ENHANCED ACTIVE FRONT STEERING CONTROL USING SLIDING MODE CONTROL UNDER VARYING ROAD SURFACE CONDITION

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ABSTRACT

In vehicle lateral dynamic control, the handling quality or steering ability of the vehicle is determined by the yaw rate response performances. The uncertainty of tire cornering stiffness due to varying tire-road adhesion coefficient, μ caused by road surfaces perturbation during cornering manoeuvre may influence the transient performances of yaw rate response. Therefore, in this research, the enhanced control law of robust yaw rate tracking controller using the Sliding Mode Control (SMC) algorithm is proposed for active front steering (AFS) control strategy to improve the yaw rate response as desired. The vehicle lateral dynamics behaviors are described using the linear and nonlinear vehicle models. The linear 2 degree-of-freedom (DOF) single track model is used for controller design while the nonlinear 7 DOF two-track model is used for simulation and controller evaluations. The sliding surface of SMC is design based on yaw rate tracking error information. The control law equation is enhanced by integrating the uncertainty of cornering stiffness at the front wheels and to ensure the controller stability, the Lyapunov stability theory is applied. The transient performances and performance indices of AFS control responses are evaluated using the step steer and single lane change cornering manoeuvres test for varying values of μ at dry, wet and snow or icy road surfaces. The simulations results demonstrated that the proposed enhanced control law using SMC is able to track the reference yaw rate with similar transient response performances. The proposed enhanced control law also provided low performance indices of ITAE and IAE compared to the conventional control law using SMC and robust CNF control for lower value of μ at wet and snow or icy road surface. In terms of percentage of differential performance indices, the proposed control law has a better tracking ability of up to 58.45% compared to two other control laws. Therefore, this research concluded that the proposed enhanced control law using SMC has overcome the cornering stiffness uncertainty in AFS control strategy for different road surfaces during cornering manoeuvre and this enhancement is expected as a knowledge contribution to vehicle lateral dynamic study.

ABSTRAK

Di dalam kawalan sisi dinamik kenderaan, kualiti pengendalian atau keupayaan-pengemudian kenderaan ditentukan oleh prestasi sambutan kadar rewang. Ketidaktentuan kekakuan belokan kerana pekali geseran tayar-jalan, μ yang pelbagai dan berubah-ubah disebabkan oleh gangguan permukaan jalan semasa pengemudian membelok boleh mempengaruhi sambutan fana kadar rewang. Oleh itu, dalam penyelidikan ini, hukum kawalan ditambahbaik pada pengawal teguh penjejakan kadar rewang menggunakan algoritma kawalan mod gelongsor (SMC) dicadangkan sebagai strategi kawalan aktif stereng hadapan seterusnya menambahbaik sambutan kadar rewang seperti yang dikehendaki. Tingkahlaku dinamik sisi kenderaan dihuraikan dengan menggunakan model kenderaan lelurus dan tidak lelurus. Model lelurus 2 darjah kebebasan (DOF) jejak tunggal digunakan untuk merekabentuk pengawal manakala model tidak lelurus 7 darjah kebebasan (DOF) dua-jejak digunakan untuk simulasi dan penilaian pengawal. Permukaan gelangsar pada SMC adalah direkabentuk berdasarkan maklumat ralat penjejakan kadar rewang dan ketidaktentuan kekakuan belokan pada roda hadapan dimasukkan di dalam persamaan hukum kawalan ditambahbaik dengan kestabilan dianalisis menggunakan teori kestabilan Lyapunov. Prestasi fana dan indeks prestasi sambutan kawalan AFS dinilai menggunakan ujian kemudi langkah dan perubahan lorong tunggal untuk pelbagai nilai μ pada jalan kering, basah dan salji atau berais. Keputusan simulasi menunjukkan bahawa hukum kawalan yang ditambahbaik menggunakan SMC berkeupayaan menjejak kadar rewang rujukan dengan prestasi sambutan fana yang hampir sama. Hukum kawalan ditambahbaik yang dicadangkan juga menunjukkan indeks prestasi ITAE dan IAE yang rendah berbanding hukum kawalan konvensional menggunakan SMC dan kawalan teguh CNF untuk nilai μ yang lebih rendah iaitu di permukaan jalan basah dan bersalji atau berais. Dari segi perbezaan peratusan indeks prestasi, hukum kawalan yang dicadangkan mempunyai keupayaan pengesanan yang lebih baik sehingga 58.45% berbanding dua hukum kawalan yang lain. Oleh itu, disimpulkan bahawa hukum kawalan ditambahbaik yang dicadangkan menggunakan SMC dapat mengatasi ketidaktentuan kekakuan belokan di dalam strategi kawalan AFS untuk permukaan jalan yang pelbagai dan berubah-ubah semasa pengemudian membelok dan penambahbaikan ini dijangkakan sebagai sumbangan pengetahuan kepada kajian dinamik sisi kenderaan.

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LIST OF ABBREVIATIONS

LDWS - Lane Departure Warning System
LKS - Lane Keeping System
AFS - Active Front Steering
ARS - Active Rear Steering
4WAS - Four Wheel Active Steering
CNF - Composite Nonlinear Feedback
SMC - Sliding Mode Control
DOF - Degree of Freedom
CoG - Centre of Gravity
DYC - Direct Yaw Moment
ASC - Active Steering Control
ABS - Antilock Braking System
TCS - Traction Control System
ESC - Electronic Stability Control
EBD - Electronic Brakes Distribution
FLC - Fuzzy Logic Control
PID - Proportional Integral Derivative
LPV - Linear Parameter Varying
QFT - Quantitative Feedback Theory
MRAC - Model Reference Adaptive Nonlinear Control
LQR - Linear Quadratic Control
GIMC - Generalized Internal Model Robust Control
ISO - International Standard Organization
SAE - Society of Automotive Engineers
SILS - Software In The Loop Simulation
HILS - Hardware In The Loop Simulation

SISO	-	Single Input Single Output
VSC	-	Variable Structure Control
ISM	-	Integral Sliding Mode
SSM	-	Step Steer Manoeuvre
SLCM	-	Single Lane Change Manoeuvre

LIST OF SYMBOLS

μ - tire-road adhesion coefficient

δ_f - front wheel steer angle

δ_c - corrective steer angle

δ_{fd} - driver steer angle

δ_{sw} - driver steering wheel angle

φ - roll angle

θ - pitch angle

ψ - yaw angle

$\dot{\varphi}$ - vehicle roll rate

$\dot{\theta}$ - vehicle pitch rate

$\dot{\psi}$ - vehicle yaw rate

F_y - vehicle lateral force

F_x - vehicle longitudinal force

F_z - vehicle vertical force

M_x - vehicle roll moment

M_y - vehicle pitch moment

M_z - vehicle yaw moment

F_{xi} - tire longitudinal force

F_{yi} - tire lateral force

M_{zi} - tire yaw moment

β - vehicle side slip

m - vehicle mass

d - vehicle width track

l_f - distance of front axle to CoG

l_r - distance of rear axle to CoG

I_z - moment of inertia

C_f - nominal front tire cornering stiffness

C_r - nominal rear tire cornering stiffness

v - vehicle speed or velocity of CoG

v_x - vehicle longitudinal velocity

v_y - vehicle lateral velocity

λ_i - tire slip ratio

α_i - tire side slip angle

I_{wi} - wheel inertia

ω_i - wheel angular acceleration

R_i - wheel radius

T_{ei} - driving torque

T_{bi} - braking torque

v_{wi} - wheel's ground contact speed

α_f - front tire side slip angle

α_r - rear tire side slip angle

$\hat{C}_f$ - actual front tire cornering stiffness

$\hat{C}_r$ - actual rear tire cornering stiffness

$\hat{C}_f$ - actual front tire cornering stiffness

ΔC_f - deviation value of front tire cornering stiffness

ΔC_r - deviation value of rear tire cornering stiffness

β_d - desired vehicle side slip

r_d - desired vehicle yaw rate

β_{lim} - bounded vehicle side slip

r_{lim} - bounded vehicle yaw rate

k_u - cornering stability factor

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CHAPTER 1

INTRODUCTION

1.1 Research Background and Motivation

Nowadays, a vehicle play a very important role as a means of transportation to travel from one place to another place. For daily activities, the ground vehicle such as car passenger is becoming main necessary in human life. One of the essential aspects of ground vehicle is its dynamics control to ensure the vehicle is moving in a stable and safe condition. The vehicle dynamics control may be divided into 3 types of control action i.e. longitudinal control, lateral control and vertical control [1–4]. Conventionally, the longitudinal control which closely related to the vehicle acceleration, speed and braking are controlled by the driver via throttle and brake paddle. For the lateral control, the handling or steer-ability is accomplished via the driver's steering wheel while for the vertical motion, the suspension actuator will influence the ride comfort of the vehicle.

The lateral force that exists in vehicle dynamic motion has a significant influence to the vehicles handling and lateral stability. During cornering manoeuvre, a proper handling of the vehicle is necessary so that the driver can control the vehicle to follow the road path. In the vehicle handling and stability issues, steering control by the driver is crucial as it will determine the direction of the vehicle and its yaw motion's stability.

In taking a cornering, the vehicle could skidding and drifting out from the path depending on the vehicle's speed and tire-road friction coefficient, μ. In this condition, an average driver may exhibit panic reactions where he/she is inappropriate to control the steering in an effective manner. This situation could lead the vehicle to become unstable and cause an accident. There are two common situations of unstable vehicle called understeer and oversteer conditions as depicted in Figure 1.1. If the μ were small or if the vehicle speed were too high, then the vehicle would be unable to follow the nominal motion required by the driver where it would instead travel on a trajectory of

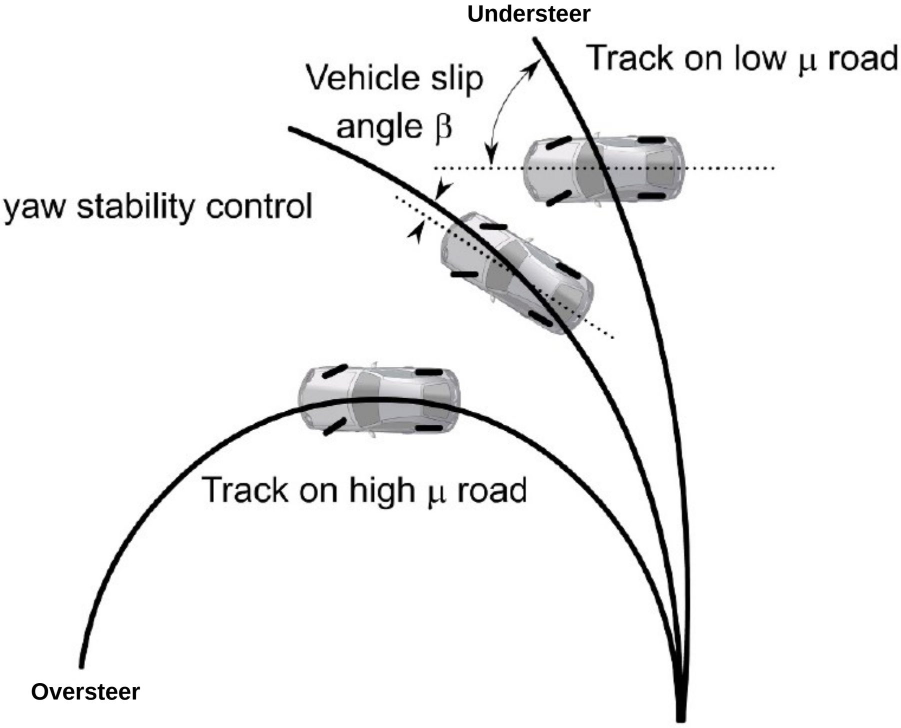

Figure 1.1: Understeer and oversteer of cornering manoeuvre [1]

larger radius (smaller curvature), as shown in the upper curve. This circumstances is known as understeer condition. On the other hand, the lower curve shows the trajectory that the vehicle would follow in response to a steering input from the driver if the road surface were dry and had a high μ. In this oversteer condition, the high μ is able to provide the lateral force required by the vehicle to go through the curved road. In the case of oversteer, on a constant radius turn, the steer angle will have to decrease as the vehicle's speed will be increased. If the μ is very small, it might not be possible to entirely achieve the nominal yaw rate motion that would be achieved by the driver on a road surface with high μ . In this case, the yaw stability control system would partially succeed by making the vehicle's yaw rate closer to the expected nominal yaw rate, as shown by the middle curve. In this case known as neutral steer, on a constant radius turn, no change in the steering angle is required. To avoid the above circumstances, the lateral dynamics control has become a major concern among vehicle researchers and manufacturers to provide an active safety feature of vehicle handling. With this feature, it could assist the driver to keep the vehicle stable on the desired path and prevent from drifting out of the road as shown in the middle curve of Figure 1.1. As an active safety

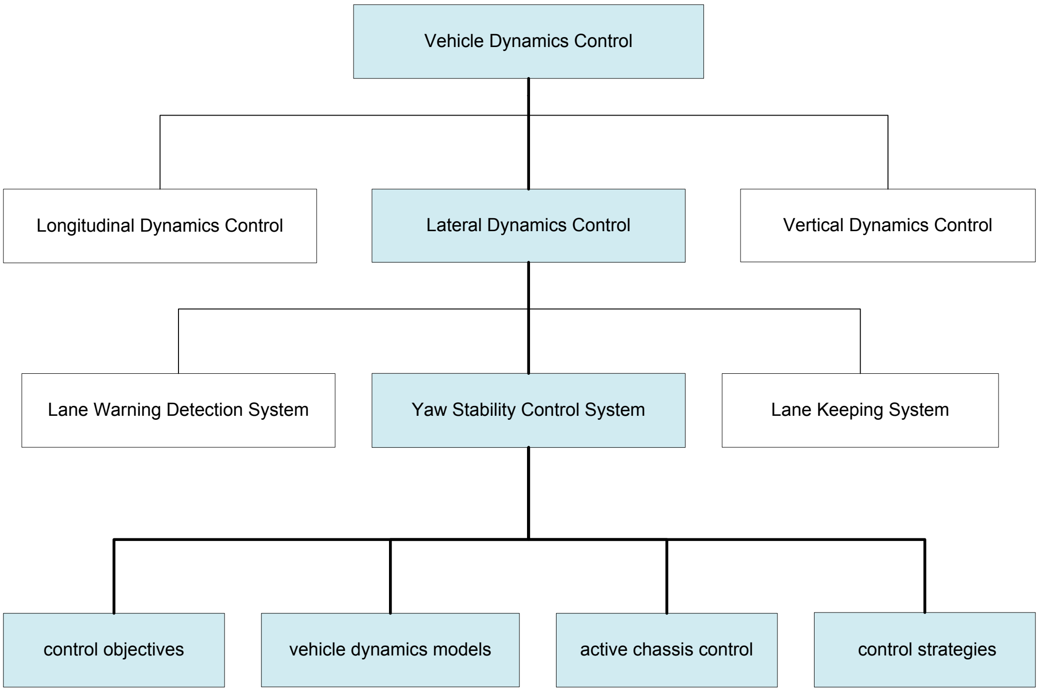

Figure 1.2: Yaw stability control system for vehicle lateral dynamic control

features of the car passenger is becomes important, this research is emphasize on the vehicle handling to improve the lateral dynamics control.

According to [1–4], there are three types of lateral dynamics control has been investigated and developed by researchers in academics and automotive industry i.e. a yaw stability control system, lane departure warning system (LDWS) and lane keeping system (LKS). Compared to LDWS and LKS which required a special hardware and software in the vehicle and also extra devices on the road, a yaw stability control system is purely based on the vehicle kinematics and dynamics. Hence, a yaw stability control system is becoming a favourite approach for vehicle lateral dynamics control. To design an effective yaw stability control system, it is essential to determine the main elements of the control system. These elements may consist of control objectives, vehicle dynamic models, active chassis control and control strategies as depicted in Figure 1.2. A yaw stability control objectives are deeply concerned with the vehicle's yaw rate and the side slip angle. Controlling an actual yaw rate close to the desired yaw rate response means improving the handling of the vehicle. As discussed in [3, 5], the improvement of vehicle handling is achieved by reducing the yaw-rate error between the actual yaw rate and the desired yaw rate based on the driver's steering input. On the other hand, the control of side-slip angle close to steady state condition's value means maintain the lateral stability of the vehicle. Thus, by keeping the yaw rate close to the nominal motion of driver's intended and vehicle side-slip angle as steady state condition, a yaw stability control system could improve the handling and lateral stability performances during taking a cornering manoeuvre.

The vehicle models that described the behaviour of lateral dynamic is necessary in yaw stability control system. An appropriate linear and nonlinear vehicle model with tire dynamics models for controller design and simulation will be reviewed and determined. To analyze the yaw stability control, the planar vehicle models in lateral and longitudinal motions which neglected the pitch and roll motions could be utilised.

According to [1–4], a yaw stability control system could be implemented via active chassis control that based on braking and/or steering actuator. In the differential braking or active torque distribution which utilize the brake actuator, a yaw stability control is achieved based on direct yaw moment control principle where the required yaw moment is generated by the controller to track the desired yaw rate response and side-slip angle. In active steering control, a steering wheel angle that commanded by the driver is modified by adding corrective steering angle from the designed controller. Nowadays, research on direct yaw moment control based on braking system has been established and already available in modern vehicles. Therefore, active steering control studies are preferred and becomes popular research topics among researcher.

Active steering control is effective for steady state condition of driving i.e. the tire dynamics is exhibit as a linear characteristics during low to mid range of vehicle lateral acceleration. The early works on active steering control has been implemented in [6–8]. In active steering control, the driver steer angle is modified by added with corrective steer determined by controller in order to track the desired yaw rate. In general, active steering control can be categorised into active front steering (AFS) control, active rear steering (ARS) control and four wheel active steering (4WAS) control. Modern car passenger is usually fitted with front wheel steering actuator system, therefore the AFS control is more attracted in active steering control compared to two others. In AFS control, the main objective is to ensure the designed controller is able to track the desired yaw rate produce by the reference model. It is required that the actual yaw rate has fast response and good tracking capability in following the desired response. By keeping the vehicle yaw rate close to the nominal motion of driver's intended, AFS control could improve the handling quality of the vehicle during cornering manoeuvre.

There are numerous control strategies has been explored in yaw stability control system studies. In order to achieve the control objectives, a particular control algorithm is formulated and applied such as classical proportional-integral-derivative control, linear quadratic control, static state feedback control, model predictive control, fuzzy logic control, composite nonlinear feedback control and few others. Although all these control schemes performed very well for tracking the desired yaw response, their designed purpose are not to cater the perturbation and disturbance especially in real driving conditions.

One of the perturbation that may exist during driving the road vehicle is various road surfaces such as dry, wet and snow or icy road. Therefore, there are various value of tire-road friction coefficient, μ and its also varying according to the changes of actual road surfaces along the driving path. According to the vehicle dynamics studies, the various value of μ make the vehicle cornering stiffness becomes uncertainty when the vehicle in cornering manoeuvre. To overcome the uncertainty due to this circumstances, robust control algorithms are proposed such as internal model control, optimal guaranteed cost coordination control, H_∞ control, quantitative feedback control, sliding mode control, μ-synthesis control and robust CNF control. To determine an appropriate robust control algorithm for AFS control, these previous control strategies and algorithms are reviewed and analysed in Chapter 2. From the literature review and analysis, these control algorithm does not design to overcome the deviation of cornering stiffness uncertainty when the value of μ is varying from one value to another i.e. when the road surface is suddenly changed. Therefore, this research gap has motivated this research to propose an enhanced AFS control law.

1.2 Problem Statement

The handling quality of ground vehicle depends on the performances of yaw rate response. To ensure a good and better handling quality, a vehicle should have a fast response and minimum oscillation towards the steady state motion. On various road surfaces condition that directly contact with the tires may influence the tire forces and vehicle lateral dynamics during cornering manoeuvre. The tire-road friction coefficient, μ which depends on road surface condition are ranged between from 0.1 to 1 may cause the uncertainty of tire cornering stiffness where an actual tire cornering stiffness and lateral tire forces are depending on this value of μ. Consequently, the various of μ and uncertainty of cornering stiffness will influence the transient performances of yaw rate response and affect the handling quality of the vehicle. Therefore, a robust yaw rate tracking controller is necessary to improve the transient performances of yaw rate response and enhanced the handling quality.

Based on the literature review analysis, the sliding mode control (SMC) is identified as a robust control algorithm that posses simplest designed procedures i.e. two steps only which are design the sliding surface and design the control law. On top of that, it has robustness properties to the uncertainties due to any perturbations in the system or external disturbances. There are numerous research studies in vehicle dynamics control especially yaw stability control system has applied and improved this robust control algorithm. Therefore, the SMC is examined for the AFS control strategy in this research. In the previous AFS control research works that implemented the SMC, the control law designed to only accommodate the cornering stiffness uncertainty for the fixed or dedicated value of μ for a particular road surface. In real driving conditions, the varying of μ i.e. road surface condition is changed from one to another suddenly during a cornering manoeuvre is unexpected. The deviation of cornering stiffness uncertainty due to this circumstances is not considered in previous AFS control law designed.

To ensure the proposed enhanced AFS control law could overcome this problem, the effect of tire cornering stiffness uncertainty is evaluates with various value of μ i.e. for dry, wet and icy/snow road surface conditions. These three road conditions are considered as a classical assumption that implemented in previous studies. To extend the effectiveness of yaw rate tracking controller capability, a sudden or immediate changes of μ is conducted for four different circumstances in this research. The proposed enhanced AFS control law is evaluated for the changes of dry to wet road surface, wet to dry road surface, wet to snow/icy road surface and snow/icy to wet road surface. This analysis which is never carried out in AFS control strategy is considered as a new analysis in AFS control studies.

1.3 Research Objectives

The main goal of this research is to enhance the lateral dynamics and handling quality of the vehicle. Specifically, this research embarks with the following objectives:

i. To improve the yaw rate response performances of AFS controlled vehicle
ii. To design an enhanced AFS control law using the sliding mode control (SMC) algorithm under various and varying road surface conditions.
iii. To implement the proposed enhanced AFS control law and evaluate the yaw rate responses under various and varying road surface conditions.

1.4 Scope of Works

To achieve an above objectives, this research are implemented within the scopes of work as follows;

i. The 7 degree-of-freedom (DOF) two track nonlinear model is used to simulate a full vehicle model while the linear 2 DOF single track model is utilized for the controller design. For the lateral motion analysis, the vehicle models are assumed moving on planar motion with constant speed while roll and pitch motions are neglected as assumed and analyzed by other prominent researchers in vehicle dynamics studies [1–3]. For validation purpose, the responses of 7DOF vehicle model are compared with CarSim vehicle model i.e. the commercial software of vehicle dynamics as conducted in [9] and other research works.

ii. The vehicle parameters are taken from the [9] which is based on sedan car of Ford Taurus GL.

iii. The front wheel steer angle input of AFS control is only up to 2 degree for low to mid range of lateral acceleration.

iv. The propose enhance control law for AFS control strategy is focus on vehicle yaw rate as a control objective with the vehicle side slip is assumed not exceed the bounded value.

v. Only the front tire cornering stiffness is treated as uncertainty of vehicle parameters due to varying road surface conditions as its effected the performances of yaw rate response.

vi. The controller design and evaluation is conducted in fully computer simulation. The vehicle models and controller design are established using Matlab/Simulink environment.

vii. Two controller gains of SMC are taken from previous research in [10, 11]. The AFS control law designed in this research is re-visited and improvised as enhanced AFS control law.

viii The proposed enhanced control law is evaluate, compared and analyzed with conventional control and CNF robust control.

1.5 Thesis Organization

This thesis is organized in five chapters. Chapter 1 briefed the research background and motivation, problem statement, research objectives, scope of works and thesis structure.

Chapter 2 reviews the vital elements for a yaw stability control system design i.e. the yaw control objectives, vehicle dynamic models, active chassis control and control strategies with the focus on identifying suitable criteria to improve the performances of yaw rate response in AFS control. The fundamental of robust control of SMC to achieve the control objective are also reviewed in this chapter.

In Chapter 3, the AFS control design methodology which consists of vehicle dynamic models, test manoeuvres and enhanced control law design procedure are discussed. The linear 2 DOF single track model for controller design and 7 DOF nonlinear two track model for controller evaluation are presented and explained. The design procedures of enhanced AFS control law for robust yaw rate tracking controller using the sliding mode control (SMC) are detailed in this chapter.

In Chapter 4, the results of AFS control simulations obtained are presented. The steers input, vehicle model validations with CarSim software and the vehicle's yaw rate responses of proposed enhanced control law are compared with the conventional control law and robust CNF control are discussed and analysed. The transient performances of yaw rate response and the performance index of ITAE and IAE are evaluated and analysed for various and varying road surface conditions.

Finally, Chapter 5 concludes this research work, research contributions and recommend some future works that can be further investigated.

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Appendix A List of Publications

Indexed Journal (SCOPUS)

1. **MK Aripin**, Yahaya Md Sam, Kumeresan A Danapalasingam, Kemao Peng, N Hamzah, MF Ismail, "A review of active yaw control system for vehicle handling and stability enhancement." International Journal of Vehicular Technology, Vol.2014, Article ID 437515, 15 pages, 2014.
2. **MK Aripin**, YM Sam, AD Kumeresan, Peng Kemao, MF Ismail, "A review on integrated active steering and braking control for vehicle yaw stability system Jurnal Teknologi.", Vol.71,No.2, pp.105-111, Jurnal Teknologi (Sciences and Engineering), 2014.
3. **MK Aripin**, YM Sam, Kumeresan AD, MH Che Hasan, M Fahezal Ismail, "Improving Transient Performances of Vehicle Yaw Rate Response Using Composite Nonlinear Feedback." Journal of Theoretical & Applied Information Technology, Vol.95,No.11, pp.2567-2576, 2017.
4. MHC Hasan, YM Sam, **MK Aripin**, MH Harun, SH Mohamad, "Implementation of robust composite nonlinear feedback for active front steering based vehicle yaw stability." Jurnal Teknologi (Sciences and Engineering), Vol.79,No.5-2, pp.39-43, 2017.
5. L Ramli, YM Sam, Z Mohamed, **MK Aripin**, MF Ismail, "Composite nonlinear feedback control with multi-objective swarm optimization for active front steering system." Jurnal Teknologi (Sciences and Engineering), Vol.72,No.2, pp.13-20, 2015.

Indexed conference proceedings

1. **MK Aripin**, YM Sam, AD Kumeresan, K Peng, MHC Hasan, MF Ismail, "A yaw rate tracking control of active front steering system using composite nonlinear feedback control" in Asia Simulation Conference (AsiaSim), pp.231-242, Singapore, 2013.

2. **MK Aripin**, YM Sam, Kumeresan Danapalisingam, R Ghazali, M Fahezal Ismail, " Uncertainty modeling and high performance robust controller for active front steering control" in 10th Asian Control Conference (ASCC), pp.1-6, Sabah, 2015.
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