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MODELS AND CONTROL METHODOLOGIES FOR IC ENGINE IDLE SPEED CONTROL DESIGN

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Abstract: This paper surveys different internal combustion engine models and control design methodologies for the idle speed control (ISC) application. Linear engine models used for control system synthesis and analysis, as well as nonlinear models for computer simulation and control design validation, are discussed. The survey includes both classical designs, often seen in production, and those based on advanced control theory such as H_∞ and l_1 control. Over 50 papers are listed as references.

Keywords: Automotive control; idle speed control; engine model; LQG control; robust control; feedforward control.

1. INTRODUCTION

Idle Speed Control (ISC) represents one of the most generic and basic automotive control problems, and a typical challenge confronted by automotive control researchers and practitioners. On the average, vehicles consume about 30 percent of their fuel in city driving during idling (Jurgen, 1995), and it is expected that with increased traffic loads this percentage will further increase in the future. It is therefore important to optimize vehicle and powertrain operations at idle, especially with respect to often-conflicting requirements of improved fuel economy, reduced emissions, guaranteed combustion stability, and good noise, vibration and harshness (NVH) quality.

In general, the engine idle speed as measured in revolutions per minute (rpm) should be as low as possible for improved fuel economy. The rule of thumb is that every 100 rpm decrease in idle speed is approximately equivalent to one mile per gallon improvement in the Constant Volume Sample (CVS)-based fuel economy. However, these low vehicle speeds should not unduly compromise vehicle NVH, accessory (*e.g.*, alternator) performance, and engine combustion quality. For example, any possibility of engine stalling must be prevented under all operating conditions. In addition, the transition from/to idle speed should be smooth and well controlled.

The primary ISC goal is to maintain a desired engine speed or rpm despite the ever-present torque disturbances due to accessory loads such as air conditioning, power steering, and alternator, and due to engagements of the automatic transmission. Moreover, the control should be effective and robust for large production volumes of engines operating in different idle speed regimes (loads, temperatures), with different aging history, and being driven by different customers, for thousands of miles under vastly different environmental conditions.

The main input to the idle speed controller is the engine speed. Additional inputs may include throttle position, vehicle speed, various feedforward indicators of loads from automatic transmission, air conditioning, power steering and battery charging system, and other measurements such as engine coolant temperature and barometric pressure, reflecting the environmental operating condition. The main control output or actuation scheme is provided by controlling the amount of air supplied to the engine.

In most production implementations, the amount of air is controlled via a throttle bypass valve, which, as its name implies, steers the intake manifold air flow around the (closed) primary throttle plate. The bypass valve also provides additional air during starting, and serves as an electronic dashpot during sudden deceleration. This prevents stalling, and facilitates smooth transitions from higher engine rpms to idle speeds. In some production implementations, the bypass valve is supplemented with a number of additional solenoid valves, each triggered by a different accessory load signal (Probst, 1993). As an alternative to the bypass valve(s), it is possible to control the primary throttle directly (referred to as the electronic throttle control), via DC or stepper motors, instead of conventional mechanical linkages.

While the air control path can provide large control authority, its disadvantage is that it is relatively slow, due to the intake manifold dynamics and subsequent intake-to-power-related delays. A much faster actuation path is provided through spark control. Typically this is done by retarding a spark with respect to its maximum torque-production capabilities. To facilitate both torque decrease as well as increase, the spark is often *a priori* retarded by a certain nominal amount when entering the ISC mode. A disadvantage of spark control is its limited authority, since excessive retards can cause combustion instabilities, catalyst overheating and engine stalls. The amount of allowable spark change is also constrained by the limitation of the ignition coiling circuits. A third input, the air fuel ratio, is sometimes included in the ISC design as a control variable (Baumgartner, et al 1986). In most cases, however, the air-fuel ratio variable is reserved for emission control purposes, and not used for speed regulation. Thus, a good ISC design will judiciously use the complementary strengths of the air and spark control paths.

The ISC problem is well-suited for closed-loop control and can be a natural candidate for a benchmark example to assess different advanced control methodologies. The present paper surveys different ISC-oriented engine models, and the corresponding control techniques. These include designs based on classical methods most often seen in production vehicles, as well as different "modern" control alternatives such as LQ, H_∞, μ-synthesis, and l_1-optimization-based methodologies. The primary focus of the paper will be on work at Ford Motor Company. Relevant experience with different ISC models and control strategies will be summarized and, as appropriate, comparatively evaluated in terms of relative strengths and possible shortcomings. In addition, representative examples of work outside of Ford will also be briefly discussed.

2. ISC MODELS

With the possible exception of neural network and fuzzy-logic-based controllers, most control techniques used for the ISC design require models of the relevant plant dynamics. The main plant of interest for the ISC problem at hand is the engine itself. The present survey will be primarily focused on spark-ignition, four-stroke, internal combustion engines, operating around idle speed. The latter is characterized by low engine speeds (typically between 500 to 1,000 rpm), low to medium engine torque, and a closed primary throttle.

Some of the first engine models for ISC studies were developed by Powell (1979), Dobner (1980), Powell and Powers (1981) and Coats and Fruechte (1983), based in part on prior simple, albeit fundamental, models from Hazell and Flower (1971). Typically, the model development starts with a nonlinear description of (average) engine combustion torque dynamics. Such a model is derived by a mix of first-principle, physical laws, and identification techniques using empirically obtained dynamic step response and steady-state data for engine mass air flow (MAF) rate and torque as functions of rpm, throttle or bypass valve opening area, manifold (absolute) pressure (MAP), air-fuel ratio and spark (Powell and Cook, 1987; Powell, 1987).

An example of a typical nonlinear engine toque production model from Butts *et al.* (1995) is shown in Fig. 1. The model includes

- a nonlinear functional relation f_1 between the (average) steady-state flow rate $\dot{m}$ and the control input signal - the bypass valve duty cycle u_1;
- manifold filling dynamics resulting in a manifold average pressure P, assumed to be uniformly distributed throughout the manifold;
- torque production delay for the air and fuel variables;

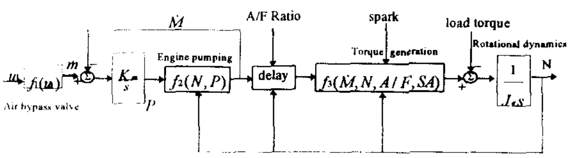

Fig. 1: Nonlinear engine model for idle speed control

- engine pumping effects in terms of the air charge from the intake manifold to cylinder - represented as a nonlinear function f_2 of engine speed N and manifold pressure P;
- torque production relation f_3 obtained by regressing steady-state dynamometer data as a function of cylinder air flow rate $\dot{M}$, engine speed N, air-fuel ratio A/F, and spark advance SA;
- engine rotational dynamics, which typically include flywheel and impeller inertia.

The model does not include exhaust gas recirculation (EGR) dynamics, since the EGR is not used at idle. Also, the fuel path wall wetting effects have been ignored, assuming that they will be appropriately compensated for through a separate transient fuel strategy. It is also assumed that the valve operates in the sonic flow region (a typical condition for low load operation), where the flow rate is independent of the pressure drop across the valve, and is only a function of the valve opening area.

A simple linear version of the above model can be easily obtained for the case of a constant A/F ratio (Sobolak, 1983; Takahashi *et al.*, 1985; Jackson, 1988; Mills, 1992). The corresponding model is shown in Fig. 2, with the data typical for a 5.0L V8 engine operating with a transmission in neutral and the air conditioning on (Mills, 1992). A very good correlation with experimental test data was obtained for a wide range of idle operating conditions, with dominant mode frequency varying from 2.15 to 4.1 rad/sec, and corresponding damping ratios from 0.27 to 0.46. Some tuning of the precalculated model parameters was needed (typically within 10-20%), due to underlying assumptions such as a linear model structure and a constant air-fuel ratio (Mills, 1992).

Further model simplifications are made possible by noting from Fig. 2 that the path from the bypass valve input u_1 to the engine output speed N appears as a second-order transfer function with an additional delay term. The second order dynamic is a result from two first-order dynamic elements: manifold filling dynamics and engine rotational dynamics. The pure delay term is due to the intake-to-combustion stroke delay, and is typically equivalent to 180 to 360 degrees of crank angle, with possibly even larger values for some fuel-injection schemes (Hrovat *et al.*, 1996). For the ISC problem, this delay should not be neglected, since it often constitutes the dominant dynamics of the resulting closed-loop system.

A discrete version of a linear model was used by Morris *et al.* (1981), as a basis for a "gray-box" approach to model development (Sans, 1988). More specifically, the model structure was established with the help of the underlying physics, and then the Landau model reference identification technique was applied to obtain the relevant parameters on an engine dynamometer. In addition, the authors changed the independent variable from time to crank angle. This reduced the variability of the model parameters with respect to engine speed, although in the case of the ISC, the engine speed changes should be, by intent, relatively small.

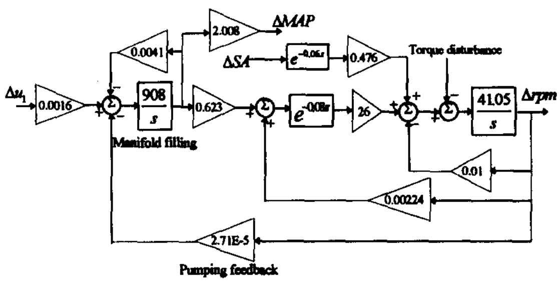

Fig. 2: Linear model of a 5.0L engine for constant A/F

Similar considerations apply for the spark-to-rpm path, except that the corresponding delay term is now smaller, and there is one additional zero. The resulting simplified model is shown in Fig. 3. It includes the torque load disturbance, which acts through a path similar to the spark advance, except for the absence of the delay term. This model structure was used in engine dynamometer tests by Williams *et al.* (1989) to establish relevant engine parameters. Parametric estimation techniques, particularly prediction error methods (Ljung, 1987), were found to give good model fits.

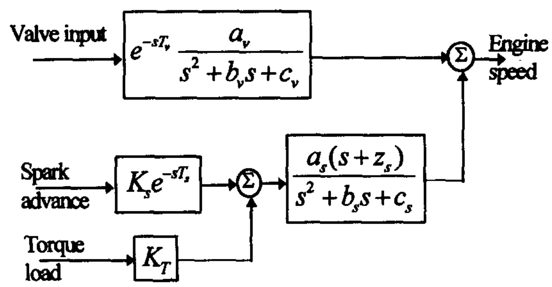

Fig. 3: Simplified "gray-box" model structure

The above ISC models include only engine breathing and torque production dynamics. These models can be expanded to explicitly include bypass valve (the actuator) and accessory load (disturbance) dynamics (Inoue and Washino, 1990). Further extensions may include engine-transmission block dynamics; vehicle body flexible effects; steering column shake vibration modes (Radcliffe *et al.,* 1983; Nishimura and Katsuyuki, 1986); and multirate sampling properties (Powell *et al.*, 1987). More sophisticated models, which incorporate the dynamics associated with engine cycle events and cylinder-to-cylinder variations, are used in the control system designs that are targeted at reducing the idle speed fluctuation due to the variability in individual cylinders (Shim, *et al.*, 1995; Connolly and Yagle, 1992).

3. CONTROL METHODOLOGIES

The complete ISC problem encompasses a number of different operational phases, such as transition from/to idle, target speed tracking, and regulation of a desired engine speed, which is the main ISC goal. The present section will primarily focus on the usage of different control techniques for the idle speed regulation.

As discussed before, the spark advance offers a faster control path, which is especially beneficial in containing the first engine speed drop, after a sudden engine load change (Powell and Powers, 1981). This can be seen in Fig. 4 which shows a comparison between simulation and actual vehicle data for the cases of no control (Morris and Powell, 1983), with intake air control (or throttle-only control, referred to on the plot) and a coordinated air bypass valve/spark control (throttle/spark control, as referred to on the plot). The addition of spark control reduces the rpm undershoot duration from approximately 2 seconds (40 combustion events) to only 1 second. The corresponding rpm undershoot magnitude is reduced to 100 rpm from the original 150-200 rpm.

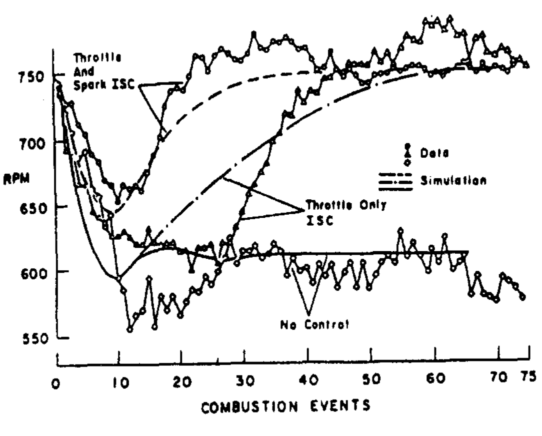

Fig. 4: Effects of spark on ISC performance

An additional insight was obtained through the root locus analysis (Morris *et al.*, 1982; Morris and Powell, 1983). The inner-loop, spark feedback of the engine speed error essentially leads to increased damping of the engine rotational mode, which in turn facilitates the use of higher control gains in the outer loop, the bypass valve path. The favorable properties of the spark feedback loop led to its usage in production.

A typical production ISC strategy includes a PID control for the air loop, a proportional feedback control for the spark loop, several feedforward controls using accessory load information, and other ad hoc compensation schemes for temperature, barometric pressure and other environmental conditions. Since the primary objective of the ISC system is to track a constant desired speed by manipulating the bypass valve, the PID control, especially the integral portion, is consider as the core of the ISC strategy. An effective way of tuning the idle speed PID controllers was provided *via* a sensitivity-guided design (Kokotovic and Rhode, 1986; Hrovat and Johnson, 1991). The control gain sensitivities were used to minimize a performance cost function based on engine speed errors. While this method used a fixed control structure, other optimization-based methods will be discussed next.

The LQ-based optimization was applied by a number of authors (Powell and Powers, 1981; Powers *et al.*, 1983; Morris and Powell, 1983; Takahashi *et al.*, 1985; Baumgartner *et al.*, 1986; Abate and DiNunzio, 1990; Fraser *et al.*, 1992). Powell and Powers (1981) used a five-state, continuous-time engine model to establish the potential benefits of added spark feedback. Abate and DiNunzio (1990) demonstrated through experimental implementation the superiority of an LQ-based controller over a more conventional, PID-based counterpart.

H_∞ methods were also applied as a natural extension of LQ (or H_2) techniques toward more robust control designs (Williams *et al.,* 1989; Carnevale and Moschetti, 1993). The method requires some trial-end-error adjustments of frequency weighting functions penalizing excessive actuator efforts, and system sensitivity terms. The resulting controller was reminiscent of a frequency-shaped PI controller for the bypass valve, and a PD controller for the spark. Through an experimental comparison, Carnevale and Moschetti (1993) developed an H_∞ controller which gave a slightly faster but noisier response than the corresponding LQ counterpart. Although the authors neglect the intake-to-combustion delay in the analysis, it is believed that the main trends and conclusions would still hold if this term were included.

While the H_∞ controller by Williams *et al.* (1989) resulted in improved robustness with respect to an "optimized" PID controller (Hrovat and Powers, 1990), it could not maintain stability for large engine model variations. To explicitly include these large plant perturbations or "uncertainties" Hrovat and Bodenheimer (1993) used the μ synthesis technique. The resulting controller is capable of containing two extremely different idle speed operation points. The corresponding closed-loop response to unit torque step disturbance is shown in Fig. 5 as full lines.

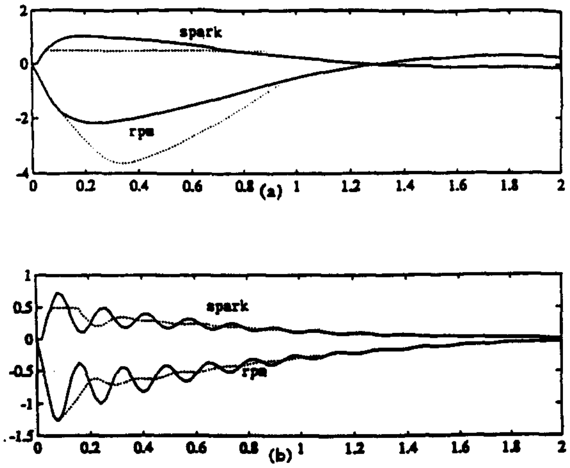

Fig. 5: ISC performance of μ-synthesized controller and model predictive control: (a) nominal; (b) perturbed plant.

However, the engine with the above μ-synthesized controller became unstable when hard constraints on the spark advance were introduced. To alleviate this problem, Hrovat and Zheng (1994) applied the Model Predictive Control (MPC) technique. While the unconstrained performance now deteriorated slightly, the constrained system was stable for both extreme operating conditions (Fig. 5, dotted lines).

Additional ISC improvements are made possible through the feedforward control of known or measurable disturbances, such as, for example, air conditioning or power steering loads. Powell and Powers (1981) performed one of the first studies demonstrating the potential benefits of the feedforward. Butts *et al.* (1995) addressed the question of optimal feedforward controls using the l_1 paradigm, where the ISC performance has been expressed directly in the time domain. Although the related computations are somewhat involved even for the SISO case, the approach provides a benchmark for the best possible ISC performance that can be achieved through feedforward compensation. It is also suggested that for practical implementation, a phase-lead compensation can be used to replace the l_1 feedforward control to achieve similar results.

Representative simulation results from (Butts *et al.*, 1995) are shown in Fig. 6. The benefits of feedforward and a faster actuator can be clearly seen. Substantial further improvements are possible with preview controls, which utilize the advance knowledge about a disturbance. For example, Fraser *et al.* (1992) and Hrovat (1995) have shown that only a few tenths of a second advance knowledge of a torque disturbance can lead to up to a tenfold reduction of the peak engine speed fluctuation. At the same time, spark usage and bypass valve bandwidth can be substantially reduced. Since most disturbances to an ISC system, such as the air conditioning, electrical fan, etc., are also controlled by the engine control module, such preview controls can be made possible by coordinating the engagement of certain accessory loads with the idle bypass valve.

Other approaches to the ISC design include robust design based on QFT (Jayasuriya and Franchek, 1994; Hamilton and Franchek, 1996), Kharitonov theorem (Olbort and Powell, 1989; Abate *et al.*, 1994), adaptive control (Mihelc and Citron, 1984), fuzzy logic (Abate and Dosio; 1990, Vachtsevanos, 1993), and nonlinear designs based on input-output linearization and sliding mode control (Kjergaard *et al.*, 1994). However, some of the work referred above ignores the intake-to-combustion delay. In addition, the neural-network-based approach was also investigated for the ISC design (Puskorius and Feldkamp, 1993; 1994; Gorinevsky and Feldkamp, 1995), where it is shown that substantial improvement over PID-based controls can be achieved with efficient training algorithms. Further improvements in the ISC performance are achieved by taking into account the alternator dynamics (Jackson, 1988; Kouadio *et al.*, 1996). In particular, the latter reference reports improved air-fuel ratio control, and prevention of engine stalling through a reversible alternator control.

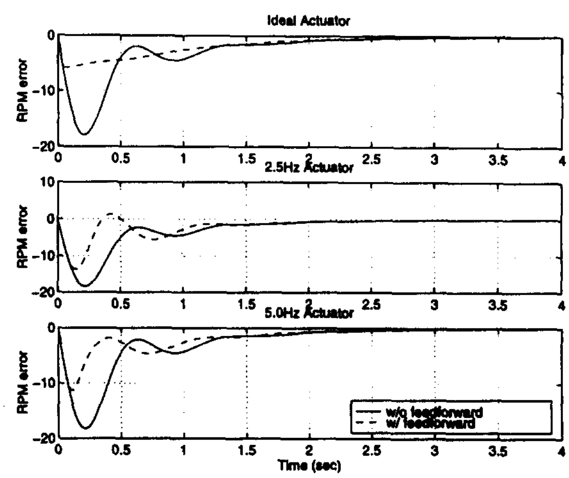

Fig. 6: ISC with l_1 feedforward control for different actuator bandwidths

All the design methods discussed above use the engine speed information for feedback. An ISC scheme which is based on engine torque regulation has also been proposed (Watanabe *et al.*, 1992). Instead of regulating the engine speed directly, this design put the emphasis on maintaining the engine torque to provide high idle quality. However, because engine torque is not a standard measured variable, such a scheme has to rely on an internal model to provide an estimate of engine torque on-line, and thus it leads to a more complicated strategy.

Another important aspect of engine idle speed control is to achieve smooth transition between idle speed and open throttle operations. In a typical ISC strategy, this transition is managed by a control scheme separated from the speed regulation function. There are two primary functions that the control scheme is designed for: one is to pre-position the bypass valve properly in the open throttle operation; another is to facilitate the speed transition from high engine speed to idle speed immediately after the closure of the primary throttle and before the speed regulator takes over the control.

Since the smooth transition has to be achieved for the entire range of engine operation, it is necessary to consider the more complicated nonlinear model for design and analysis purposes. Furthermore, unlike in the speed regulation case where the engine speed is usually sufficient to characterize the performance of a given control system, the performance during the transient is dictated by the NVH quality, derivability and other more subjective attributes. Therefore, it is more difficult to characterize the performance in terms of conventional control variables such as engine speed. The lack of a linear design model coupled with indirect performance measurements has made it difficult to apply well-developed control design methodologies to the ISC transition management. Consequently, far fewer results are reported in the open literature on the topic, and the subject matter is addressed mostly in an ad hoc fashion.

4. CONCLUDING REMARKS

Although most production ISC implementations are still rule-based with some classical, PID control flavor, the application of "modern" control techniques has contributed some useful guidance and insight, and has led to improved performance. This includes introduction of the spark intervention, sensitivity tuning, and robust, adaptive, feedforward and preview controls. A judicious application of these and similar concepts should lead to further improvements in ISC performance and robustness. Additional future work should address the potentials of fuel control, and a transition from/to the ISC mode.

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