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Application of Adaptive Thresholds in Robust Fault Detection of an Electro-Mechanical Single-Wheel Steering Actuator

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Abstract: A fault detection scheme has been developed for an electromechanical steering actuator under closed-loop control. The closed-loop system is modeled as a 2^{nd} order system with bounded parameter uncertainties given by the performance specifications. The residual is generated using an observer-based method. A dynamic adaptive threshold is generated based on the inputs and the measured system outputs to account for the residual deviating from zero under fault-free conditions due to parameter uncertainties. In addition to this, the error of the controlled system output due to a disturbance is handled by the residual evaluation function. This method is tested on a simple simulation as well as experimental data.

Keywords: model-based fault detection, adaptive threshold, steer-by-wire, parameter uncertainty

1 INTRODUCTION

Automotive steer-by-wire (SBW) systems have been investigated extensively in order to exploit the additional degrees of control freedom for vehicle dynamics control to improve safety and drive assistance functions. However, the failure of a steering actuator can lead to severe vehicle instability (Niederkofler et al. (2011)), making it a safety critical system. A fault should therefore be detected in a timely fashion, to allow reactive measures, such as control reconfiguration, to be taken to restabilise the vehicle. Several studies have been conducted regarding fault detection of SBW systems. These include approaches viewing the actuator at the level of the electric motor (Thomsen & Blanke (2006)), considering the steering system as a whole including the forces arising from the road-wheel interaction (Pisu et al. (2004)), or a combination the above (Gadda (2008)).

Handling the effects of unknown disturbances and model uncertainty is an important consideration in practical fault detection algorithms. In active approaches to robustness, the effects of disturbances and uncertainties are completely or approximately decoupled from the effects of faults on the residual using nullspace methods (Varga (2011)). Passive approaches to robust fault detection and isolation (FDI) calculate the effects of these uncertainties on the residual and consider this in the evaluation of the residual value to decide on the fault status of the system. One such approach, the use of adaptive thresholds, has been applied in literature to systems with bounded parametric uncertainties using a variety of methods. One method is the use of interval observers to produce a bound for the possible system states (Benothman et al. (2007), Puig et al. (2008)), while another involves the manipulation of state and error dynamic equations to calculate an upper bound on the residual (Pisu et al. (2004), Hashemi & Pisu (2011)).

The main contribution of this paper is the extension of the method in (Hashemi & Pisu (2011)) to deal directly with uncertainties in the physical model parameters. The steering actuator from the ROboMObil (Brembeck et al. (2011)) provides an application example. The ROboMObil is a prototype intelligent electric vehicle with four wheels that are independently driven and steered by electromechanical actuators integrated into “wheel robot” units (Figure 1). These are characterised by their ability to steer through a total angle range of approximately 125°, thus enabling sideway driving.

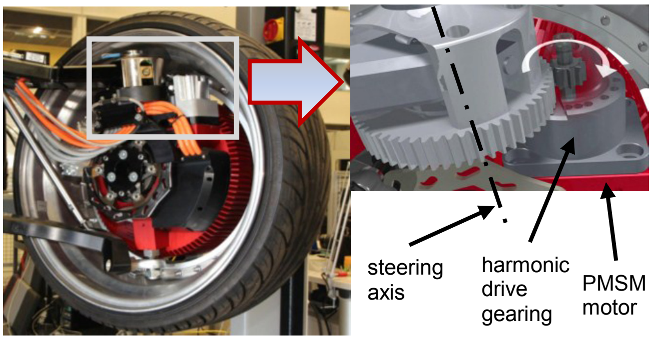

Figure 1: The electromechanical steering actuator integrated into the “wheel-robots”

The paper is organised as follows. Section 2 describes the model of the electromechanical steering actuator. Sections 3 and 4 describe the fault detection scheme and the calculation of the adaptive threshold. Application of the proposed methods to the steering actuator is presented in section 5, with numerical validation using simulations and experimental data in section 6. This is followed by a closing discussion and description of future work in section 7.

2 SYSTEM DESCRIPTION

The steering actuator consists of a permanent magnet synchronous motor (PMSM) and a harmonic drive gear system. Its output shaft is connected to a spur gear which meshes with a larger spur gear rotationally fixed to the steering axis. Angular position sensors are mounted on the motor’s rotor as well as on the steering axis. The local position controller in Figure 2 receives an angular position demand from the vehicle dynamics controller (VDC). The fault diagnosis module needs to detect critical failures in the vehicle, one of which is the failure of the steering actuator to track the demanded position, with only the demanded and the measured values of the steering position available.

2.1 Block Diagram of the Steer-By-Wire Actuator

The electromechanical actuator is controlled by a cascade architecture, with an inner angular velocity control loop and an outer angular position control loop (see Figure 2). The dynamics of the current control in the field-oriented controller (FOC) has a significantly lower time constant compared to the mechanical dynamics, therefore we will assume that the rate controller commands the motor current directly. Friction in the actuator is considered as part of torque disturbance d. The saturation for motor current is ignored in this analysis as it is rarely reached in normal operation. The rate limiter is activated regularly in normal operation, but it will not be considered in this analysis.

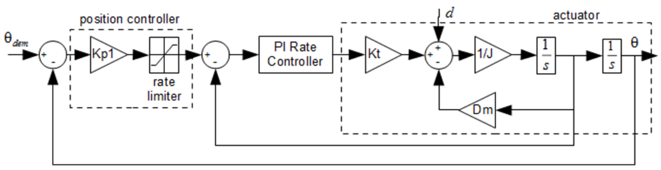

Figure 2: Block diagram representation of the controlled steering actuator

In the case where the rate limiter has not reached saturation, the transfer function from the demanded steering angle to the actual steering angle is given by:

$$\frac{\theta(s)}{\theta_{dem}(s)} = \frac{K_{p1}K_t(K_i+K_p s)}{Js^3+(K_tK_p+D_m)s^2+K_t(K_i+K_{p1}K)s+K_tK_iK_{p1}} \qquad (1)$$

The parameters definitions and their values for the actuator under investigation are defined in Figure 2 and Table 1.

Table 1. Controlled actuator model parameters

Parameter	Symbol	Value
Total inertia (at motor)	J	4e^{-5} kgm^2
Total damping (at motor)	D_m	5e^{-4} Nms/rad
Motor torque constant	K_t	0.053 Nm/A
Rate control P-gain	K_p	0.115
Rate control I-gain	K_i	3.34
Position control P-gain	K_{p1}	40
Motor rate limit	ω_{rl}	366.5 rad/s

2.2 Approximation with a Black-box Actuator Model

The real actuators are affected by uncertain non-linear effects such as internal friction, as well as unknown external load torques arising mainly from forces at the tyre-road interface, which are dependent on vehicle dynamic states, complex tyre behaviour and environmental parameters (Rajamani (2006)). The controller is specifically designed to robustly address these phenomena, with possible measures such as gain scheduling, friction compensation and suppression of mechanical resonances through frequency shaping filters. For the design of the fault detector, we consider a simplified "black-box" view of the actuator under closed-loop position control, with bounded dynamic properties given by performance specifications. The method remains applicable when the closed-loop system model is approximately determined through system identification techniques. The aim of this work is to detect a deviation from this specified behaviour while minimising false triggers due to modelling uncertainties that are defined as acceptable.

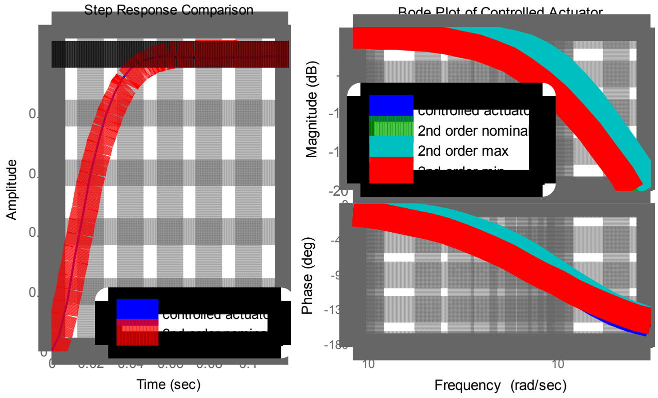

Figure 3: Left: Step responses of the modelled steering actuator and the 2nd order approximation, Right: Bode plot of the controlled actuator compared to those given by the parameter bounds

From Figure 3, it can be seen that the frequency response of the actuator transfer function (1) is closely approximated by the second order filter transfer function with the following state space form.

$$\dot{x} = \begin{bmatrix} -D & -K \\ 1 & 0 \end{bmatrix} x + \begin{bmatrix} K \\ 0 \end{bmatrix} u$$
$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} x \qquad (2)$$

where $D = 2\zeta\omega_n, K = \omega_n^2$, with the parameter values $\omega_n = 90\, rad/s$, $\zeta = 0.9$. The input is given by $u = \theta_{dem}$, and the output is $y = \theta$. Figure 3 also shows a comparison of the step responses. The frequency response of the controlled actuator is compared to those of the black-box model at the limits of the parameter bounds in the bode plot shown in Figure 3. The parameters have the ranges:

$$\omega_n \in [75\ rad/s,\ 105\ rad/s],\ \ \zeta \in [0.8, 1.0]$$

We can see that the nominal frequency response of the closed-loop system lies within the tolerance band.

3 FAULT DETECTION SCHEME

The fault detection architecture is based on the generation of a residual utilising an observer based method. An adaptive threshold is calculated based on the inputs, system states and bounds on model uncertainties. The residual is compared to this dynamic threshold and the result is further processed before making a decision on the fault status. The general fault detection architecture is depicted in Figure 4. In this application, we have scalar inputs and outputs of $u = \theta_{dem}$ and $y = \theta$ respectively.