AN ACTIVE FRONT STEERING CONTROL BASED ON COMPOSITE NONLINEAR FEEDBACK FOR VEHICLE YAW STABILITY SYSTEM

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To my employer, Universiti Teknikal Malaysia Melaka for supporting my study

To my beloved family for their encouragement and love

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ABSTRACT

Vehicle stability control (VSC) is one of important topics in vehicle dynamics and active automotive control. This research is focusing on vehicle stability control by active steering system that utilizes steering control method to improve stability of the vehicle. This stability control system is solely based on kinematic and dynamics motion of vehicle. The development of mathematical model of vehicle dynamic that includes body and tyre dynamics is one of the most important steps to make sure the result obtain is close as possible to actual system. In the other hand, an analysis of transient state is very crucial in control system performance where one of the objectives is to track reference signal as fast as possible with minimum overshoot, fast settling time, and without exceed nature of actuator saturation limit. Hence, in order to achieve this target, a robust and high performance of control algorithm is essential for vehicle stability control. In this research project report, a Composite Nonlinear Feedback (CNF) strategy is used to control yaw rate of vehicle through active steering. Extensive computer simulation is performed with considering a various profile of cornering manoeuvres with external disturbance to evaluate its performance in different scenarios. The performance of the proposed controller is compared to conventional Proportional Integration and Derivative (PID) for effectiveness analysis.

ABSTRAK

Kawalan kestabilan kenderaan adalah salah satu topik penting dalam dinamik kenderaan dan kawalan aktif kerangka. Kajian yang dijalankan ini akan difokuskan pada kawalan kestabilan melalui sistem stering aktif yang menggunakan kaedah kawalan stering bagi memperbaiki kestabilan sesebuah kenderaan. Sistem kawalan kestabilan ini berasakan sepenuhnya kepada gerakan kinamatik dan dinamik sesebuah kenderaan. Pembinaan model matematik bagi dinamik kenderaan yang melibatkan dinamik keranka dan tayar adalah salah satu langkah penting untuk memastikan keputusan yang diperolehi adalah sehampir yang mungkin dengan sistem yang sebenar. Selain itu, analisis keadaan fana adalah sangat penting dalam prestasi sistem kawalan dimana salah satu objektif adalah menjejaki isyarat rujukan secepat mungkin dengan penghasilan telajak yang minimum, masa reda yang cepat, dan tanpa melepasi tahap tepu yang normal bagi sesebuah penggerak. Oleh itu, dalam mencapai sasaran ini algoritma pengawal yang mantap dan berprestasi tinggi adalah menjadi satu kemestian dalam kawalan kestabilan kenderaan. Dalam laporan kajian ini, strategi Komposit Suapbalik Tak linear (CNF) digunakan untuk mengawal kadar rewang kenderaan melalui kaedah stering aktif. Simulasi komputer yang ekstensif digunakan dengan mengambil kira pelbagai gerakan dan profil selekoh dan juga gangguan luaran untuk menilai tahap kecekapan kawalan yang dibina dalam situasi-situasi berbeza. Kebolehan pengawal yang disyorkan akan dibandingkan dengan pengawal Perkadaran, Pengamiran dan Pembezaan (PID) yang konvensional untuk menganalisis tahap kecekapan.

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LIST OF SYMBOLS

δ	-	Wheel steering angle
T_{bi}	-	Braking torque at i^{th} wheel
v	-	Vehicle velocity at centre of gravity
β	-	Vehicle side slip angle
$\dot{\Psi}$	-	Vehicle yaw rate
$\dot{\Psi}_d$	-	Desired vehicle yaw rate
α_i	-	Sideslip angle at i^{th} wheel
λ_i	-	Tyre longitudinal slip ratio at i^{th} wheel
v_i	-	Tyre ground contact point velocity at i^{th} wheel
ω_i	-	Tyre rotational speed at i^{th} wheel
F_{xi}	-	Longitudinal tyre force at i^{th} wheel
F_{yi}	-	Lateral tyre force at i^{th} Wheel
F_{zi}	-	Tyre normal load at i^{th} Wheel
C_{yf}	-	Nominal tyre cornering stiffness at front wheel
C_{yr}	-	Nominal tyre cornering stiffness at front wheel
l_f	-	Distance from the vehicle center of gravity to the front axle
l_r	-	Distance from the vehicle center of gravity to the rear axle
l	-	Wheel base of vehicle
T	-	Track of vehicle
h	-	Vertical distance from CG of sprung mass to roll axis
J_z	-	Moment of inertia of car body
J_w	-	Wheel moment of inertia
R	-	Tyre radius
m	-	Total mass of the vehicle
μ	-	Road adhesion coefficient of road

n_s	-	Steering wheel ratio
g	-	Gravity = 9.81 m/s^{-2}
ρ	-	Nonlinear locally Lipschitz function
u_L	-	Linear state feedback of CNF
u_N	-	Nonlinear state feedback of CNF
γ	-	1st nonlinear parameter gain of CNF
φ	-	2nd nonlinear parameter gain of CNF
x_e	-	State equilibrium point
r	-	Reference signal of control system
ξ_∞	-	Damping ratio of closed loop system

LIST OF ABBREAVIATIONS

VSC	-	Vehicle Stability Control
ASC	-	Active Steering Control
AFS	-	Active Front Steering
ESP	-	Electronic Stability Program
DYC	-	Direct Yaw Moment Control
FWS	-	Front Wheels Steering
4WS	-	Four Wheels Steering
CNF	-	Composite Nonlinear Feedback
PID	-	Proportional Integration Derivative
SMC	-	Sliding Mode Control
ISM	-	Integral Sliding Mode
LQR	-	Linear Quadratic Regulator
MPC	-	Model Predictive Control
LMI	-	Linear Matrix Inequalities
QFT	-	Quantitative Feedback Theory
DOF	-	Degree of Freedom
CG	-	Center of Gravity
SISO	-	Single Input Single Output
MIMO	-	Multi Input Multi Output
IAE	-	Integral of Absolute Error
ITAE	-	Integral of Time multiplied Absolute Error

CHAPTER 1

INTRODUCTION

1.1 Vehicle Stability

Safety factor is very important issue in vehicle design and handling. Vehicle safety system can be divided into two parts, which are passive and active safety system. Passive safety technologies can be seen such as belts, safety glass, and air bags. The systems are designed to prevent or reduce the damage to the pedestrians, passengers, and the vehicles involved after the accident has occurred. Meanwhile, in driver assistance and active safety system have received much attention from researcher because it can prevent vehicle from accident. Their development is continuously conducted to meet current demand that always keep increasing on the safety of vehicles. For example, vehicle stability control (VSC), collision avoidance (CW/CA), smart cruise control (SCC), lane keeping support, lane change assistance and collision warning, and automated parking assistance have been extensively studied with many developments that have been explored since the 1990s (Yu et al. 2008).

The improvement and enhancement of vehicle dynamic control using active control such active steering control, intelligent braking system, traction control, active suspension system and combination of these methods are actively conducted so that a ground vehicle will have a better stability and handling quality which can provide safety and comfort driving for the driver. Vehicle stability control (VSC) is one of the important topics in vehicle dynamics and active chassis control and purposely to maintain the vehicle keep on the road or desired track/path where lateral force that exists in vehicle dynamic motion has great influence to the vehicle stability.

Yaw stability control system that purely based on kinematic and dynamics motion of vehicle is one of lateral control system that has been developed by researchers. The main objectives of vehicle yaw stability control are to control the yaw rate, vehicle sideslip or combination of them. Two major approaches of yaw stability control are using active steering control (ASC) and direct yaw moment control (DYC) that based on braking system such as active differential or active braking. A dynamic motion of vehicle is very nonlinear due to its robustness of uncertainties characteristics and disturbance that have great influences to vehicle stability. Hence, in order to cater this problem, a robust control algorithm is essential for vehicle stability control. These systems are believed to reduce the risk of accidents, improve safety, and enhance comfort and performance for drivers. The introduction of these new advanced driver assistance and active safety systems open new possibilities in accident prevention.

Active steering is an effective tool and most popular to control vehicle handling in where active front steering type has attracted more and more attention. Originally, this technology developed by German BMW Company and ZF Lenksysteme GmbH Company in 2003 as optional equipment for BMW vehicle from E60 5 Series and E63 6 Series models. This type of active front steering is use a power electric variable gear ratio power steering technology. The gear ratio is been controlled such that varies the degree that the wheels turn in response to the steering wheel. For the next generation's vehicle, the steer by wire system (SBW) is the one of the advanced technologies that will replace current electro mechanical system. The advantage of this system is it can prevent mechanical linkages of column shaft between steering wheel system and front wheel system.

1.2 Project Overview

In vehicle stability control, there are two common situations of vehicle dynamic during unstable condition that called understeering and oversteering as shown in Figure 1.1. Others possible situation occurred when vehicle disturbed by side wind and split road coefficient. All these conditions can be controlled by using Active Steering, Differential Braking, Traction Control, Active Suspension, or combination of these strategies.

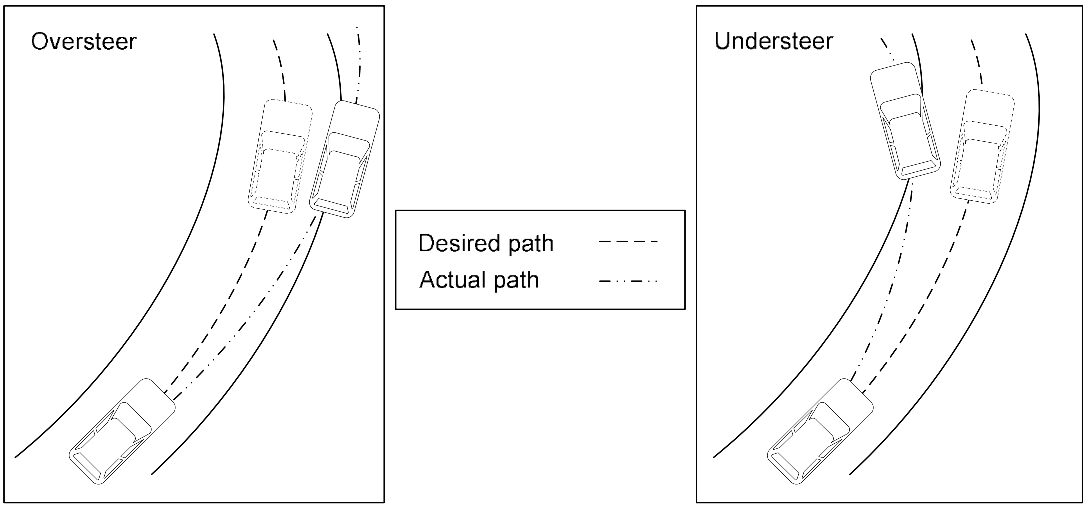

Figure 1.1 Understeering and oversteering situations

A skid normally occurs when the speed of the car is too fast for the normal road conditions. A skid hardly ever occurred at a slow speed. Severe braking can also cause a skidding. Many dangerous situations occurred on the roads because a car driver does not react fast enough at the beginning of skidding or rollover. Even on a normal road, sudden movement of the steering could make a car skid and will cause a critical driving situation. For example, when child crossing the road unexpectedly, this will force the driver to an evasive action. The inexperienced driver who caught in this kind of situation will easily overreact and destabilizes the car.

The aim of this study is to use CNF based active front steering control for vehicle yaw stability control of typical passenger cars for general some cornering manoeuvres with external disturbance. A vehicle control system using a 2 DOF controller that based on Composite Non-Linear Feedback (CNF) algorithm, will be proposed to enhance vehicle stability and improve system response especially during transient state.

1.3 Objective of Study

This research embarks on the following objectives:

I. To establish the dynamics modelling of vehicle.
II. To propose an Active Front Steering (AFS) based on Composite Nonlinear feedback (CNF) for Vehicle Stability Control (VSC).
III. To enhance performance of Vehicle Yaw Stability by using the proposed controller.

To achieve these objectives, various parameters involved such as vehicle construction parameters, tyre coefficient, and velocity will be considered. The vehicle modelling that involved body and tyre dynamic will be explored. Two main vehicle outputs, which play main important factor of vehicle stability, vehicle side slip and yaw rate will be observed and demonstrated by using the computer simulations. Performance of the proposed controller will be compared to conventional PID technique. Theoretical verification of the proposed controller on its stability and reachability will be accomplished by using a Lyapunov’s second method theory. The performance of the AFS system will be then observed by using extensive computer simulation that will be performed using MATLAB software and SIMULINK Toolbox subjected to various types of test manoeuvres and disturbance.

1.4 Scope of Project

The research work carry out in this project are concentrated to the following aspects:

I. Mathematical modelling of vehicle body and tyre dynamic vehicle using Matlab Simulink.
II. Implementation of Composite Nonlinear Feedback (CNF) control scheme for Active Front Steering (AFS) control in vehicle yaw stability system.
III. Simulation, validation and analysis of the Composite Nonlinear Feedback (CNF) performance based Active Front Steering (AFS) method.
IV. Evaluation of Composite Nonlinear Feedback (CNF) based Active Front Steering (AFS) control performance with Proportional Integral Derivative (PID) control strategy.

Research in vehicle stability is very wide to be explore, so some parameter need to be ignored without scarifies important factors involved in this CNF based active front steering research.

1.5 Research Methodology

The methodology of this research can be described by flow chart as shown in Figure 1.2.

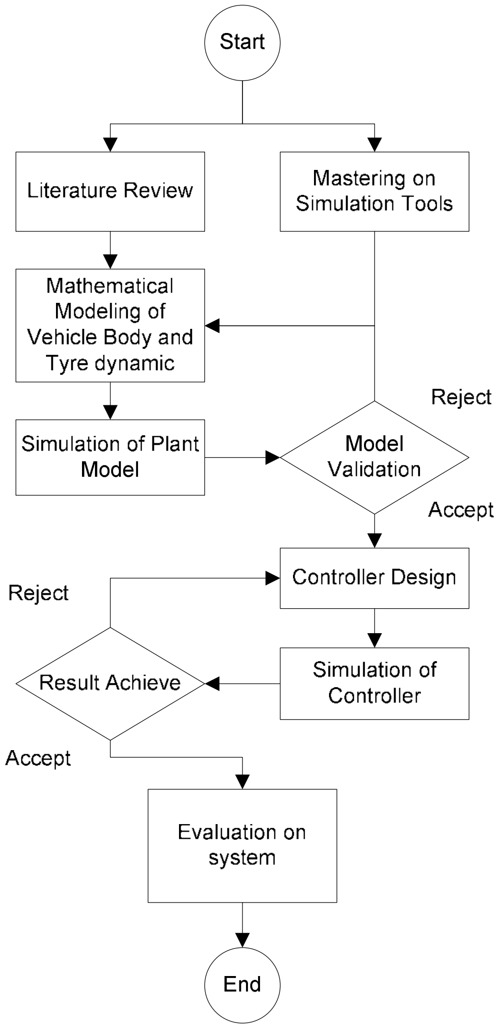

Figure 1.2 Research methodology flow chart

Start point of this research is a literature review where existing founding of vehicle stability conduct by researcher need to be carry out. On this stage, fundamental knowledge is very important. The basic knowledge for physic law applied in vehicle body and tyre dynamic need to be refreshing. Basic control knowledge such as state space, differential equation and stability law, include control strategy have to straighten as well. Thus, besides reading research papers, some fundamental books also need to read out. Besides of doing literature review, exercises and tutorials need to be done for mastering the simulations tools and some preliminary simulations need to be carried out as well.

The next step for this research is development of plant model. On this stage, car model based on two-track yaw plane have been carried out. Vehicle modelling contains body and tyre dynamics. A car body dynamic with 7 Degree of Freedom (DOF) will be constructed to model a vehicle as closed as actual one. Tyre dynamic model also is considered and in this research, Magic Formula is used in tyre modelling due to it is widely used by researchers. This research will be stressed on a dynamic mathematical modelling of vehicle and CNF control algorithm. The performance of proposed controller then will be evaluated by different types and level of car manoeuvres on nominal road adhesion coefficient, speed and disturbance as well. The task is to ensure stability, prevent skidding of vehicle, and remain the car at the desired path. This will be considered of the dynamics relationship of a car and take into account the yaw movement and lateral motion that make the car unstable.

The Active Front Steering system control strategy is required to minimize the yaw rate and side slip angle errors of vehicle during cornering manoeuvre. Various parameters will be observed such as relationship between slip angles and lateral forces on tire and uncertainties on the friction of the road surface and vehicle speed. Relationship on vehicle inputs, which is front wheel steering angle applied effect on vehicle side slip and yaw rate without controller have been evaluate by Matlab simulation software as preliminary result. Even though active steering control can overcome some of the vehicle handling problem, it only capable to drive the vehicle at moderate cornering level only. To overcome this limitation, controller with integration of active breaking is more effective method especially during high vehicle speed where tyre vehicle dynamic start to react in nonlinear regime. This automatic feedback system can assist the driver to overcome such dangerous situations. Robustness of the control system with respect to the various cornering manoeuvres and disturbance are very important.

After establish plant model and consider of control strategy, control solution has been considered. Basic controlling algorithm will be evaluated first. In this stage, famous conventional Proportional Integration and Derivative (PID) method is used. Then, new control strategy for active front steering car system will be proposed based on the Composite Nonlinear Feedback Control (CNF) approach. A CNF technique is proposed to improve the performance of the vehicle stability and road handling characteristic of the car especially at transient stage. To ensure the robustness of the proposed controller, various cornering manoeuvres together with disturbance will be applied to the system.

Finally, the proposed controller will be evaluated with extensive simulation work to determine the performance. Then, the performance of the system using CNF will be compared with PID technique, which is performed in previous work. The results will be then verified and analysed in time domain as typical linear analysis.

1.6 Literature Review

Vehicle stability implementation by active steering control can be seen in many research papers, mostly by Active Front Steering (AFS) (Q. Li et al. 2009; Ohara & Murakami 2008; Ma et al. 2010; Zhang et al. 2008; Mammar & Koenig 2002; Nam et al. 2009; Zheng & Anwar 2009; Kawaguchi et al. 2007; Guo & Feng 2011; Falcone, Borrelli, et al. 2008; Y. C. Chen et al. 2010; Marino et al. 2011; Kunsoo Huh 1999; Nor Maniha 2006; Fujimoto & Yamauchi 2010; Wanzhong et al. 2011; Namuduri et al. 2009; Wen et al. 2009; Q. Li et al. 2010; Solmaz, Corless & R Shorten 2007; Yamauchi & Fujimoto 2008). This is an effective way to ensuring stable cornering at moderate levels by driver commanded steering. Based on active steering actuator, there are two type of approach available today which are Mechatronics-angle-superposition and a new steer-by-wire (SBW) technology. For old approach, such in Tongue (2005) show a BMWs active steering mechanism who is a pioneer of this front steering system technology. Implementation of fully steered wheel control (Both front and rear wheels), also known as Four Wheel Steering

(4WS) is another type of active steering system and can be found in some papers (B. Li & Yu 2009; F. Du et al. 2010; Nor Maniha 2006; Ghani & Sam 2007; Wen et al. 2009) and even though this method seems more complicated but it is more efficient way to control vehicle stability. This can be seen during high level of speed cornering, the steady yaw rate of vehicle for 4WS is less than AFS that means at same cornering, driver workload can be reduced drastically.

Direct Yaw Moment Control (DYC) method also widely used by researchers (Mirzaei 2010; B. L. Boada et al. 2005; Canale et al. 2008) until today. It is an effective solution for high tyre slip angles, where tyre region is not linear anymore. To extend performance of a stability system in wider range, ASC and DYC Integration (He 2005; Ding & Taheri 2010; Falcone, Eric Tseng, et al. 2008; Tjønnås & Johansen 2010; Baslamisli et al. 2011) was made. Besides, others methods are such as controlling vehicle stability by Integration of ASC and Active Suspension (Lai & Deng 2009) and ASC and DYC with Active stabilizer also available (D. Li et al. 2008). These methods proposed by researchers to improve vehicle limit performance and mainly to enhance ride comfort.

From all these papers that have been read, maximum degree of freedom (DOF) for nonlinear vehicle model used is 27 which use CarSim vehicle dynamic modelling software from Mechanical Dynamics Corporation (MSC) (B. Li & Yu 2009; Marino et al. 2011; Nam et al. 2009; Solmaz, Corless & R Shorten 2007; Solmaz, Corless & Robert Shorten 2007). Reduce order version of 14 DOF vehicle model also been used (Canale & Fagiano 2010; Kunsoo Huh 1999). The 8 DOF vehicle model as in F. Du et al. (2010) and He (2005) is a simplify version which present roll, yaw, longitudinal, lateral and rotation motion of four wheels of car. By assuming stiff suspension of vehicle will simplify again vehicle body dynamic, producing vehicle model of 7 DOF (Ma et al. 2010; Mammar & Koenig 2002; Nam et al. 2009). The 7 DOF is so called nonlinear yaw plane two track model is less complex and low computational burden, thus become favour among researcher. The use of 2 DOF vehicle model (Q. Li et al. 2009; Ohara & Murakami 2008; Y. C. Chen et al. 2010; Fujimoto & Yamauchi 2010; Q. Li et al. 2010) is still available and it is a basic modelling to present vehicle motion. Other than that, the ADAMS/CAR software also is used for simulation result validation (Zhang et al. 2008; Guo & Feng 2011). This software is highly dependable and it used to simulate the real vehicle before the prototype is built (Westborm and Frejinger, 2006).

In the research of active steering, most of researcher did not mention about type of tyre dynamic equation used in their controlled plant. This is because of in this control system, tyres still in linear regime so it is not relevant to discuss about tyre dynamic where only become important when active braking controller is used. However, when they use CarSim software to present vehicle plant model automatically we know that the Magic formula is used. However, without consider tyre dynamic that may tend to enter nonlinear region we cannot see limitation of active steering realistically. There is several method to represent tyre model and most famous one is Pacejka tyre model so called Magic Formula (Ma et al. 2010; Mammar & Koenig 2002; Kawaguchi et al. 2007; Kunsoo Huh 1999). Other than that, is such as Dugoff tyre model which use in paperwork of F. Du et al. (2010). Linearize version of Magic formula also can be used when assuming tyre lateral slip angle is almost zero (Canale & Fagiano 2010). Even though above mention tyre modelling is use to formulate a tyre behaviour accurately, but by assuming tyre in linear region is still relevant to present overall plant behaviour in low level cornering manoeuvres as in some papers (Ghani & Sam 2007; Fujimoto & Yamauchi 2010).

Various control strategies have been proposed by researchers to improve vehicle stability by active steering method. As highly demand on electric vehicle nowadays, research area for typical vehicle now expending into electric vehicle as well (Nam et al. 2009; Fujimoto & Yamauchi 2010; Yamauchi & Fujimoto 2008; Wanzhong et al. 2011) and thus open a new field and more opportunities to be explore.

Four wheel active steering has been investigate base on analysis of deficiency of conventional 4WS method (B. Li & Yu 2009). A model following control structure based on 2 DOF single track model is designed to follow desired yaw rate and side slip angle of vehicle. Optimal control theory was used in this research and reported that this method has better handling performance compare with conventional one if disturbance is not considered. To cater uncertain parameter that very complex in vehicle system with external disturbance and perturbation, Sliding Mode Controller is used by F. Du et al. (2010), for 4WS vehicle model. This robust controller can overcome greatly influence of uncertain factor on the manoeuvrability of 4WS car and effectively prevent the loss of vehicle stability. Besides, it also can ensure the car steering quality by prevent steering from making significant change.

Ohara & Murakami (2008), proposed a Proportional Derivative (PD) controller for active front steering vehicle. Strength of this research was they use side slip observer in controlling the yaw rate of vehicle. Side slip angle value, which is very important for stabilizing a vehicle in real world, cannot obtain directly from typical sensor. The novel linear observer that has minimum estimation error then was compared with conventional linear observer.

Controlling of vehicle yaw stability by Fuzzy logic based AFS also can be seen (Ma et al. 2010). In this method, the yaw rate error and its derivative are applied to the controller inputs. The performance of designed controller then has been implementing on 8 DOF nonlinear vehicle model and verified trough simulation and it is proved that this method capable to control yaw stability of car effectively.

Development of an AFS by Quantitative Feedback Theory (QFT) presented by Zhang et al. (2008). This type of controller have a robust performance that required to ensure steering response not influence by uncertain quantities such vehicle mass, velocity, and road conditions. A multi DOF nonlinear vehicle model was co simulated by Matlab Simulink and ADAM/CAR to evaluate the performance of a new controller. Under various manoeuvres and road conditions, the control system had robust performance to improve the dynamic response so that vehicle always maintain in it desired path.

Mammar & Koenig (2002) proposed Linear Fractional Transformation (LTF) based feedfoward and feedback H_∞ control to improve vehicle handling after investigate stability aspects of vehicle lateral motion. The control action is applied as a summation of user input and corrective angle produced by controller. The synthesis method simply allows time domain direct specification objectives such in reference model matching. By obtain both feedback from both yaw rate and front steering angle, we can achieves the decoupling of lateral and yaw motion and yaw damping of vehicle simultaneously (Zheng & Anwar 2009). Trade-off between robust decoupling and yaw rate damping through adjustment of feedback gain respected to vehicle velocity can be used for gain schedule steering controller to provide the desired yaw rate damping while maintain the yaw lateral motion decoupled.

Other than that, there are many others control method proposed in active front steering such as Adaptive Nonlinear Control (Kawaguchi et al. 2007), Model Predictive Control (MPC) (Falcone, Borrelli, et al. 2008), Mu Control Theory (Y. C. Chen et al. 2010), Fuzzy logic (Q. Li et al. 2010) and PID (Namuduri et al. 2009).

As reviewed in previous paragraph, so far there are no research works for Composite Nonlinear Feedback so called CNF technique applied in vehicle stability. This is a nonlinear control technique, where consists of a linear feedback law and a nonlinear feedback law without any switching element. The purpose of linear feedback is to yield a closed-loop system with a small damping ratio for a quick response, but not exceeding the actuator limits. The nonlinear feedback then is used to increase the damping ratio as the system output approaches the target reference, so that overshoot phenomena can be avoided.

CNF technique has been propose by Z. Lin et al. (1998) as a new method to achieve accurate tracking in linear system. In that paper, he continues his previous work with Saberi (1995) and demonstrates the effectiveness of CNF implementation on modern flight control application. Their works extend later by Turner et al. (2000) for high order multivariable linear system, and successfully demonstrate at Helicopter pitch control and MIMO missile control and then applied CNF in hard disk and prove that CNF can beat Time Optimal Control in asymptotic tracking situation. His group also had expend CNF to more general technique by introduce 3 different cases in control feedback method, i.e. the state feedback, the full order measurement feedback and reduced order measurement feedback.

Selection of nonlinear gain in CNF is very important to ensure controller can track smoothly and not sensitive to variation of amplitude of target reference. In that means Lan & B. M. Chen (2007) review some of nonlinear function and introduce new function with solution to find suitable value of nonlinear function parameter by solving minimization problem. They investigate two performance criteria, the Integral of Absolute Error (IAE) and the Integral of Time multiplied Absolute value Error (ITAE) where both can be used to tuned nonlinear parameter. This research work also has been carry out for some researchers (Lan et al. 2010).

Classical CNF control method cannot be implementing directly on singular system. The study on this matter has be carried out by introduce pre-linear feedback law to singular system and this guarantee the impulsive freeness (D. Lin et al. 2010). The CNF solution for system with disturbance proposed by Peng et al. (2005) during considering friction and nonlinearities in hard disk drive (HDD) servo system. The enhance CNF control technique has a feature to composite disturbance without scarifying overall tracking performance. Similar study has been carried out then by some researcher for a system with unknown constant disturbance (Schmid & Lan 2007; Guoyang & Wenguang 2006).

As part of research in robust CNF to handle disturbance, Cheng & Peng (2007) introduce a new technique without integrator term as usually used from previous work. The basic idea of this method is based on combination of disturbance estimation and compensation into original framework of CNF so the steady state bias of disturbance can be eliminate, with at the same time retain the performance of initial CNF control.

To track general target reference , CNF can be developed by introducing reference generator, which able to produce more general reference such as sinusoidal and others wave profile (Cheng et al. 2007). This method comprises the modified CNF control law and reference generator to tracking a target reference with fast settling time without overshoot and proven in XY-table trajectory tracking control.

As been reviewing so far, current CNF technique cannot handle uncertainties situation, which is normal in most application. Due to this disadvantage, integration with others controller is necessary. In that means, Mondal & Mahanta (2011) combine CNF with Discrete Integral Sliding Mode (ISM) to achieve high transient performance on uncertain systems. As result, new proposed CNF-ISM controller successfully designed on SISO and MIMO uncertain systems and has superior transient performance compare with normal ISM.

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