

Model-Based and Signal-Based Gearbox Sensor Fault Detection, Identification and Accommodation

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ABSTRACT

The emergence of tougher environmental legislations and ever increasing demand for increased ride comfort, fuel efficiency, and low emissions have triggered exploration and advances towards more efficient vehicle gearbox technologies. The growing complexity and spatial distribution of such a mechatronic gearbox demands precise timing and coordination of the embedded electronics, integrated sensors and actuators as well as excellent overall reliability. The increased gearbox distributed systems have seen an increased dependence on sensors for feedback control, predominantly relying on hardware redundancy for faults diagnosis. However, the conventional hardware redundancy has disadvantages due to increased costs, weight, volume, power requirements and failure rates. This paper presents a virtual position sensor-based Fault Detection, Isolation and Accommodation (FDIA), which generates an analytical redundancy for comparison against the actual sensor output. The proposed FDIA scheme has been validated experimentally using an electro-hydraulic test rig and the gearshift simulation model, including the non-linear hydraulic actuator dynamics.

INDEX TERMS: Actuator dynamics, Gearshift control, Fault diagnosis, Sensor and actuator faults, Virtual sensor

CITATION: Manyala, J., "Model-Based and Signal-Based Gearbox Sensor Fault Detection, Identification and Accommodation," *SAE Int. J. Commer. Veh.* 7(1):2014, doi:10.4271/2014-01-9025.

I. INTRODUCTION

THE benefits of hybrid variants of Automated Mechanical Transmissions (AMTs) such as the Dual Clutch Transmissions (DCTs) include shift quality improvement by balancing friction work done by the twin clutches, which translates into improved ride comfort, fuel efficiency and low emissions. However, actuator system dynamics and controls remain critical challenges to attaining the full benefits of such a mechatronic gearbox, which demands precise timing and coordination of the embedded electronics, integrated sensors and actuators as well as excellent overall reliability. The growing complexity and spatial distribution of such a distributed gearbox has seen increased dependency on sensors for feedback control [1]. Consequently, the accuracy of the sensor signals needs to be high, and this puts special demands on the sensors output signals diagnostic capabilities in order to be able to discern errors due to system dynamics from the sensors specific faults.

Sensors play a key role in feedback control and assessment of systems state, and are expected to operate in dynamic environments in which more than one parameter changes. Advanced sensors for detecting dynamic parameters in harsh gearbox environments must provide not only high signal-to-noise ratio in a wide dynamic range but also possess diagnostic capability. A sensor fault can be defined as an arbitrary type of inconsistent measurement, which may not be

correctable using calibration techniques. Due to the non-linear and stochastic nature of these complex faults, it is often a challenge to diagnose systemic failures using conventional signal processing techniques either in the time or frequency domain. Typical sensor faults include offsets where the output is subject to a time invariant alteration of the correct value, sensitivity drift in which readings variance might be subject to degradation or incipient faults through trajectory changes of the monitored process. Furthermore, the faults can be masked by normal system maneuvers or deviations such as changes in the operating conditions due to load changes. This makes it quite challenging to eliminate such interferences using classical filtering techniques [2].

Efficacy of a fault diagnostic scheme is largely dependent on the amount, timely and quality of information available for decision making. Many approaches have been proposed for sensors fault diagnosis in a gearbox using either hardware or analytical redundancy. However, the conventional hardware redundancy has disadvantages due to increased cost, weight, volume, power requirements and failure rates. Such factors necessitate alternative non-hardware redundancy techniques. Analytical fault diagnostic schemes are classified as either model-based, knowledge-based or signal-based techniques. Model-based methods include parity generation, state estimation and residuals generation among others. The most

popular scheme is the residuals generation, which are quantities that are over-sensitive to the malfunctions. The residual is zero if the system is fault free but deviate from zero if a fault occurs.

Prior art on non-linear observer-based residual state estimates includes non-linear unknown input observer with a single state transformation that decouples the state estimates from disturbances [3], non-linear observer for bilinear systems with unknown input [4]. Fault diagnosis using neural networks have also been studied [5]. One limitation of these previous studies is that they failed to address sensor faults detection, isolation and accommodation within an electro-hydraulic actuation system with varying external load or process supervision in transient states, which can have significant effect on the system dynamics. This paper presents a virtual position sensor-based Fault Detection, Isolation and Accommodation (FDIA) by providing an analytical redundancy channel for comparison against the actual sensor output. The proposed FDIA scheme predicts the gearshift actuator dynamics for a given set of input parameters, and has been validated experimentally using an electro-hydraulic test rig and the gearshift simulation model, including the nonlinear hydraulic actuator dynamics.

Virtual sensors also known as proxy sensors are software modules that utilize measurable signals or virtual sensor inputs in order to reconstruct a signal of interest [6]. As part of fault detection methodologies, virtual sensor reduces hardware redundancy, power, space and associated costs. Virtual sensors can be developed from mathematical models based on the physics of the system and first principles. However, such mathematical models are often either unavailable, exact parameter values are unknown, or too complex. Typically, virtual sensors are often based upon system identification techniques. For instance, virtual sensors using model-based FDIA methods have been applied for faults diagnosis in the aircraft industry based on mathematical description of the system dynamics [7-8]. However, limited attention has been paid towards applying similar techniques in the harsh vehicle gearbox environment. Furthermore, the non-linear hydraulic actuator dynamics such as valves hysteresis, non-linear pressure/flow relations, fluid viscosity fluctuations, valve drifts, offsets and thermal sensitivity can adversely affect the gearbox faults diagnosis. The novelty of this paper is the development of an accurate virtual shift yoke position sensor using a non-linear input-output model.

2. GEARSHIFT ACTUATION

Gearshift actuation in a twin clutch gearbox can be controlled by the hydraulics using valve assembly, with a complex maze of passages that distribute pressurized fluid to the actuators inside the gearbox [9]. Electronic gearbox management can be controlled by the transmission control module (TCM), which calculates optimum gear ratios and regulates the actuators to engage gears at the optimal time, increasing driving comfort and decreasing fuel consumption. The TCM initiates a gear

change in response to the inputs from the driver, engine and the gearbox. Engine and gearbox status data are transmitted through the controller area network (CAN), which is an international standard intra-vehicle communication network. A block diagram of an electrohydraulic actuator system is shown in Fig. 1, comprising the TCM, hydraulic actuators, gears/shafts and sensors.

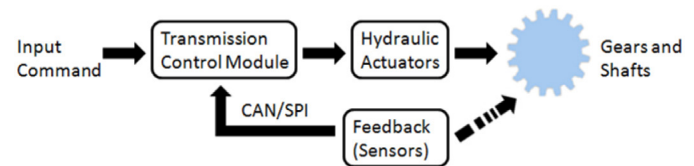


Fig. 1. Block diagram of an electro-hydraulic gearshift actuator system.

2.1. Hydraulic Actuator System

A schematic view of a gearshift actuator system is shown in Fig. 2. It consists of the following: 1) Hydraulic system, 2) Actuator piston, 3) Shift yoke position sensor, 4) Shift yoke, 5) Synchronizer sleeve and hub, 6) Lower gear, 7) Higher gear, 8) Input shaft, 9) Output shaft, 10) Input shaft angular velocity sensor, 11) Output shaft angular velocity sensor, 12) Clutch, and 13) Connection to the wheels. The shift yoke position, input shaft and output shaft angular velocity and line pressure are the available measurements from the sensors y_1 , y_2 , y_3 and y_4 respectively. The actuator comprises two hydraulic lines, each connected to the valves, separated by the actuator piston. The end of the piston houses the shift yoke position sensor while the end of the shift yoke is attached to the synchronizer sleeve. The differential force on both sides of the hydraulic lines forces the piston and yoke to accelerate when the lines are pressurized to engage or disengage the gears [10].

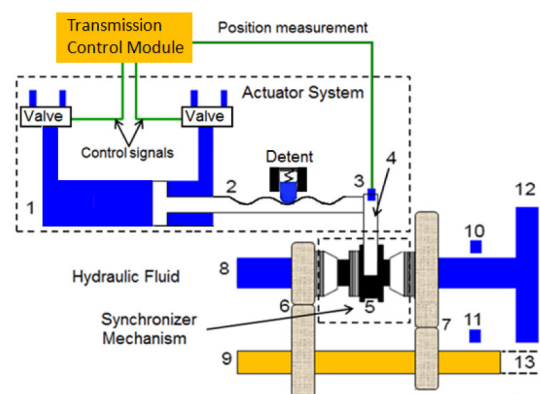


Fig. 2. An overview of the synchronization system showing the actuator, the input and output shafts, and the synchronizer mechanism.

2.2. Hydraulic Valve System

The fluid flow distribution in a proportional valve is governed by non-linear equations which can be expressed in the simplest form as follows [11]:

$$Q_i = \begin{cases} k_d w x_{sp} \sqrt{P_s - P_i} & x_{sp} \geq 0 \text{ (extension)} \\ k_d w x_{sp} \sqrt{P_i - P_r} & x_{sp} < 0 \text{ (retraction)} \end{cases} \quad (1)$$

$$Q_o = \begin{cases} k_d w x_{sp} \sqrt{P_o - P_r} & x_{sp} \geq 0 \text{ (extension)} \\ k_d w x_{sp} \sqrt{P_s - P_o} & x_{sp} < 0 \text{ (retraction)} \end{cases} \quad (2)$$

where Q_i and Q_o represent fluid flows into and out of the valve respectively. k_d is the metering coefficient, w is the orifice area gradient that relates the spool displacement, x_{sp} , to the orifice area. P_s is the pump pressure while P_i and P_o are the line input and output pressure respectively. P_r is the return pressure. A hydraulic proportional circuit highlighting P_s , P_i , P_o and P_r is shown in Fig. 3.

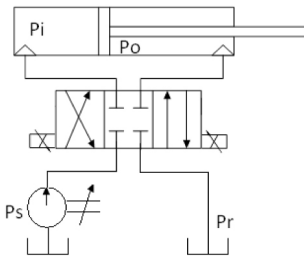


Fig. 3. Scheme of a Hydraulic proportional circuit.

Continuity equations for the fluid flow through the cylinder, neglecting any leakage flow across the actuator's piston can be expressed as follows:

$$Q_i = \frac{V_i(X)}{\beta} \dot{P}_i + A_i v \quad (3)$$

$$Q_o = \frac{V_o(X)}{\beta} \dot{P}_o + A_o v \quad (4)$$

where A_i and A_o are the effective piston areas, β is the effective bulk modulus of the hydraulic fluid, v is the actuator's linear velocity while $V_i(X)$ and $V_o(X)$ are the fluid volumes trapped on the sides of the actuator, which are functions of the displacement, X . The relationship between the spool displacement, x_{sp} , and the input voltage, u , for a proportional valve can be expressed as a first order system as:

$$u = \frac{\tau}{k_{sp}} \dot{x}_{sp} + \frac{1}{k_{sp}} x_{sp} \quad (5)$$

where τ and k_{sp} are the gains describing the valve dynamics that define the turbulent hydraulic fluid flow through an orifice. The electromagnetic valve dynamics are covered in great detail in [12]. The valve subsystem includes a mass, spring and

damper that results from the combined effect of pressure and magnetic forces. This can be summed up using Newton's second law as follows:

$$m_s \frac{d^2}{dt^2} x(t) + b \frac{d}{dt} x(t) + k(x(t) + \delta) = F_m(t) + F_{prs} \quad (6)$$

where m_s is the spool mass, b and k are the damping and spring coefficients respectively, δ is the spring pre-tension and F_{prs} is the pressure force. Relationship (6) is achieved using the magnetic force and feedback force created by the pressure inside the left and right chambers by the plunger movement. The piston dynamics can be expressed as follows [13]:

$$F_{prs} = (A_1 - A_2)P_{sup} + (A_3 - A_4)P_{out} \quad (7)$$

where P_{sup} and P_{out} are the pressures at the supply and output valve ports, whereas A_1 , A_2 , A_3 and A_4 denotes the various spool lands areas which are affected by P_{sup} or P_{out} in different directions.

2.3. Electronic Gearshift Control

Electronic gearbox management systems typically operate on event-driven basis by selecting the gear that provides the optimal torque to meet the prevailing driving conditions with the engine operating in the most favorable map range, such as the range that attains the best fuel economy. An overall gearshift quality improvement strategy needs to meet the following objectives: minimization of the mean vehicle deceleration due to traction loss, reduction of the gearshift duration, and minimization of driveline oscillations resulting from the transmitted torque variations as well as clutch and gearbox operations [14]. The control parameter adjustment for each shift schedule can be determined in an optimization calculation by means of an empirical model of the gearshift behavior.

2.3.1. Gearshift Control Logic

Studies have been conducted to fine tune the gearshift strategies. Most of these studies have focused predominantly on the vehicle speed, with the engine typically modeled as a mass inertia which accepts throttle angle as the input to produce a mean torque at the crankshaft [15]. In this work, gearshift control logic has been modeled in Simulink incorporating a state-flow that drives the actuator based upon the vehicle speed and throttle position. As previously mentioned, the gearshift logic determines the optimal time to perform a gearshift during the drive cycle. For the actuator control scheme, a decoupled simulation model has been established in which the actuator parameters that have been calculated from both physical measurements and finite element analysis (FEA) such as current, pressure, force and displacement characteristics are incorporated in the form of look-up tables.