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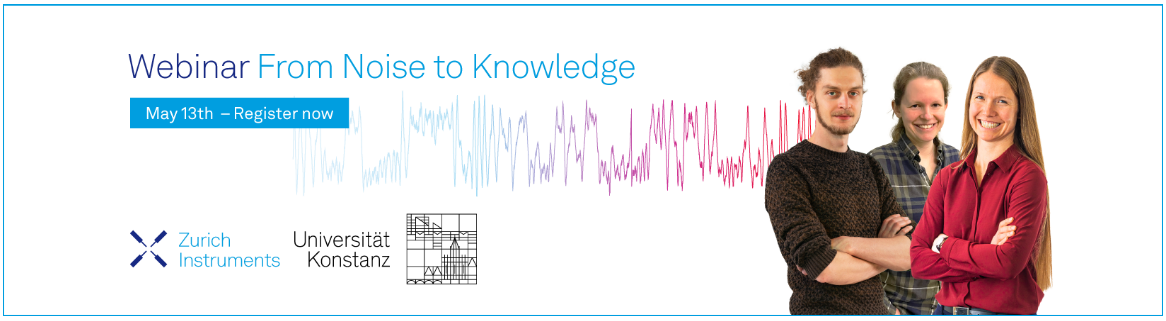

Misfire Detection Based on Switched State Observer of Hybrid System in Internal Combustion Engine

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Abstract. This paper proposes a novel switched state observer of hybrid system using Luenberger sliding mode observer to estimate crankshaft angular acceleration which is further applied to detect misfire fault. The output error of hybrid system of internal combustion engine (engine speed) and the designed observer (estimated speed) is taken as input of observer to estimate crankshaft acceleration. Convergence of hybrid system is proven through Lyapunov stability theory. The experimental results show that the presented estimated technique has a higher accuracy and can be effectively used to misfire detection compared with reduced-order observer and sliding mode observer.

INTRODUCTION

Misfire detection of internal combustion engine (ICE) plays a significant role in energy conservation and reducing economic losses due to inadequacy burning, the damage of three-way catalytic converter, etc. The techniques of misfire detection can mainly be categorized into method based on data and method based on model at present. The method of misfire fault diagnosis based on model has an advantage over method based on data [1]. In this study, the method based on model of misfire detection is presented. The basic philosophy of fault diagnosis model is acquiring residual generation that can be generalized into three types: (i) Fault detection filters; (ii) Observer design; (iii) Parameter estimation.

Numerous techniques of misfire detection have been proposed previously in the literature [2]. Most of approaches have their foundations on methodology model design including artificial neural network [3], state observer design [4], wavelet analysis and statistical analysis method [5], etc. Sliding mode observer has been widely employed for state variable estimation because of its effectiveness in applications for computational efficiency as well as its robustness on parametric variations and modeling uncertainties [4]. Due to problems encountered that the acceleration value is unavailable in vehicle and misfiring cylinder needs to be identified, hence, a switched state observer using Luenberger sliding mode technique is proposed in this study, which takes crankshaft speed as input and estimates crankshaft acceleration. Moreover, compared with reduced-order observer (ROO) and first order sliding mode observer (FOSMO), the proposed method using estimated acceleration of first order Luenberger sliding mode observer (FOLSMO) can effectively realize misfire detection under steady working condition.

DESCRIPTION OF CRANKSHAFT DYNAMIC MODEL

Hybrid Model of ICE

Hybrid model is essentially a discrete event model (DEM), which describes a dynamic changing process of multiple cylinder engine. A four-cylinder and four-stroke engine is modeled as a hybrid system with four identical

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minimum phase linear time invariant (LTI) subsystems in this study. Each time instant fuel combustion only occurs in one of the four cylinders (power cylinder) while the other processes of compression, suction and exhaust are occurring in other three cylinders (load cylinder). Once power stroke of the active subsystem is completed, next power stroke will be initiated and switched to another subsystem. Each subsystem is sequentially actuated during an ignition cycle (720 degrees). The output of the hybrid system is a vector sum of all these subsystems. Assuming that air-fuel ratio of ICE is stoichiometric and the whole combustion energy is instantaneously generated at the beginning of the power stroke and is delivered to flywheel at a constant rate in a steady state and a constant load of hybrid system. Further, a five-tuple model $<\alpha, X, \Gamma, \sum, \Psi>$ of hybrid system for an ICE is proposed [6], where α represents active subsystem, the vector X consists of velocity and acceleration, $\Gamma = \{G(s)\}$ is a state space model and $G(s)$ is transfer function of subsystems, $\sum$ represents transition process, Ψ defines the initial condition of each subsystem.

Nonlinear Subsystem Modeling of Hybrid System and Model Linearization

Based on crankshaft dynamic analysis, the nonlinear subsystem model of ICE has been proposed by [6]. The description of nonlinear equation of hybrid system can be expressed as

$$\frac{d^2v}{dt^2} + \frac{f}{m}\frac{dv}{dt} + \frac{e}{m}v = \frac{\Upsilon\eta_s}{mx}\frac{Q_u}{\Delta t} \tag{1}$$

The above formula defines a nonlinear subsystem model about the crankshaft speed when the power is added to the engine by fuel combustion. Where dv/dt is the derivative of time about linear velocity v of piston, m is the mass of the engine moving assembly (piston, connecting rod, crankshaft and flywheel), f is coefficient of friction and e is a function of the crankshaft angular speed. Internal energy Q_u added in the subsystem by burning air-fuel mixture is utilized to perform work with the constant efficiency $\eta_s = 0.3$. Moreover, Δt is infinitely small of time and $\Upsilon = 1.4$ is adiabatic coefficient. x is a continuous variable of instantaneous piston position. Consider that the piston always moves between top dead center (TDC) and bottom dead center (BDC), then x can never be zero. Assuming that a constant finite power Q produced by burning of air-fuel mixture is added to a cylinder when piston is at the TDC and the subsystem delivers power $Q(x) = Q_u/\Delta t$. Hence, the right side of equation (1) is a smooth function. x_t is defined as piston position at the TDC. Linearizing the subsystem at the TDC under the steady-state condition, the nonlinear model can further be rewritten as

$$\frac{d^2v}{dt^2} + k_2\frac{dv}{dt} + k_1 v = \frac{\Upsilon\eta_s}{mx_t}Q \tag{2}$$

where $k_2 = f/m$ and $k_1 = e/m$. Due to the assumption that the system is delivered power at a constant rate, Q is taken as constant ($Q = Q(x)$). Therefore, the expression becomes a linear differential equation.

METHODOLOGY BASED ON FAULT DIAGNOSIS MODEL

The burning of air-fuel mixture in a cylinder produces high pressure inside combustion chamber that directly accelerates the piston. As the pressure inside cylinder gradually reduces, the piston starts to decelerate. When misfire occurs in one or more cylinder(s), the piston continue to decelerate and a larger valley value would be observed. Therefore, the methodology of misfire diagnosis can be described as a changing rule in curves. In this scheme, a switched state observer (shown in next two parts) would be used by hybrid subsystem changing its active cylinder of ICE. And the error value can be observed and provided to reference model as input.

State Space Description

According to the equation (2), each subsystem of hybrid system can be represented as a second order linear system with crankshaft velocity and acceleration as two states and internal energy Q as the input. Under ideal conditions, it is assumed that each cylinder of engine is identified and operates in a balanced mode, e.g., same power is added to each cylinder (no misfire condition). Therefore, assuming that internal energy Q of each subsystem is constant. Then the state space of four subsystems can be rewritten as

$$\dot{v}_{1n} = v_{2n} \tag{3}$$

$$\dot{v}_{2n} = -k_2 v_{2n} - k_1 v_{1n} + CQ \tag{4}$$

where $n = 1,2,3,4$ represents subsystem number and $C = \Upsilon \eta_s / m x_t$ is a constant. v_{1n} and v_{2n} denote the crankshaft velocity and acceleration of each subsystem, respectively.

First Order Luenberger Sliding Mode Observer Design

A novel Luenberger sliding mode observer is introduced in this study, which includes two inputs, e.g., one input corresponding to internal power added to piston and another input is the speed error. Assuming $\hat{v}_1$ and $\hat{v}_2$ denote the estimation of system states v_1 and v_2, FOLSMO of each subsystem can be defined as

$$\dot{\hat{v}}_1 = \hat{v}_2 \tag{5}$$

$$\dot{\hat{v}}_2 = -k_2 \hat{v}_2 - k_1 \hat{v}_1 + L e_1 + \mathrm{K}\,\mathrm{sgn}(e_1) + CQ \tag{6}$$

where L is Luenberger gain, K is sliding mode gain, e_1 is crankshaft speed error, $\mathrm{sgn}(\bullet)$ is sign function. Subtracting equation (3) and (4) from equation (5) and (6), the error dynamic system can be formed as

$$\dot{e}_1 = e_2 \tag{7}$$

$$\dot{e}_2 = -k_2 e_2 - k_1 e_1 + L e_1 + \mathrm{K}\,\mathrm{sgn}(e_1) \tag{8}$$

where e_1 and e_2 represent crankshaft speed and acceleration respectively, $L e_1 + \mathrm{K}\,\mathrm{sgn}(e_1)$ provides an extra signal that is a negative bias equal to the discrepancy between the reference model input and actual input to system. And the stability of the error dynamics ensures that the estimated states converge to the actual system states. The following stability analysis of error dynamic system of hybrid system is presented. The characteristics equation for the error dynamics of each individual subsystem can be found

$$s^2 + k_2 s + k_1 = 0 \tag{9}$$

The stability of formula (9) indicates that each subsystem is stable and a common Lyapunov function exists. Giving in the work [7] can be found that a switched system is stable for an arbitrary switching sequence if a common Lyapunov function exists for all subsystems. Therefore, the proposed switched state observer is stable and estimated states can converge to states of the actual system.

EXPERIMENTAL RESULTS AND DISCUSSION

In the experiment, the proposed misfire fault technique is conducted in a four-cylinder ICE and its details are listed in Table 1. The designed observer is respectively operated on no fault and single cylinder misfire condition. Periodic impulse train of switched linear hybrid system is produced by phase delay of $T/4, T/2, 3T/4$. Additionally, the gain E_i of each subsystem is set as zero to produce misfire event.

TABLE 1. Parameter value and specifications of ICE

Parameter	Value and Unit	Parameter	Value and Unit
Engine Type	4-Cylinder 4-Stroke	Mass of Engine Moving Assembly	$20Kg$
Crank Radius	35 mm	Crankshaft Angular Speed	$100\,rad/s$
Piston Stroke	29.6mm	Power Generated in Cylinder	$10hp$

The result of crankshaft speed tracking using FOLSMO under signal cylinder misfire fault condition is shown in Fig.1 that a large negative peak of crankshaft speed is observed and the corresponding misfire cylinder number can be identified by short dash line. And Fig.1 shows that the reconstructed crankshaft speed can track ideal value effectively. The speed tracking error provided in Fig.2 converges to zero, which can prove that the proposed FOLSMO is ultimately stable under steady state conditions.

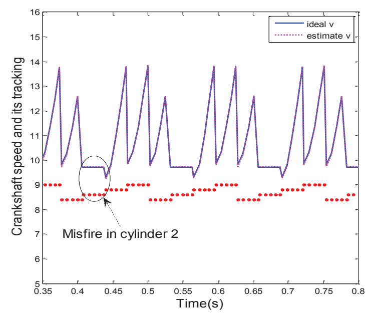

Figure 1. Speed tracking result

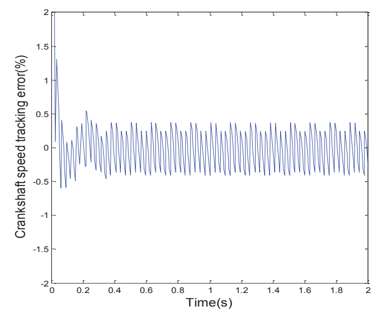

Figure 2. Speed tracking error

The estimated results of crankshaft acceleration using FOLSMO under no fault and single cylinder misfire condition are provided in next two figures, which clearly shows that misfire characteristic is obvious and a large fluctuation in acceleration wave can be observed. Further, the overall acceleration has a reduction drastically when misfire event occurs. Hence, it is assumed that estimated acceleration can be applied to identify misfire fault. Additionally, a comparison of performance in estimating crankshaft acceleration is listed in Table 2, which shows that reconstructed data using FOLSMO has a higher accuracy compared with FOSMO and ROO. The designed ROO has a fastest convergence speed. Further, the convergence time using FOLSMO is slightly shortened with respect to FOSMO.

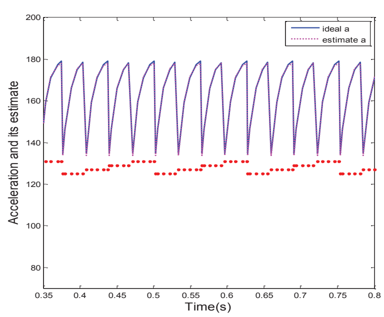

FIGURE 3. Acceleration in healthy condition

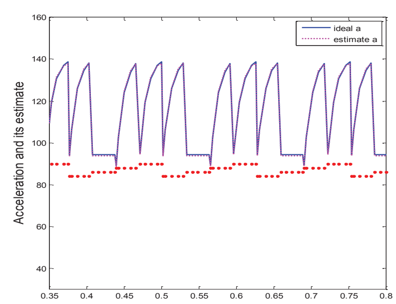

FIGURE 4. Acceleration in single cylinder misfire

TABLE 2. Performance comparison of designed observer

Type	Condition	Acceleration Error	Condition	Acceleration Error	Convergence Time
ROO	No Fault	0.5% ~ 5.2%	Misfire	-0.9 ~ 7.8%	$0.12s$
FOSMO	No Fault	-1% ~ 0.3%	Misfire	-1.1 ~ 0.8%	$0.4s$
FOLSMO	No Fault	-0.2% ~ 0.8%	Misfire	-0.6 ~ 0.7%	$0.3s$

CONCLUSION

This study proposes a switched state observer of hybrid system using FOLSMO which can be applied to misfire detection of ICE. Compared with ROO and FOSMO, FOLSMO achieves a higher accuracy in estimating crankshaft acceleration and it can also effectively identify misfire event under steady working conditions. Additionally, the designed FOLSMO shortens convergence time. Further, we plan to develop the estimated acceleration or other parameters which can be used to multi-cylinder misfire detection.

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