Modelling and Control of Four-Wheel Anti-lock Braking System

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Received: December 2011 Revised: April 2012 Accepted: May 2012

ABSTRACT:
Minimal stopping distance, guaranteed steering ability and stability are the three most important purposes in Anti-lock Braking System (ABS) realm. The ABS system is a nonlinear, time variant and multivariable system with some uncertainties. Some research work has been carried out on ABS control systems using intricate methods, which are expensive to implement. In this paper at the first step, the system interference is decreased via decoupling matrix and the ABS is controlled with a robust diagonal controller. In fact, a decentralized control technique is used for our ABS control mechanism. At the second step, we exploit a multivariable technique in linear control to attack the problem. This is the Designed Linear Control with Multivariable Technique. The Optimal Eigenstructure assignment with the Genetic Algorithm (GA) method is also applied. Simulation and comparison studies are used to show the effectiveness of the proposed methods.

KEYWORDS: ABS, Four-Wheel Model, Decentralized Control, Eigenstructure Assignment, Uncertainty, GA.

1. INTRODUCTION

The car industry has undergone Major changes during the past decades. Advanced technical developments have radically changed the present car. These differences are in convenience, safety and performance. An important part in the car is its braking system. Braking system can ensure a safe and reliable drive and save lives. Anyone with a driving experience, especially in rainy and slippery roads, knows that controlling the vehicle in this condition is very difficult and causes the danger of slipping and losing control. This Importance of Anti-lock Brake in the slippery road, specifies the response of a driver with fear and shows the errors of another driver and the passer-by. ABS avoids the locking of the wheels and leads to increased steering ability and guarantees the stability the car. The first application of the anti-lock brake system was in bomber B-47 in 1947, followed using anti-lock brake in BMW and Mercedes Benz in 1978. In ABS brake, with chary of the continued moment of brake, we try to decrease the measured distance and keep the balance of the car. Up to now many procedures for controlling ABS have been proposed. Examples of these are fuzzy control [1-2], adaptive control [3-4], intelligent control [5-7] and nonlinear control [2, 8-9] have been used. In this paper, two new methods consisting of decentralized control and eigenstructure assignment with genetic algorithms have been proposed. This is the generalized state feedback method (consisting of the eigenvalues and the associated eigenvectors). Advantages of this procedure are the simple operation of the controller and its moderate cost. In part 2, the four-wheel system will be demonstrated, and the brake and vehicle systems are modeled. In part 3, the decentralized control procedure will be studied and then the parameters of the PID controller will be tuned using the Cohen-Coon method. Eigenstructure assignment & genetic algorithm (GA) will be finally considered as it will be needed to learn GA to find the state feedback matrix. In part 4, the results of simulations will be discussed. Finally, the paper is concluded in part 5.

2. MATHEMATICAL MODELING

To demonstrate the system, we need to find the dynamic equations of body, wheels, hydraulic brake and tire. The body dynamic equations have 3 degree of freedom consisting of longitudinal speed, side speed, and yaw rate [10-11].

$$\dot{v}_x = -\frac{1}{m}[(f_{x_1} + f_{x_2})\cos\delta + f_{x_3} + f_{x_4} - (f_{y_1} + f_{y_2})\sin\delta] + v_y r$$

$$\dot{v}_y = \frac{1}{m}[-(f_{x_1} + f_{x_2})\sin\delta + f_{y_3} + f_{y_4} + (f_{y_1} + f_{y_2})\cos\delta] - v_x r \qquad (1)$$

$$\dot{r} = \frac{1}{I_Z}[-L_f(f_{x_1} + f_{x_2})\sin\delta + l_f(f_{y_1} + f_{y_2})\cos\delta - L_r(f_{y_3} + f_{y_4}) + T_f(f_{x_1} - f_{x_2})\cos\delta + T_f(f_{y_1} - f_{y_2})\sin\delta + T_r(f_{x_3} - f_{x_4})]$$

Dynamic equation of each wheel (ω) without consent rate motion energy of engine [1,4] is:

$$\dot{\omega}_i = \frac{1}{I_\omega}[f_{x_i}R_\omega - T_{bi} - B\omega], \qquad i = 1,2,3,4 \qquad (2)$$

Tire, when we focus on low contact area with road have special importance. The famous tire Model for 4 wheel system is the Calspan model under normal force (F_Z) which is [5,11]:

$$F_{Z_1} = F_{Z_2} = (\frac{m}{4} + m_f)g - \frac{ma_x h}{(l_r + l_f)}$$

$$F_{Z_3} = F_{Z_4} = (\frac{m}{4} + m_f)g + \frac{ma_x h}{(l_r + l_f)} \qquad (3)$$

The longitudinal and lateral friction forces (F_x, F_y) are obtained by Describing the Figures 2 and 3. The equation of changes in output pressure of hydraulic brake system will be given by (4) with regard to figure 4 [2, 12] and the slip in each wheel is as in (5)[12].

$$\dot{P}_i = \frac{A_1}{c_f}cd_1\sqrt{\frac{2}{\rho}(P_p - P_i)} - \frac{A_2}{c_f}cd_2\sqrt{\frac{2}{\rho}(P_i - P_{low})} \qquad i = 1,....,4 \qquad (4)$$

$$S_i = 1 - [(R_\omega \omega_i)/(V_{\omega_i}\cos\alpha_i)] \qquad i = 1,....,4 \qquad (5)$$

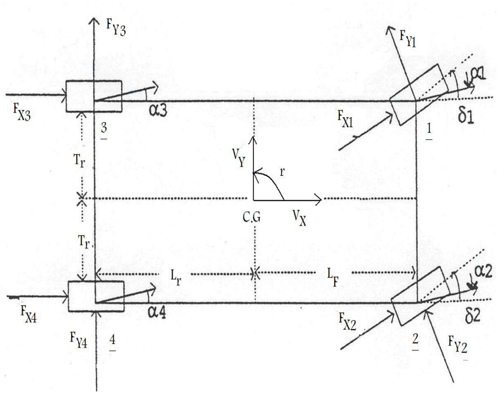

Fig.1. Four-Wheel Model.

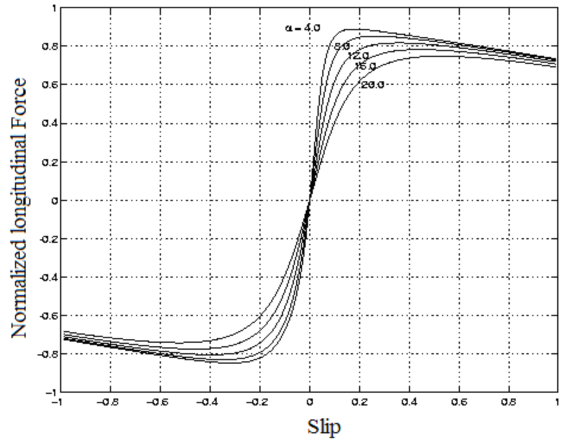

Fig.2. Normalized longitudinal force vs. slip.

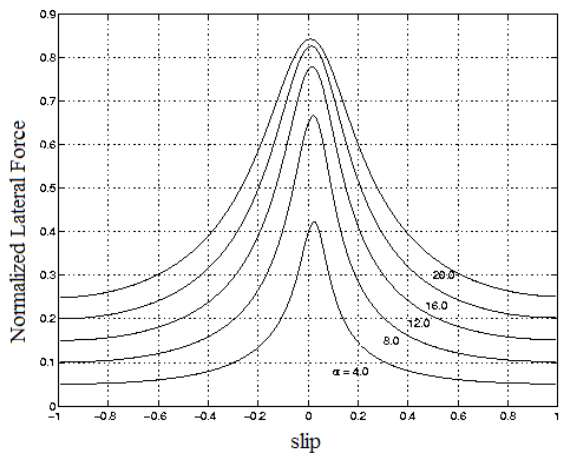

Fig. 3. Normalized lateral force vs. slip.

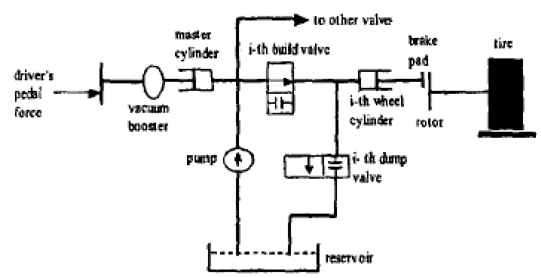

Fig. 4. Hydraulic brake system.

The slip angle (α) and speed of generating (V_ω)of each vehicle are as in the following:

$$V_{\omega_1} = \sqrt{(V_x - T_f r)^2 + (V_y + L_f r)^2}$$

$$\alpha_1 = -\delta + Tg^{-1}[(V_y + L_f r)/(V_x - T_f r)]$$

$$V_{\omega_2} = \sqrt{(V_x + T_f r)^2 + (V_y + L_f r)^2}$$

$$\alpha_2 = -\delta + Tg^{-1}[(V_y + L_f r)/(V_x + T_f r)]$$

$$V_{\omega_3} = \sqrt{(V_x - T_r r)^2 + (V_y + L_r r)^2} \quad (6)$$
$$\alpha_3 = -\delta + Tg^{-1}[(V_y + L_r r)/(V_x - T_r r)]$$
$$V_{\omega_3} = \sqrt{(V_x + T_r r)^2 + (V_y - L_r r)^2}$$
$$\alpha_3 = -\delta + Tg^{-1}[(V_y - L_r r)/(V_x + T_r r)]$$

Table 1. List of symbols and parameters.

Symbol	Value	Parameter
f_{xi}		Longitudinal friction force
T_f	0.78 M	Half front axel
T_r	0.78 M	Half rear axel
I_ω	4.07 KGM	Moment of inertia of wheel
h	0.53 M	Height of the sprung mass
R_ω	0.33 M	Wheel radius
B	0.02KM/S	Viscous friction coefficient
a_x		Vehicle linear acceleration
C_f	$10\frac{m^5}{KgF}$	Coefficient of the flow and the time derivative function of hydraulic pressure
P_{low}	$6000\frac{KgF}{cm^2}$	Constant reservoir pressure
ρ	$1\frac{Kg}{m^3}$	Fluid density
f_{yi}		Lateral friction force
m	1301 KG	Total Mass
$m_{f,r}$	40 KG	Front and rear wheel mass
L_f	1 M	Distance from center of gravity to front axle
L_r	1.45 M	Distance from center of gravity to rear axle
I_z	1627 KGM	Inertia moment
T_{bi}		Brake torque
A_1	$0.003m^2$	Effective orifice aria of the build valve
A_2	$0.006m^2$	Effective orifice aria of the dump valve
P_p	$5\frac{KgF}{cm^2}$	Constant pomp pressure
P_i		Hydraulic Pressure
$Cd_{1,2}$	0,1	The coefficient

Linearization will be done with constant longitudinal speed and little δ, i.e., $\sin\delta = \delta$ and $\cos\delta = 1$. Therefore F_{X_1}, F_{X_2} will be as on the figures 2 and3 and $V_X = R_\omega \omega_i$.

$$\begin{cases} \frac{fx}{fz} = 5s \\ \frac{fy}{fz} = -2s + 0.42 \end{cases} \quad s < 0.2$$
$$\begin{cases} \frac{fx}{fz} = -0.16s + 0.88 \\ \frac{fy}{fz} = -0.125s + 0.175 \end{cases} \quad s > 0.2 \quad (7)$$

So we can show (8) (note that the dynamic equations of body, wheels and tire and see table 1)

$$\dot{v}_x = -4.23(s_1 + s_2 + s_3 + s_4)$$
$$\dot{v}_y = -1.69(s_1 + s_2 + s_3 + s_4) - 32r$$
$$\dot{r} = 1.28s_1 - 3.99s_2 + 4.6s_3 - 0.68s_4$$
$$\dot{\omega}_i = 0.4s_i - 0.245T_{bi} \quad i = 1,...4 \quad (8)$$
$$\dot{s}_i = -\frac{1}{32}(\dot{v}_x + \dot{\omega}_i) =$$
$$0.132(s_1 + s_2 + s_3 + s_4) + 0.0041s_i - 0.0025$$

In this system we have two uncontrollable and three unobservable poles. Tracking goal is S=0.2 to have maximum longitudinal friction force in this slip. As the tracking system is uncontrollable, we can't use Eigenstructure assignment. This is due to the system uncertainties (longitudinal speed, side speed and yaw rate). After reducing the state space equations from 11 to 8(see equation 8), the system will be controllable and observable and the method will be applied.

3. CONTROL DESIGN

We use two methods for control design. In the first method we use the diagonal matrix and two PID controllers. PID controllers are mainly implemented by two amplifiers and ten Op-Amps in the industry. In the second method we use the modern and linear method because Eigenstructure Assignment serves the three purposes and will be discussed in section 3.2.

3.1. Decentralized control

In a MIMO system there is a phenomenon called interference. This phenomenon causes all of the inputs to influence all of the outputs. Mayne suggested that, before starting to design the individual loop compensators, a cross-coupling stage of compensation should be introduced. This stage should consist of either a constant gain matrix or a sequence of elementary operations and its purpose is to redistribute the "difficulty of control" among the loops. Mayne proposes three compensations or decoupling matrix [13]. Figure5 shows the structure of the decentralized control.

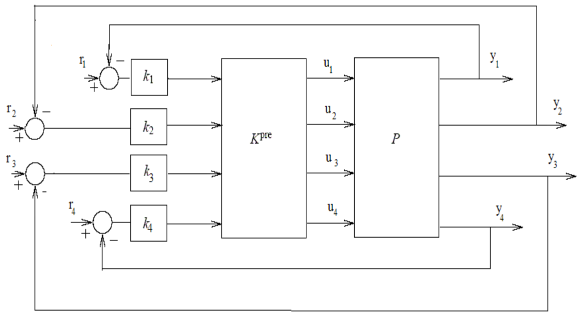

Fig.5. Decentralized control

One way that is effective in these systems is the decentralized control procedure in which the system interference is reduced through the decoupling matrix, and then the control of the system is similar to a SISO model [13]. To design k_1 ,k_2, k_3 ,k_4 we implement the PID system controller, and for controller tuning we offer Cohen-Coon method. Regarding (9), the proportional gain of the diagonal controller times the decoupling matrix, which itself is also diagonal, must be greater than 150 times the identity matrix to reduce the interference of the system i.e.

$$k_{ii} \times K_{ii}^{pre} > 150 \quad (9)$$

We tune the PID parameters with the help of the C-C (Cohen- Coon) method, in which the minimum of error integral specifies where to apply the poles. The intuitive design criterion is to omit the disturbance effect. The controller's parameters are appointed as (8) [14]. The process model is considered with three parameters.

$$G_p(s) = \frac{Ke^{-LS}}{1+TS}.$$

We can specify T, L, and K by the step response of the system.

$$K_p = \frac{1.35}{a}(1+\frac{0.18\tau}{1-\tau}) \ , \ a = \frac{KL}{T} ,\tau = \frac{L}{L+T}$$

$$T_d = \frac{0.37-0.37\tau}{1-0.81\tau}L \ , \ T_i = \frac{2.5-2\tau}{1-0.39\tau}L \quad (10)$$

In the ABS system, parameters are specified as:

$L = 0.5 \quad T = 1 \quad K = 1 \quad a = 0.5 \quad \tau = 0.33$

$K_p = 2.94 \quad , \quad T_i = 1.05 \quad , \quad T_d = 0.13$

3.2. Eigenstructure Assignment

We are now intended to follow the analysis of the conditioning of the pole placement problem in [13, 15-18] with the multi-input case which is called the generalized state feedback. State feedback matrix not being unique in the MIMO system, there are many degree freedoms (DF) in this choice.

These degrees of freedoms are used for the following purposes: 1) consisting of the eigenvalues and the associated eigenvectors, 2) Designing K (gain feedback matrix) as decrease control cost, 3) designing K for system robustness. The multi-input time-invariant linear system is as the following:

$$\dot{x} = Ax(t) + Bu(t); x(0) = x_0 \quad (11)$$

With $A \in C^{n \times n}$,$B \in C^{n \times m}$. For which the following problem will be considered: PROBLEM: *Multi-input pole placement (MIPP):* Given a set of n complex numbers: $P = \{\lambda_1, \lambda_2, \cdots, \lambda_n\} \subset C$ find a matrix $K \in C^{n \times m}$ such that the set of eigenvalues of $A - BK$ be equal to P (we assume in the real case that P is a closed complex conjugation set). It is well-known [18] that a *feedback gain* matrix K that solves this problem for all possible sets $P \subset C$ exists if and only if (A, B) is *controllable*,

$$\text{rank}[A - \lambda I_n \ , B] = n, \forall \lambda \in C \quad (12)$$

$$\text{or rank}[B, AB,..., A^{n-1}B] = n \quad (13)$$

State feedback equation with tracking system is:

$$\begin{bmatrix} \dot{x}(t) \\ \dot{q}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ q(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ I \end{bmatrix} r \quad (14)$$

$$y(t) = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ q(t) \end{bmatrix}$$

$q_i = -Kv_i$ for $i = 1,2,\ldots,n$ relates eigenvalues and associated eigenvectors [15-16]. Then

$$\begin{bmatrix} v_i \\ \cdots \\ q_i \end{bmatrix} = [\alpha_{i1} \quad \alpha_{i2} \quad \cdots \quad \alpha_{in}] \begin{bmatrix} S_1(\lambda_i) \\ S_2(\lambda_i) \\ \vdots \\ S_n(\lambda_i) \end{bmatrix} \quad (15)$$

Therefore $[v_i^T \quad q_i^T]^T$ must be at null space $s_i(\lambda_i) = [A - \lambda_i I \quad B]$ so that the feedback gain matrix is $K = -[q_1 \quad q_2 \quad \ldots \quad q_n] \times [v_1 \quad v_2 \quad \ldots \quad v_n]$.

We can use this method if $\begin{bmatrix} B & A \\ 0 & -C \end{bmatrix}$ is full rank.

ABS system has eight states plus four additional states due to the use of integrators (see Figure 6).

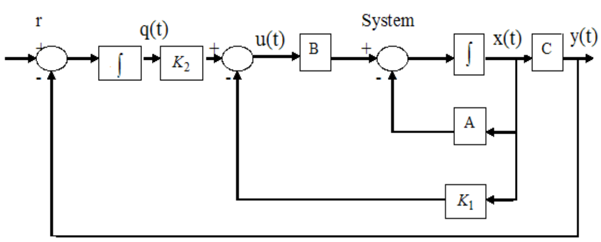

Fig. 6. Tracking system.

3.3. GENETIC ALGORITHM (GA)

GA simulates the survival of the fittest among individuals over consecutive generation for solving a problem. Each generation consists of a population of character strings that are analogous to the chromosome that we see in our DNA. Each individual represents a point in a search space and a possible solution. The individuals in the population are then made to go through a process of evolution. GAs are based on an analogy with the genetic structure and behavior of chromosomes within a population of individuals using the following foundations: Individuals in a population compete for resources and mates. Those individuals most successful in each 'competition' will produce more offsprings than those individuals that perform poorly. Genes from `good' individuals propagate throughout the population so that two good parents will sometimes produce offspring that are better than either parent. Thus each successive generation will become more suited to their environment. A population of individuals is maintained within search space for a GA, each representing a possible solution to a given problem. Each individual is coded as a finite length vector of components, or variables, in terms of some alphabet, usually the binary alphabet {0, 1}. To continue the genetic analogy these individuals are likened to chromosomes and the variables are analogous to genes. Thus a chromosome (solution) is composed of several genes (variables). A fitness score is assigned to each solution representing the abilities of an individual to `compete'. The individual with the optimal (or generally near optimal) fitness score is sought. The GA aims to use selective `breeding' of the solutions to produce `offspring' better than the parents by combining information from the chromosomes. The GA maintains a population of n chromosomes (solutions) with associated fitness values. Parents are selected to mate, on the basis of their fitness, producing offspring via a reproductive plan. Consequently highly fit solutions are given more opportunities to reproduce, so that offspring inherit characteristics from each parent. As parents mate and produce offspring, room must be made for the new arrivals since the population is kept at a static size. Individuals in the population die and are replaced by the new solutions, eventually creating a new generation once all mating opportunities in the old population have been exhausted. In this way it is hoped that over successive generations better solutions will thrive while the least fit solutions die out. New generations of solutions are produced containing, on average, better genes than a typical solution in a previous generation. Each successive generation will contain more good `partial solutions' than previous generations. Eventually, once the population has converged and is not producing offspring noticeably different from those in previous generations, the algorithm itself is said to have converged to a set of solutions to the problem at hand [19-20].

The ABS system output is S_i , $i = 1,2,3,4$. We therefore have $48\,\alpha$ (each state produce four null space), so State feedback matrix not being unique in the MIMO system, hence α will be very difficult to be calculated. Therefore we get help from Genetic Algorithm (GA).

4. RESULTS AND DISCUSSIONS

We trained two different ABS controllers using different training scenarios. The first (decentralized control) and second (optimal eigenstructure) ABS controller was trained with two road surfaces, We first set the speed of the car to 115 km/h in dry road with $\mu_{nom} = 0.85$ (dry asphalt) (please see fig. 7,8,9 and 10), we uses simulink6.0 in matlab 7.

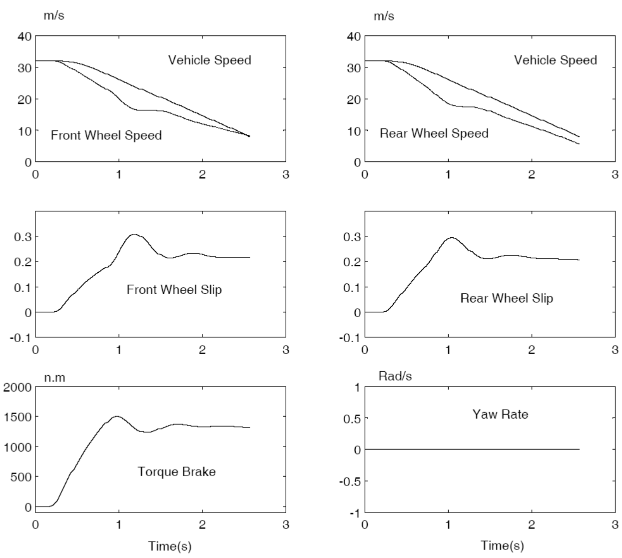

Fig. 7. Simulation results of the nonlinear system in a dry road, with 115km/h, and $\mathbf{k_{ii}} \times \mathbf{K_{ii}^{pre}} = \mathbf{150}$.

The results are depicted in Fig. 7 and 8 with proportional gains variable in the decentralized control. The vehicle's parameters are specified according to Table 1.

Fig. 7 shows decentralized control in the dry and uniform road with decoupling matrix(150 times the identity matrix) . maximum of slip is 0.3, suspend time is 2.8(sec), suspend distance is 60 (meter), yaw rate is 0(degree) and maximum of torque brake is 1500 (n.m). in this controller maximum of control signal is 30.

Fig. 8 shows decentralized control in the dry and uniform road with decoupling matrix(1161 times the identity matrix) . maximum of slip is 0.22, suspend time is 2.56(sec), suspend distance is 53 (meter), yaw rate is 0(degree) and maximum of torque brake is 1496 (n.m). in this controller maximum of control signal is

232.

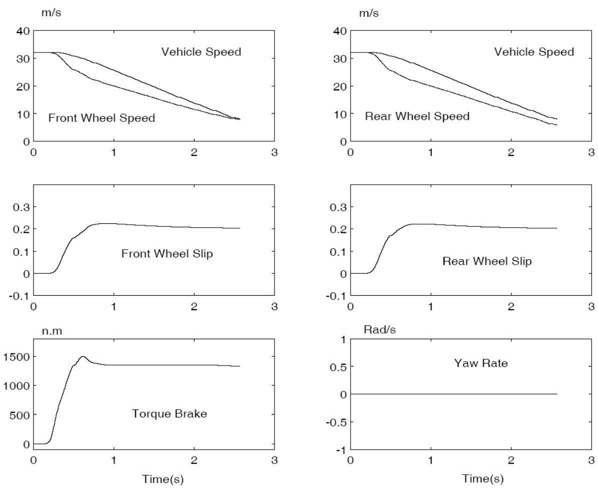

Fig. 8. Simulation results of the nonlinear system in a dry road, with 115km/h, and $\mathbf{k_{ii} \times K_{ii}^{pre} = 1161}$.

The fig. 9 and 10 show the speed and slips of 4 wheels, torque brake and yaw rate of vehicle in the dry road based on minimizing $\int_0^\infty e^2 dt$ and $\int_0^\infty (e^2 + u^2) dt$.

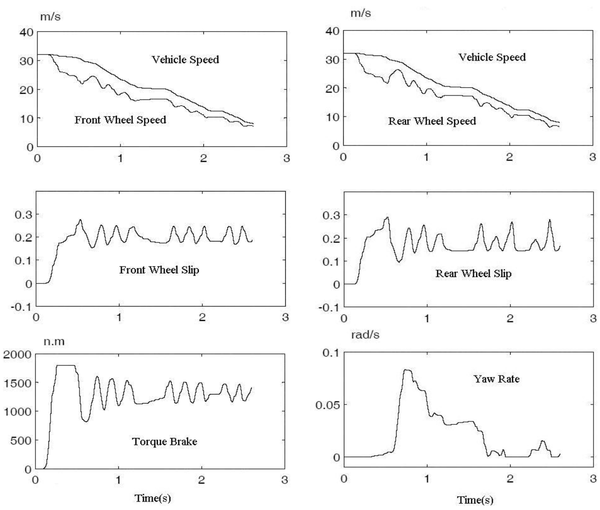

Fig. 9. Simulation results of the nonlinear system in a dry road, with 115km/h, and fitness function ($\int_0^\infty e^2 dt$)

Fig. 9 shows optimal eigenstructure assignment method in the dry and uniform road with fitness function (square of integral error). Maximum of slip is 0.29, suspend time is 2.60(sec), suspend distance is 53.5 (meter), yaw rate is 4.7(degree) and maximum of torque brake is 1800 (n.m). In this controller maximum of control signal is 240.

Fig. 10 shows optimal eigenstructure assignment method in the dry and uniform road with fitness function (square of integral error and control signal). Maximum of slip is 0.25, suspend time is 2.80(sec), suspend distance is 60 (meter), yaw rate is 0.8(degree) and maximum of torque brake is 1400 (n.m). In this controller maximum of control signal is 30.

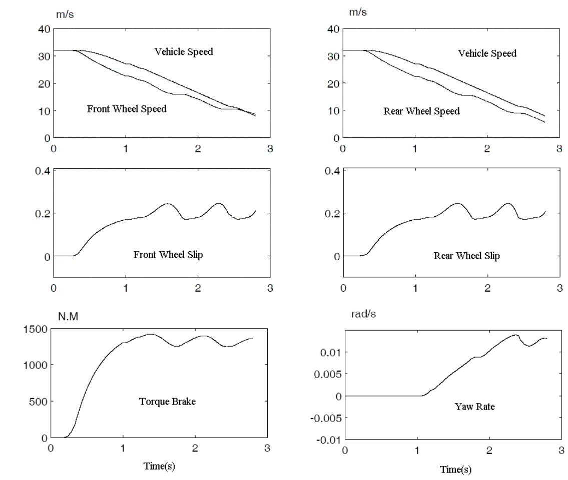

Fig. 10. Simulation results of the nonlinear system in a dry road, with 115km/h, and fitness function ($\int_0^\infty (e^2 + u^2) dt$)

In non-uniform roads, after the car has passed 35m, enters the icy road which has a friction coefficient of $\mu_{nom} = 0.5$ and after passing 25m re-enters the dry road. Fig. 11 and 12 show the speed and slips of four wheels, brake torques and yaw rates of the vehicles wheels in the non-uniform road based on the change of proportional gain.

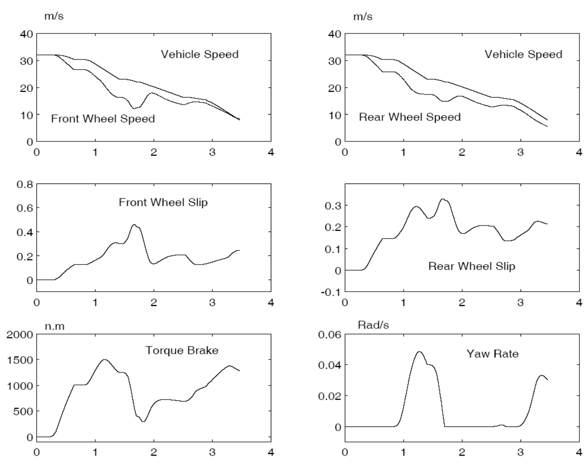

Fig. 11. Simulation results of the nonlinear system in a non-uniform road, with 115km/h, and $\mathbf{k_{ii} \times K_{ii}^{pre} = 150}$.

Fig. 11 shows decentralized control in the non-uniform road with decoupling matrix (150 times the identity matrix). Maximum of slip is 0.46, suspend time is 3.45(sec), suspend distance is 72 (meter), yaw rate is 2.86(degree) and maximum of torque brake is 1500 (n.m). In this controller maximum of control signal is 63.

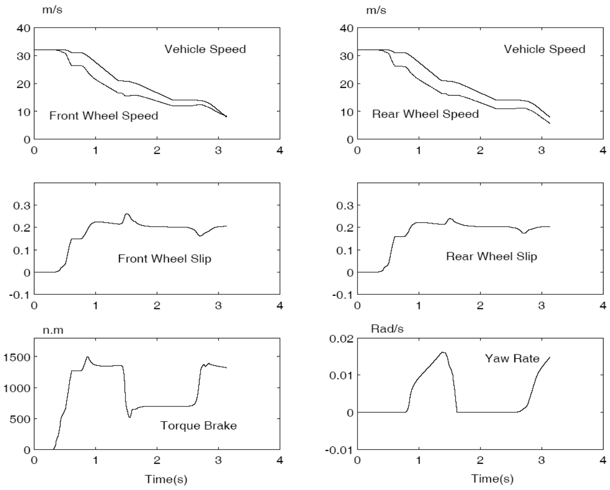

Fig. 12. Simulation results of the nonlinear system in a non-uniform road, with 115km/h, and $\mathbf{k_{ii} \times K_{ii}^{pre} = 1161}$.

Fig. 12 shows decentralized control in the non-uniform road with decoupling matrix (1161 times the identity matrix). Maximum of slip is 0.26, suspend time is 3.13(sec), suspend distance is 63 (meter), yaw rate is 0.9(degree) and maximum of torque brake is 1498 (n.m). In this controller maximum of control signal is 332.

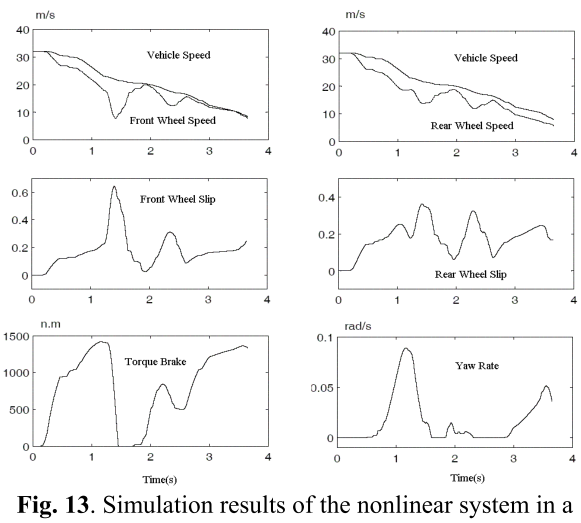

Fig. 13. Simulation results of the nonlinear system in a non-uniform road, with 115km/h, and $\mathbf{(\int_0^\infty (e^2+u^2)dt)}$

Fig. 13 shows Optimal eigenstructure assignment method in the non-uniform road with fitness function (square of integral error and control signal). Maximum of slip is 0.65, suspend time is 3.65(sec), suspend distance is 75 (meter), yaw rate is 5.16(degree) and maximum of torque brake is 1417 (n.m). In this controller maximum of control signal is 66.

In the first step we compare our methods with fuzzy controller by designing a Genetic Neural Fuzzy Antilock-Brake-System Controller [5]. Suspend time is 2 sec (vehicle speed is=72 km/h, vehicle mass is=1500kg, and in a dry road). If we change vehicle data according to [5], suspend time will be changed to 1.75 sec (for Eigenstructure Assignment method). In [2] by using robust sliding mode, suspend time is 3.2 sec (vehicle speed is=100 km/h, vehicle mass is=1100kg, dry road) our vehicle with upper speed and mass suspend time is 2.8 sec (Figures (7, 10)). In the comparison with previous control methodologies, we see that the decentralized control and Eigenstructure Assignment although simpler and perhaps of lower implementation cost, gives acceptable and robust performance.

5. CONCLUSIONS

In this paper a four wheel system with regard to Calspan model for tire and dynamic equation of hydraulic brake system was used. In the first step with the use of decentralized control method and the decoupling matrix, we designed a diagonal PID controller with C-C method. It was seen that the advantages of decentralized control for ABS is its simplicity and cheapness. The results of simulation show that systems with disturbance have suitable performance under this method. Coefficient friction is disturbance in this paper.

In the second step, we designed a linear control for Anti-lock Brake system using eigenstructure assignment method and getting help from genetic algorithm theory for a low control cost and system robustness. The minimization was done with two optimal fitness function using GA ($\int_0^\infty e^2 dt$ and $\int_0^\infty (e^2+u^2)dt$), where longitudinal speed, side speed, yaw rate, total mass and normal force (tire) have been considered with uncertainty. Disturbance in ABS system was considered to be the road change of circumstances (non-uniform road coefficient friction

Has change by 45% with regard to the uniform road). The simulation result shows that using control signal in the integral will obtain low cost and suitable performance. So the goals enumerated in the abstract for an ABS system are secure.

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