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DEVELOPMENT OF FAULT TOLERANT CONTROL STRATEGIES FOR NONLINEAR ELECTROMECHANICAL SYSTEM

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ABSTRACT

High performance control with guaranteed safety and reliability for braking systems is a challenging task due to the high nonlinearity and system uncertainties. This Paper developed a diagnosis integrated fault-tolerant control (FTC) strategy for the braking system. In fault free case the nominal controller is in operation for achieving the best performance. If fault occurs, the controller will be automatically reconfigured based on the fault information provided by the diagnosis system. The model is a time-based simulation of an anti-lock braking system (ABS) under hard braking conditions. The system fault is modeled as the uncertainty of system and can be tolerated by parameter adaption. All parameters coupled with the faulty measurement are replaced by its approximation. The tracking performance of the controlled system is guaranteed and the considered faults tolerated.

Key words: Fault, Tolerant, brake, Control, Nonlinear.

INTRODUCTION

Hydraulic systems can be broadly classified into two categories. The first category according Zhang (2004) is industrial hydraulics, which is typically applied in mechanical production systems, such as extrusion molding machines, pressers, rolling mills, etc. The second is mobile hydraulics, which is the core components of steering, braking, suspension and power-train system of the vehicles and also popular in the robot manipulators, ship rudders, airplane landing gears and so on (M¨unchhof, 2006). The reliability and safety of the systems are most important issues of automated systems. Usually, a small fault can have a serious effect to control system, such as actuator malfunction or sensor offset, sometimes even crushes the system. If faults can be detected and identified earlier, the collapse of whole system can be avoided, if a controller is able to tolerate possible faults automatically, the control is known as fault-tolerant control (FTC). Usually the FTC needs the fault information from FDI system. The controller can react to the fault and can be automatically reconfigured. A system which includes the capacity of detecting, isolating, identifying or classifying faults is called a fault diagnosis system. During the last two decades many investigations have been made using analytical approaches, based on quantitative models. The idea is to generate signals that reflect in consistencies between nominal and faulty system operation. Such signals, termed residuals, are usually generated using analytical approaches, such as observers (Patton *et al* 2000), parameter estimation (Isermann, 1994) orparity equations (Gertler, 1998) based on analytical(or functional) redundancy.

METHODOLOGY

The back stepping methodology was used in this research. A major advantage of back stepping is the flexibility to avoid cancellations of useful nonlinearities and achieve regulation and tracking properties. The back stepping controller can be reconfigured by integrating parameter adaption or changing the internal model. The system or actuator faults can be modeled as unknown parameters of the system. Hence, these faults can be tolerated by parameter adaption. The sensor faults are brought into the system by the controller and can be modeled as uncertainties of the controller parameters. Hence, the system model for controller design should be changed so that the effect of the sensor fault can be compensated or eliminated.

System Design and modeling

The goal of adaptive back stepping model is for improving fault diagnosis and fault tolerant control strategies for non linear system. It is a kind of reconfigurable control, which can maintain the control performance or at least, guarantee the stability of whole system in the event of faults. It contains not only a control law but also the fault diagnosis subsystem, which helps the reconfiguration of controller. The structure of FTC can be generally described as shown in Fig. 1. FTC system contains two layers: supervision and execution. The supervision layer monitors the system behavior through the inputs, measurements and system model. The fault diagnosis block will give all the information about faults. The results are used by controller redesign mechanism to make an appropriate decision. The execution layer is similar to usual control loop. The feature is that the controller should be reconfigurable, which means the controller can react to the fault. With this architecture the reliability and safety of the system can be improved.

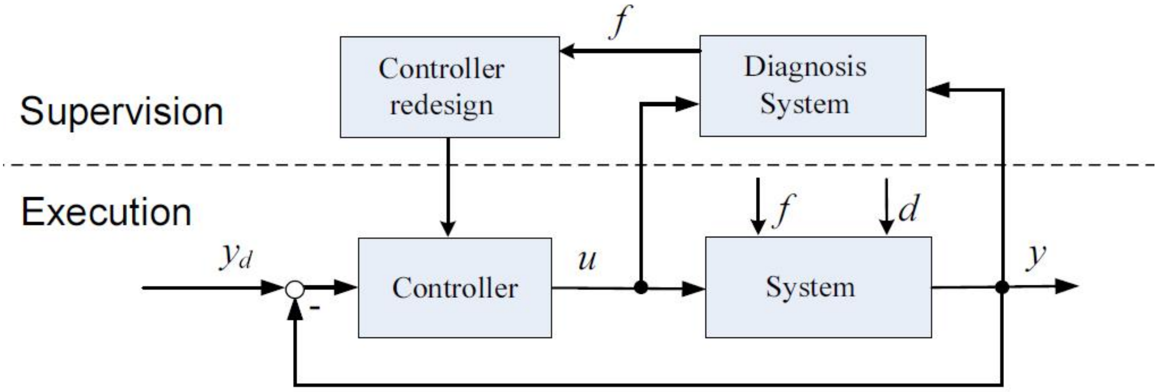

Fig 1: Fault tolerant control design

The longitudinal velocity of the vehicle and the rotational speed of the wheel constitute the degrees of freedom for this model. The governing equations for the motions of the vehicle model are as follows:

For braking force balance in longitudinal direction (vehicle)

$$Ma_x = -\mu F_N \rightarrow m\frac{dVx}{dt} = -\mu F_N \quad 1$$

Slip ratio is defined according to:

$$\lambda = \frac{Vx-\omega R}{Vx} \quad 2$$

Where, Vx = velocity of vehicle
ax= acceleration of vehicle
ω = rotational speed of wheel
αω = angular acceleration of wheel
Tb = braking torque
λ= slip ratio
μ = friction coefficient
R = radius of tire
m = mass of the model

State space representation of above equation is presented below. During braking, the slip ratio is dependent on the input torque u and the vehicle velocity Vx.

The relation of the frictional coefficient versus wheel slip ratio, provides the explanation of the ability of the ABS to maintain vehicle steer ability and stability, and still produce shorter stopping distances than those of locked wheel stop. The friction coefficient can vary in a very wide range, depending on factors like:

(a) Road surface conditions (dry or wet),
(b) Tire side-slip angle,
(c) Tire brand (summer tire, winter tire),
(d) Vehicle speed, and
(e) The slip ratio between the tire and the road

Friction model used here gives value of coefficient of friction as a function of velocity and slip ratio.

$$\mu(\lambda, V_x) = \left[C_1\left(1 - e^{-c2\lambda}\right) - c3\lambda\right]\left(e^{-c4Vx}\right) \qquad 3$$

Where
C1 is the maximum value of friction curve;
C2 the friction curve shapes;
C3 the friction curve difference between the maximum value and the value at **λ**= 1; and
C4 is the wetness characteristic value. It lies in the range 0.02–0.04s/m.

The effective coefficient of friction between the tire and the road has an optimum value at particular value of wheel slip ratio. This value differs according to the road type. For almost all road surfaces the frictional coefficient value is optimum when the wheel slip ratio is approximately 0.2 and worst when the wheel slip ratio is 1 in other words when wheel is locked. So, objective of ABS controller is to regulate the wheel slip ratio (**λ**) to target value of 0.2 to maximize the frictional coefficient (μ) for any given road surface.

A proportional controller attempts to control the output by applying input to the system which is in proportion to measured error (e) between the output and the set-point. Here control torque is

$$U = K_p e \qquad 4$$

*Where*Kp is known as the proportional gain of the controller.

$$e = \lambda_d - \lambda \qquad 5$$

In order to model the ABS with different controllers system incorporating the dynamic equations is modeled in Simulink environment. Fig 2 shows the block diagram of the Simulink model representing vehicle dynamics during straight line braking.

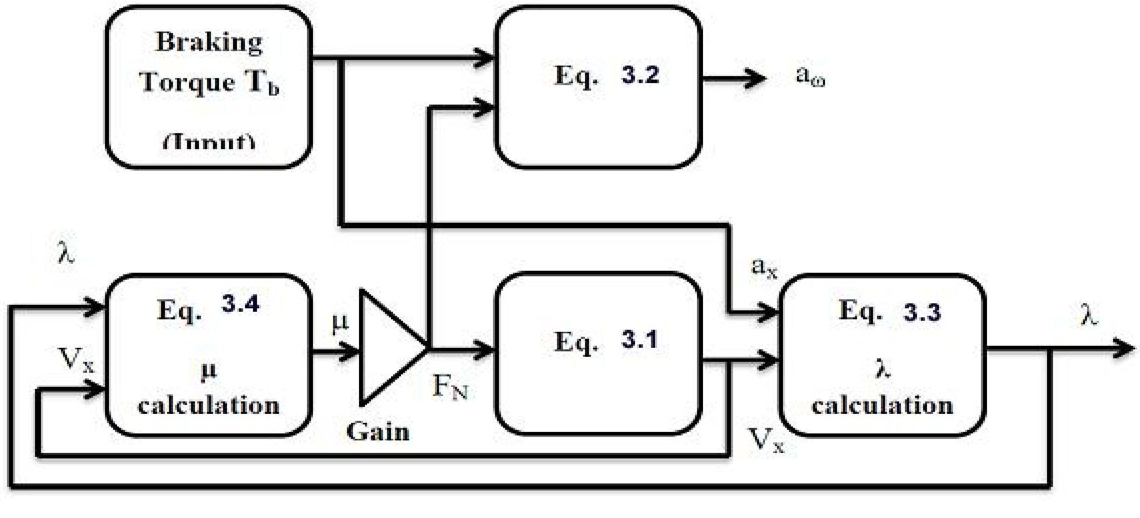

Fig 2: Block Diagram Representing Dynamics of Equations

System Implementation and Simulation

The adaptive back stepping model for fault diagnostic and fault tolerant control was implemented using MATLAB simulation to show how fault detection and isolation can be controlled by implementing adaptive back stepping model. The model is a time-based simulation of an anti-lock braking system (ABS) under hard braking conditions.

The wheel rotates with an initial angular speed that corresponds to the vehicle speed before the brakes are applied. A separate integrators was used to compute wheel angular speed and vehicle speed. Two speeds were used to calculate slip, which is determined by Equation 6. Note that we introduce vehicle speed expressed as an angular velocity.

$Wv = \frac{V}{R}$6a

$Wv = \frac{Vv}{Rr}$ 6b

$Slip = 1 - \frac{Ww}{Wv}$ 6c

Where

Wv = Vehicle speed divided by wheel radius
Vv = Vehicle velocity
Rr = wheel radius
Ww = wheel angular velocity

From these expressions, we see that slip is zero when wheel speed and vehicle speed are equal, and slip equals one when the wheel is locked. A desirable slip value is 0.2, which means that the number of wheel revolutions equals 0.8 times the number of revolutions under non-braking conditions with the same vehicle velocity.

RESULTS AND DISCUSSIONS

The simulation results were presented in tables 1-4, table 1 for Variations in vehicle speed and wheel speed with changes in time, for braking system without adaptive back stepping algorithm, table 2 for vehicle slip with changes in time, for braking system without adaptive back stepping algorithm, table 3for Variations in vehicle speed and wheel speed with changes in time, for antilock braking system using adaptive back stepping algorithm for Variations in vehicle speed and wheel speed with changes in time, for antilock braking system using adaptive back stepping algorithm, table 4 for vehicle slip with changes in time, for antilock braking system using adaptive back stepping algorithm.

Table 1: **Simulated data from the braking system without anti-lock braking system**

Time (sec)	Vehicle Speed (radian/sec)	Wheel Speed (radian/sec)
0	70.40	70.40
1	69.89	68.14
2	68.14	65.08
3	65.16	60.6
4	60.79	55.43
5	55.7	47.91
6	49.32	35.22
7	43.83	0
8	39.46	0
9	35.14	0
10	30.68	0
11	26.08	0
12	21.14	0
13	16.98	0
14	12.34	0
15	8.11	0

16	3.65	0
17	0	0

Table 2: **Simulated data for vehicle slip from the braking system without adaptive back stepping algorithm for the anti-lock**

Time (sec)	Vehicle Slip
0	0
1	0.02
2	0.05
3	0.07
4	0.09
5	0.13
6	0.27
7	1
8	1
9	1
10	1
11	1
12	1
13	1
14	1
15	1
16	1
16	1

Table 3 **Simulated data from the adaptive back stepping algorithm for the anti-lock braking system**

Time (sec)	Vehicle Speed (radian/sec)	Wheel Speed (radian/sec)
0	70.40	70.40
1	70.39	68.31
2	67.82	65.04
3	64.76	60.74
4	60.93	55.14
5	55.82	48.24
6	49.53	37.49
7	43.24	36.41
8	36.8	27.74
9	30.58	25.97
10	24.07	17.87
11	18.06	14.76
12	11.36	9.91
13	4.93	3.95
14	0	0

Table 4**Simulated data for vehicle slip from the adaptive back stepping algorithm for the anti-lock braking system**

Time (sec)	Vehicle Slip
0	0
1	0.02
2	0.04
3	0.07

4	0.09
5	0.13
6	0.24
7	0.16
8	0.23
9	0.15
10	0.26
11	0.18
12	0.16
13	0.14
14	1

In table 1, it can be observed that the wheel locks up in about seven seconds. The braking, from that point on, is applied in a less-than-optimal part of the slip curve. The distance traveled by the vehicle is plotted for the two cases. Without ABS using adaptive back stepping algorithm, the vehicle skids about an extra three seconds longer to come to a stop.

CONCLUSION AND RECOMMENDATIONS

The proposed adaptive back stepping algorithm for non linear system diagnosis and fault tolerant control was tested on a math lab simulation with the aim of correlating theory with practice, and not aimed at producing a prototype. Hence limited test runs were conducted and full evaluation of the controller on a real vehicle was not carried out. However, a braking and cornering maneuver would be an interesting aspect to be investigated. Future work will involve testing the antilock braking system controller on an actual vehicle. Also this project describes a simple model for an Anti-Lock Braking System (ABS). It simulates the dynamic behavior of a vehicle under hard braking conditions. The model represents a single wheel, which may be replicated a number of times to create a model for a multi-wheel vehicle.

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