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Automotive Engine Control with Rational Function Satisfying inequality Constraint

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Abstract: The major drive of current engine development is to increase fuel economy. It has become very essential to manage the restriction due to the boundaries which divide the engine operation conditions into the normal and the abnormal ones such as knocking and misfiring because an optimal operation condition is often close to such a boundary. It indicates that required controls must satisfy inequality state constraints derived from identified boundaries. This paper describes a model following control satisfying the inequality state constraint of knocking with an explicit rational function which is easy to be implemented on production ECUs. The proposed control design was successfully applied to a simple engine model.

Keywords: automotive control, internal combustion engine, control design, inequality constraint, rational function, algebra, symbolic manipulation, model following control

1. INTRODUCTION

The current major drive of automotive internal combustion engine development is to improve fuel economy. High internal and external EGR (Exhaust Gas Recirculation) ratios and lean burn have been adopted to reduce the pumping loss but the approaches tend to cause misfiring. High compression ratio increases the combustion efficiency but it tends to cause knocking. Down sizing with turbocharged engines also tends to cause knocking as well. Knocking and misfiring avoidances are typical examples of the inequality state constraints in current engine control designs. Engine control developments have often encountered inequality state constraint problems as recent automotive engines have been highly optimized and the optimal operation condition tends to be on a boundary of constraint. Therefore, one of the current important control design problems is to obtain the manipulations $u \in R^m$ such as the throttle valve opening angle, the sapark advance, the variable intake and exhaust valve timing, the EGR ratio as represented by

$$u = \arg \min_{u \in R^m} \int_0^t \left\{ (tor - ref)^2 + \eta^2 fuel \right\} dt \qquad (1)$$

subject to

$$\frac{dx}{dt} = f(x, u) + \delta, E(\delta) \neq 0 \qquad (2)$$

$$y = g(x) \qquad (3)$$

$$h(x, u) < 0 \qquad (4)$$

where tor is the engine torque that is an element of x, ref is the reference of torque control, $x \in R^n$ is a state vector, $y \in R^p$ is an output vector, (2) is a general representation of dynamics of engine behavior, and $h \in R^{(n+m)} \rightarrow R^q$is a functions due to the constraints such as input ranges and speeds, the exhaust gas emissions, knocking, misfiring, and the temperature limit of catalyst. The first term in the integration of (1) corresponds to the requirement of sufficient drivability and the second term requires to reduce the amount of injected fuel. It is easy to design model following controls which allow the engine torque to track the reference from a desired torque model when a state constraint does not need to be considered. But, it is not easy to manage especially inequality state constraints. Toyota provided a benchmark problem as a student competition and an engine simulator to ECC2015 so that students tuckled to design an engine control minimizing the fuel consumption subject to avoiding knocking and misfiring (Watanabe2015).

IMI (Institute of Mathematics for Industry) of Kyushu University has studied boundary modeling for engine control designs and DoE (Design of Experiments) which can reduce experiments in engine calibrations (IMI2015). MPC (Model Predictive Control) can determine the input at each control timing by solving an optimal control problem in finite durations however it requires the time consuming computation. Simplifying plant models and shortening the prediction horizon are often applied to reduce the computation resources however such the methods may tend to loose the advantage of MPC. Ohtsuka proposed a very high speed MPC algorithm C/GMRES (Ohtsuka2004) but it still requires time consuming calculation. That is a serious issue of MPC because the speed of production ECU (Electronic Control Unit) is only around 300MHz in reality. Therefore, the trend to multi and many cores is an imporatnt to mitigate the issue but it requires the parallelization of embedded codes which is also a tough problem.

Zerz (Zerz2015) and Yuno (Yuno2015) published an algebraic control design for polynomial input affine systems

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of which the framework deals with equality constraints also represented by polynomial function. It is well known for control engineers that inequality constraints are transformed to equality constraints by introducing slack variables. It gives a strong motivation to seek a simple control with polynomial and rational functions which can deal with inequality state constraints because it can be easily implemented on production ECUs.

This paper describes a model following control which satisfies a state inequality constraint and is represented by an explicit rational function with the states, the reference and slack variables which transfers an inequality constraint to the equality constraint. This paper consists of six sections. Following the introduction, the section 2 briefly introduces algebraic control design, the section 3 describes a very simple engine model with the knocking boundary to which the proposed control is applied, the section 4 explains the proposed control design, the section 5 demonstrates the effect of proposed model following control satisfying a prescribed inequality constraint, and the final section summarizes the study.

2. ALGEBRAIC CONTROL DESIGN

In this section, algebraic control design is briefly introduced. Consider the polynomial input affine system represented by

$$\frac{dx}{dt} = f(x) + g(x)\,u \tag{5}$$

where $x \in R^n$ is a state vector, $u \in R^m$ is an input vector, f is a polynomial function of $R^n \rightarrow R^n$, and g is a polynomial function of $R^{n\times m} \rightarrow R$. For the system, the input of (5) which makes the state satisfy

$$h(x) = 0 \tag{6}$$

is given by

$$\begin{aligned} u(x) = u_0(x) + c_1(x)\,u_1(x) + \\ c_2(x)\,u_2(x) + \ldots + c_L(x)\,u_L(x) \end{aligned} \tag{7}$$

under the sufficient and the necessary conditions, where h is a polynomial function of $R^n \rightarrow R$, from u_0 to u_L are determined algebraically, in other words, they are given by a symbolic manipulation based on Grobner basis (Adams1994), and c_1 to c_L are arbitrary functions with the state vector x (Zerz2015). The system and the constraints with the polynomial functions can be extended to the ones with rational functions.

By introducing a slack variable σ, the inequality constraint represented by

$$h(x) < 0 \tag{8}$$

is transformed to the equality constraint given by

$$h(x) + \sigma^2 = 0 \tag{9}$$

(Yuno2016). The approach insists that controls which satisfy inequality state constraints are represented by explicit polynomial with x and σ. However, it satisfies only the constraint of (9). The differentiation of (9) gives

$$\frac{\partial h(x)}{\partial x}\frac{dx}{dt} + 2\sigma\frac{d\sigma}{dt} = 0 \tag{10}$$

and the substitution of (5) to (10) gives the equality constraint,

$$\frac{\partial h(x)}{\partial x}\left\{f(x) + g(x)\,u\right\} + 2\sigma\xi = 0 \tag{11}$$

where $\xi = du/dt$. Therefore, algebraic control design is applied to the augmented system represented by

$$\frac{d}{dt}\begin{bmatrix} x \\ \sigma \end{bmatrix} = \begin{bmatrix} f(x) \\ 0 \end{bmatrix} + \begin{bmatrix} g(x) & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} x \\ \xi \end{bmatrix} \tag{12}$$

Thus, (7) is written by

$$\begin{aligned} u(x,\sigma) = u_0(x,\sigma) + c_1(x,\sigma)\,u_1(x,\sigma) + \\ c_2(x,\sigma)\,u_2(x,\sigma) + \ldots + c_L(x,\sigma)\,u_L(x,\sigma) \end{aligned} \tag{13}$$

for the augmented system (12). The input (13) which is represented by an explicit polynomial function makes the right hand side of (9) be constant. Thus, (8) is satisfied by (13) when the initial condition $x(0)$ and $\sigma(0)$ satisfies

$$h(x(0)) + \sigma(0)^2 = 0 \tag{14}$$

Unfortunately, rational input affine systems are more desirable to approximate the representation of the air dynamics in the plenum chamber than polynomial ones. Therefore, it should be extended to deal with rational input affine systems. However, algebraic control design gave the strong motivation to explore a model following control satisfying the inequality state constraints represented with rational functions.

3. VERY SIMPLE ENGINE MODEL

Current spark ignition engines have many manipulations including THR (THRottle valve), SPA (SPark Advance), VVTI (Intake Variable Valve Timing), VVTE (Exhaust Variable Valve Timing), VLI (Variable Intake valve Lift), and EGR (Exhaust Gas Recirculation). The major purpose of engine development is to improve fuel economy thus it is the reason why the criterion represented by (1) have been applied to almost all engine controls even implicitly. Recent automotive engines have the redundancy of the manipulation inputs to achieve the required engine torque and the redundancy is used to increase the fuel economy of developed engine. The highest priority is assigned to the drivability rather than the fuel economy. It indicates that the engine operation condition of achieving the required torque is determined to minimize the fuel consumption by using the the redundant inputs although there is a case in which constraints may not allow the engine to realize the required torque. From this point of view, the torque control with an inequality constraint is the most fundamental problem. Therefore, a torque control with an inequality state constraint is considered on an ordinary spark ignition engine without the redundant manipulations such as VVTI, VVTE, VVTL, and EGR in this study.

A simple engine model and a simple state constraint are derived in the following part of this section as this is only a preliminary study to explore how to manage inequality state constraints. The modeled engine is a spark ignition engine with four cylinders. Fig.1 briefly shows the considered engine but only the intake system and a cylinder are drawn. Neglecting the friction loss, the torque