerating [8]. Furthermore, because of the total driving longitudinal force unchanged, it can be improving vehicle steerability and stability at all stages, from normal to critical driving without the reduction in vehicle longitudinal acceleration.

III. PRINCIPLE OF HILS FOR TVD

As shown in Fig.2, the HILS system is divided into the blocks of software and hardware. Each part of the system is explained in the following sections.

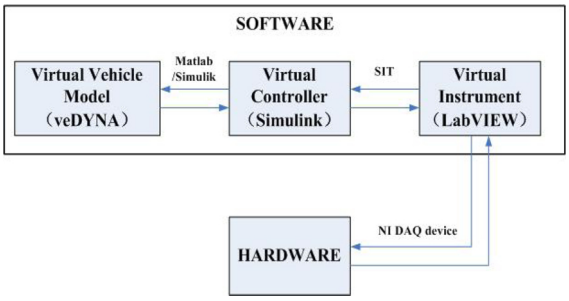

Figure 2. Structure of the HILS system.

A. *Virtual Vehicle Model by veDYNA*

veDYNA is a proven and versatile vehicle dynamics simulation tool based on a high-precision vehicle model, which is equally suited for the simulation of passenger cars, all-wheel sports vehicles, and Formula 1 race cars. The open and modular model architecture implemented in MATLAB and Simulink allows easy and straightforward incorporation of user-specific model components and external vehicle controllers.

In this paper, the general structure and parameter data of a 4WD BMW 325I are used as reference to configure the vehicle model with TVD applied to both the front and rear axles, which is built in veDYNA. In this paper, the maximum of vectoring torque T_v controlled by TVD is 300Nm. The main parameters of the vehicle model are shown as Table I where m is the mass of vehicle, I_z is moment of inertia of vehicle about the z-axis, J_w is moment of inertia of the wheel , $k_{\alpha f}$ and $k_{\alpha r}$ are cornering stiffness coefficient of front tire and rear tire respectively, h_g is the height of vehicle gravity center, a and b are the distances from center of mass of vehicle to front and rear axle, d_f and d_r are the distances between the centre of the two front wheels and two rear wheels, L is the wheelbase.

TABLE I. THE MAIN PARAMETERS OF THE VEHICLE MODEL

m(kg)	I_z (kg.m^2)	J_w (kg.m^2)
1296	1750	0.8
d_f (m)	d_r (m)	h_g (m)
1.405	1.399	0.45
$k_{\alpha f}$ (N/rad)	$k_{\alpha r}$ (N/rad)	r (m)
-35000	-35000	0.286
a(m)	b(m)	L(m)
1.25	1.32	2.57

B. *Virtual Controller by Simulink*

The virtual controller of the HILS system is developed in Simulink of which Engineers can use the plentiful provided function blocks easily to build their own controllers

according to their control objective and algorithm, which is the core of electronic control systems.

In this paper, the virtual controller of the HILS system is composed of three main blocks: reference vehicle model, yaw moment controller and TVD model, as shown in Fig.3. The reference vehicle model computes the desired vehicle motion based on the driver commands. The yaw moment controller based fuzzy logic compares the actual vehicle motion with the desired vehicle motion, and provides the desired yaw moment. Finally the TVD model distributes vectoring torque from side to side to realize the desired yaw moment which acts on the vehicle to improve its cornering performance.

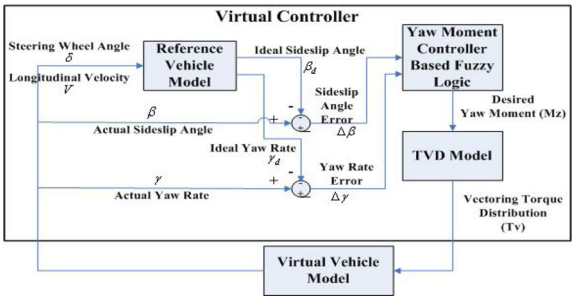

Figure 3. Structure of the virtual controller.

C. Communication between System Software and Hardware

Due to the incapability of connecting Simulink with system hardware directly, NI LabVIEW and PXI devices are used as a platform between software and hardware, which is the key point to implement the HILS. In this paper, the hardware of the HILS system is the experiment platform for transmission simulating the rear right wheel of the virtual vehicle as shown in Fig.4.

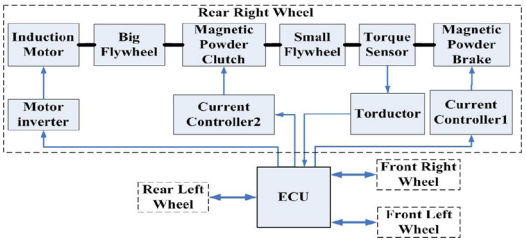

Figure 4. Structure of the experiment platform for transmission.

According to Fig.5, wheel rotation dynamic model is showed in (2). A half of input torque T_d / 2 from the virtual vehicle model is translated to analog voltage output to the converter by NI LabVIEW and PXI devices, then the inverter controls the induction motor to run at an angle acceleration $\dot{\omega}$. while the braking torque produced by the magnetic powder brake simulates the friction force F_f between tire and road, the direction and magnitude of vectoring torque T_v generated by TVD is realized by engaging or cutting off the magnetic powder clutch. Both the big flywheel and the small one represent the inertia for other components of wheel axle. The magnetic powder clutch and brake are respectively controlled by the current controller 2 and 1. The torque sensor real time acquires the signal of vectoring torque T_v transmitted by the magnetic powder clutch which then go back to the rear right wheel of the virtual vehicle model through LabVIEW.

$$J_w\dot{\omega} = T_d / 2 \pm T_v - F_f r \qquad (2)$$

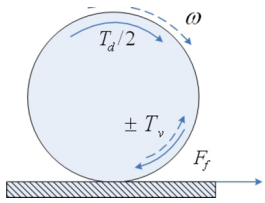

Figure 5. Wheel rotation dynamic model.

The ECU is a high performance PC which is equipped with NI PXI-8196 embedded controller and PXI-6259 multifunction DAQ device.

D. Integration of HILS System

In order to implement the integrated simulation by virtual vehicle model, virtual controller and virtual instrument, certain interface toolkits must be applied to combine with them. Firstly, LabVIEW communicates with Simulink by Simulation Interface Toolkit (SIT) developed by Simulink. In this paper, the friction force between rear right wheel and road from virtual vehicle model is transmitted by SIT to LabVIEW platform, then to the magnetic powder brake by DAQ device. Meanwhile, the actual vectoring torque produced by the magnetic powder clutches and acquired by the torque sensor is first transmitted to LabVIEW platform by DAQ device, then to Simulink by SIT and finally to the rear right wheel of the virtual vehicle model based on veDYNA. The observer and control interface for HILS system based on LabVIEW is created as showed in Fig.6.

While the HILS system is running, the interface can real time display the curve of the yaw rate, the sideslip angle, the longitudinal acceleration, and the actual vectoring torque for the virtual vehicle by clicking the top label. On the front page of the interface, there are the virtual instrument indicators of odometer, tank, panel respectively displaying the vehicle longitudinal velocity, the vehicle longitudinal and lateral acceleration, and the steering wheel angle.

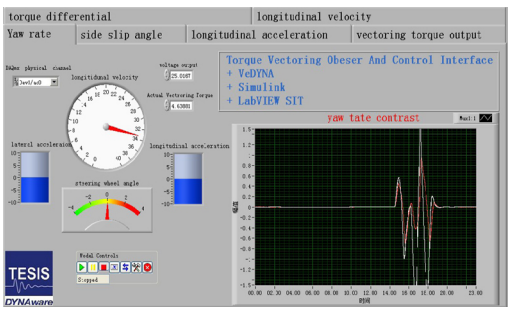

Figure 6. Observer and Control Interface for HILS System.

IV. RESULTS OF HILS AND ANALYSIS

In order to verify the advantages of the proposed TVD and the effectiveness of the control law described above in vehicle handling performance, we respectively implement a double lane change maneuver (DLCM) and a slalom maneuver (SM) which are both set up in veDYNA for the HILS system. The road adhesion coefficient of both the maneuvers is 0.8.

A. Double Lane Change Maneuver

The objective of this type of maneuver in this paper is for the vehicle to speed up in one lane from 0km/s to 120km/h , then turn left to enter a second lane and remains in that lane for a certain distance before returning to the original lane.

As showed in Fig.7~8, the yaw rate and the sideslip angle of the vehicle without control deviate from their reference value obviously, which means that the vehicle drifts and fails to follow the specified lane. While applying the TVD and the ESP controller respectively, the yaw rate almost exactly traces its reference value. The sideslip angle is also reduced significantly even smaller than the reference value. Thus, the vehicle stability and maneuverability are improved by both the TVD and the ESP controller even to the same extent.

However, according to the Fig.9~10, due to the braking system is the actuator of ESP, the vehicle longitudinal acceleration becomes fluctuating and the longitudinal velocity reduces compared with the TVD when it is working, which is not suitable for racing events when not only the maneuverability but also the vehicle acceleration is most concerned. So the TVD can achieve the vehicle stability and maneuverability improvement with small energy loss.

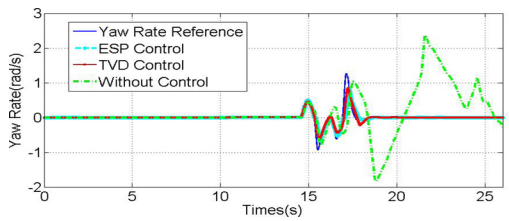

Figure 7. Yaw rate during DLCM.

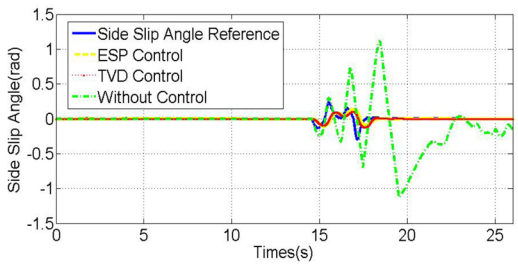

Figure 8. Sideslip Angle during DLCM.

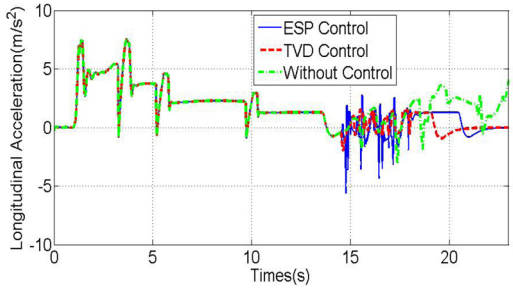

Figure 9. Longitudinal velocity during DLCM.

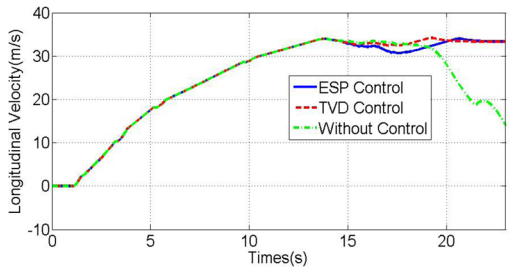

Figure 10. Longitudinal velocity during DLCM

B. Slalom Maneuver

The procedure of slalom maneuver makes the selected vehicle drive through a series of cones positioned at a prescribed distance between each other. In this paper, the vehicle is accelerated to the speed of 75km/h, and then follows a sinusoidal path through the cones at constant speed.

According to the Fig.11~14, the yaw rate and the sideslip angle of the vehicle under the control of TVD are smaller than those of the vehicle under the control of ESP or without control. Especially the vehicle longitudinal acceleration gets fluctuating severely while controlled by the ESP. However, the vehicle longitudinal acceleration under the control of the TVD is relatively smoother even than that without control, which improves the vehicle cornering performance and stability without greatly influencing the vehicle ride comfort.

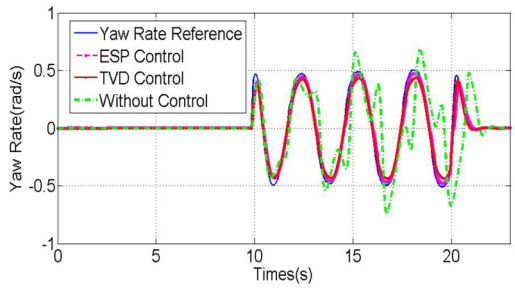

Figure 11. Yaw rate during SM

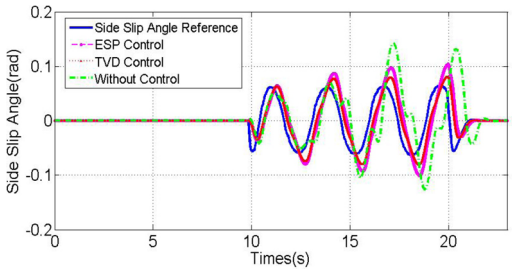

Figure 12. Sideslip angle during SM

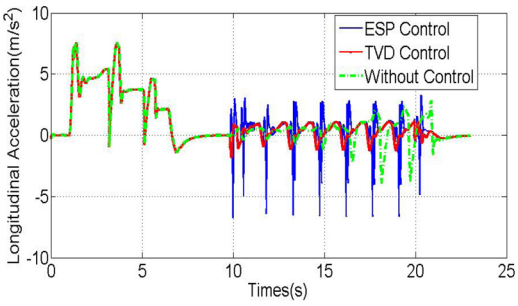

Figure 13. Longitudinal acceleration during SM

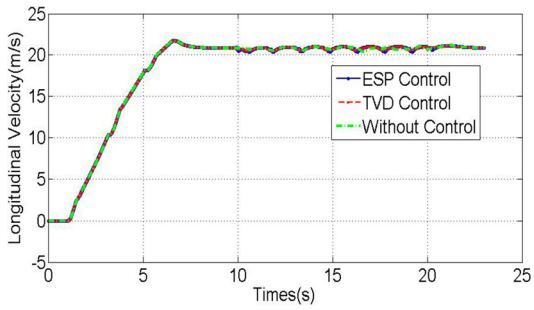

Figure 14. Longitudinal velocity during SM

C. *Vectoring Torque Response*

The comparison between the actual vectoring torque and the desired one output by TVD is shown in Fig.15~16. Deviation exists especially where the curve of the desired vectoring torque is straight which means the vehicle is actually straight driving without the requirement of vectoring torque. The reason is that the signal of the actual vectoring torque is interfered by the vibration signal that the experiment platform for transmission produce while HILS is carried out. The actual torque is mostly a little smaller than the desired one also with time lag, because the inertia of the whole system makes the actual torque need time to reach the required one which changes rapidly with the maneuver state. Considering the dynamic response process of the hardware, the comparisons and analysis of the simulation results above indicates that the control algorithm can meet the requirement of enhancing the vehicle stability and tracking performance effectively.

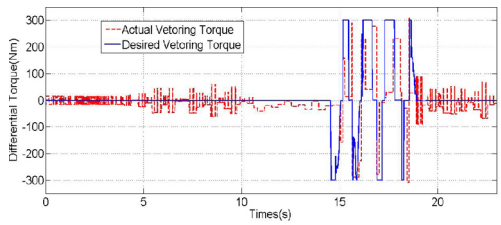

Figure 15. Comparison of vectoring torque output by TVD during DLCM

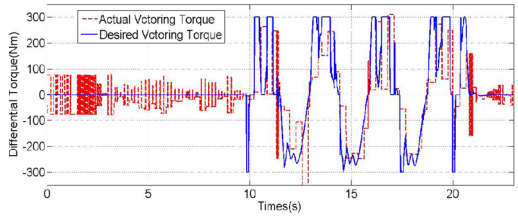

Figure 16. Comparison of vectoring torque output by TVD during SM

V. CONCLUTION

In this paper, the hardware-in-loop simulation method based on virtual technology integrated by veDYNA, Simulink and LabVIEW is implemented to verify the effectiveness of the proposed TVD in the vehicle yaw motion enhancement. HILS results showed that the proposed TVD controller improving vehicle steerability and stability without much energy loss and much influence in the vehicle ride comfort compared with the ESP.

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