

Disturbance Estimation Based Modeling Technique for Control and Prediction in Controllable Mechanical Turbo-Compounding System

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ABSTRACT

Modeling techniques matter a lot in many fields of engine engineering. Models are requested not only for control design but also for dynamic prediction. However, problems might be encountered during modeling process either because of the system complexity or the unaffordable modeling cost. As a result, a new modeling technique based on disturbance estimation is proposed in this paper. By employing the proposed modeling technique, models are set up in real time with the online information from input and output. The uncertainties of system dynamics are handled as internal disturbance of the system, while the perturbation from outside are taken as the external disturbance, and the combination of the two can be estimated online by a kind of active observer called extended state observer (ESO). Then a dummy variable which is equal to the sum of the known dynamics, estimated disturbance and control input can be used to establish a new simpler system, based on which control and prediction based management can be designed. Deductively, the real control variable can be solved out by the dummy variable equation. Simulation studies are conducted upon the tracking control and energy management of a controllable mechanical turbo-compounding system to verify the effectiveness of the proposed solution. This method is believed costs less than pure mechanism modeling method and is able to incorporate the total disturbance of the operating system into the system dynamics without sacrificing the computation speed, demonstrating satisfying accuracy, which is appealing for model based control and management in engine engineering.

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INTRODUCTION

Modeling is a very crucial technique for both control and prediction based management in engine engineering. On one hand, static Maps are still playing the dominant role in industrial application, which naturally brings a large scale of calibration work. On the other hand, Mean value model (MVM) has prevailed for decades in the research field. One of the most popular applications of mean value model is for control purpose, a lot of papers can be traced in this use. For instance, the University of Michigan established a mean value model for control of Homogeneous Charge Compression Ignition (HCCI) [1]. General Motors Corp. set up a fast-running mean value engine model with sufficient accuracy developed in GT-Power [2]. The mean value model has also been used for dynamic prediction in engine engineering. The Federal University of Santa Maria built a Map through a mean value model that combines speed and load to achieve the required power with the best engine efficiency [3]. Delphi Corp. has developed a mean value model for estimating the exhaust manifold pressure in production application [4].

Mean value model has acquired further preference in the modeling of turbocharged engine system. Many literatures can be found to support the prevalence of its application in turbocharged engines. For

example, a mean value model has been presented for the transient operation of a 1.6 liter turbocharged indirect injection diesel engine [5]. Mean value models were established for automotive control applications [6, 7]. Some even used the mean value model for Fault detection and isolation (FDI) [8].

Although the widespread utilization of mean value model in the engine related field, to establish a satisfactory mean value model has become more difficult as the studied compound system become more complex. For instance, the modeling, of a power turbine equipped turbocharged engine, into a mean value model with desired accuracy is proved not to be an easy task. However, the control and energy management upon the described turbo-compounding system is very practical and necessary. Consequently, we are motivated to propose a new disturbance estimation based modeling technique to predict the dynamics in real time, only from the input and output information.

The proposed disturbance estimation based modeling technique is realized by using an active disturbance estimation observer, extended state observer (ESO), which was firstly proposed by Jingqing Han as a part of Active disturbance rejection control (ADRC) [9] and further simplified by Zhiqiang Gao into linear form for easier industrial

application [10]. Some mature industrial applications have proved the advantage of ADRC technology over the industrial standard solutions [11]. Here in this paper, by using the ESO, we are going to show, on one hand, how to reconstruct the model to be immune to internal and external disturbances for system dynamics prediction, on the other hand, how to cancel the total disturbance in real time to force the system to behave like a canonical system and based on which do control design.

The rest paper are organized as follows. The problem formulation is introduced in Section 2, and solution is proposed in Section 3. Then case study is given in Section 4, a discussion of improving overall efficiency is presented in Section 5. At last, conclusion is given in Section 6.

PROBLEM FORMULATION

A controllable mechanical turbo-compounding (CMTC) system is employed as an example to demonstrate how to do predict and control with a disturbance observer in this paper. The structure of the CMTC system can be described as shown in Fig. 1.

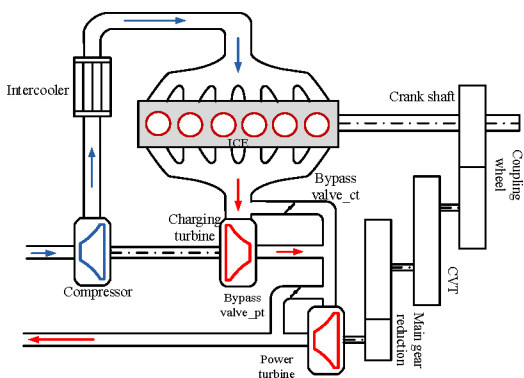


Figure 1. The configuration diagram of controllable mechanical turbo-compounding (CMTC) system

The exhaust energy originated from the internal combustion engine (ICE) is the driving energy of the considered mechanical turbo-compounding (CMTC) system. Power turbine is mounted downstream charging turbine to recover waste heat from the exhaust. The recovered energy is coupled onto the crank shaft by transmitting from main gear reduction through continuously variable transmission (CVT) and then to coupling wheel. There are two waste gates in the system. One is in parallel with charging turbine which is used to regulate intake pressure of the engine, denoted as *bypass valve_ct* in Fig. 1. The other is in parallel with power turbine to modulate the MFR (mass flow rate) through power turbine, denoted as *bypass valve_pt*. CVT is designed in this system to regulate the power turbine operation point by adjusting the speed ration between the power turbine and the crank shaft under the given engine operation situation. The control research of the CMTC based on static Maps has been explored in [12].

In this paper, both the *bypass valve_ct* and CVT are assumed able to adaptively operate on the optimum points under the whole driving cycle conditions. The power turbine bypass valve *bypass valve_pt* is

designed as the only controllable actuator, and our former research has proved that the power turbine can work optimally only when switch control mode is employed [13].

Youssef Ismail et al [14, 15] investigated the influence of turbo-compounding system upon combustion, pumping work, exhaust gas recirculation (EGR) rate and engine thermal balance, showing that pumping loss is the main influence exerting on engine by power turbine. Consequently, the overall efficiency of CMTC system is fulfilled by optimum match between power turbine generated power and pumping loss via regulating power turbine bypass. In other words, the controlled variables in this paper is power turbine generated power and pumping loss, while the control variable is the opening and closing of power turbine bypass.

Based on the given background, we are going to explore two problems in this paper.

Problem 1: If the CMTC works as an independent system, how to keep the overall efficiency of the system optimum along a whole driving cycle by the switch control of power turbine bypass?

Problem 2: If the CMTC works as a part of a waste heat recovery system, where the power turbine generated power is requested in real time according to the upper energy manager's decision. Then the problem is, how to track the upper manager's requested power by the switch control of power turbine bypass?

Remark 1: Please note that in a real engine waste heat recovery system, the control strategy of power turbine bypass is usually designed included in the upper energy manager, thus it is the CVT to be controlled to follow the upper manager's needed power. In this paper, for the sake of convenience, we assume the CVT is designed optimally suitable to the driving cycle, and the power turbine bypass is the only control variable.

SOLUTION

The main idea of the solution proposed in this paper is to estimate or control based on the real-time information of the CMTC operating process, which is obtained by disturbance estimation from the input and output information. That is to say, it is the information of the process rather than equations of the process to be obtained from the following given method.

In order to obtain the real-time information of the CMTC operating process, we have to firstly acquire the input and output information of the system. According to the aforementioned given background, the only controllable actuator is the power turbine bypass, relating with the power turbine intake flow rate, which is the only input information of the CMTC system, denoted as u in this paper. There are two output information concerned in this study. The first one is the real power generated by turbine power, let it as x_1 , the second one is the pumping loss of the engine in CMTC system, denote it as $\bar{x}_1$. For the same CMTC system, x_1 increases at the expense of $\bar{x}_1$ along the regulation of u .

According to our former offline study, both the dynamic relationship from u to x_1 and from u to $\bar{x}_1$ can be assumed as second order systems. That is to say the two relationship can be formulated as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f + bu \\ y = x_1 \end{cases} \quad (1)$$

where, u is the power turbine intake flow rate; f is the total disturbance including the internal disturbance and the external disturbance; b is an unknown gain; y is the power generated by turbine power.

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \bar{f} + \bar{b}u \\ \bar{y} = \bar{x}_1 \end{cases} \quad (2)$$

where, $\bar{f}$ is the total disturbance including the internal disturbance and the external disturbance; $\bar{b}$ is an unknown gain; $\bar{y}$ is the engine pumping loss.

Based on the above two equations, the aforementioned two problems can be reformulated as follows:

Problem 1: How to keep the overall efficiency of the CMTC system be optimum along the whole driving cycle by regulating control variable u based on model (1)-(2)?

Problem 2: How to track the given y by regulating control variable u based on model (1)?

Next, the solution to the problem 1 and problem 2 will be given one by one.

Solution to Problem 1

Before comes to the solution, we need firstly introduce the efficiency assessment indicator, overall efficiency, which is defined as the output power of the CMTC system from one unit fuel energy, and can be written as follows:

$$\eta_{overall} = \frac{W_e + \eta_t y - \bar{y}}{W_{fuel}} \quad (3)$$

where, W_e denotes the prototype engine power. η_t is the transmission efficiency of power turbine. W_{fuel} represents the supplied fuel energy per unit time. This efficiency can be used to assess the fuel-saving potential of the CMTC system.

For a given CMTC system and a given driving cycle, different manage strategies upon the control variable u will make different $\Delta = \eta_t y - \bar{y}$, thus consequently result different overall efficiency

$\eta_{overall}$

In order to maximize the fuel-saving potential of the CMTC system, we have to constantly keep $\Delta = \eta_t y - \bar{y} > 0$, otherwise the overall efficiency of the CMTC system would be worse than that of the prototype engine.

Considering the switch control mode of power turbine bypass is employed in this paper, then the online energy management strategy upon power turbine bypass for the purpose of optimum overall efficiency can be described briefly as follows:

if $\eta_t y - \bar{y} > 0$

then shut down the power turbine bypass;

else open the power turbine bypass.

end

However, owing to different kinds of inertia exist in the real CMTC system, decision-making based on the measured information of y and $\bar{y}$ wouldn't be enough. We'd better make the decision exactly before the undesired influence has been produced. Accordingly, the rule $\eta_t y - \bar{y} > 0$ used to make decisions should be replaced with a better predictive criterion.

According to the equations (1)-(2), $f + bu$ and $\bar{f} + \bar{b}u$ are the accelerative terms of model (1) and (2) separately, which naturally can be used to forecast the system's next step dynamics. Then the above online energy management strategy upon power turbine bypass can be rewritten as:

if $(f + bu) - (\bar{f} + \bar{b}u) > 0$

then shut down the power turbine bypass;

else open the power turbine bypass.

end

where u is the default control strategy of power turbine bypass; b and $\bar{b}$ are decided by parameters tuning, which in other words, are decided by the designer. Then the coming question is how to obtain the information of f and $\bar{f}$.

Next, we will take model (1) as an example to illustrate how to acquire the system total disturbance information from the input and output information.

By treating f as an extra state variable and assuming it as one time differentiable, $x_2 = f$ and let $\dot{f} = k$ with k unknown, then system (1) can be rewritten as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ \dot{x}_3 = k \\ y = x_1 \end{cases} \quad (4)$$