



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Sharma, R;Dennis, P;Manzie, C;Nešić, D;Brear, MJ

Title:

Real time model predictive idle speed control of ultra-lean burn engines: Experimental results

Date:

2011-01-01

Citation:

Sharma, R., Dennis, P., Manzie, C., Nešić, D. & Brear, M. J. (2011). Real time model predictive idle speed control of ultra-lean burn engines: Experimental results. 18th IFAC World Congress: IFAC Proceedings Volumes (IFAC-PapersOnline), 44, (1 PART 1), pp.13004-13009. IEEE. <https://doi.org/10.3182/20110828-6-IT-1002.00634>.

Persistent Link:

<https://hdl.handle.net/11343/299855>

# Real time model predictive idle speed control of ultra-lean burn engines

R. Sharma\* P. Dennis\* C. Manzie\* D. Nešić\*\* M. J Brear\*

\* *Department of Mechanical Engineering, The University of Melbourne, Parkville, Australia, (e-mail: manziec@unimelb.edu.au, p.dennis@pgrad.unimelb.edu.au, sharmar@unimelb.edu.au*

\*\* *Department of Electrical and Electronic Engineering, The University of Melbourne, Australia (email: d.nesic@ee.unimelb.edu.au)*

---

**Abstract:** Idle speed control of ultra-lean burn engines continues to be a major challenge for automotive industry owing to its multivariable nature and constraints on the control system design due to performance specifications and hardware limitations. In this paper, we present a model predictive approach for the idle speed control of lean burn internal combustion engines via a fuel assisted control strategy. The idea is to use fuel flow as the primary control variable to compensate for sudden fluctuations in engine load while the spark angle is maintained at to yield maximum brake torque (MBT). In addition, by constraining the engine operation in ultra-lean mode emissions of oxides of nitrogen  $NO_x$  are contained within their acceptable minimum. The technique is applied on a hydrogen fueled internal combustion engine ( $H_2ICE$ ). First a control oriented model of  $H_2ICE$  is presented followed by the formulation of model predictive control based ISC scheme to regulate fuel flow, spark timing and throttle. The practicality of the MPC scheme is illustrated first by comprehensive simulations and then backed by experimental validations.

*Keywords:* Idle speed control, lean-burn engines, model predictive control.

---

## 1. INTRODUCTION

Idle speed control (ISC) problem is to maintain the engine idle speed at a pre-defined set point while rejecting the load disturbances. An average passenger car spends significant amount of time in its normal city driving during idling. Consequently, it is crucial to optimize the engine operation at idle so as to minimize fuel consumption and reduce emissions. The persistent emphasis to adequately address this problem is compounded by the rising oil prices, exhausting oil reserves and increasingly stringent legislative emissions regulations.

For gasoline engines, the problem of ISC has now been well researched both in the industry and the academia (Hrovat and Sun [1997]). Coordinated spark angle and throttle actions deliver the necessary control action for maintaining engine operation at idle while the air-to-fuel ratio is maintained at the stoichiometric proportions to minimize emissions. The primary control is throttle which due to manifold filling and emptying has slow response to the load fluctuations. So, spark angle is used as a second control input to delivers quick torque in the face of load disturbances. In order for the spark to be quick in disturbance rejection, it is retarded from MBT (maximum brake torque) value to maintain some torque reserve. This torque reserve is used to provide for sudden load

fluctuations. The downside of retarding the spark is that it comes at the expense of fuel economy.

To minimize reliance on crude oil and reduce emissions of greenhouse gases, a widely adopted possible solution is to use alternative gaseous fuels like natural gas and hydrogen and operate the engines in ultra-lean burn mode (White et al. [2006], Das et al. [2000]). In ultra-lean burn mode, mixture of air and fuel contains much less fuel in comparison to stoichiometric proportions. Consequently, combustion temperatures are low enough such that  $NO_x$  formation rates are too slow and engine-out emissions are negligible. Furthermore, unthrottled operation (a consequence of high intake manifold pressures) is feasible even at low loads (as are during engine idling) resulting in significant drop in pumping losses leading to much improved engine efficiency.

Nevertheless, to ensure ultra-lean burn operation, high manifold pressures and MBT spark, the engine control inputs are subject to constraints in addition to the hardware limitation. Moreover, the engine speed should not drop below the acceptable minimum even in the face of sudden load changes to eliminate any possibilities of engine stalling. Therefore, optimizing the engine operation at idle is a multivariable control problem where the control inputs and engine states are subject to constraints (Manzie and Watson [2003]). A commonly adopted approach to tackle such problems is the so called model predictive control and is adopted for the controller development in this paper (Mayne et al. [2000]).

---

\* This work was supported by Energy Technology Innovation Strategy (ETIS) and Advanced Centre for Automotive Research and Testing at Melbourne University, Australia.

In this paper a model based technique to the idle speed control of ultra-lean burn engines is proposed. The approach is to develop a model predictive controller which optimizes the engine operation at each sampling instant so as to maintain the engine speed at the idle speed set-point while simultaneously ensuring that the optimal control inputs remain within acceptable bounds. Any sudden changes in the load torque demand are compensated by varying the fuel flow and hence the requirement for spark retard from MBT (as in conventional gasoline engines) can be relaxed. Similar approach, whereby a fuel assisted approach to compensate for load fluctuations in gasoline engines, are presented in (Kerns and Surnilla [2006], Grizzle et al. [2001]). As a result, best torque is obtained while optimal fuel economy is achieved by maximizing  $\lambda$  value at a given operating point or operating range. Simultaneously, the engine operation with high manifold pressures is prompted to eliminate losses due to throttling. The effectiveness of the model predictive controller is illustrated first by simulation and backed by real time experimental validation conducted on engine-dynamometer facility.

The paper is organized as follows: in section 2 a control oriented mathematical model of the engine is presented. This is followed by the idle speed control design in section 3 where first idle speed control problem for ultra-lean burn engines is presented followed by the development of a model predictive controller in subsections 3.1 and 3.2, respectively. The controller is implemented for the idle speed control of  $H_2ICE$  in section 4 whereby the results of simulation and experimentation are presented and discussed in subsections 4.1 and 4.2, respectively.

## 2. ENGINE MODEL

This section presents a control oriented mathematical model of spark-ignition engines which is used to devise a model based control scheme. A reduced order model with two states is used, states of which include, intake manifold pressure  $P_{im}$  and engine speed  $N_e$ . The dynamics of intake manifold pressure are governed by manifold filling and emptying dynamics while those of the engine speed are based on rotational dynamics of the crankshaft. Accordingly, the dynamics of  $P_{im}$  and  $N_e$  are given by the following set of differential equations:

$$\frac{dP_{im}}{dt} = \frac{\gamma RT_{amb}}{V_{im}} (\dot{m}_{im_{in}}(P_{im}, u_{th}) - \dot{m}_{im_{out}}(P_{im}, N_e)) \quad (1)$$

$$\frac{dN_e}{dt} = \left( \frac{1}{J_e} \right) (T_{q_e}(P_{im}, N_e, u_{SA}, u_\lambda) - T_{load}) \quad (2)$$

where,  $u_{th}$ ,  $u_{SA}$  and  $u_\lambda$  are the control variables and denote throttle area in  $m^2$ , spark angle in degrees before top dead center (BTDC) and air-to-fuel ratio stoichiometric, respectively.  $T_{load}$  is the load torque disturbance. Functions  $\dot{m}_{im_{in}}$ ,  $\dot{m}_{im_{out}}$  and  $T_{q_e}$  stand for mass-flow in and out of the intake manifold and engine brake torque, respectively. A regression for  $T_{q_e}$  at idle can be obtained using idle speed data. Expressions of  $\dot{m}_{im_{in}}$  and  $\dot{m}_{im_{out}}$  are given as follows (Guzzella and Onder [2004]):

$$\dot{m}_{im_{in}} = \frac{P_{amb}}{\sqrt{RT_{amb}}} u_{th} \Psi \left( \frac{P_{im}}{P_{amb}} \right) \quad (3)$$

$$\dot{m}_{im_{out}} = \frac{P_{im} V_d n_{cyl} \eta_{vol} N_e}{4\pi RT_{im}} \quad (4)$$

where,

$$\Psi \left( \frac{P_{im}}{P_{amb}} \right) = \begin{cases} \sqrt{\gamma} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}, & \frac{P_{im}}{P_{amb}} \leq 0.5283 \\ \sqrt{\frac{2\gamma}{\gamma-1} \left( \left( \frac{P_{im}}{P_{amb}} \right)^{1.4} - \left( \frac{P_{im}}{P_{amb}} \right)^{1.7} \right)}, & \frac{P_{im}}{P_{amb}} > 0.53. \end{cases}$$

In (1)-(2),  $J_e$ ,  $V_{im}$ ,  $n_{cyl}$ ,  $\eta_{vol}$  and  $V_d$  represent engine inertia, intake manifold volume, number of cylinders, volumetric efficiency and volumetric displacement and are engine specific quantities. Values of the remaining constants used in expression (1)-(2) are summarized in Table 1.

Table 1.

Ratio of specific heats, $\gamma$	1.38
Gas constant, $R$	287.058 $Jkg^{-1}K^{-1}$
Intake manifold temperature, $T_{im}$	300 K
$P_{amb}$	101325 Pa
$T_{amb}$	289 K

**Remark** It may be noted that the mean-value engine models of the form (1)-(2) have often been adopted in the idle speed control literature (see for example Stotsky et al. [2000], Li and Yurkovich [2001], Manzie and Watson [2003]). By using the properties of engine dynamics and engine geometry it is possible to demonstrate that a high order control oriented mean value model of turbo-charged spark ignition engine can be closely approximated by a 5<sup>th</sup> order system states of which include pressures in intake manifold, intercooler and exhaust manifold and speeds of engine and turbocharger (Sharma et al. [2009]). Noting that when the engine is operating at idle the turbocharger is rotating at very low speed and consequently does not provide any appreciable boost in the intake side of the engine. This permits us to reduce the engine model order to second with only two states namely, intake manifold pressure ( $P_{im}$ ) and engine speed ( $N_e$ ) while ignoring the dynamics of the states corresponding to turbocharging.

## 3. IDLE SPEED CONTROL OF ULTRA-LEAN BURN ENGINES

### 3.1 Idle speed control problem

Idle speed control problem is to maintain the engine speed at a pre-defined set-point while rejecting the load disturbances. Consequently, in its simplest form idle speed control problem can be seen as a disturbance rejection and a tracking problem. The idle controller design is governed by the requirements of minimization of fuel consumption and the emissions reduction. In the context of ultra-lean burn engines (for example  $H_2ICE$ ), these objective are tantamount to meeting of the constraints on the engine states and the control inputs as discussed in the following:

- (1) *Engine speed,  $N_e$* : Engine speed should be maintained at a predefined set-point. The choice of the set point is crucial as it has a direct impact on the fuel consumption. It is obvious that lower the engine speed at idle will result in lower fuel consumption. However, lowering of the idle speed set-point is limited by two

factors. Firstly, as the engine speed is lowered noise, vibration and harshness (NVH) quality deteriorates. Secondly, in the face of sudden changes in the load disturbances the under speeding may completely stall the engine and the engine control system should completely eliminate the possibility such an undesirable event.

- (2) *Manifold pressure,  $P_{im}$* : Intake manifold pressure is to be maintained as close as possible to the ambient so as to achieve unthrottled operation. This minimizes the pumping losses ensuring better fuel economy and improved engine efficiency.
- (3) *Air to fuel ratio,  $u_\lambda$* :  $u_\lambda$  is the primary input for idle speed control and is used to promptly reject the load disturbances. However, its operational range is upper and lower bounded by practical considerations. In order to minimize  $NO_x$  emissions (the only engine out emissions in the context of  $H_2ICE$ ), engine should be operated ultra lean. On the other hand, as the value approaches a limiting value (called lean limit) the combustion stability deteriorates rapidly.
- (4) *Spark Angle,  $u_{SA}$* : In the conventional gasoline engines,  $u_{SA}$  is mainly used for disturbance rejection by retarding the value which yields best torque (MBT). This, however, came at the expense of fuel economy. In the context of the idle speed control of ultra-lean burn engine spark retard is no longer required as the excess torque is delivered by adjusting the fuel flow. Hence,  $u_{SA}$  can be maintained at the MBT value at throughout the idle operation. Nevertheless, the spark timing should be maintained with 0 to 50 crank angle degrees BTDC under all conditions (Heywood [1988]).
- (5) *Throttle,  $u_{th}$* : The primary constraining factor with  $u_{th}$  is its slow response due to the lag in the manifold filling dynamics. Additionally, the throttle opening area is constrained by hardware limitations.

Thus, our control objective is to design a tracking and disturbance rejection control strategy subject to constraints associated with the engine states and control variable.

### 3.2 Model predictive control formulation

The multivariable nature of the control problem and presence of constraints prompt the use of model predictive control theory to address the problem of idle speed control of ultra-lean burn engines. To develop a model predictive idle speed controller, let us rewrite the engine model (1)-(2) in the following standard nonlinear state-space representation:

$$\dot{x} = f(x, u, T_{load}) \quad (5)$$

$$y = Cx \quad (6)$$

where,  $x = [P_{im}, N_e]^T \in \mathcal{X} \subset \mathbb{R}^2$  and  $x = [u_{th}, u_{SA}, u_\lambda]^T \in \mathcal{U} \subset \mathbb{R}^3$ .  $\mathcal{X}$  and  $\mathcal{U}$  are compact sets and the function  $f : \mathbb{R}^2 \times \mathcal{U}$  denotes the right hand side of the set of equations (1)-(2).

The use of linear discrete time MPC entails linearization and discretization of control oriented engine model (5)-(6). Upon linearization, the following linear model is resulted:

$$\delta\dot{x} = A\delta x + B\delta u + B_d\delta T_{load} \quad (7)$$

$$\delta y = C\delta x \quad (8)$$

where,

$$A = \left. \frac{\partial f}{\partial x} \right|_{x^0, u^0, T_{load}^0}, \quad B = \left. \frac{\partial f}{\partial u} \right|_{x^0, u^0, T_{load}^0},$$

$$B_d = \left. \frac{\partial f}{\partial T_{load}} \right|_{x^0, u^0, T_{load}^0}, \quad C = I_2$$

and  $x^0$ ,  $u^0$  and  $T_{load}^0$  represent the nominal values of the engine states, control inputs and load disturbance.  $\delta x = x - x^0$ ,  $\delta u = u - u^0$  and  $\delta T_{load} = T_{load} - T_{load}^0$  describe the deviations of  $x$  and  $u$  from the nominal value.

Next step is to discretize the linearized continuous time engine model (7)-(8) with sampling period  $T_s$  to obtain following linear discrete time state space representation

$$\delta x_{k+1} = A_k \delta x_k + B_k \delta u_k + B_{d_k} \delta T_{load} \quad (9)$$

$$\delta y_k = C_k \delta x_k \quad (10)$$

Let  $k$  be the current time instant,  $x_k$  be the current state and  $u_{k-1}$  be the previous input. We define the following cost function:

$$J_N(x_k, \Delta \mathbf{u}_k) = \sum_{i=0}^N \left[ (x_{k+i} - x_{ref})^T Q (x_{k+i} - x_{ref}) \right. \\ \left. + \Delta u_{k+i}^T R \Delta u_{k+i} \right. \\ \left. + (u_{SA} - u_{MBT})^T R_{MBT} (u_{SA} - u_{MBT}) \right] \quad (11)$$

where,  $x_{ref} = [P_{im,ref}, N_{e,ref}]^T$  is the reference vector,  $\Delta \mathbf{u}_k = [u_k, \dots, u_{k+N-1}]$  represent sequence of control inputs over horizon length  $N$  where  $\Delta u_{k+i,k}$  with  $i = 0, \dots, N$  denotes the change in control inputs and  $u_{MBT}$  represents the spark angle for MBT (maximum brake torque).

Clearly,  $J_N(x_k, \Delta \mathbf{u}_k)$  as per (11) penalizes deviation in states and sudden changes in control inputs, and ensures that the spark timing is maintain to yield MBT. Weighting matrices  $Q$  and  $R$  are chosen to be positive definite matrices of the following form:

$$Q = \begin{bmatrix} Q_{P_{im}} & 0 \\ 0 & Q_{N_e} \end{bmatrix}, \quad R = \begin{bmatrix} R_{th} & 0 & 0 \\ 0 & R_{SA} & 0 \\ 0 & 0 & R_\lambda \end{bmatrix} \quad (12)$$

and  $R_{MBT} > 0$ .

Thus, the model predictive controller solves the following optimization problem each sampling instant:

$$\min_{\Delta \mathbf{u}_k} J_N(x_k, \Delta \mathbf{u}_k) \quad (13)$$

subject to

$$\delta x_{i+1} = A_k \delta x_i + B_k \delta u_i + B_{d_k} \delta T_{load}; \quad i = k+1, \dots, k+N \quad (14)$$

$$x_{min} \leq x_{i,k} \leq x_{max}; \quad i = k+1, \dots, k+N \quad (15)$$

$$u_{min} \leq u_{i,k} \leq u_{max}; \quad i = k, \dots, k+N-1 \quad (16)$$

$$\Delta u_{min} \leq u_{i,k} \leq \Delta u_{max}; \quad i = k, \dots, k+N-1 \quad (17)$$

$$x_{k+N,k} = x_{ref} \quad (18)$$

where,  $x_{i,k}$  for  $i = k+1, \dots, k+N$  denote predicted states given state  $x_{k,k}$  with  $x_{k,k} = x_k$ .

In the above formulation, (14)-(17) denote the constraints on the engine states and control inputs while (18) signifies the terminal constraint.

#### 4. APPLICATION TO IDLE SPEED CONTROL OF $H_2ICE$

Idle speed control of ultra-lean burn engines using model predictive controller of the form (13)-(18) is now illustrated on  $H_2ICE$ . For  $H_2ICE$ , in principle, nitrogen oxides ( $NO_x$ ) are the only undesirable engine out emissions, formed by the thermal dissociation and oxidation of nitrogen in air during combustion. In additions, the low lean-flammability limit of hydrogen allows stable combustion at highly dilute conditions. The coupled effect is that when  $H_2ICE$  is operated in ultra-lean burn mode the combustion temperatures are low enough such that  $NO_x$  formation rates are too slow and engine out emissions are negligible.

The tests are performed on a Ford Inline 6 cylinder 4 Liter engine. An idle speed control model for this engine is given by (1)-(2) where regressions for engine torque  $T_{qe}$  and  $\eta_{vol}$  are obtained from idle speed data and are given by the following expressions:

$$\begin{aligned} T_e = & 136.14 - 0.002P_{im} + 111.1u_\lambda - 6.2u_{SA} - 2.1N_e \\ & - 1.9u_\lambda^2 - .16u_{SA}^2 + .86 \times 10^{-7}P_{im}^2 - .0025P_{im}u_\lambda \\ & - .55 \times 10^{-5}P_{im}u_{SA} + .17 \times 10^{-3}P_{im}N_e \\ & + 3.5u_\lambda u_{SA} - 2.34u_\lambda N_e + .09u_{SA}N_e \end{aligned} \quad (19)$$

$$\eta_{vol} = \eta_{vol_1}(P_{im}) \times \eta_{vol_2}(N_e) \quad (20)$$

$$\eta_{vol_1}(P_{im}) = 1 + \frac{1}{r_c} \left[ 1 - \left( \frac{P_{amb}}{P_{im}} \right)^{\frac{1}{\gamma}} \right] \quad (21)$$

$$\eta_{vol_2}(N_e) = \gamma_0 + \gamma_1 N_e \quad (22)$$

The values of the constant parameter which characterize this engine are given in Table 2.

Table 2.

Inertia, $J_e$	0.15 kg-m <sup>2</sup>
Intake manifold volume, $V_{im}$	$4 \times 10^{-3}$ m <sup>3</sup>
$V_d$	$7.6902 \times 10^{-4}$ m <sup>3</sup>
$n_{cyl}$	6
Compression ratio, $r_c$	10.3
$\gamma_0$	0.43042
$\gamma_1$	0.0018766

A regression for  $u_{MBT}$ , used in (11), as a function of  $P_{im}$ ,  $N_e$  and  $u_\lambda$  is given as follows:

$$u_{MBT} = 9.6281u_\lambda - 0.00011P_{im} + 0.19469N_e - 2.2704$$

The values of the constraints imposed on the states and control inputs, as per (15)-(17) are presented in Table 3.

Table 3. Constraints on engine states and control inputs

$x_{min}$	$[0.52 \times 10^5, 525]^T$
$x_{max}$	$[1.01 \times 10^5, 4000]^T$
$u_{min}$	$[0, 10, 2.0]^T$
$u_{max}$	$[9.9e-05, 50, 5.5]^T$
$\Delta u_{min}$	$[-10^{-5}, -10^{-1}, -10^6]^T$
$\Delta u_{max}$	$[10^{-5}, 10^{-1}, 10^{-6}]^T$
$N$	4

#### 4.1 Simulation results

The controller is implemented in Simulink using MATLAB Embedded functions. For simulations we consider a step change in load followed by a change in the idle speed set-point. The disturbance rejection is carried out by modifying the  $u_\lambda$  (fuel flow).

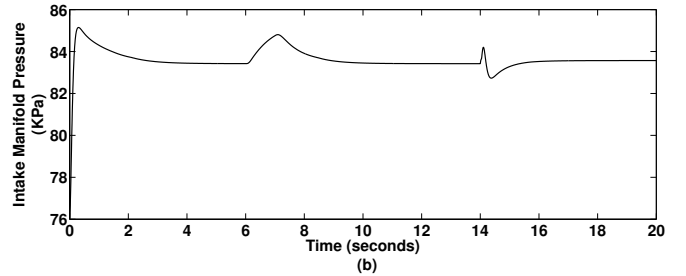
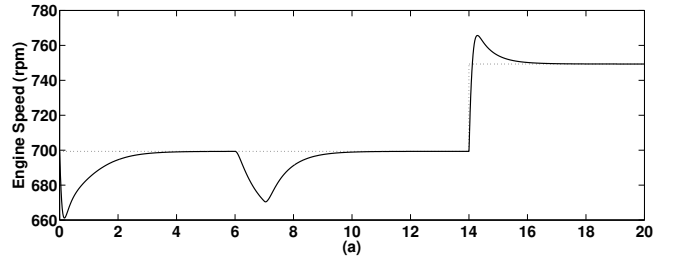


Fig. 1. Simulation responses of intake manifold pressure and engine speed

#### 4.2 Experimental results

**Experimental setup** The experiments are performed on the engine dynamometer facility. The idle speed controller is programmed in Simulink using Embedded MATLAB function. For rapid control prototyping dSpace MicroAutoBox (MAB) equipped with a 300 MHz Power PC micro-processor and MATLAB Real Time Workshop are used. Crankshaft and camshaft signals are captured used variable reluctance sensors. Throttle valve is actuated via a DC motor and controlled using pulse width modulation and a H-bridge. Two bosch ignition modules (each comprising of three channels) are used to drive the ignition

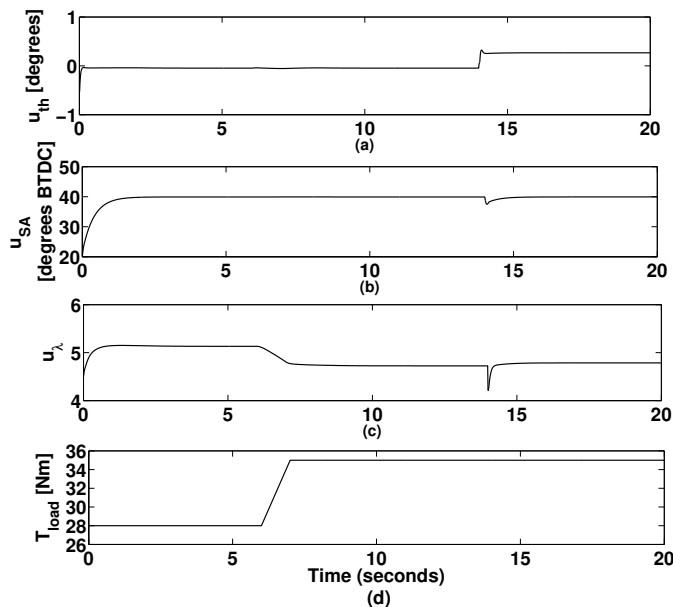


Fig. 2. Simulation responses of Engine control variables and load disturbance input

coils while 'Prins fuel injection system' (which generates peak and hold current command) is used for the purpose of driving the gas injectors.

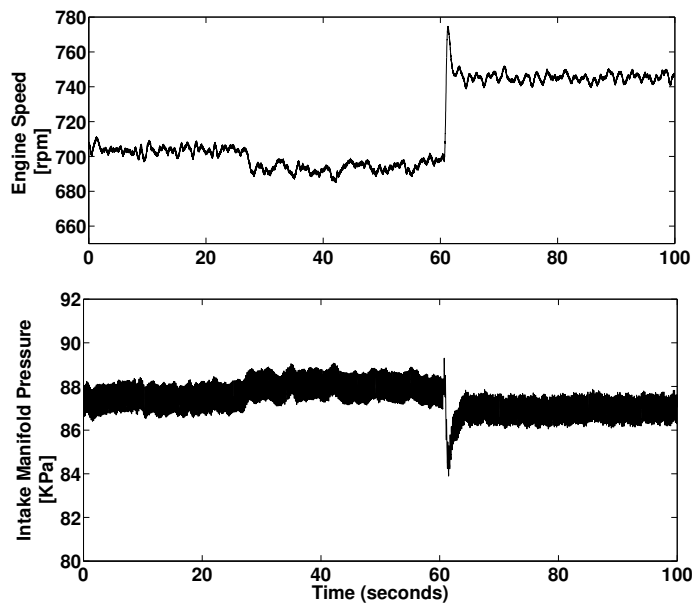


Fig. 3. Experimental responses of intake manifold pressure and engine speed

## REFERENCES

- Das, L.M., Gulati, R., and Gupta, P.K. (2000). A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels. *International Journal of Hydrogen Energy*, 25(8), 783–793.
- Grizzle, J.W., Buckland, J., and Sun, J. (2001). Idle speed control of a direct injection spark ignition stratified

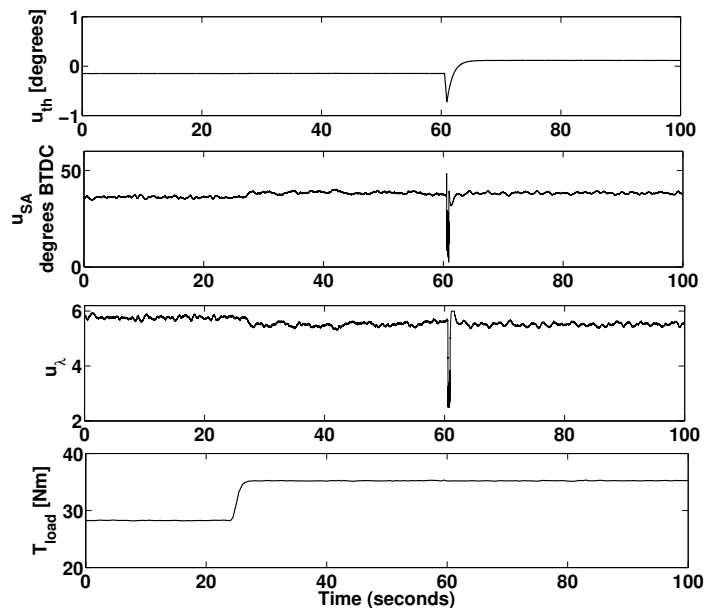


Fig. 4. Experimental responses of Engine control variables and load disturbance input

charge engine. *International Journal of Robust and Nonlinear Control*, 11(11), 10431071.

Guzzella, L. and Onder, C. (2004). *Introduction to Modeling and Control of Internal Combustion Engine*. Springer.

Heywood, J. (1988). *Internal Combustion Engine Fundamentals*. McGraw Hill.

Hrovat, D. and Sun, J. (1997). Models and control methodologies for ic engine idle speed control design. *Control Engineering Practice*, 5(8), 1093–1100.

Kerns, J. and Surnilla, G. (2006). Fuel assisted idle speed control of lean burn gasoline engines. In *SAE*, Paper Number: 2006-32-0009.

Li, X. and Yurkovich, S. (2001). Sliding mode control of delayed systems with application to engine idle speed control. *IEEE Transactions on Control Systems Technology*, 9(6), 802–810.

Manzie, C. and Watson, H.C. (2003). A novel approach to disturbance rejection in idle speed control towards reduced idle fuel consumption. *Proceedings of Institute of Mechanical Engineers*, 217, 677–690.

Mayne, D., Rawlings, J., Rao, C., and Sckaert, P. (2000). Constrained model predictive control: Stability and optimality. *Automatica*, 36, 789–814.

Sharma, R., Nešić, D., and Manzie, C. (2009). Control oriented modeling of turbocharged (tc) spark ignition engine. In *SAE World Congress*, Document number 2009-01-0684.

Stotsky, A., Egardt, B., and Eriksson, S. (2000). Variable structure control of engine idle speed with estimation of unmeasurable disturbances. *J. Dyn. Sys., Meas., Control*, 122(4), 599–604.

White, C., Steeper, R., and Lutz, A. (2006). The hydrogen-fueled internal combustion engine: a technical review. *International Journal of Hydrogen Energy*, 31(10), 1292–1305.