

Rapid Transient Fuelling Calibration Method for the PFI SI Engine

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ABSTRACT

This paper presents an experimental calibration method for the feedforward fuelling controller for a PFI SI engine. A recently proposed method [1] is extended from the idle to the torque delivery region and uses a Riccati designed rather than Parameter-Space linear element. Dynamic input signals are applied to air path, load and fuel entering the engine to excite the air-to-fuel ratio dynamics. A nonlinear inverse compensator is obtained directly from the observed input-output behaviour. Least squares black-box identification is used to generate the compensator using an algebraic NARX structure. The resulting inverse compensator not only acts as the feedforward controller but also linearises the fuelling path and therefore makes the system well suited for robust linear feedback control. The feedforward compensator is experimentally demonstrated and subsequently a robust H-infinity feedback controller is designed, implemented and the complete system experimentally validated.

The technique offers several benefits over conventional fuelling calibration. The technique offers a rapid and efficient 'one-shot' approach to identify large regions of the conventional fuel map whilst at the same time capturing transient effects. Accordingly, the fuelling calibration can be carried out with significantly less engine testing whilst achieving improvements due to the dynamic nature of the compensator.

INTRODUCTION

Vehicle manufacturers are under increasing pressures from both customer expectations and tightening emissions requirements to continually improve air-to-fuel control.

Good control of the air-to-fuel ratio (AFR) can have a significant impact on an engine's transient performance and tailpipe emissions. The three way catalytic convertor has an excellent conversion efficiency provided combustion takes place at stoichiometric conditions. Prolonged periods of operation away from stoichiometric result in poor exhaust gas conversion from HC, CO and NO_x into CO₂, N₂ and H₂O [2].

AFR control is implemented in engine management systems as a combination of a fast acting feedforward controller together with feedback action used to correct for any small steady state deviations.

The conventional feedforward controller is based on a first-principle, physically derived model of the engine's air and fuel path dynamics [3]. An air path model is used to estimate the mass of air expected to enter a cylinder based on manifold dynamics, engine capacity, throttle angle, pumping dynamics and engine speed. The fuel path dynamics which account for the fuel puddling, injector, vaporization and fuel entrainment dynamics are then used to determine the injector pulse width to deliver the mass of fuel required to obtain a stoichiometric ratio.

These models are included in the engine management system and have a series of 'calibration parameters' which are determined by a series of dynamometer mappings. A methodology to reduce the experimental and tuning burden by reducing the number of calibration parameters of these extensive models is given in [4].

An alternative method for obtaining the feedforward controller is proposed here based on nonlinear black-box identification of the engine. The system dynamics over a set operating envelope are excited by an appropriate set of identification signals. Some input-output causal assignments of these signals are then reversed to allow the direct identification of a feedforward fuelling

controller for this operating envelope. This controller is a partial inverse of the forward (non-inverted) system and as such also acts as a linearising filter in the inverted path. As a result, this makes the system with compensator well suited for subsequently applying robust linear feedback control. It may be expected that the total fuelling calibration of the entire operating region could be achieved by relatively few scheduled controllers with this approach.

Direct identification of the feedforward controller offers several benefits over conventional approaches. Because the method involves identification data which is rich with transients, the resulting controller is inherently suited to dealing with transient behaviour. Furthermore, the method is less experimentally intensive because only relatively short data sets are required.

A recent publication [5], demonstrated neural networks useful for fuelling control. The authors generate a feedforward controller based on an inverse neural network of the fuelling path from identification data between key engine variables and a close coupled universal exhaust gas oxygen (UEGO) sensor fitted to one cylinder. Feedback was obtained by an estimate of the AFR as identified in the model. An inverse algebraic NARX approach to the fuelling and calibration has been demonstrated over the idle speed region in [1], where the linearization of the feedforward controller was used in a multivariable feedback scheme to control engine speed and AFR. Direct inverse control has also been applied to idle speed problem in [6] where model parameters are found using genetic algorithms.

EXPERIMENTAL SETUP

The engine used experimentally is a spark ignited, Ford Zetec, 1.6l, four cylinder, 16 valve, double overhead cam with sequential electronic fuel injection. The engine is fitted with a cable operated throttle and is primarily controlled by a Ford production EEC IV electronic engine control unit. Actuation of the spark advance (SA), air bleed valve (ABV) duty cycle (DTY) and fuel pulse width (FPW) can be switched to operate from a series of powerstage units controlled from dSPACE. This is interfaced to a desktop PC for data acquisition and implementation of real time code generated using MATLAB, SIMULINK and Real-Time Workshop software. Load is applied to the engine crankshaft through a low inertia dynamometer operating in torque mode, also operated through dSPACE. Additional sensors include a Bosch wideband UEGO, fitted to the confluence point on the exhaust system to measure the AFR and a pressure transducer which is installed in the inlet manifold for measuring manifold absolute pressure (MAP). An optical angle encoder is mounted to the crankshaft. Sampling of the signals occurs once per degree of crankshaft rotation to allow for any signal processing prior to down-sampling. Prior to the identification, the signal from the UEGO was filtered off-line using a non-causal filter to remove frequencies greater than controller sampling frequency

(corresponding to 180 deg crankshaft rotation). A 180 deg moving window integration was used for the MAP signal as this was considered to give a better representation of the air flow during an entire engine event.

DIRECT IDENTIFICATION OF FEEDFORWARD FUELLING CONTROL

Direct inverse control is conceptually straightforward in that the nonlinear dynamics of the forward system G can be removed by pre-filtering the system with its dynamic inverse K . Ideally, the compensated system GK is thus a unity forward path, other than for any time delay which exists in G . Figure 1 shows the concept for the case of fuelling control, where the desired output λ_{demand} is the input to the system pre-filter which computes the FPW necessary to give the correct measured λ at the output of G .

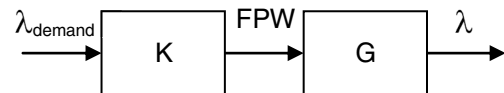


Fig 1. Feedforward fuelling controller concept

SYSTEM EXCITATION

Identification and model validation data sets were obtained by collecting a relatively short but information rich sequence of input / output behaviour. The AFR as measured in the exhaust stream at the UEGO is governed by the mass of air and fuel entering the cylinders. These are determined by the throttle angle or ABV DTY, torque load (T_L) and FPW. Thermal conditions such as coolant or air temperature are also known to have a significant effect on the AFR dynamics. The work here however is limited to a fully warmed up engine. Nevertheless the proposed method provides an improved feedback capability which will compensate for significant variation in dynamics.

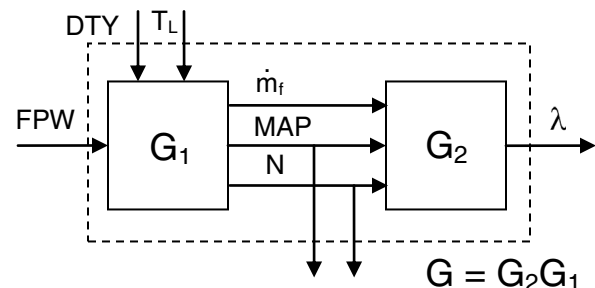


Fig 2. Forward model of the fuel and air path

Simultaneous excitation of the torque load, air and fuel creates a data set with the combined dynamics which affect the AFR. Relationships between the measured variables, integrated-MAP, N , FPW and λ are then determined by an appropriate identification scheme.

Figure 2 shows the forward model used for collecting the identification data.

Input signals to excite the torque load and air were generated by scaled uniformly distributed numbers with a bias. The switching period of these signals was chosen to maximize the transient performance of the feedforward controller whilst achieving the necessary DC dynamics. The FPW was pegged to the integrated-MAP signal to prevent the engine becoming excessively rich or lean. A zero-mean scaled random number was then superimposed on this to prevent the signals having complete correlation. Details of the signal properties are given in table 1. The effect of these signals caused fluctuations in engine speed between 900 – 2200 rpm, and changes in integrated-MAP of between 50 – 110 bar whilst perturbing λ in the range 0.75 to 1.3. The engine signals used in the identification data set are displayed in fig. 3.

Table 1. Properties of the identification signals

Signal	Range	Period [s]
ABV DTY [%]	0.44 – 0.58	1.2
Load [V]	0.8 to 1.2	2
FPW [μ s]	2500 – 7000	1.5

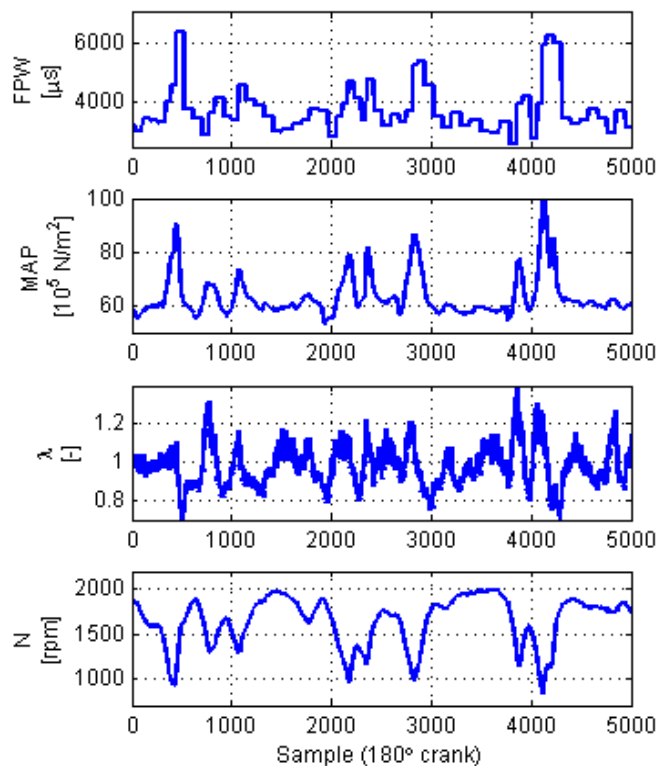


Fig 3. Nonlinear identification dataset.

ALGEBRAIC NARX

An algebraic NARX model is used in the sequel for the feedforward compensator. With this approach, the

design engineer has some freedom over the choice of structure and can therefore tailor this to meet any computational constraints of the powertrain control module (PCM) in terms of the number of regressors and their complexity. The general form of the SISO NARX structure is [7]:

$$y(k) = F(y(k-1), \dots, y(k-n_y), u(k), \dots, u(k-n_u))$$

where the output y , at event k , is determined by F , a nonlinear function of y , at the previous event $k-1$, up to a maximum lag of n_y , and u , at k and previous inputs up to a maximum delay of n_u .

To limit the total number of possible regressors, delays were limited to 3 (n_u and $n_y = 3$). Nonlinearities with respect to each term were restricted to inverse and square terms.

ORDINARY LEAST-SQUARES

The feedforward compensator may be identified by a number of techniques including neural networks, generic algorithms and various least squares techniques. The algorithm used here was the well understood ordinary least squares [8].

INVERSE NARX IDENTIFICATION

Identification data was obtained by dynamically perturbing load, air and fuel which naturally leads to a forward model of MAP, N and FPW to predict λ . This forward model is depicted in fig. 4(a).

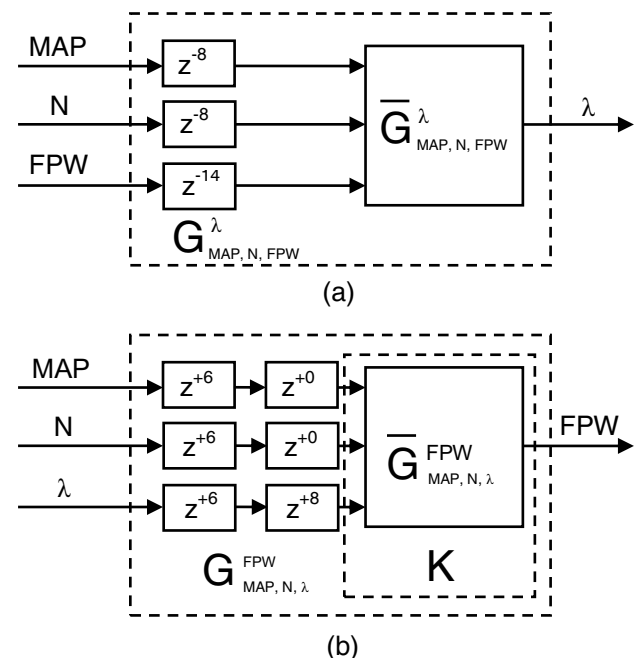


Fig 4. Synchronized partial inverse controller.

The inverse compensator is intended to predict the correct FPW based on MAP, N and λ demand to obtain a desired output level of λ . In the proposed scheme it is