Sliding Mode Idle Speed Ignition Control Strategies for Automotive Engines

M S Srai[1], H Sindano[2], N E Gough[3] and A C Cole[4,1]

1.0 Introduction

In recent years it has become apparent that control system design based on conventional linear transfer function or state-variable feedback suffers from several serious disadvantages including:

i) It requires an accurate model, which cannot be attained by current identification procedures

ii) The control is not robust to unstructured uncertainties such as additive or multiplicative parameter variations

However, an alternative and potentially improved class of control systems involves sliding mode control, in which the actuating signal is changed in a jump-wise manner, depending on the position of the state-trajectory in state space.

Under certain conditions the state trajectory exhibits a stable high frequency sliding mode in which the state trajectory tracks a defined hyperplane towards the desired steady-state. Major advantages of the method over conventional linear controls are that

i) The trajectory may be constrained to be within certain regions of the state space, thus preventing expensive or dangerous transients that commonly arise in high-gain linear systems

ii) Actuation involves only a simple form of switching (on-off) control that is easily implemented using (say) a relay or stepper motor with locally-mounted integrated circuits

iii) Unlike many traditional controller designs, it takes into account the fact that in practice, control action is always finite

iv) The control is robust in the sense that the sliding mode is relatively insensitive to model inaccuracy or external disturbances [1]; thus it is applicable to cases where the system model is poorly defined or time-varying.

This affords the opportunity of simplifying the complex and uncertain time varying processes that occur within automotive engines and to develop new methods of controlling their performance.

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1.0 Ignition System Models

1: Technology Innovation Centre, University of Central England in Birmingham, UK
2: Sagem-Johnson Controls, Aston Science Park, Birmingham, UK.
3: School of Computing and Information Technology, University of Wolverhampton, UK
4: Technology Innovation Centre, University of Central England in Birmingham, UK

In an attempt to reduce complexity of the ignition control strategy, the ignition idle strategy is first investigated. For more complex systems [2], the intake airflow is also used to control idle speed resulting in the following state model of the system:

$$\begin{bmatrix} \Delta\dot{p}_m / p_{m0} \\ \Delta\dot{n}/ n_0 \end{bmatrix} = \begin{bmatrix} -(\partial f_1 / \partial p_m).p_{m0} / \tau_n \dot{m}_{a0} & -(\partial f_1 / \partial n).n_0 / \tau_n \dot{m}_{a0} \\ (\partial f_2 / \partial p_m).p_{m0} / \tau_J T_0 & (\partial f_2 / \partial n).n_0 / \tau_J T_0 \end{bmatrix} \begin{bmatrix} \Delta p_m / p_{m0} \\ \Delta n / n_0 \end{bmatrix} + \begin{bmatrix} 1/\tau_n \\ 0 \end{bmatrix} \Delta\dot{m}_a / \dot{m}_{a0} \tag{1}$$

Here p_m = manifold pressure, and n=engine speed are the states and m_a=intake air is the input controlling the idle speed system. Maps $f_1(n, p_m)$, $f_2(n, p_m)$ calculate airflow rate out of the manifold and combustion torque, *T*, respectively, and can be linearised at various operating points (denoted by suffix 0). With this model the state feedback controller can be designed as

$$\Delta\dot{m}_a / \dot{m}_{a0} = -[k_1 \quad k_2] \begin{bmatrix} \Delta p_m / p_{m0} \\ \Delta n / n_0 \end{bmatrix} \tag{2}$$

These gains can be determined by pole-placement, optimisation or using sliding mode control for a more robust solution in the face of uncertainties in the system model.

However, since the simpler models, particularly on motorcycles do not vary the air-intake the above model must be modified in terms of the combustion torque being controlled directly via the ignition advance angle θ as follows:

$$\begin{bmatrix} \Delta\dot{p}_m / p_{m0} \\ \Delta\dot{n}/ n_0 \end{bmatrix} = \begin{bmatrix} -(\partial f_1 / \partial p_m).p_{m0} / \tau_n \dot{m}_{a0} & -(\partial f_1 / \partial n).n_0 / \tau_n \dot{m}_{a0} \\ (\partial f_2 / \partial p_m).p_{m0} / \tau_J T_0 & (\partial f_2 / \partial n).n_0 / \tau_J T_0 \end{bmatrix} \begin{bmatrix} \Delta p_m / p_{m0} \\ \Delta n / n_0 \end{bmatrix} + \begin{bmatrix} 0 \\ f_0 \end{bmatrix} \Delta\theta / n_0 \tau_J T_0 \tag{3}$$

where $f_0(\theta) = \partial T / \partial \theta$.

A similar state-feedback control methodology can be proposed for the control of engine speed.

1.1 Companion Form Models

Monitoring the manifold pressure is expensive and also cannot be achieved without modification to hardware on simpler models. An alternative companion form model in which the engine speed and its derivatives are the state variables of interest can therefore be developed [3] in terms of the non-linear combustion torque as follows:

$$T = f(m_a, n, A/F) + g(m_a, n, \theta) \tag{4}$$

for which the ignition advance angle serves as input and the air fuel ratio A/F is a further source of uncertainty. The combustion torque is used to accelerate the engine after overcoming the load T_L, which can contain terms in rate of change of acceleration, or jerk, a determining factor for drivability. The torque equation may then be modelled as

$$J dn/dt + T_L(n, dn/dt, d^2n/dt^2) = f(m_a, n, A/F) + g(m_a, n, \theta) \tag{5}$$

A scenario in which, for example, the load is linearly related to acceleration and jerk can be described by

$$(J-L) dn/dt + I\, d^2n/dt^2 == f(m_a, n, A/F) + g(m_a, n, \theta) \tag{6}$$

with possible non-linear load dependency on n incorporated into f. In state form

$$\begin{bmatrix} \Delta \dot{n} \\ \Delta \ddot{n} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ (1/I)\partial f/\partial n & (L - J)/I \end{bmatrix} \begin{bmatrix} \Delta n \\ \Delta \dot{n} \end{bmatrix} + \begin{bmatrix} 0 \\ \partial g/\partial \theta \end{bmatrix} \Delta\theta / I \qquad (7)$$

This model is a controllable companion form having the advantage of needing to monitor only the engine speed being controlled and, (via processing), its derivative. As with all such Companion models it may suffer the disadvantage of ill conditioning, which could be further compounded by the division by I (possibly very small).

Instead of assuming that the cylinder air mass m_a and air fuel ratio A/F remain constant, any changes could be either modelled as an uncertainty or incorporated into a multi-input model as follows:

$$\begin{bmatrix} \Delta \dot{n} \\ \Delta \ddot{n} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ (1/I)\partial f/\partial n & (L - J)/I \end{bmatrix} \begin{bmatrix} \Delta n \\ \Delta \dot{n} \end{bmatrix} + (1/I) \begin{bmatrix} 0 & 0 & 0 \\ \partial g/\partial \theta & \partial g/\partial m_a & \partial g/\partial (A/F) \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta m_a \\ \Delta (A/F) \end{bmatrix} \qquad (8)$$

This representation could be problematic, however, due to the singularity of the input matrix, which can only be overcome by resorting to its generalised inverse in the design of a sliding mode control algorithm. Alternatively, the system may be decomposed into separate ignition, air-intake and AFR scalar decentralised sub-systems.

2.0 The Sliding Mode Control Algorithm

Sliding mode control systems possess all of the properties of high-gain feedback systems [4] and the control may be designed as a decentralized system in which the main actuation takes place at the local plants, but is coordinated by a central controller. The method is not restricted to linear systems.

2.1 Non-linear Implementation

Under the discontinuous sliding control

$$u = -Kx \qquad (9)$$

the state x of the system (*cf.* (5)-(7))

$$\dot{x} = f(x) + g(x,u) \qquad (10)$$

is constrained on the surface

$$s(x) = Cx = 0 \qquad (11)$$

The uncertainties in the state matrix can be written in additive form as

$$|\hat{f} - f| = F \qquad (12)$$

while uncertainties in the input matrix incorporated in multiplicative form as

$$B = (I + \Delta)\hat{B} \qquad (13)$$

where ^ indicates nominal values. The latter indicates that the uncertainties belong to the range space of the input matrix making the sliding mode immune to their effects. Then the control

$$u = -\hat{B}^{-1}(\hat{f} + k\,\mathrm{sgn}(s)) \qquad (14)$$

can be chosen where the sliding surface s is the difference between the state x and a desired trajectory. The switching gains *k* can always be found, are unique and non-negative [5]. If these gains are calibrated to be large enough then the effects of F and □ can be minimised or even completely eliminated. That is, variations in engine temperature or A/F ratio need not be monitored, merely their extremal values calculated. A desired trajectory may be specified as

$$s = c_1 (n - n_0) + c_2\, dn/dt = 0 \qquad (15)$$

in which n_0 is the desired idle speed and the coefficients determine the time constant of the idle speed response. The controller design (9)-(13) is equally applicable to the scalar or multivariable case. In the former, the effects of air intake and A/F ratio can be modelled as uncertainties, while for the latter, either or both are designated as control inputs.

2.2 A Scalar Sliding Mode Idle Speed Control Ignition Strategy

Here, the ignition advance angle will be modified to satisfy the engine idle speed requirements as part of an overall ignition timing strategy.

2.2.1 Normal Running

This is derived from inputs of engine speed, total intake area and engine temperature to base ignition advance and ignition engine temperature correction maps. Further corrections are provided for air intake temperature, ambient pressure, gear selected and fuel cut-off. However, normal running is mutually exclusive to idle running. Nevertheless, it may be possible to combine base ignition and idle advance maps, together with the corrections, into a single map with parameters having a wider variation which can be compensated for by sliding mode control.

2.2.2 Knock Advance

Base knock advance is dependent also via a mapping of engine speed and intake area but is controlled through the air intake temperature correction. Again, there is scope for combining maps and using air intake temperature as an additional control.

2.2.3 Cranking Advance

The above ignition advance strategies are disabled during cranking when advance angle is set independently.

2.2.4 Idle Speed Advance

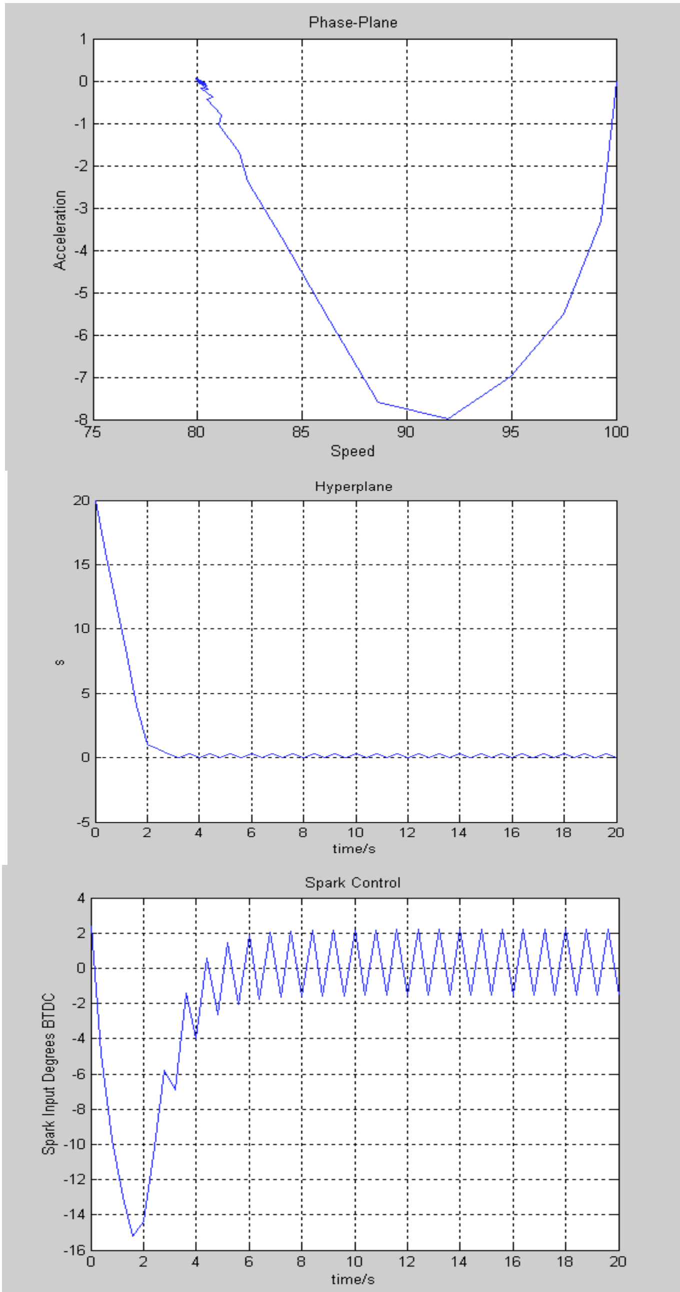
In each of these subsystems, the engine speed is seen to be the key state or feedback signal, whereas engine and/or intake air temperature plays a lesser role. A considerable simplification in the system model is affected by ignoring the latter (as a state). It is then anticipated that any inaccuracy incurred can be dealt with by calibration of a sufficiently large sliding mode gain. Moreover, the model obtained is more evidently consistent with the torque-based models (7) and (8).

The system (7) was simulated under the control (14) with the hyperplane $s=[c_1 \;\; c_2]=[1 \;\; 1]$, for extreme values of $\partial g / \partial \theta$, which may vary from –0.5 to +0.5 N/kg/m/rad.

These preliminary results are shown in figs.1 and 2 below, respectively, for nominal values of *I, J* and *L*.

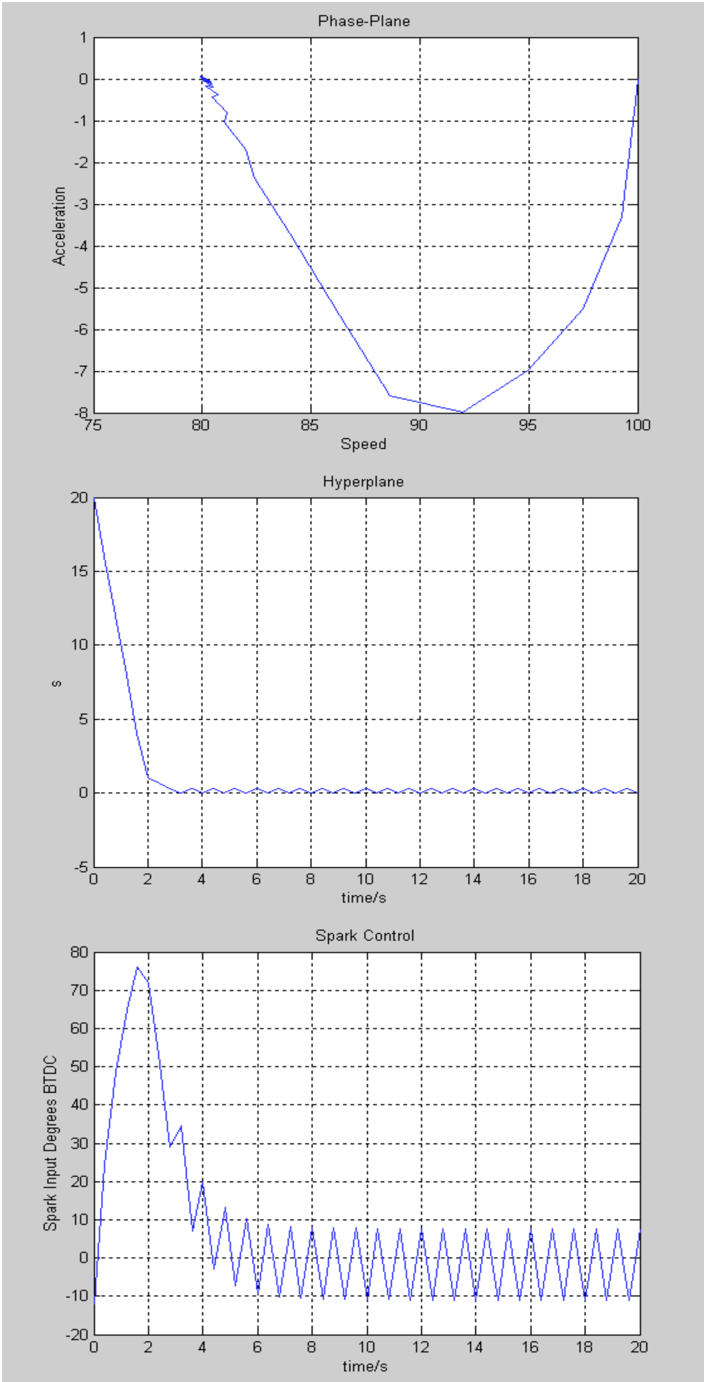
The form (13) of the input uncertainty ensures that there is a minimal effect on the system response due to immunity of the sliding mode control to parameter variations belonging to the range space of the input matrix [6]. In Figure 1, the response meets the hyperplane in finite time, while the spark advance varies by +/-1 degree to maintain the idle speed at 80 rad/s, from an intial value of 100 rad/s.

Figure 1: Extreme Variation in Input Matrix Parameters : Cylinder Full



These levels of switching gain are too high and not required for the lesser parameter variation simulated in Figure 2, below resulting in a higher variation in phase angle than is necessary. Variations (12) in the parameters of the system matrix have no discernible affect on the response for either simulation.

Figure 2: Cylinder Empty



3.0 Application of Sliding Mode Control to a Real Time Engine Model

The success of the theoretical simulation of the linearised off-line engine model motivates application to a public domain real-time model [3] of the SI engine.

The main problems anticipated with such an application are the large time constants and dead-times involved, especially at idle speed operating points and the variation of spark angle required in order to prevent operation in prohibited regions causing knock.

Both of these problems are a challenge for the sliding mode controller. The linearised engine model used therefore is a variation of (3), in which the air-charge m replaces the pressure p as the state, which represents the intake sub-system via $\Delta p=-(RT/V)\,\Delta m$ and speed n represents the output. The model thus becomes

$$\begin{bmatrix}\Delta\dot{m}\\ \Delta\dot{n}\end{bmatrix}=\begin{bmatrix}-300 & 0.5\\ 2700 & -10\end{bmatrix}\begin{bmatrix}\Delta m\\ \Delta n\end{bmatrix}+\begin{bmatrix}0\\ 5\end{bmatrix}\Delta\theta \qquad (16)$$

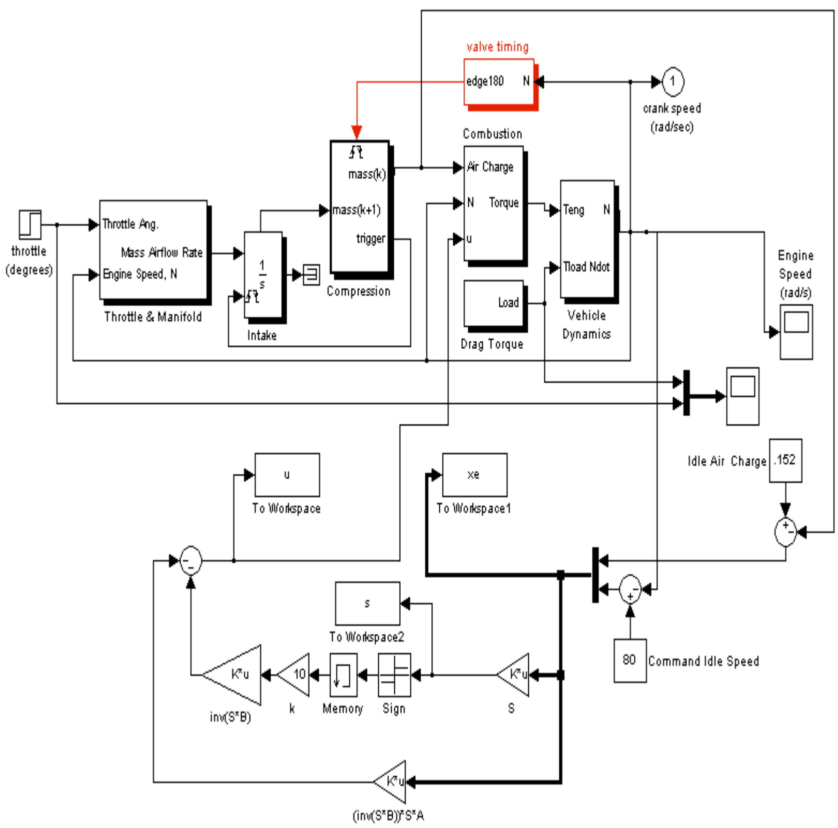
Due to the constraint of minimising the spark shift, an appropriate hyperplane can be defined to minimise the effect of Δm as

$$S=[9\ 1] \qquad (17)$$

The controller applied to the real-time engine model is depicted in Figure 3, below.

Figure 3

Sliding Mode Idle Speed Control Engine Model



Simulation results show stable behaviour for the given hyperplane, for which the solution converges as shown in Figure 4.

An idle speed within 1 rad/s of the command is reached and maintained despite the dead times involved. The system remains stable for applied load torques of up to 50 Nm, though high loads do affect the final speed attained.

Figure 5 shows how the sliding regime forces the error to the origin of the state-space.

Figure 4

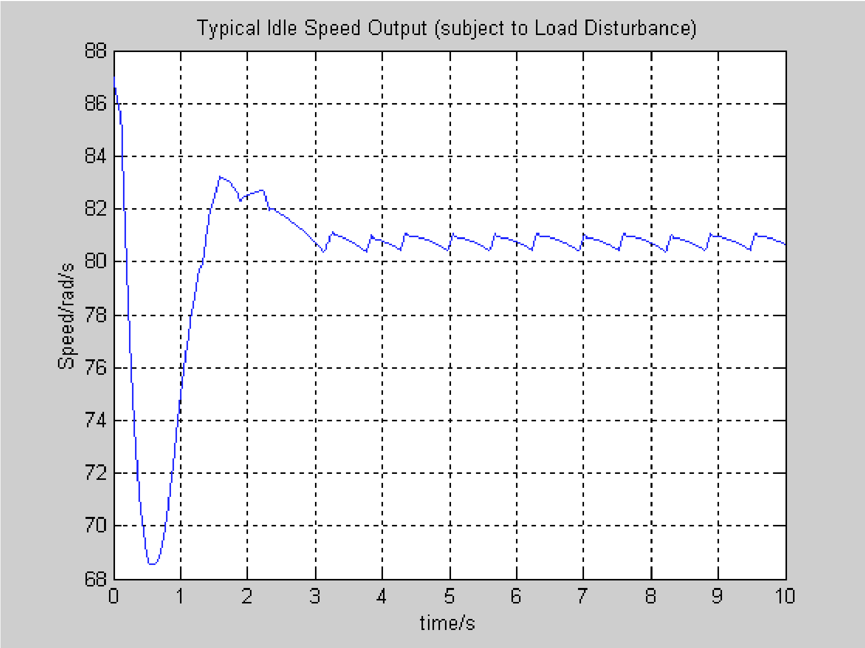
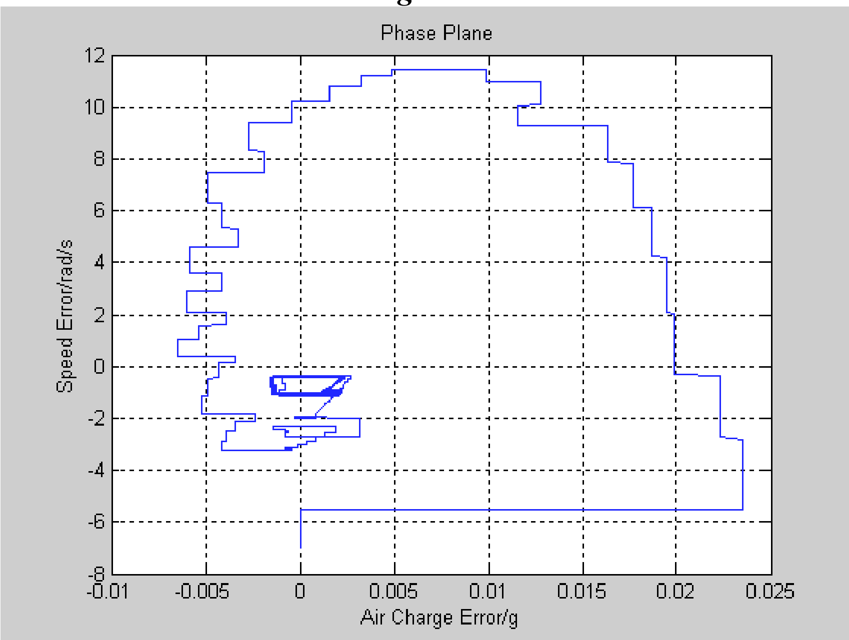
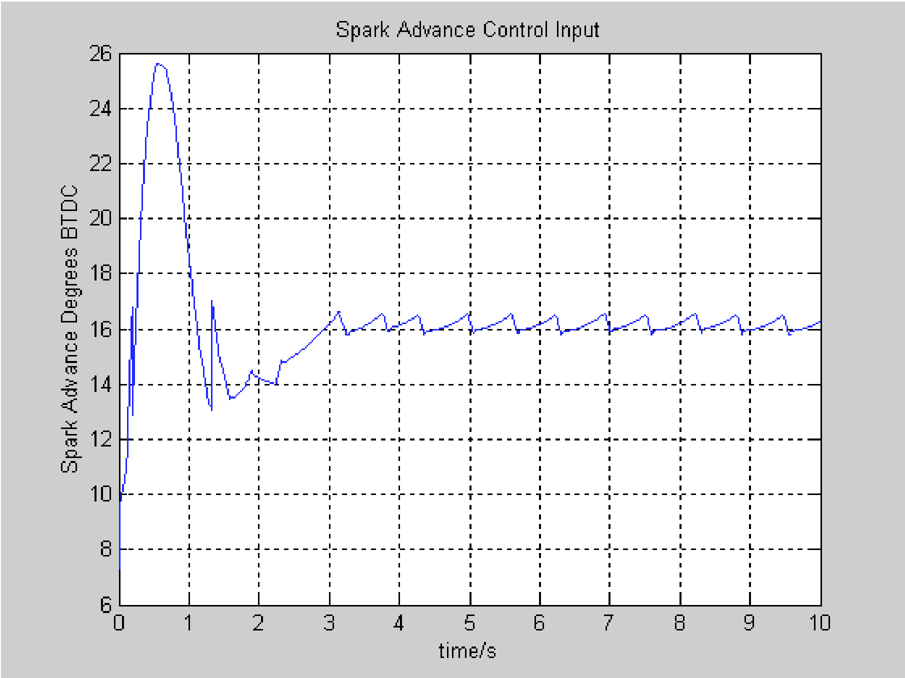


Figure 5



The constraint of minimising the spark shift is achieved as shown in Figure 6 where an initial advance of 15 degrees is shifted eventually by approximately 1 degree and a minimal switching (0.5 degrees) maintains the sliding mode. The initial large excursion, though still within limits of practicability may be reduced further by using a boundary value smoothing function [7], such as saturation instead of the sign function for switching control.

Figure 6



4.0 Conclusion

A sliding mode can be established for linearised engine models with spark advance inputs for various state-space representations.

This is a different problem from control using throttle input, where there is not such a restriction on input variations, which may cause the engine to knock.

Simulations have shown that idle speed may be regulated using the sliding mode algorithm but constraints on spark input must be observed by minimising the input variation.

This itself motivates the design of the permissible hyperplane. In particular, variations due to the troublesome intake sub-system can be designed out and variations due to speed itself can be minimised by implementing the sliding mode control only upon detection of idle operating conditions by the engine management system.

It remains to implement this strategy in real-time using hardware in the loop and to fine tune or smooth the control action using a boundary-layer saturation type non-linearity.

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