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IMPLEMENTATION OF ROBUST COMPOSITE NONLINEAR FEEDBACK FOR ACTIVE FRONT STEERING BASED VEHICLE YAW STABILITY

Mohd Hanif Che Hasan[a]*, Yahaya Md Sam[b], Muhamad Khairi Aripin[c], Mohamad Haniff Harun[a], Syahrul Hisham Mohamad[a]

[a]Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[b]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
[c]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

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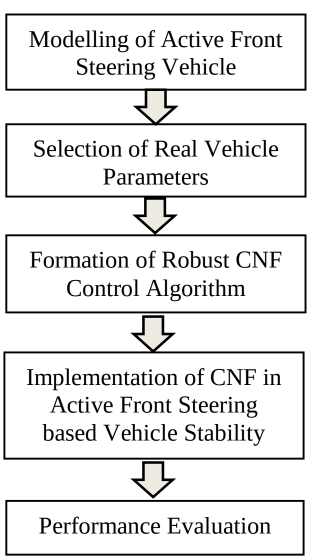
*Corresponding author
hanif.hasan@utem.edu.my

Graphical abstract



Abstract

In this paper, Robust Composite Nonlinear Feedback (CNF) was implemented on Active Front Steering (AFS) vehicle system for yaw stability control. In this control system, the main objective is to get excellent transient response of vehicle yaw rate and at the same time resist to side wind disturbance. To cater unknown constant disturbance, non-integral function for Robust CNF version is used. Meanwhile for vehicle model, 7 degree of freedom vehicle body with Pacejka Tire formula model for typical passenger car is used to simulate controlled vehicle. The computer simulation by Matlab software is performed to evaluate the system performance in J-Turn and Single sine steer with magnitude from 1 to 3.1 degree with additional 400 Nm external side wind disturbance. By using typical Proportional Integration and Derivative (PID) control auto-tuned by Matlab as comparison, the new designed controller demonstrates higher capability to track reference signal faster and having minimal tracking error during disturbance occur where having less than 0.01 degree compared 0.22 degree by PID. The Robust CNF based designed control system is able to compensate disturbance effect efficiently and also has super-fast tracking as classical CNF.

Keywords: Active Front Steering, yaw rate control, Vehicle Stability Control, Robust Control, Composite Nonlinear Feedback

1.0 INTRODUCTION

Vehicle yaw stability design based on active steering can be found throughout many research studies. The scheme highly efficient to control vehicle yaw stability at moderate level of cornering. Within active front steering, there are many control methods proposed by researchers such as PID [1], Fuzzy logic [2], Sliding Mode Controller (SMC) [3], Mu Control Theory [4], and Classical CNF [5, 6].

The Composite Nonlinear Feedback (CNF) control technique was first proposed in vehicle yaw stability in yaw rate tracking control [5]. In this research work, the classical CNF which is a nonlinear control technique without disturbance consideration was used in tracking yaw rate of vehicle for stability control. The work then has been extended further by evaluating the performance of system in various input signal with side wind disturbance effect [7]. Beside yaw rate tracking, the CNF control method also are applied in vehicle stability via direct yaw moment as in recent years studies [8, 9].

Originally, the CNF control algorithm was introduced by Z. Lin [10] as a nonlinear control method for accurate and fast tracking in linear system. The work extend later [11] for high order multivariable linear system and successfully applied on the missile control and helicopter pitch control. Furthermore in [12], the hard disk servo position controlled by CNF has beat Time Optimal Control and show a significant result. Besides, by studying on 3 types of control feedback method (normal state, full order measurement, and reduced order measurement feedback), the CNF become more matured technique.

One of the important step in CNF design is the selection of nonlinear gain. The step is very important for smooth tracking and amplitude variation resistance. By solving minimization problem, a suitable value for nonlinear function parameter can be found. Two performance criterion are investigated, which are the Integral of Absolute Error (IAE) and the Integral of Time multiplied Absolute Error (ITAE) [13, 14].

The CNF control algorithm has been enhance to make it more robust toward system with disturbance. In [15], the enhanced CNF control which applied on hard disk drive (HDD) servo has a capability to compensate disturbance without scarifying original tracking performance. Beside, researcher also consider their work on a system with unknown constant disturbance [16]–[18]. One of the technique applied for handling this type of disturbance is a technique without integrator term [18]. The basic idea of this technique is a combination of disturbance compensation and estimation into original framework.

There are 4 sections involve in this paper. First section consists of an introduction to AFS and review of CNF itself. A controller designed followed by simulation result will be discuss letter. Finally, conclusion and future work recommendation are mixed in last section.

2.0 METHODOLOGY

This research work is utilize ISO type vehicle with nonlinear two-track yaw plane vehicle body model, and come with individual wheel dynamics. The vehicle model contain 7 Degrees of Freedom (DOF) where velocity, side slip, yaw rate, and wheel slips of vehicle, are considered as independent state vectors. The Pacejka Model that famously known as Magic Formula is used for tyre model. In order to design a controller using CNF, linearization is essential. The linear model or so called bicycle model is obtained and use in this research as in previous work [7].

The vehicle yaw stability via AFS method is suitable for the vehicle handling during low and moderate level of cornering. In this level, tyre reaction behaviour is in a linear region. The control objective is to track desired yaw rate generated from reference model as closed and fast as possible. When the objective is fulfilled, vehicle respond will follow linearly to steer input and remain unchanged until reach it limitation. To produce desired yaw rate reference, reference model is created. The reference model is created based on 2 DOF bicycle model as in previous work [7].

The classical CNF technique is not consider external disturbance that may happen in a system. The basic CNF do not consider on level of bias information, so that it cannot follow a given reference properly. Consequently, enhancement version of CNF algorithm is introduced where bounded constant disturbance able to compensate.

There are two objectives during design a CNF controller. The objective of linear feedback part is to get a very minimal damping ratio for immediate response and for a nonlinear feedback objective is to maximize a damping ratio when the output nearly reach the target reference to prevent from overshoot. A linear system with actuator saturation with consideration of external disturbance can be stated as bellow:

$$\dot{x}(t) = A\,x(t) \; + \; B\,sat\big(u(t)\big) + E\omega(t),$$
$$with\; x(0) = x_0, and\; y(t) = C\,x(t) \qquad (1)$$

Where $u \in \mathbb{R}$, $x \in \mathbb{R}^n$, $y \in \mathbb{R}^p$, $h \in \mathbb{R}$, and $\omega \in \mathbb{R}$ are the control input, state vector as controlled output, measured output, and disturbance vector respectively. The controller is design based on state feedback case where state vector is consider as controlled output and it is measurable. In this Robust CNF, vector ω is bounded and consider as unknown constant disturbance. The matrix A and B are sterilisable, the matrix A and C are detectable, and all the matrixes should be invertible and there are no invariant zero at s=0 [18].

The Robust CNF is design based on standard procedure. The design steps is similar with basic CNF, with some additional procedure for disturbance because it contains additional equation for disturbance consideration. The first step is to consider a linear feedback law with disturbance compensation term as Equation 2. As the system equation given in Equation 1, linear state feedback will be

$$u_L = [F \quad F_\omega]\begin{pmatrix} x \\ \omega \end{pmatrix} + Gr \qquad (2)$$

where r is a step command input, similar with basic CNF, F is set such that $A + BF$ asymptotically stable and a closed loop system $C(sI - A - BF)^{-1}B$ have a properties such as low damping ratio. In this work, the matrix F value is obtain by getting suitable value based on simulation output. There are no specific technique to find this value, however the optimization method such H_2 and H_∞ approaches are one of the proper way. The matrix G is a scalar and given by $G = -[C_2(A + BF)^{-1}B]^{-1}$. And additional matrix in this algorithm, $F_\omega = G[C_2(A + BF)^{-1}E]$.

Secondly, configuration of nonlinear feedback law is performed as classical method. We will not discuss here this step because it is similar to previous work done in [7]. Another term, equilibrium point x_e can be find with additional revision as follow:

$$x_e = G_e r + G_\omega \omega \tag{3}$$

Combination of the linear and nonlinear part of both feedback laws is a final step in this this controller design. It form a complete robust CNF law as in Equation 4.

$$u = u_L + u_N = [F \quad F_\omega]\begin{pmatrix} y \\ x \\ \omega \end{pmatrix} + Gr + \rho(r,h)B^T P\left(\begin{pmatrix} y \\ \omega \end{pmatrix} - x_e\right) \tag{4}$$

The parameters used for a vehicle and tyres model in this research obtain from [19]. Both of models represent average passenger car and Pacejka Tire Model (PTM) data for 205/60R15 tyre. The reference model construction is based on below function

$\dot{\Psi}_d = 7.0654\,\delta_d$ with saturation limit, $20.2140\ Deg/s$

Meanwhile for bicycle model parameter, we used same data as previous work [7] as follow

$$\begin{pmatrix} \dot{\beta} \\ \ddot{\psi} \end{pmatrix} = \begin{bmatrix} -3.9026 & -0.9839 \\ 6.9689 & -3.8942 \end{bmatrix}\begin{pmatrix} \beta \\ \dot{\psi} \end{pmatrix} + \begin{bmatrix} 2.2343 \\ 35.9250 \end{bmatrix}\delta + \begin{bmatrix} 0 \\ 3.2807e-4 \end{bmatrix}\omega$$

Base on all these parameters, Robust CNF for AFS based Vehicle Yaw Stability is designed and simulate by Matlab/Simulink. The Robust CNF control parameters are obtained as follows.

$F = [0.5 \quad \text{-}0.005]$, $\qquad P = \begin{bmatrix} 0.8224 & 0.0562 \\ 0.0562 & 0.1535 \end{bmatrix}$

$G = 0.2321$, $\qquad G_e = \begin{bmatrix} \text{-}0.1711 \\ 1 \end{bmatrix}$

$\varphi = 0.03$, and $\qquad \gamma = 0.2$

Note that all given parameters as above are same with previous work [7] with additional two parameters for robust CNF as follow.

$$F_\omega = -5.8664e-6, and\ G_\omega = \begin{bmatrix} -0.4706e-5 \\ 1 \end{bmatrix}$$

3.0 RESULTS AND DISCUSSION

The designed system was tested with various pattern and cornering level manoeuvres with existence of external disturbance to evaluate the performance and robustness of design controller. In addition, comparison was made with PID controlled and passive vehicle without AFS capability. Two type of inputs patterns are used, J-Turn and single sine inputs which come with 400 Nm magnitude of side wind disturbance as shown in Figure 1 and Figure 2.

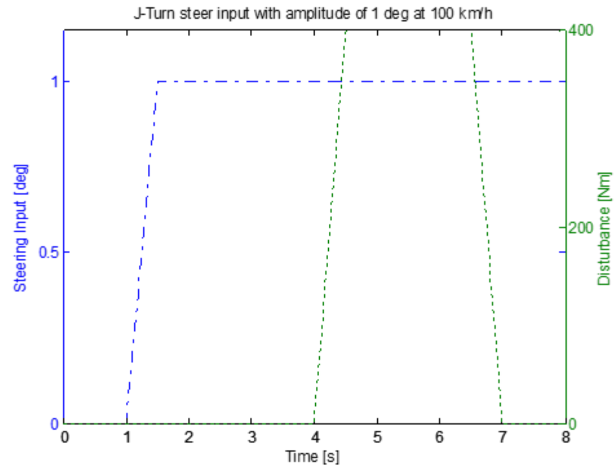


Figure 1 J-Turn input steer of 1° with disturbance

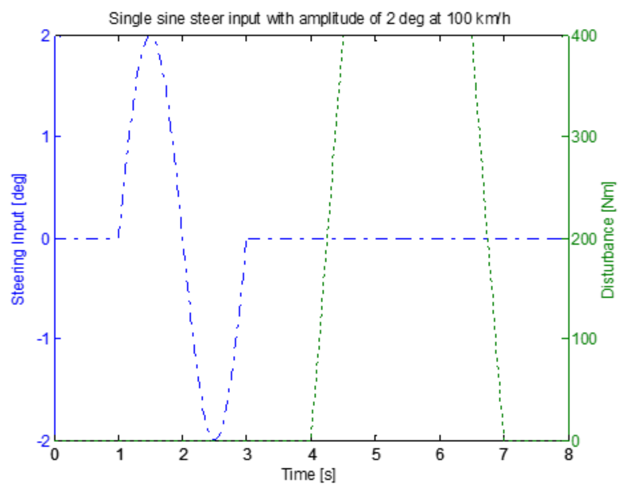


Figure 2 Single sine input steer with disturbance

3.1 J-Turn Manoeuvre with Disturbance.

When the input steer with J-Turn pattern and level of 1° is set, the simulated vehicle will generate lateral acceleration of 3.45 ms^{-2} and this is about 0.35 from gravity constant (0.32g). At this level, controlled vehicle can perform well and the Robust CNF controller is the best ones compare to others. The result of simulation for yaw rate and tracking error are shown in Figure 3 and Figure 4. During perturbation occurred, the Robust CNF vehicle yaw rate almost not affected. In addition, the new controller was capable to demonstrate super-fast tracking as classical CNF during transient response and at the same time able to handle external disturbance properly.

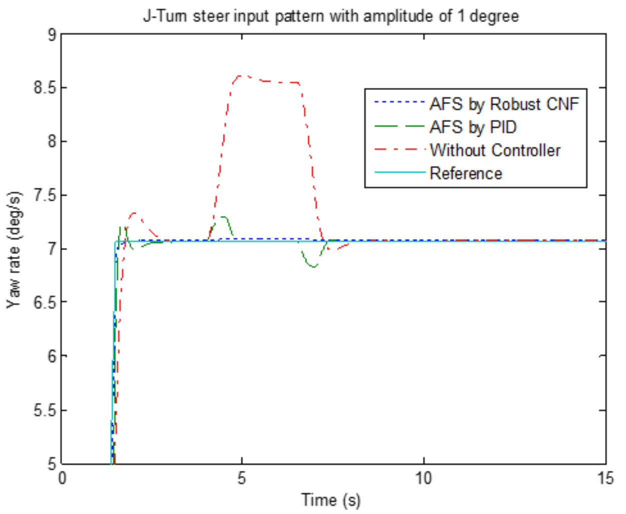


Figure 3 Yaw rate response during J-Turn input of 1° with disturbance of 400 Nm

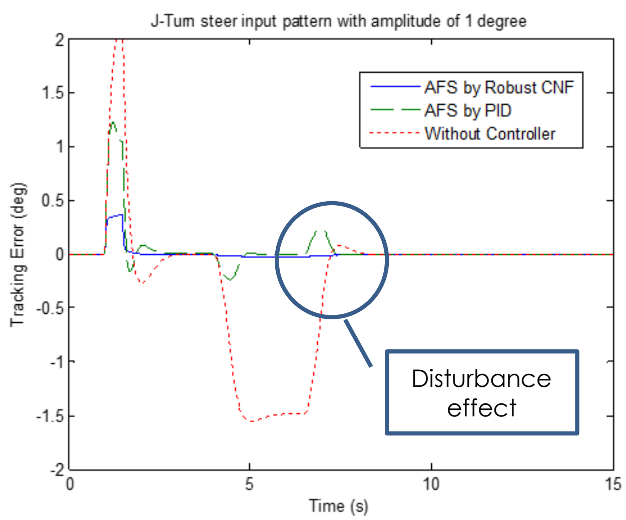


Figure 4 Yaw rate tracking error response during J-Turn input steer of 1° with disturbance of 400 Nm

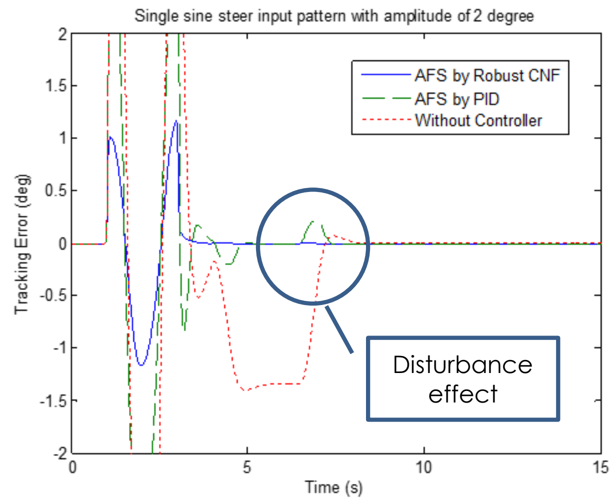


Figure 5 Yaw rate tracking error response during Single sine input steer of 2° with disturbance of 400 Nm

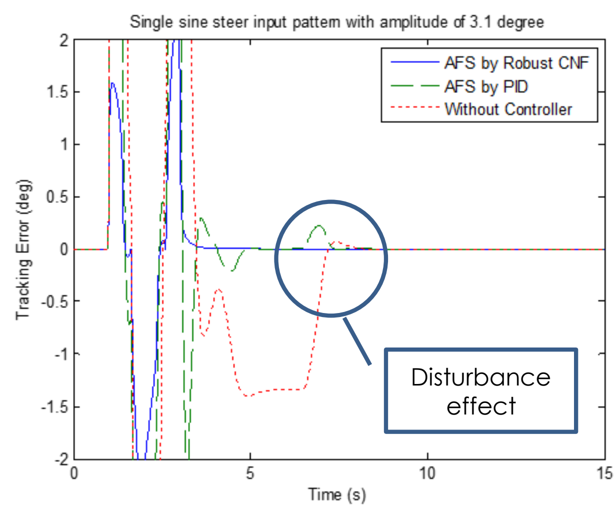


Figure 6 Yaw rate tracking error response during Single sine input steer of 3.1° with disturbance of 400 Nm

3.2 Single Sine Manoeuvres with Disturbance

When the input steer with Single Sine pattern and level 1° until 3.1° are set, the manoeuvres will produce lateral acceleration from low level to peak level. During peak level, vehicle handling have reach it operating limit or safety critical conditions where the vehicle behaviour is not linear anymore. The steer amplitudes of 2°, 3.1°, and 7.1° will generate lateral acceleration of 0.48g, 0.7g, and 0.93g respectively. In normal road condition with speed of 100km/h, normal vehicle start to enter nonlinear region when lateral acceleration is about 0.3g. Based on recent study, any AFS based controller only suitable to operate up to 0.6g only [19]. The simulation result for yaw rate tracking error for single sine input of 2° and 3.1° shown in Figure 5 and Figure 6.

Based on the results, both controllers can perform well with Robust CNF have greatest performance in term of transient respond and robustness. There is some effect in tracking error came from side wind disturbance for PID controlled vehicle. However, that kind of disturbance almost not effected for the Robust CNF controller. Generally, the main advantage of any vehicle equipped with AFS based stability control is their ability to compensate any side wind disturbance especially when vehicle move on straight line. The only difference is on how much vehicle effected by disturbance.

4.0 CONCLUSION

The Robust Composite Nonlinear Feedback technique is designed based on non-integral function and successfully applied on active front steering based vehicle yaw stability system. The proposed controller performance has been evaluated in term of transient response and robustness towards disturbance. As a comparison, a most popular conventional Proportional Integrated Derivative controller is used. Based on simulation result, we found that the new designed Robust CNF controller is a great controller with capability to produce excellent response time, almost no overshoot, and able to compensate any bounded constant disturbance. The proposed Robust CNF however unable to expend limitation of effective region in typical AFS based vehicle yaw stability, where it only suitable for vehicle handling up to moderate cornering level. Beside, this technique also may not robust enough to cater parameter uncertainties that may vary and happen in some of controlled plant model.

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