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AIR FUEL RATIO CONTROL IN LIQUEFIED PETROLEUM GAS INJECTED SI ENGINES*

Chris Manzie[1], Harry Watson[2], Marimuthu Palaniswami[1]

[1]*Department of Electrical and Electronic Engineering*
[2]*Department of Manufacturing and Mechanical Engineering*
The University of Melbourne, Victoria, Australia, 3010

Abstract: *Despite being one of the fastest growing alternative fuel sources, little attention has been given to control of the air fuel ratio at the point of combustion in liquefied petroleum gas (LPG) engines. In this paper a mean value engine model is presented for LPG throttle body injected engines. Based on this model, a control algorithm capable of adapting to errors in both the fuel and air systems is proposed to ensure accurate stoichiometric fuel injection control. Simulation results are presented to validate the proposed approach. Copyright © 2002 IFAC*

Keywords: Fuel injection, automotive control, adaptive control, radial basis function networks, recursive algorithms.

1. INTRODUCTION

Liquefied petroleum gas (LPG) is based around propane and butane mixtures along with minor components such as ethane, pentane, butylenes, propylene and ethylene, although the exact mixture depends on factors including geographic reservoir location, climate and local market prices. LPG has many properties that make it a suitable alternative to gasoline as a fuel for spark ignition engines. The simpler chemical composition of the major constituents leads to a better overall burn, and thus lower HC and CO emissions. Other advantages include minimal need for cold start enrichment, and almost immediate availability of full power to the engine because the fuel readily converts to its gaseous form so there is no need to wait for the inlet manifold to be hot to aid evaporation. There are also benefits to the mechanical performance of the engine, with dramatic reductions in combustion chamber and spark plug deposits, as well as up to 50% longer engine life courtesy of reduced cylinder bore wear since LPG does not wash oil from the cylinder walls.

Recent studies such as (Arcoumanis, 2000) estimate the percentage of LPG vehicles worldwide at around 1% of the total fleet, the majority of which includes converted engines running using an LPG carburetor, as well as dedicated LPG engines using either CFI or SEFI injection of liquid or gaseous LPG. However despite the large amount of literature devoted to the control of air fuel ratio in petrol injected engines (e.g. (Hendricks et al., 1993), (Won et al., 1998), (Manzie et al., 2000)), there is no discussion of air fuel ratio (AFR) control in LPG engines. With an anticipated tightening in the environmental specifications for LPG engine emissions, this promises to be an increasingly important research area.
The difficulties faced in accurate control of LPG engines are somewhat different to petrol (gasoline) injection. In petrol-injected engines, fuel pooling in the intake manifold, where part of the injected fuel strikes the intake manifold wall and condenses forming a fuel film, is a well-documented concern. Several fuel film compensation algorithms have been proposed to deal with this problem, e.g. (Manzie et al., 2000), (Hendricks et al., 1993). Fortunately the properties of the fuel film can be readily known, as petrol composition is relatively constant, especially for emissions certification. However the composition of LPG is considerably more variable, with mixtures in Australia varying from almost pure propane to propane to butane ratios of nearly 1:1. Given that butane is a component of both petrol and LPG it is likely that some fuel pooling may still take place in LPG injected engines.

Another effect of the varying content of the fuel is it alters the air fuel ratio required for stoichiometry. Stoichiometric AFR is required to ensure the catalytic converter efficiency is optimized, and thus the emissions from the tailpipe are minimized. Catalytic converter efficiency falls off sharply with deviations from stoichiometry, and the objective of the fuel injection control strategy should be to maintain the air fuel ratio within 1% of stoichiometry even during transient operating conditions.

In this paper, injection of LPG at the throttle body is considered as it represents the most likely first step at a dedicated production line LPG vehicle without a gas carburetor. A mean value model is described in Section 3, along with the underlying assumptions, and is used later in Section 7 to generate simulation results. In Section 4 the compensation and correction process for errors in the airflow estimation is described, while in Section 5 variations in the fuel film parameters are considered, and the proposed adaptive control scheme incorporating both of these previous sections is detailed in Section 6.

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2. NOMENCLATURE

The following nomenclature is used in this paper:

Symbol	Meaning
α	Throttle angle
β , β_s	Observed & stoichiometric AFRs
λ	Ratio of observed to stoichiometric AFR
τ_f	Fuel film evaporation time constant
$AFI(f)$	Air fuel influence function (Cho & Hedrick, 1989)
$C_{\max}$	Maximum torque of the engine
$f=\dfrac{m_f}{m_f+m_a}$	Fuel fraction in the intake manifold
I	Equivalent rotational inertia of the engine
m_f , m_a	Mass of fuel & air in the manifold
$\dot{m}_{ai}$, $\dot{m}_{fi}$	Mass flow rates of air & fuel into the manifold
$\dot{m}_{co}$	Mass flow rate of charge out of the manifold
$\dot{m}_{fc}$	Mass flow rate of controlled (injected) fuel
M_{eq}	Equivalent molar mass of the fuel-air gas mixture in the manifold
n	Engine speed
P_f , P_b , P_{pc}	Frictional, pumping and peripheral load power losses
P_m , T_m , V_m	Intake manifold pressure, temperature and volume
R	Universal gas constant
$SI(-)$	Spark influence function (Cho & Hedrick, 1989)
t_d	Air fuel ratio propagation delay
t_{tp}	Torque production delay
T	Sampling interval
X	Fuel split parameter

3. MEAN VALUE ENGINE MODEL OF THE INTAKE MANIFOLD FOR THROTTLE BODY INJECTION OF LPG

Single point injection usually takes place at or near the throttle body and the injected fuel is then distributed within the intake manifold. A charge mixture is inducted into the cylinders from the manifold as each inlet valve opens. Under the assumption of uniform mixing of air and fuel in the intake manifold, the control strategy then centers on maintaining the desired air fuel ratio in the intake manifold itself. In terms of mean value modeling, there are three state variables that must be considered after the injection process is completed. Firstly, the engine speed is used as a state variable for the engine dynamics system encompassing speed dynamics and load. The intake manifold pressure is used to describe the state of the intake manifold and can be related to the total mass of fuel and air gases, $m_f + m_a$, in the intake manifold by the ideal gas law,

$$P_m = \frac{RT_m\left(m_a + m_f\right)}{V_m M_{eq}} \quad (1)$$

The three state equations used to describe the intake manifold and engine system are as follows:

$$\frac{dn}{dt} = \frac{C_{\max} AFI(f) SI(-) \dot{m}_{co}\left(t - t_{tp}\right)}{I.n} - \frac{P_f + P_b + P_{pc}}{I.n} \quad (2)$$

$$\frac{dP_m}{dt} = \frac{RT_m}{V_m M_{eq}}\left(\dot{m}_{ai} + \dot{m}_{fi} - \dot{m}_{co}\right) \quad (3)$$

$$\frac{df}{dt} = \frac{m_a}{\left(m_a + m_f\right)^2}\left(\dot{m}_{fi} - f\dot{m}_{co}\right) - \frac{m_f}{\left(m_a + m_f\right)^2}\left(\dot{m}_{ai} - (1-f)\dot{m}_{co}\right) \quad (4)$$

The form of these state equations is similar to the state equations for a natural gas manifold in (Gangopadhyay & Meckl, 2001), although it appears the fuel fraction state equation was incorrectly derived in that paper. The other major difference is we will consider the presence of a fuel film in Section 5.

The mass flow of air past the throttle plate and into the manifold is given by a parametric function of manifold pressure and throttle angle of the form described in (Cho & Hedrick, 1989):

$$\dot{m}_{ai} = \dot{m}_{ai(MAX)} f_1(\alpha) f_2\left(P_m\right) \quad (5)$$

The mass of charge flow out of the manifold and into the engine, $\dot{m}_{co}$, is given by the known speed density equation, and makes the assumption of uniform mixing of gases in the intake manifold

$$\dot{m}_{co} = c_1 \eta_{vol} P_m n \quad (6)$$

The mass flow rate of fuel into the intake manifold $\dot{m}_{fi}$ is subjected to the process of fuel pooling, and so may not be equal to the mass flow rate of the control (injected) fuel, $\dot{m}_{fc}$. Fuel pooling has a large effect during transient conditions and is discussed in more detail in Section 5.

4. STEADY STATE ERROR COMPENSATION

The desired mass of fuel into the manifold can be expressed as the sum of the amount of fuel required to get the charge mixture in the manifold to the desired set point and an amount of fuel proportional to the air passing through the throttle body into the intake manifold.

$$\dot{m}_{fi} = \frac{\Delta m_{f(des)}}{T} + \frac{\dot{m}_{ai}}{\beta_s} \quad (7)$$

Note that once the desired mixture is reached, the first term on the right hand side of (7) will be zero, so it only influences the control during start up conditions. Hence the control signal is primarily dependent on estimating both the mass of air passing the throttle body and the value of stoichiometric air fuel ratio. In general, a nominal value of air mass past the throttle is available, whether this is from an air mass flow sensor located close to the throttle, or obtained from a parametric model calibrated for the engine.

Errors associated with the nominal value are now considered, and the true value can be related to the nominal value by an equation of the form $\dot{m}_{ai} = (1+\delta_i)\dot{m}_{ai-n}$. In this equation, the error term δ_i may be a function of other engine parameters such as throttle angle and manifold pressure.

The total airflow into the manifold can be divided by the stoichiometric AFR, β_s, to provide the desired fuel flow into the manifold. This can be rearranged in terms of the estimated stoichiometric AFR ($\hat{\beta}_s$) :

$$\begin{aligned} \frac{1}{\beta_s}\dot{m}_{ai} &= \frac{1}{\beta_s}(1+\delta_i)\dot{m}_{ai-n} \\ &= \frac{1}{\hat{\beta}_s}(1+\bar{\delta}_i)\dot{m}_{ai-n} \end{aligned} \qquad (8)$$

Here $\bar{\delta}_i = \frac{\hat{\beta}_s}{\beta_s}\left(1 - \frac{\beta_s}{\hat{\beta}_s} + \delta_i\right)$.

The estimated stoichiometric AFR may be approximated for the given fuel composition or left at a set level. If $\bar{\delta}_i$ is estimated, the estimate $\hat{\delta}_i$ can be used in the control law, and the estimate improved based on exhaust feedback from the exhaust gas oxygen (EGO) sensor, also known as a lambda sensor.

The narrowband lambda sensor is located in the exhaust and gives the output $sign(1-\lambda)$ after a transport delay, t_d. The transport delay is speed dependent and originates from the fact that it takes some time for the fuel to pass through the inlet manifold, then two engine cycles for the fuel entering the cylinder to exit, plus some time for the exhaust gases to reach the sensor and also there the response time of the sensor itself.

The approach that will be considered here is to use a radial basis function (RBF) network with Gaussian nodal transfer functions to estimate the error term, $\bar{\delta}_i$. Details of the transfer function and structure of the RBF network may be found in (Manzie et al., 2000). The error, $\bar{\delta}_i$, is assumed to be a nonlinear function of both throttle angle and intake manifold pressure, as these form the two input parameters to the equation used to model $\dot{m}_{ai}$. The weights in the radial basis function network will be continually updated based on the output feedback, and this will provide adaptation to allow for engine ageing and sensor deterioration. The binary feedback term will be used to update the network, rather than a continual air fuel ratio measurement as in (Manzie et al., 2000). The weight update law is a version of gradient descent modified to cope with the binary feedback:

$$\dot{\mathbf{W}} = -k_w sign(1-\lambda(t-t_d))\mathbf{G}(t-t_d) \qquad (9)$$

In equation (9), $\mathbf{W}$ represents the weight vector of the network and $\mathbf{G}$ is a vector containing the outputs of each node in the radial basis function network.

The use of a narrowband sensor (binary signal) means there will be some oscillation about $\lambda = 1$ since the updates have the same magnitude regardless of distance from the desired air fuel ratio. Coupled with a propagation delay for the error information to become available, this will result in the air fuel ratio passing the desired operating level and continuing until the sign of the feedback term switches. Whilst small oscillations are not a problem, the magnitude of the update parameter, k_w, should be small enough to ensure the oscillations remain within a 1% boundary. A wideband lambda sensor would speed up convergence and alleviate the oscillations in the simulations since the update magnitudes could be more precisely tailored to the error magnitudes (ie large updating for large errors and vice versa). However measurement noise in a real engine makes a completely flat lambda trace impossible even with a wideband sensor. Also financial constraints ensure the narrow band sensor should be used if permissible by the control algorithm.

5. TRANSIENT ERROR COMPENSATION

The problem of fuel pooling in the intake manifold is now considered, especially in the light of changing parameters in the pooling model. Fuel pooling occurs when some fraction, X, of the injected fuel condenses in the intake manifold wall, forming a fuel film. The film also evaporates with some time constant, τ_f, and the evaporation adds to the total amount of fuel vapour in the manifold. In petrol engines this film has been observed at up to 1mm thick, and is of course temperature and pressure dependent. In steady state operation the rate of evaporation of the fuel film is equal to the loss of injected fuel to the fuel film, and its effect is negligible, however the effect is significant during transient operating conditions.

If the fuel parameters are known, then compensation for the fuel pooling effects can be performed. The parameters are dependant on both the engine operating point and the fuel composition. Whereas in petrol engines the composition remains roughly the same, in LPG engines the composition is much more variable and this makes it difficult to use a functional relationship for the parameters.

Models of the fuel film in petrol-injected engines are described repeatedly in the literature, and are generally similar to the structure proposed in (Hendricks & Sorenson, 1990). In the discrete time domain the model has the form shown in (10).

$$\begin{bmatrix} \dot{m}_{fi} \\ \dot{m}_{ff} \end{bmatrix}_{k+1} = \begin{bmatrix} 0 & 1 \\ 0 & 1-T/\tau \end{bmatrix} \begin{bmatrix} \dot{m}_{fi} \\ \dot{m}_{ff} \end{bmatrix}_{k+1} + \begin{bmatrix} 1-X \\ XT/\tau \end{bmatrix} \dot{m}_{fc} \qquad (10)$$

This model is parameterized by the fuel split parameter, X, and the evaporation time constant, τ, both of which are time varying. The sampling interval is T. Currently research is being conducted to verify the presence of a fuel film in LPG engines, although in this paper the fuel film is modeled as in the equation above, albeit with different constants to those typically found in petrol injection.

In order to estimate the parameters, an ARMA model for $\dot{m}_{fi}$ is constructed and a recursive least squares algorithm is used to update an estimate of the difference equation parameters. These can then be converted back to the fuel film parameters, which may then be used in a fuel film compensation strategy.

There are several minor drawbacks with using this RLS approach. Firstly, the use of an RLS algorithm relies on output magnitude information rather than sign, requiring a wideband sensor in the feedback. Also during steady state operation, the effects of the fuel film become negligible since evaporation of the fuel film is equal to the fraction of injected fuel lost to the film. If the RLS estimator is left to run during this period the estimated system will converge to the form $\dot{m}_{fi}(k) = \dot{m}_{fi}(k-1)$ and all fuel film dynamics will be lost. This may be overcome by switching off the estimator during steady state operation. Similarly, if during transient operation the fuel film dynamics are only slightly excited, their effect on the AFR may be 'hidden' in oscillations brought about by updates of $\dot{m}_{ai-n}$ or noise in the lambda measurements. Therefore the criteria for turning on the RLS estimator should be tightened to include only those situations where a throttle transient occurs and a deviation above some threshold is observed in the air fuel ratio.

6. PROPOSED CONTROL SCHEME

The proposed control scheme is illustrated in the following diagram.

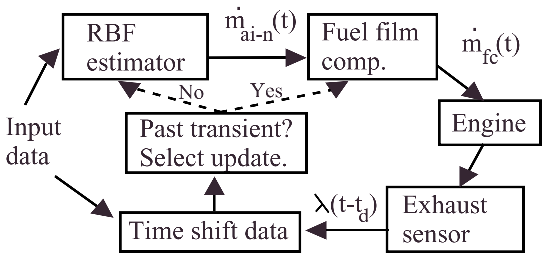

Figure 1: Block diagram of proposed control scheme.

The operation is described as follows. The RBF network is used in conjunction with a nominal mass of air flow measurement or calculation to estimate the mass of air flowing into the manifold for a given throttle angle and intake manifold pressure pair. This estimate is then divided by the estimate of stoichiometric air fuel ratio to predict the desired amount of fuel into the manifold. This value is then fed into a one-step-ahead controller using the current estimates of the fuel film parameters to determine the amount of fuel to inject, $\dot{m}_{fc}$, to deliver the desired amount of fuel. Once the resulting air fuel ratio becomes available (after a transport delay), it is used with the time shifted system states as a feedback term to update one of the estimates as follows:

- If the AFR corresponds to steady state operation it is used to update the RBF network estimate of mass of air flow into the intake manifold
- If transient operation is detected, and the air fuel ratio is outside a certain boundary of stoichiometry, it is assumed that the fuel film dynamics have been excited and the resulting linear UEGO sensor is used to update the estimate of fuel film parameters via a recursive least squares algorithm
- Otherwise update nothing – assume transient operation is good enough.

7. SIMULATION RESULTS

Simulation results were obtained from a mean value engine model described in Section 3. The simulation results were divided into separate areas to emphasize the effects of each part of the algorithm. The RBF network size was 100 nodes spread evenly throughout the $P_m - \alpha$ space. Only the weights were updated, and these were initialized to zero (assumes there is no initial error) and updated based on the feedback of the narrowband lambda sensor. A sampling interval of 0.01 seconds was used.

Simulation 1: In the first simulation it was considered that the fuel pooling effects were negligible – this is equivalent to assuming the fuel parameters are known exactly and compensated for. The true stoichiometric AFR and the estimated stoichiometric AFR were assumed to be the same, i.e. $\hat{\beta}_s = \beta_s = 15.45$. Errors were applied to the nominal airflow in the form:

$$\delta_i = 0.05 + 0.03\frac{\alpha}{90} + 0.03\frac{P_m}{P_{atm}} \tag{11}$$

A throttle change of 10 degrees over a period of 100ms every 2.5 seconds was then presented to the controller.

From the results shown in Figure 2 it is clear that the performance is initially poor (the error is >5%) due to the unmodelled error, but the network quickly learns and the AFR is maintained within the desired boundary. As explained earlier, the oscillations observed in AFR after 5 seconds are due to their being a time delay in obtaining the AFR feedback, and during this time the network overshoots the zero error point in its learning.

Simulation 2: In the next simulation, the same operating conditions were used but the estimate of stoichiometric AFR, $\hat{\beta}$, was wrongly assumed to be 15.65. The results for AFR using the same throttle scenario as in Simulation 1 are shown in Figure 3.

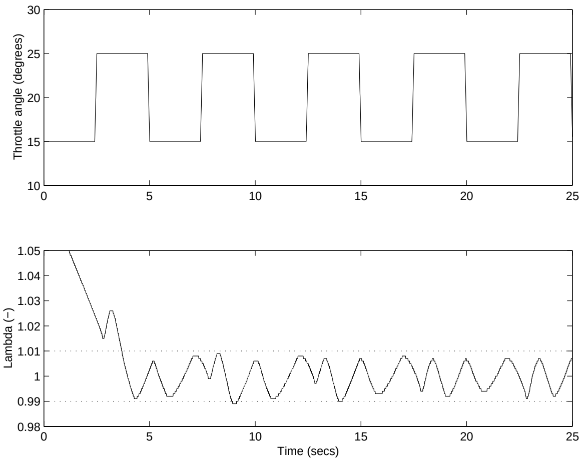

Figure 2: (Top) Throttle applied to simulated engine. (Bottom) Lambda observed for incorrect δ_i and 1% boundary on stoichiometry.

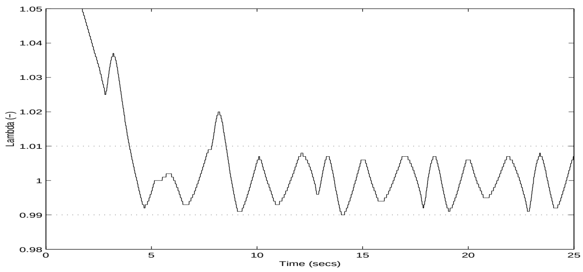

Figure 3: Lambda observed for incorrect $\hat{\beta}$ and δ_i with 1% boundary on stoichiometry.

Having an incorrect $\hat{\beta}_s$ is equivalent to having a larger constant parameter in δ_i, so the initial error is slightly larger. However the system learns at the same rate and the desired performance objectives are obtained within 10 seconds.

Simulation 3: The effects of including a fuel film in the simulations were now investigated. In this simulation the air system and stoichiometric AFR were assumed to be known, i.e. δ_i =0 and $\hat{\beta} = \beta = 15.45$. To demonstrate the effects of the fuel film on air fuel ratio, the first simulation demonstrates a 15 degree throttle change over a period of 100ms occurring every second. The 'true' fuel film parameters were assumed to be X =0.2 (about 25-30% of the value expected with petrol injection), and τ =0.05. Deviations in lambda in Figure 4 are observed up to almost 5%, which clearly indicates the need for some form of compensation.

Simulation 4: The RLS estimator was now used with initial estimates taken as $X(0)$ =0.28 (40% error) and $\tau(0)$ =0.04 (20% error). The resulting AFR trace is shown in Figure 5.

From this result a significantly improved performance compared to the previous case with no compensation is observed even with the initial 'bad' estimates of the parameters. This justifies the switching off of the RLS estimator and using the current estimates when the deviations are not too severe. In Figure 6 the convergence of the fuel parameters to their true values is shown.

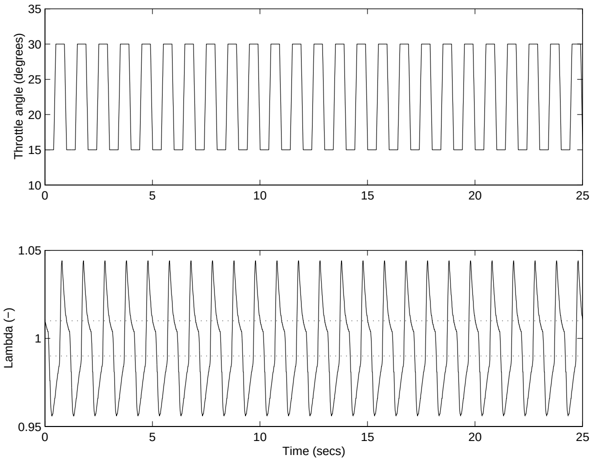

Figure 4: (Top) Throttle applied to simulated engine. (Bottom) Lambda observed for no transient compensation.

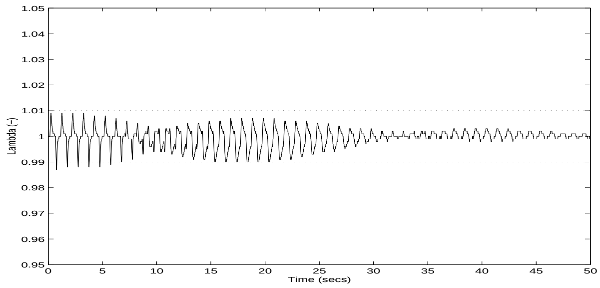

Figure 5: Lambda observed with transient compensation, but no steady state errors.

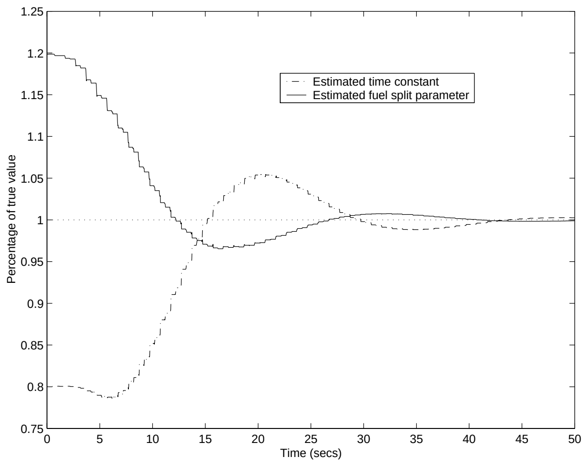

Figure 6: Convergence of fuel parameters.

Simulation 5: As a final simulation, all sources of error were considered at once. In this case the error on the mass airflow was taken to be $\delta_i = 0.05 + 0.03\dfrac{\alpha}{90} + 0.03\dfrac{P_m}{P_{atm}}$, $\hat{\beta}$ was estimated (wrongly) to be 15.65, and the fuel film parameters were initially estimated as before. A threshold of $\lambda = 1 \pm 0.004$ was applied to the RLS estimation. A throttle change of 10 degrees in 100ms every 5 seconds from 15 to 25 degrees was presented to the system and the resulting AFR is seen in Figure 7.

In this case convergence of the fuel parameters stops some way off their true values $X(120)$ =0.22, $\tau(120)$ =0.038, however this is still sufficient to maintain the AFR within desired limits even during the sharp throttle transients.

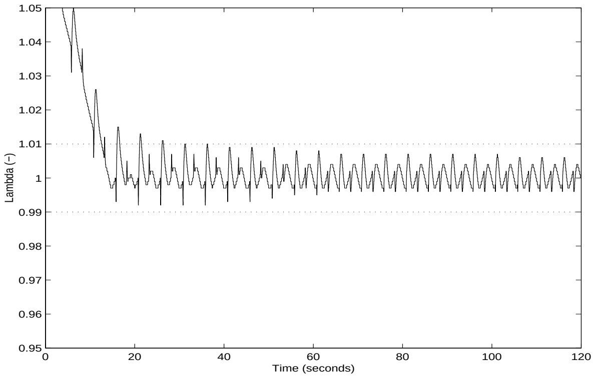

Figure 7: Lambda observed for errors considered on both fuel parameters and air system.

8. DISCUSSIONS

There are several possible limitations with the proposed scheme brought about by certain assumptions that have been made. Firstly uniform mixing and flow within the intake manifold has been assumed as a mean value model has been used. While uniform mixing of fuel and air can be facilitated by the use of multiple injections per engine cycle (instead of one long injection), there are no guarantees that equal air fuel mixtures will reach the different intake port. In this case it may be necessary to change the pulse width of the multiple pulses to attempt to normalize flows within the manifold.

Secondly the presence of a fuel film for LPG injection has been assumed. As a result, a wideband UEGO sensor has been used in the RLS algorithm. If it is found during experimentation that the fuel pooling effects are negligible, the wideband sensor is not necessary but the results from Simulations 1 and 2 using the RBF error estimator with the narrowband lambda sensor are still valid.

In Simulation 2 the stoichiometric AFR was estimated incorrectly and the RBF network was shown to correct for this source of error. However the correction is not complete until the RBF input (or engine operating point) enters all areas that are mapped. In light of this it is clearly preferable to have accurate knowledge of the true stoichiometric AFR, and methods to achieve this are currently under investigation.

In Simulations 4 and 5, the fuel film parameters were treated as constants and updated. As was discussed the true values of the parameters vary depending on engine operating point. The convergence of the RLS algorithm is too slow to treat the parameters as constant throughout the entire operating range of the engine so it is necessary to use a look up table approach, with the fuel parameters specified for a certain range of engine operating points. The parameters within those operating points can then be updated.

Engine results for a 4.0l, six cylinder, Ford AU engine are presently being obtained, and are necessary to completely validate the proposed approach.

9. CONCLUSIONS

A mean value engine model for LPG throttle body injected engines was presented to provide a basic platform for testing the validity of control algorithms under a variety of simulated conditions.

An adaptive control strategy using a RBF network to estimate the air system and a RLS algorithm to estimate the fuel film parameters has been proposed for stoichiometric AFR control in LPG throttle-body injected engines. This is the first adaptive control strategy applied to LPG injected engines. The proposed system is updated online and is capable of dealing with errors in the air system, fuel parameters and estimated stoichiometric air fuel ratio. Simulation results were presented to demonstrate the effectiveness of the scheme under the assumption of uniform mixing of the fuel and air in the intake manifold.

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