Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 117 (2017) 27–36

Energy Procedia

www.elsevier.com/locate/procedia

1st International Conference on Power Engineering, Computing and CONtrol, PECCON-2017, 2-4 March 2017, VIT University, Chennai Campus

Simulation and Design of Decentralized PI Observer Based Controller for Nonlinear Interconnected Systems of the Diesel Engine Airpath

Rohith Kamath, Dr. Vivek Venkobarao, Prof. Subramaniam C.K [1]

Continental Automotive Components, Bangalore, India.
Vellore Institute of Technology, Vellore, India.

Abstract

During the development of ECU software, physical/environment model plays major role in simulation and prediction of engine behavior. Hence it is necessary to bring simulation results from the model as close as possible to the real environment. Once the model is mature enough it is used as a bench mark for designing a control strategy.

The present paper deals with the identification of most influencing parameters (MIP) for given operating condition to have a desired behavior of the airpath model. The airpath model is validated with reference model. Multi input multi output (MIMO) model is cross verified with recordings and the MIMO model is benchmarked. The author describes in detail the application of statistical study needed to arrive at a decision which is supported by the nature of outcome by having probabilistic studies of MIP.

A small signal analysis via perturbation is done on the model to check the stability and response of the system in steady state. The model with and without observer is simulated to check the performance of the model.

Keywords: Observer; Engine Models; Control Systems.

1

* Rohith Kamath. Tel.: +91-80-6679-6154 .
E-mail address: Rohith.Kamath@continental-corporation.com

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 1st International Conference on Power Engineering, Computing and CONtrol.
10.1016/j.egypro.2017.05.103

1. Introduction

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

There are legion work done with conventional thermodynamic approaches, some of which are highlighted by Aguilera-Gonza [6], who developed a pressure model for diesel engine and proposed a Parallel Distributed Compensation Fuzzy controller be applied to regulate the intake and exhaust manifold pressures in a four-cylinder diesel engine air-path system accompanied with EGR and VGT. Junmin Wang [7], describes a hybrid robust nonlinear control approach for modern diesel engines operating multiple combustion modes; in particular, low temperature combustion and conventional diesel combustion modes. An innovative control system is designed to track different key engine air-path operating variables at different combustion modes as well as to avoid singularity which is inherent for turbocharged diesel engine running multiple combustion modes.

Observers use the plant input and output signals to generate an estimate of the plant's state, which is then employed to close the control loop. Observers are utilized to augment or replace sensors in a control system. The observer was first proposed and developed by Luenberger in the early sixties of the last century (Luenberger, 1966; 1971; 1979). Since the early developments, observers for plants with both known and unknown inputs have been developed resulting in the so-called unknown input observer (UIO) architectures, such as, for example, those in (Bhattacharyya, 1978; Chen and Patton, 1999; Chen et al., 1996; Corless and Tu, 1998; Darouach et al.).

Observers for systems with unknown inputs play an essential role in robust model-based fault detection (Chen and Patton, 1999; Edwards et al., 2000; Edwards and Spurgeon, 1998; Jiang et al., 2004; Saif and Xiong, 2003). The basic idea behind the use of observers for fault detection is to form residuals from the difference between the actual system outputs and the estimated outputs using an observer. Once a fault occurs, the residuals are expected to react by becoming greater than a prespecified threshold. When the system under consideration is subject to unknown disturbances or unknown inputs, their effect has to be decoupled from the residuals to avoid false alarms

In this paper, we present design procedures for full and reduced-order observers for systems with unknown system response. The unknown input can be a combination of un-measurable or unmeasured disturbances, unknown control action, or un-modeled system dynamics. Figure 1 shows the overall framework of the small signal model.

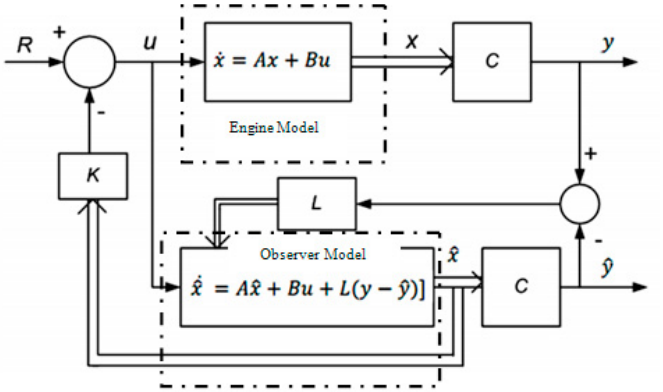


Figure 1 Framework for small signal model

Nomenclature

$\dot{x}(t)$	State matrix differential
$x(t)$	State matrix at defined time instant
$y(t)$	Output matrix – model
$d(t)$	Time sample
^	
$\hat{x}(t)$	Observer state matrix
L_1,N,L_2,B,A	Observer gains

2. Mathematical analysis

A Pressure Model for the Air-Path is simulated from literature. This model captures the dynamics of pressure changes at intake and exhaust manifold and they are regulated by EGR and VGT for a diesel system [7]. The diesel engine air-path schematics are shown in Figure 2.

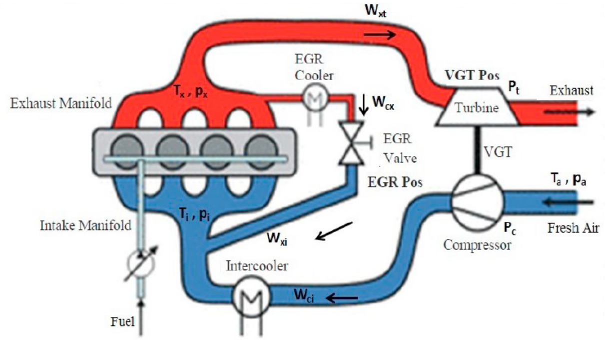


Figure 2 Diesel engine airpath model

The mathematical model for the intake of the diesel engine airpath is derived by author in [8]. The model is converted to steady state by making the differential part to 0.

$$\begin{bmatrix} \dot{p_i} \\ \dot{p_x} \\ \dot{P_c} \end{bmatrix} = \begin{bmatrix} -k_i a_2 N & 0 & k_i a_1 \rho_1 \\ k_x a_2 N & 0 & 0 \\ 0 & 0 & -k_\tau \end{bmatrix} \begin{bmatrix} p_i \\ p_x \\ P_c \end{bmatrix} + \begin{bmatrix} k_i & 0 \\ -k_x & -k_x \\ 0 & k_\tau a_3 \rho_2 \end{bmatrix} \begin{bmatrix} W_{xi} \\ W_{xt} \end{bmatrix} + \begin{bmatrix} 0 \\ W_f \\ 0 \end{bmatrix}$$

The steady state equation of the above is

$$\begin{bmatrix} p_i \\ p_x \\ P_c \end{bmatrix} = \frac{-\begin{bmatrix} k_i & 0 \\ -k_x & -k_x \\ 0 & k_\tau a_3 \rho_2 \end{bmatrix} \begin{bmatrix} W_{xi} \\ W_{xt} \end{bmatrix} + \begin{bmatrix} 0 \\ W_f \\ 0 \end{bmatrix}}{\begin{bmatrix} -k_i a_2 N & 0 & k_i a_1 \rho_1 \\ k_x a_2 N & 0 & 0 \\ 0 & 0 & -k_\tau \end{bmatrix}}$$

The above expression cannot be computed as [A] = 0.

To solve this challenge authors used generalized inverse of the matrix. The generalized inverse of a matrix is important in analysis because it provides an extension of the concept of an inverse which applies to all matrices. It also has many applications in numerical analysis, but it is not widely used because the existing algorithms are fairly complicated. A simple extension has been found to the conventional orthogonalization method for inverting nonsingular matrices. The algorithm gives the generalized inverse for any m by n matrix A, including the special case when m = n and A is nonsingular and the case when m > n and rank (A) = n. In the first case the algorithm gives the ordinary inverse of A. In the second case the algorithm yields the ordinary least squares transformation matrix.

2.1. Observer design

This paper proposes a novel, observer-based, indirect model reference fuzzy control approach for nonlinear systems, expressed in the form of a Sugeno (TS) fuzzy model. Based on this model, an adaptive observer based, indirect model reference fuzzy controller is developed to deal with external disturbances. The proposed method is robust in the existence of bounded external disturbances and it is capable of tracking a reference signal rather than just regulation. The proposed method is simulated on the airpath of Diesel engine and it is shown that it is capable of controlling this chaotic system with high performance.

Design of PI based state observer

- Has a simple linear structure in contrast to nonlinear observers;

- Is robust against disturbances and noise compared with Luenberger observer or observers without the integral part in the feedback of estimation errors;

- Estimates the states and unknown inputs simultaneously in comparison with state or disturbance observers;

- Requires no special limitations on the type of disturbances compared with other kinds of state and disturbance observers; and assumes no statistic information from process and measurement noise in contrast with EKF.

The disadvantages and limitations of PI-Observer are that

- The location where the unknown inputs affect the system is assumed as known;

- At least a nominal linear state space model of system has to be available, so that the nonlinear or unknown parts can be considered as unknown inputs; and

- To estimate both the states and the unknown inputs, more independent measurements could be required.

Figure 3 shows the internal control law of the PI observer developed.

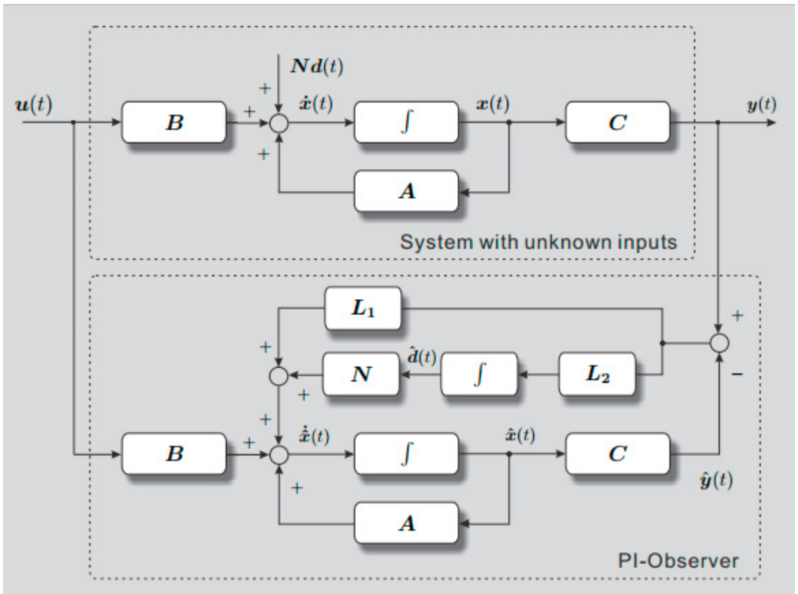


Figure 3 Internal control law of PI observer

2.1.1. Design of observer gains(C,L_2,L_1)

Reference model uses fuzzy logic as a design methodology, which can be utilized for developing linear and non-linear systems. A fuzzy logic controller does not require an exact mathematical model. It however requires a knowledge-based set of heuristic rules. These rules are impressive and are expressed in terms of linguistic variables.

The steps involved in the design of the fuzzy controller are fuzzification, rule identification and defuzzification. Fuzzification is the process of transforming crisp control variables to corresponding fuzzy variables. The error e and derivative of error Δe have been selected as inputs and cf as output in the present work. Linguistic variables used are LP, MP, SP, VS, SN, MN, LN which stand for large positive, medium positive, small positive, very small, small negative, medium negative and large negative respectively. Linear triangular membership function is used. Fuzzy rules are used to formulate the conditional statements that relate the input output fuzzy set. The system with two input variables and seven labels has a 7x7 decision table as given in Table 1. Every entry in the table represents a rule. As an example, if e is LN and delta e is LP then cf is VS.

Decisions are based on the testing of all the rules in the FIS and the rules must be combined in some manner in order to make a decision, which is known as aggregation.[12].

e \ Δe	**LN**	**MN**	**SN**	**VS**	**SP**	**MP**	**LP**
LP	VS	SP	MP	LP	LP	LP	LP
MP	SN	VS	SP	MP	MP	LP	LP
SP	MN	SN	VS	SP	SP	MP	LP
VS	MN	MN	SN	VS	SP	MP	MP
SN	LN	MN	SN	SN	VS	SP	MP
MN	LN	LN	MN	MN	SN	VS	SP
LN	LN	LN	LN	LN	MN	SN	VS

Table 1 Fuzzy rule base

3. Simulation Study

3.1. Simulink Representation

The airpath model is developed and simulated, which computes intake manifold pressure, exhaust manifold pressure, compressor power, and flow at different nodes. The simulink model being developed is shown below in Figure 4.

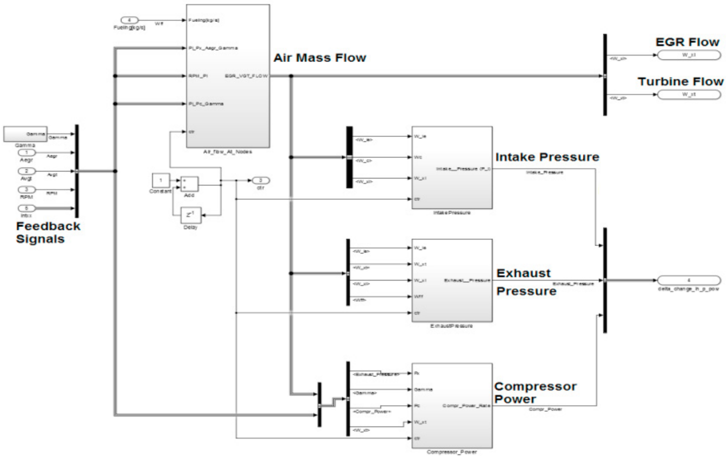


Figure 4 Simulink block diagram for air path model

Figure 5 shows the simulation results of the steady state model without an observer

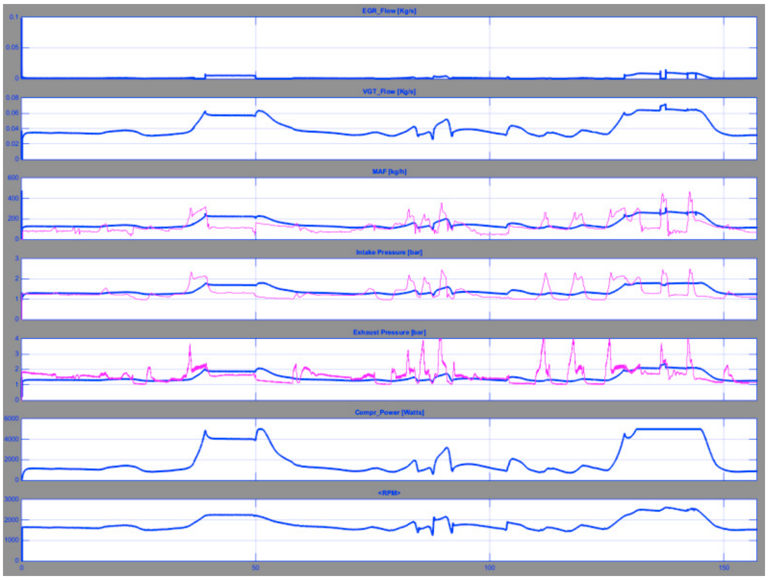


Figure 5 Simulation results without observer

--- Simulation results

--- Reference model

Figure 6 presents the flow diagram of the diesel engine airpath with observer.

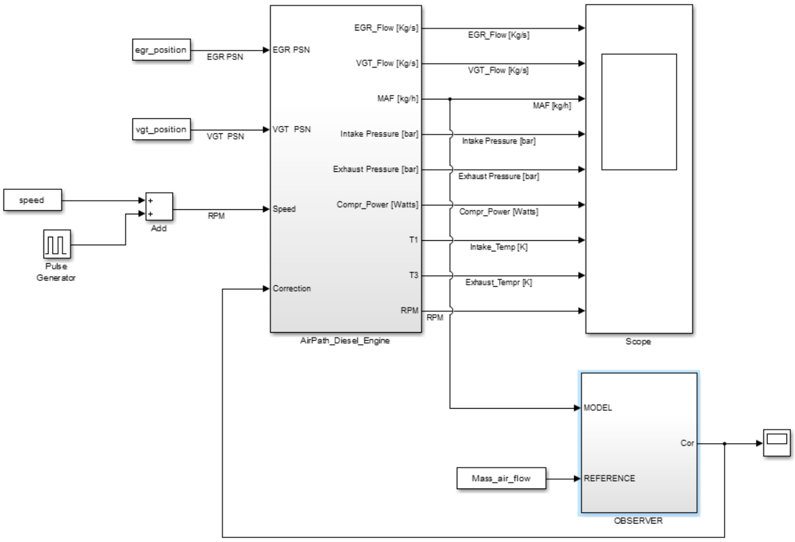


Figure 6 Diesel engine airpath with observer

Figure 7 shows the simulation results of the steady state model with an observer

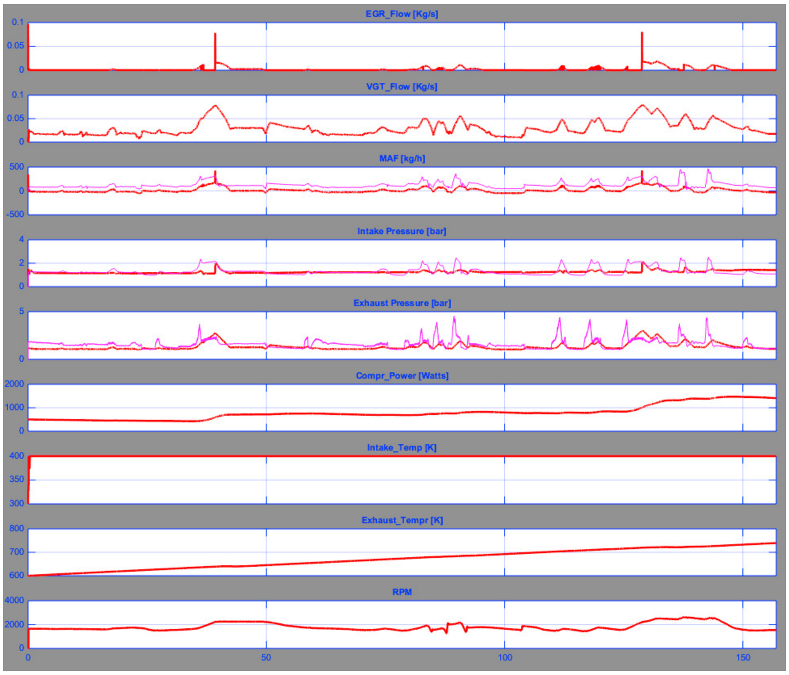


Figure 7 Simulation results with observer

--- Simulation results

--- Reference model

3.2. *Small Signal analysis and Results*

The gausian noise is fed to the speed signal and the response of the observer based system is checked.

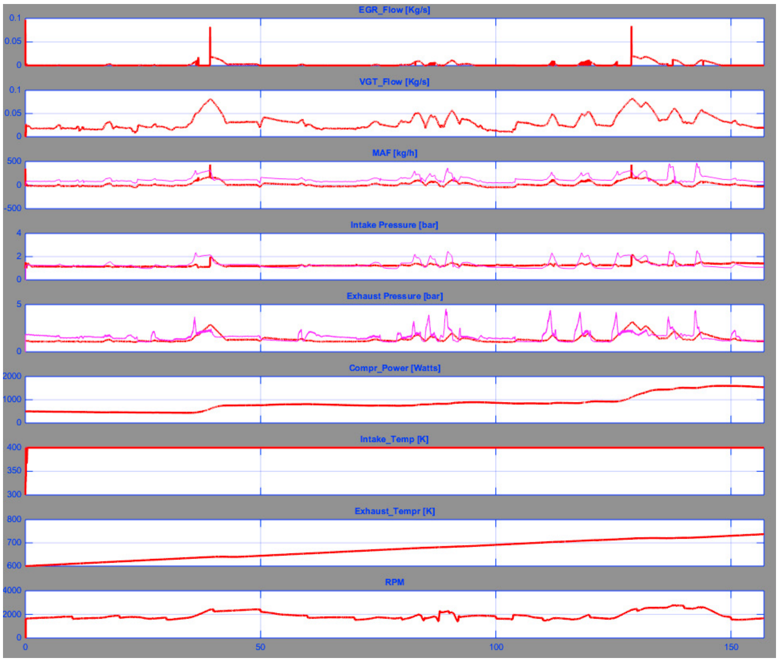


Figure 8 Simulation results with 5% noise in speed signal

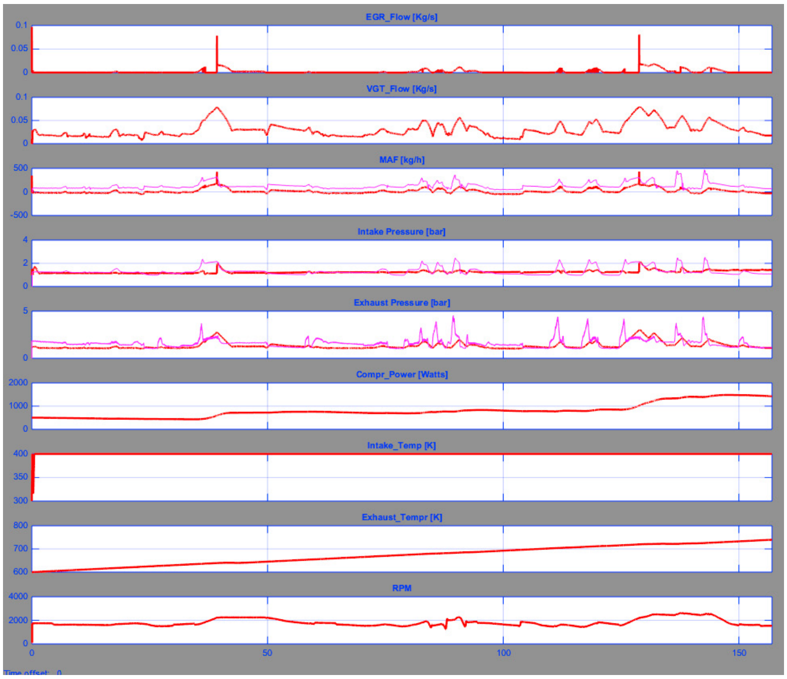
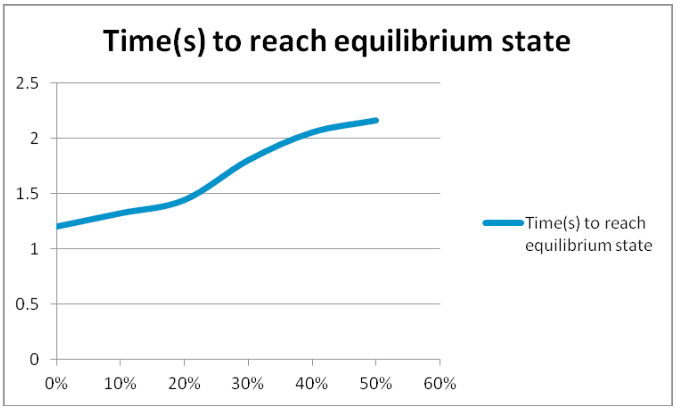


Figure 9 Simulation results with 10% noise in speed signal

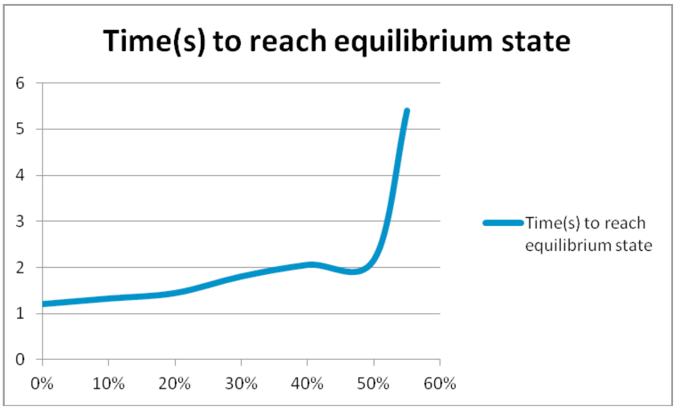
The diesel engine model is analyzed by giving perturbations in speed. Authors observe that the model returns to the equilibrium state when the disturbance is removed. This validates the steady state model for the wide disturbances. However the time to reach the equilibrium increases substantially if the disturbance exceedsing by more than 20% steady state operating point. This can be solved by introducing the disturbance accommodations in the steady state. Authors are at the moment working on this model.



X Axis *Pertabation levels in %*

Y Axis *Settling time in seconds*

Figure 10 Small signal analysis of the observer fed intake model



X Axis *Pertabation levels in %*

Y Axis *Settling time in seconds*

Figure 11 Small signal analysis of the observer fed intake model – Failure Mode

Figure 11 shows the setting time for the variation speeds as discussed in Figure 9. It is seen that when the perturbation is greater than 50% the model does not converge and the generalized inverse of [A] becomes uncontrollable and unobservable. This causes the instability in the system and thereby creating a failure in model. Authors recommend having 20% maximum allowable perturbations for all operating points there by fixing the ranges needed for the nonlinear model. This will make the model controllable and observable in all operating zones of the system.

4. Discussion/ Observations

The following results are inferred from the simulation results

1. The steady state results without observer show approximately 30% deviation from the reference model.
2. It's seen that the efficiency of the system with observer significantly improves as we move towards the desired operating zone. However it changes marginally when one of the inputs is changing and others being constant. The efficiency of the observer based prediction is maximum 92% at steady state operating points.

It's seen that the reliability of the observer gains is maximum at the operating zone and it changes substantially near the minimum range whereas it changes marginally near the maximum range

5. Conclusion

The proposed PI observers are simple and, according to the simulation and experimental results, very effective. They work better at nominal speeds and engine operating conditions. The experimental results demonstrate the practicality of the proposed approach in diesel engine intake model.

6. Acknowlwdgements

We thank the management of Continental Technical Centre India for the encouragement. Authors would like to especially thank Mr Girish Ramaswamy General Manager, Continental Automotive Components, India

References

[1] Bjarne Andresen, Peter Salamon and R. Stephen Berry, "Thermodynamics in finite time", PHYSICS TOOAY, American Insttitute of Physics, 1984.

[2] Valentina A. Mironova and Anatolii M. Tsirlin, Vladimir A. Kazakov and FL Stephen Berry, "Finite-time thermodynamics: Exergya) and optimization of time-constrained processes", J. Appl. Phys. 76 (2), 15 July 1994.

[3] Qin, Xiaoyong, et al, The universal power and efficiency characteristics for irreversible reciprocating heat engine cycles, European Journal of Physics, 2003. 24: pp. 359–366.

[4] A. AGUILERA-GONZA´ LEZ*, J. BOSCHE, A. EL HAJJAJI and I. ABIDI, "Feedback Design Air-Path Control on a Diesel Engine Based on Takagi-Sugeno Fuzzy Descriptor Systems", Mediterranean Conference on Control & Automation, Platanias-Chania, Crete, Greece, June 25-28, 2013.

[5] Junmin Wang ; Vehicle Res. Div., Southwest Res. Inst., San Antonio, TX, "Hybrid Robust Air-Path Control for Diesel Engines Operating Conventional and Low Temperature Combustion Modes", Control Systems Technology, IEEE Transactions on (Volume:16 , Issue: 6), 1138 – 1151, Nov. 2008.

[6] Pingen Chen and Junmin Wang, "Observer-Based Estimation of Air-Fractions for a Diesel Engine Coupled With Aftertreatment Systems", IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 21, NO. 6, NOVEMBER 2013.

[7] Dezong Zhao ; Dept. of Aeronaut. & Automotive Eng., Loughborough Univ., Loughborough, UK ; Cunjia Liu ; Stobart, R. ; Jiamei Deng, "Explicit model predictive control on the air path of turbocharged diesel engines", American Control Conference (ACC), 2013, 5213 – 5218, 17-19 June 2013.

[8] Rohit Kamath, Vivek Venkobarao,Prof Subramaniam, "An analytical model of diesel engine intake system for performance prediction", CMC congress pune May 10 2016

[9] Mario Santillo, Amey Karnik, "Model Predictive Controller Design for Throttle and Wastegate Control of a Turbocharged Engine", 2013 American Control Conference (ACC) Washington, DC, USA, June 17-19, 2013.

[10] Ortner, P. ; Inst. for Design & Control of Mechatronical Syst., Johannes Kepler Univ., Linz ; del Re, L, "Predictive Control of a Diesel Engine Air Path", Control Systems Technology, IEEE Transactions on (Volume:15 , Issue: 3), pp. 449 – 456, May 2007.

[11] Hemant B. Mehta*, Omprakash S. Bharti, "Performance Analysis of an Irreversible Otto Cycle using Finite Time Thermodynamics", Issue: 1, Vol. 2177, pp. 1575-1579, 2009.

[12] Vivek.V, Kumudini Devi R.P, Chellamuthu.C ' Design and development of energy efficient discharge controllers for Induction motor driven pump for Pulp and Paper Industry' published in International Journal of Modeling and Simulation ACTA press CANADA pp 45-51,2005.