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# A Disturbance Rejection-based Control Framework for SI-CAI Hybrid Combustion in Gasoline Engines

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**Abstract**: The SI-CAI (Spark ignited-controlled auto-ignition) hybrid combustion is promising in achieving smooth transition between SI and CAI combustion, but it is challenging to control due to its high sensitivity to boundary conditions. In this paper, a disturbance rejection-based control framework is proposed for the SI-CAI hybrid combustion. The complexity, nonlinearity and cross-coupling inside are stripped away by idealizing the combustion process into three decoupled integrators, for the combustion timing channel, the IMEP channel and $\lambda$ channel respectively. All other dynamics that deviate from the integrators, internal and external, are lumped as "total disturbance" for each channel. With the total disturbances estimated and cancelled in real-time via three extended state observers, the enforced plant, i.e. the parallel integrators, is controlled by three proportional controllers. To further enhance the response and reject the time-varying uncertainties, a feedforward controller assisted by parameters on-line correction controller is added as a complementary. Simulation validation confirms the superiority of the proposed framework in terms of transient response, parameter tuning, robustness, and the adaptability.



*Keywords:* SI-CAI hybrid combustion, Combustion control, Disturbance rejection control, Extended state observer, Model-parameters on-line identification.

## 1. INTRODUCTION

It is well-known that the so-called controlled auto-ignition (CAI, also known as HCCI) combustion is actually hard to control, and has very limited operation range (Chen, 2011). Additionally, the high sensitivity to operating conditions, the time-varying behavior (Sherazi, 2011), and the torque oscillation existing in mode switching with the SI combustion (Wu, 2010), limit its practical application. SI-CAI hybrid combustion seems to be more promising, as it can achieve smooth transition between SI and CAI combustion (Chen, 2011). However, challenges, such as the interactions between the early stage SI and the subsequent CAI combustion (Xu, 2014) and the serious cyclic variation (Chen, 2011), make the SI-CAI combustion more difficult to control, comparing with the CAI combustion.

Numerous control attempts have been made to put CAI combustion into application in the past. According to the philosophy adopted, these solutions can be divided into the industry paradigm and the model-based paradigm. The PID (Proportional-Integral-Differential) controller (Olsson, 2001) is one of the best representatives for the industry paradigm. It is output tracking error-based, simple to implement, and there is no need for mathematical process models. But it requires time-intensive tuning for the controller parameter (Killingsworth, 2011), and showed slow transient response (Agrell, 2005). Although tuning methods like iterative feedback (Hern, 2006) and extremum seeking (Killingsworth, 2011) were proposed, and the nonlinear feedforward controller (Agrell, 2005) for response enhancement was investigated, the problems of PID are still largely unsolved.

In comparison, the model-based paradigm takes not only the output error, but also the input information and the relationship between inputs and outputs into the control law, such as LQG, and MPC, which are well reviewed in (Tunestal, 2014). Since the combustion process is nonlinear, the piece-wise linear model (Liao, 2013) is usually used instead of single linear models, resulting in high complexity. Robust control (Souder, 2004) is tolerant to model errors, but suffers from the conservative design. Therefore, adaptive control (Larimore, 2014) is adopted in recent years. To be short, the reliance on high fidelity model limits the appeal of the model-based paradigm in practical application. Another complication on model-based paradigm is its poor calibratability (Christen, 2014): the parameters are usually not directly related to the properties that automotive calibration engineers need to influence, and cannot be tuned on-line.

Jade et. al proposed a model based speed-load transition controller, including nonlinear model-inversion-based feedforward and gain scheduled feedback based on unburned fuel, for an HCCI engine. Good combustion timing tracking performance was reported in FTP75 driving cycle (Jade, 2014). In this paper, distinguishing from traditional model-based controllers and PID-based controllers, a disturbance rejection-based control framework is proposed based on the active disturbance rejection control (ADRC) (Han, 2009).


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The hybrid combustion is idealized into three independent integrators for three control loops respectively, while all the uncertainties that deviate the integrators from the combustion system are lumped as three corresponding total disturbances to be estimated and cancelled via the extended state observer (ESO) (Han, 2009). Hence, the enforced plant is easily controlled by a simple proportional controller (P controller). Thanks to the bandwidth-based ESO tuning (Gao, 2003) and adaptive ESO tuning (Xue, 2015) method, the controller is extremely straightforward and easy to tune. To further enhance the response, model-based feedforward (FF) controller is added as a complementary, assisted by a model-parameters on-line correction controller for time-varying disturbances rejections.

Finally, simulation validation is carried out on a well-calibrated GT-SUITE model. Results prove the superiority of this controller in terms of fast response, simplicity in tuning, and the robustness against operating condition variations.

## 2. THE SI-CAI HYBRID COMBUSTION ENGINE

The SI-CAI hybrid combustion is realized using the negative valve overlap strategy (Fig. 1), based on a turbocharged four cylinder 2.0 L gasoline engine (specific parameters listed in Table 1). In order to achieved high load SI-CAI operation, both intake and exhaust valve lifts (6mm and 4mm) are designed higher than traditional NVO-based CAI combustion (Chen, 2011). Additionally, the EVC timing can be retarded near TDC (330 °CA ATDC), also for the realization of high load operation.

The exhaust valve closing (EVC) is used to control the internal exhaust gas recycled (iEGR) and the load changes as the result; and the intake valve closing (IVC) is adjusted to control the compression ratio (CR) and then influence the CA50 (crankshaft angle where 50% accumulated heat released). The spark timing (ST) is enabled to trigger the early flame kernel, then to control the subsequent auto-ignition. To cool down the in-cylinder temperature, external EGR is also introduced.

**Table 1. The hybrid combustion engine specifications**

| | |
|---|---|
| CR | 9.6:1 |
| Intake valve opening duration | 160°CA |
| Intake valve lift | 6mm |
| IVC range | 570-630°CA ATDC |
| Exhaust valve opening duration | 120°CA |
| Exhaust valve lift | 4mm |
| EVC range | 280-330°CA ATDC |
| Fuel | commercial gasoline 95 RON |

To achieve reliable combustion, the outputs including CA50, IMEP (indicated mean effective pressure) and $\lambda$ (the excessive air coefficient) need to be well tracked using the inputs, i.e., the IVC, ST, high-pressure EGR valve position, and throttle position, EVC and injected fuel mass (using the port-fuel injection strategy).

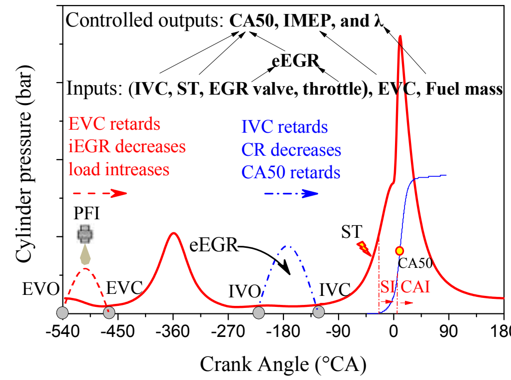


Fig. 1. Operation principle of SI-CAI hybrid combustion

## 3. DISTURBANCE REJECTION-BASED CONTROLLER

### *3.1 Control-oriented modelling*

Since the auto-ignition is affected by the spark-timing in SI-CAI hybrid combustion, we estimated CA10 using a modified version of the Arrhenius equation, by replacing the threshold "1" with a function, in terms of the spark timing (ST) and the residual gas fraction (RGF),

$$\int_{\theta_0}^{CA10} \frac{1}{N_e \cdot A_a \cdot [\lambda/(1\text{-}RGF)]^{a_1} RGF^{a_2} \exp\left(-Ea/T50\right)} d\theta \\ = \left(a_3 \cdot ST^2 + a_4 \cdot ST + a_5\right) \cdot \exp\left(a_6/RGF + a_7\right) , \quad (1)$$

where $N_e$ is the engine speed, $E_a$ is the Arrhenius activation energy, $\theta$ is the crankshaft angle, and $\theta_0$, $a_i$ are parameters to be identified. By assuming linear relationship between CA10 and CA50, we have,

$$CA50 = \left(a_8 RGF + a_9\right) CA10 + \left(a_{10} RGF + a_{11}\right) \quad (2)$$

Based on the energy conservation law, and assuming no intake reverse flow and no air shortcut flowing from the intake manifold to the exhaust manifold, the fresh air mass introduced into the cylinder can be obtained using the energy conservation law,

$$\begin{cases} N_{a,k} = \kappa \cdot \eta + \varpi \cdot \xi \\ \kappa = \dfrac{c_{p,mix} p_{im,k} V_{IVC,k}}{c_{p,\mathrm{int}} R \cdot T_{im,k}}, \varpi = -\dfrac{c_{p,EGR} \Delta\xi p_{EVC,k-1} V_{EVC,k}}{c_{p,\mathrm{int}} R \cdot T_{im,k}} \end{cases} , \quad (3)$$

where $N_a$, $N_{f,c}$, $N_{eEGR}$ are the mole number of the fresh air, cylinder-inducted fuel, and external EGR respectively, $c_{p,mix}$ and $c_{p,EGR}$ are the constant pressure specific heat capacity of the fuel air mixture in the intake manifold and the EGR gas respectively, $p_{im}$ and $p_{EVC}$ are the pressure in the intake manifold and in EVC respectively, and 1-$\xi$ is the ratio of temperature drop between two cycles, $\eta$ is the volumetric efficiency, and $R$ is the ideal gas constant.

Based on equations (1), (2), (3), and the authors' previous work in CAI modelling (Song, 2013 a), as well as the existing models summarized in (Sherazi, 2011), we can