

Systematic Model-Based Engine Control Design

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ABSTRACT

The present paper describes the development of a comprehensive engine control strategy for a 5.7 Liter eight cylinder engine with dual exhaust system. The control strategy is torque-based and distinguishes two essential control modes, engine speed control under idle engine operation and torque (load) control under normal engine operation. The controller synthesis is carried out within the context of a thoroughly model-based design paradigm. It involves the synthesis of one distinct multi-variable feedback controller for each of the two control modes. A particular focus is on synthesizing robust feedback-controllers that require very little experimental calibration. To this end, multi-variable $\mathcal{H}_\infty$ design principles are applied. The linear models underlying the controller synthesis are derived from an accurate nonlinear engine model. The fully integrated controller is experimentally validated on a test vehicle equipped with a custom-made, full-authority controller prototyping system. Experimental tests are carried out on a vehicle dynamometer and involve the first 18 cycles of the FTP test procedure (Urban Dynamometer Driving Schedule). The results confirm that the model-based engine control design approach proposed in this paper is indeed a viable approach and bears potential for significant cost and time savings without sacrificing control performance.

INTRODUCTION

Successful participation in a highly competitive market environment is often defined by how quickly one can respond to changing market parameters. This is particularly true in the automotive business where increased competitive pressure demands that new and more efficient product development practices are being adopted across all engineering competencies. For example, thanks to an increased use of CAD methods and virtual design practices the industry has already started to significantly shorten traditional product development cycle times [1]. The drive for increased productivity is ongoing and has a gripping effect on the entire industry. Engineering disciplines where traditional development methods and practices have a strong

foothold are struggling to meet the new productivity targets and stretch goals. In particular, in the area of engine control system development, initiatives to increase productivity are struggling with a legacy that has traditionally shown little appreciation for systematic controller design and that has been relying heavily on heuristic design principles and experimental system calibration. The main objective of the present paper is to illustrate benefits associated with a thoroughly model-based control system development approach, i.e., an approach that exploits plant models in all phases of the development process. Initial steps involving a comprehensive model-based approach have been described in [2]. Here, the principles described therein are embedded within a specific development framework that affords a rapid, systematic and reproducible controller design and validation process. The paper is organized as follows: After a brief introduction of the proposed model-based development framework, the design of a comprehensive multi-variable feedback controller for the test engine is described. Then, experimental results involving FTP test cycles are illustrated and discussed. The paper concludes with a summary and an assessment of observed benefits.

DESIGN FRAMEWORK

The engine controller is designed within the parameters of the design framework described in [3]. This design framework involves an accurate, control-oriented nonlinear model for the target engine, a highly modular engine controller architecture that affords plug-and-play algorithm implementation, and a model-based controller synthesis tool-set that supports and expedites the design of control features. Figure 1 illustrates the controller synthesis process within this framework. It is important to understand that this framework constitutes a virtual development environment whereby the engine model takes the place of the real engine for data procurement and interactive algorithm validation purposes. To this end the engine model is composed of reusable, modular building blocks so that its structure can be rapidly adapted with respect to changes in the target engine configuration. Furthermore, the model is part of a package that features automatic performance tuning

(i.e., the automated adjustment of selected model parameters such that the model performance matches a given set of experimental engine performance data) and the automated procurement of linear design models. Finally, the model is real-time capable and thus facilitates interactive control-system design. Hence, in case of HW changes anytime during the development stage the controller can be updated very quickly first by propagating the changes into the simulation model and then by reiterating the tool-supported design stages.

MODEL-BASED ENGINE CONROL STRATEGY

OVERVIEW

The purpose of a modern, torque-based control strategy is to operate the engine under given emission constraints such that a certain external torque demand is matched. This torque demand reflects a generalized demand for engine power. It is calculated from an aggregate of engine operating conditions, including driver input, the current transmission shift status, auxiliary power needs, wheel tracking conditions, etc.

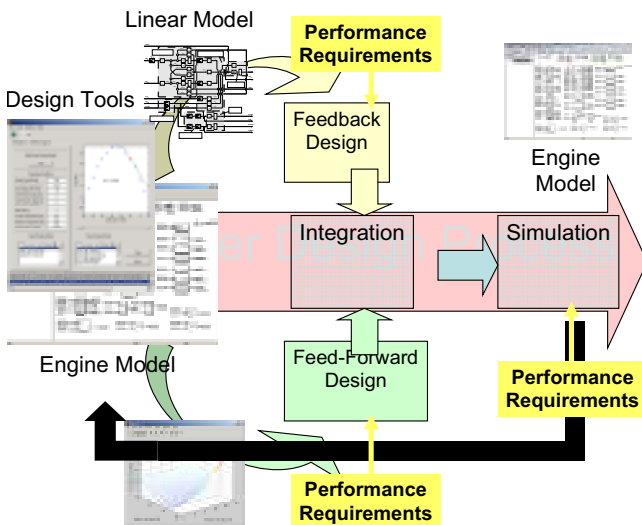


Figure 1 Graphic illustration of the controller synthesis process

A schematic illustration of a generic torque-based engine control strategy is provided in Figure 2.

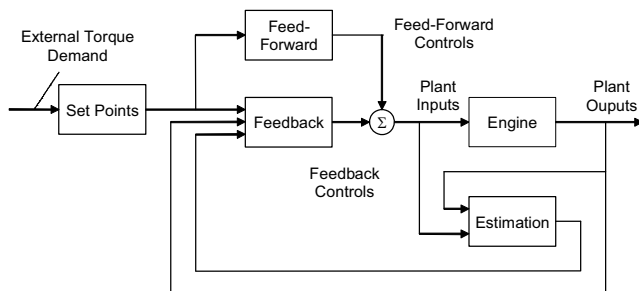


Figure 2 Torque-Based Engine Control System Structure

As outlined in this illustration, a comprehensive control strategy is composed of a number of elementary control features, including set-point calculations, feed-forward controls, feedback controls, and estimators to calculate important signals which cannot be measured. This paper concentrates on the design of the feedback control features. More specifically, the paper is focused on devising the feedback controller with a minimum of engineering effort. Complementary control features such as feed-forward control and set-point strategy features that will be needed for strategy validation will not be discussed here in detail. Suffice to say though that, within the model-based design framework proposed here, these complementary features are derived from expedient tools that utilize the accurate non-linear engine model (just like the linear design models used in the feedback controller design). The feedback control design is guided by three core principles:

- application of linear control theory
- multivariable design
- design for robust performance

The reason for focusing on linear design principles is that the underlying theoretical framework is further evolved and more mature than any other area of modern control theory. Also, there are numerous commercial tools (e.g. Matlab/Simulink) that support a variety of linear feedback control design and synthesis methods. Finally, the performance of linear controllers is very predictable and robust. This aspect is of utmost importance in a business where functional flaws in the product can lead to millions of dollars in recall penalties. A multivariable approach guarantees that all relevant system interactions between input and output signals are properly addressed. Robust feedback control design, finally, is intended to mitigate the effects of un-modeled dynamics and of parameter variations, effects which are inevitable in any context where linear models are used to approximate complex non-linear physical phenomena. It should be emphasized that there is no claim here that linear model-based control design methods are superior to any other techniques in terms of the achievable control quality. However, there is no doubt that they are superior in terms of the available tool and synthesis resources thus promising that a given control design task can be carried out in the most efficient way. In a competitive engineering world that strongly embraces the notion of “nothing beats good enough” this promise alone is reason enough to take a very good look at these techniques. To what extent they ultimately prove viable and beneficial within the context of practical engine control is precisely the focus of this paper.

H_{∞} DESIGN METHOD

There exist numerous suitable design techniques for a robust multivariable engine control design [5], [6]. Here a technique based on H_{∞} optimal control has been adopted [6] [7]. The objective of this design is to select the controller transfer function $K(s)$ such that the maximum magnitude (H_{∞} norm) of the transfer matrix

between a generalized input vector $w(s)$ (disturbances, tracking reference signals, etc.) and a generalized output vector $z(s)$ (plant inputs, internal state variables, plant outputs, etc.) of a given system interconnection is minimized (see diagram on the right side of Figure 3).

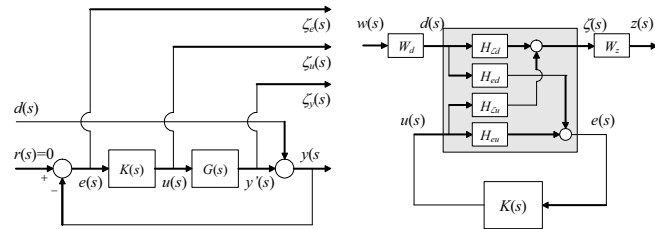


Figure 3 $\mathcal{H}_\infty$ plant interconnection diagrams

The choice of specific input and output signals within the generalized system interconnection is part of the design process and it depends on the application at hand and its particular synthesis goals. The left hand side of Figure 3 illustrates an example of such a system interconnection choice. This interconnection is often referred to as the standard S/KS/T interconnection scheme [6] because it involves the sensitivity transfer function $S = (I + GK)^{-1}$ from input d to output e , the transfer function KS from input d to output u , and the closed-loop transfer function $T = GKS$ from input d to output y' . For the present design, a subset of the S/KS/T interconnection scheme involving merely the disturbance input d and the generalized outputs e and u is adopted (hence S/KS scheme). The transfer matrix $H_{\zeta d}$ of this particular generalized interconnection scheme is given as follows:

$$H_{\zeta d}(s) = \begin{bmatrix} H_{\zeta_e d}(s) \\ H_{\zeta_u d}(s) \end{bmatrix} = \begin{bmatrix} (I + G(s)K(s))^{-1} \\ K(s)(I + G(s)K(s))^{-1} \end{bmatrix} \quad (1)$$

Obviously both the plant and the controller transfer function $G(s)$ and $K(s)$, respectively, are intrinsic components of the elements of the generalized transfer matrix $H_{\zeta d}$. In order to obtain meaningful and, most importantly, desirably shaped controller transfer functions the generalized interconnection system must be augmented with frequency dependent weighting functions as indicated in the right hand side diagram of Figure 3. According to the notation in the illustration the following relationship applies:

$$H_{zw}(s) = W_z(s)H_{\zeta d}(s)W_d(s) \quad (2)$$

The $\mathcal{H}_\infty$ design framework reflects an attempt to “flatten” the magnitude of the control system transfer function matrix H_{zw} in (2) across the entire frequency spectrum (the magnitude being determined in terms of the singular values of the transfer matrix). Hence, by properly choosing the frequency weighting function matrices W_z

and W_d , the transfer matrix $H_{\zeta d}$ can be shaped within this design framework so that it meets given specifications on any frequency band of interest. More specifically, assuming that the filter transfer function matrix W_d is chosen to be the identity matrix, the strategy to properly shape the transfer function $H_{\zeta d}$ within the $\mathcal{H}_\infty$ optimization framework is as follows (see Figure 3):

- Select the elements of the weighting function matrix W_z such that they reflect the inverse of the desired transfer functions between the signals d and ζ .

MULTIVARIABLE ENGINE CONTROL DESIGN

Plant

The plant to be controlled is a 5.7 Liter V8-cylinder SI engine. The base configuration of the plant includes two engine banks, each with an independent exhaust system, an electronic throttle actuator, and in deviation to the standard production configuration, also an EGR system and wide-range A/F-ratio (WRAF) sensors in both engine banks. A summary of the relevant plant input and output signals is provided in Table 1.

Input signals	Output signals
Throttle position	Engine speed
EGR valve position	Engine torque
Spark angle	EGR ratio
Fuel factor left bank	Engine-out equivalence ratio left bank
Fuel factor right bank	Engine-out equivalence ratio right bank
	O ₂ -storage level left bank catalyst
	O ₂ storage level right bank catalyst

Table 1 Control relevant plant input and output signals

Notice that some of the listed signals cannot be measured. To utilize these signals within a feedback control context it is necessary that suitable signal estimates be generated. For example, the engine torque can be estimated via table look-up as a function of engine speed, manifold pressure, and spark angle. Conversely, the O₂ storage level can be estimated using a Kalman-filter based O₂ storage level estimator. This approach is based on a simple catalyst O₂ storage model. The parameters and states of the catalyst model are updated according to the principles of an extended Kalman-Filter whenever the switch-type sensor downstream of the catalyst indicates full oxygen saturation or depletion (catalyst break-through). The model states and parameters monitored are the O₂ storage level, the catalyst storage capacity, and the stoichiometry bias of the WRAF sensor. The O₂ mass flow into the catalyst can be calculated from the mass air flow sensor signal and from the signal of the WRAF sensor upstream of the catalyst. As saturation and depletion conditions occur irregularly, the model states and parameters are updated at non-uniform time intervals. Under steady-state engine operating conditions the update frequency largely depends on the

accuracy of the model estimates. Thus, as the model estimates converge to their true values the occurrence of updates becomes increasingly infrequent.

Design Model

Any truly model-based control design method is based on a plant model. Here a linear plant model is utilized that maps all relevant inputs to all relevant outputs of the engine (see Table 1). A detailed signal flow chart of the plant model for the target engine is provided in Figure 4. Refer to Appendix A1 for a profound mathematical description of the model.

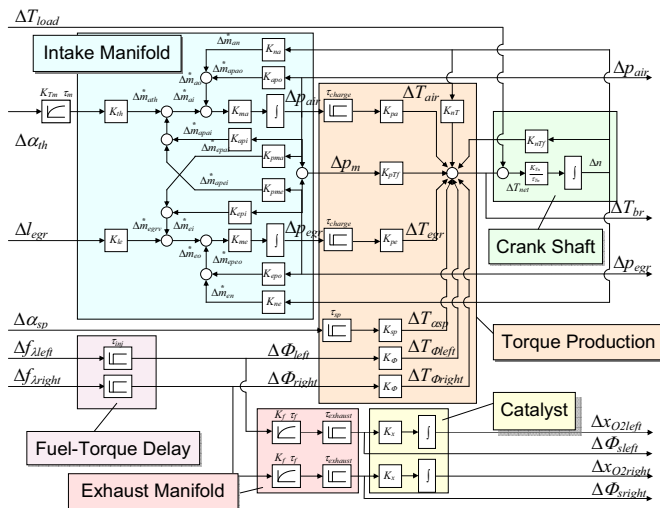


Figure 4 Schematic of linear design model

Controller Design

The main design objective is to synthesize a set of two robust linear multi-variable controllers which achieve satisfactory control performance across the entire engine operating envelope. The first controller involves engine speed feedback and is used during idle engine operation. The second controller involves engine torque feedback and is engaged during all other engine operating conditions. Each of those controllers is based on a linear design model that approximates the engine dynamics in the vicinity of a representative engine operating point: In the idle speed case the operating point involves conditions around 750 rpm and 30 kPa manifold pressure (Model A, see Appendix A1), in the normal operation case conditions around 1500 rpm and 50 kPa manifold pressure (Model B, see Appendix A1). The overall design goals can be summarized as follows:

1. zero steady state error on engine speed, engine torque, EGR ratio, and desired O₂-storage level
2. no persistent deviation of the spark angle from its nominal value
3. no EGR feedback control during idle-speed
4. avoid controller overshoot and actuator saturation

The achievable feedback control bandwidth is generally limited by the demands for stable control performance (and by design goal 4). Robust synthesis methods thus naturally lead to conservative designs. To achieve

satisfactory tracking performance the feedback control design must be complemented with appropriate feed-forward control features. The motivation for a robust design arises primarily from the fact that the plant dynamics are highly non-linear so that the parameters of the nominal linear plant model vary significantly across the entire engine operating envelope. Robust closed-loop control in the presence of significant plant uncertainty (i.e., varying plant parameters) is quantified in terms of the gain and phase margins of the nominal plant transfer function. These margins characterize the loop gain locus (i.e., the Nyquist plot of the transfer function GK) relative to the location of the Nyquist point. Ideally, the objective is to design the controller such that the loop gain locus never enters the unit circle around the Nyquist point or, equivalently, such that the sensitivity transfer function S has a magnitude smaller than one on the entire frequency spectrum. Such a design affords a gain margin from 0.5 to infinity and a phase margin of 60 degrees [5],[7]. A detailed illustration of the interconnection diagram that underlies the $\mathcal{H}_\infty$ -based multivariable controller design is provided in Figure 5. Note that, in order to enforce integral behavior in the catalyst O₂ storage control, the disturbances d_3 and d_4 are not only superimposed onto the equivalence ratio outputs but also propagated into the inputs of the catalyst models (denoted by $G_2(s)$ in Figure 5).

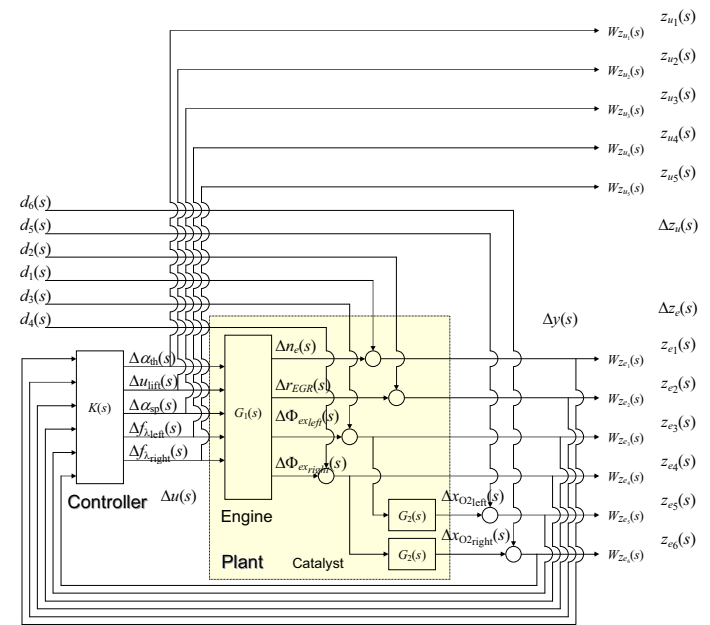


Figure 5 Detailed signal interconnection chart for $\mathcal{H}_\infty$ MIMO controller design for idle-speed conditions

The frequency weighting functions used for the $\mathcal{H}_\infty$ design are ideally composed of a set of elementary transfer function elements with minimum order, such as PI elements, low-pass (LP) elements, high pass (HP) elements, etc. The specification of particular weighting functions follows basic $\mathcal{H}_\infty$ loop-shaping rules (see, e.g. [5]). Tables A.2.1 and A.2.2 exemplify how the design goals summarized above thus translate into specifications for the frequency weighting functions.