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Electronic control of port-injected piston engines: air-fuel ratio models, delay limits and safety requirements

A literature-based review of air path and fuel-film models, feedforward-plus-feedback air-fuel ratio control, delay-limited bandwidth, sensor-failure detection and the regulatory requirements for electronic engine control.

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Abstract

Electronic engine control units (ECUs) of spark-ignition piston engines regulate fuelling, ignition and, where fitted, throttle from measurements of speed, manifold pressure, temperatures and exhaust oxygen. This paper reviews the physical models and control structures reported in the open literature for air-fuel ratio control of port-injected engines, and the regulatory text that frames the safety of electronic engine control in aviation. It derives the air path (orifice flow, manifold filling and speed-density estimation), the fuel-film model that causes transient mixture errors, and the feedforward-plus-feedback control structure with its delay-limited bandwidth. Worked examples with generic engine data show the air flow, fuel pulse width, transient lean excursion and altitude effect that a calibration must handle. The paper then summarises sensor-failure detection by analytical redundancy reported by a NASA programme and the requirements of 14 CFR 33.28 on failure analysis, control transitions, software and electrical power. The reviewed sources concern automotive and research engines and turbofan sensor validation; none reports flight data of a small unmanned-aircraft engine, and the transfer to such engines, in particular to two-stroke engines, is stated as an open question. The paper separates measured results, model results and regulatory requirements.

1. Introduction and scope

The task of an engine ECU in a spark-ignition engine is to meter the fuel that matches the air charge, to set the ignition timing, and to keep the engine inside its limits across changing ambient conditions and load. For a small aircraft the dominant ambient change is altitude, which alters air density and hence the air mass per cycle. In port-fuel-injected engines the stoichiometric fuel is typically obtained by a combination of feedforward and feedback control on the injection: the feedforward fuel is derived from the estimated cylinder air charge divided by the stoichiometric air-fuel ratio, and feedback from an exhaust-gas oxygen sensor trims it [4].

This paper treats port-fuel-injected spark-ignition engines and the control functions of air-fuel ratio, together with the safety framework for electronic engine control. It does not treat compression-ignition engines, turbine engines (except as a source of sensor-validation methods), ignition and knock control, nor the electrical and software design of a specific controller. The air-path and fuel-path models cited are from research on four-stroke automotive engines; their application to two-stroke engines, which have a different charging process, is not established by the sources reviewed. For a general introduction to the category see the site’s ECU guide.

2. Theory and governing equations

2.1 Air path

Throttle flow. The flow through the throttle is modelled as compressible flow through an orifice [3]. For an upstream pressure p_0 (Pa), temperature T (K), effective flow area A_T (m²), discharge coefficient C_D (dimensionless), gas constant R (J/(kg·K)), specific-heat ratio γ (dimensionless) and downstream pressure p_T (Pa), the choked flow is

$$\dot{m}_c = C_D A_T \frac{p_0}{\sqrt{RT}} \sqrt{\gamma} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

and the unchoked flow is

$$\dot{m}_{nc} = C_D A_T \frac{p_0}{\sqrt{RT}} \left(\frac{p_T}{p_0} \right)^{1/\gamma} \sqrt{\frac{2\gamma}{\gamma-1} \left[1 - \left(\frac{p_T}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right]}$$

where $\dot{m}$ is the mass flow rate (kg/s) [3]. Flow is choked when p_T/p_0 falls below the critical ratio $[2/(\gamma+1)]^{\gamma/(\gamma-1)}$, which is 0.528 for $\gamma = 1.4$ (calculated here).

Worked example (generic). For $C_D = 0.8$, $A_T = 2.0 \times 10^{-4}$ m², $p_0 = 101{,}325$ Pa, $T = 288.15$ K, $R = 287$ J/(kg·K), $\gamma = 1.4$: the choked flow is 0.0386 kg/s; at a pressure ratio of 0.8 the flow is 0.0316 kg/s (calculated here). The throttle can therefore pass more air than the engine consumes in the speed-density example below (0.019 kg/s), and the manifold pressure settles where the throttle flow equals the engine flow.

Manifold filling. Mean value engine models describe the dynamics of crankshaft speed, manifold pressure and air-fuel ratio over time scales long compared with the engine cycle, without describing the intake, exhaust and combustion processes explicitly [3]. The intake manifold acts as a pneumatic capacity; in the electrical analogy of [3], pressure corresponds to voltage and mass flow to current. With an ideal gas in a manifold of volume V_m (m³) at temperature T_m (K),

$$\frac{dp_m}{dt} = \frac{R\,T_m}{V_m} \left(\dot{m}_{th} - \dot{m}_{cyl} \right)$$

where p_m is the manifold pressure (Pa), $\dot{m}_{th}$ the throttle flow and $\dot{m}_{cyl}$ the flow into the cylinders (kg/s). This is the mass balance of an isothermal capacity (derived here; the sources describe the same capacity analogy).

Speed-density estimation. The air flow into the cylinders is estimated from measured manifold pressure and speed as

$$\dot{m}_{cyl} = \eta_v \frac{p_m}{R\,T_m} V_d \frac{N}{60\,n_r}$$

where η_v is the volumetric efficiency (dimensionless), V_d the displacement (m³), N the engine speed (rpm) and n_r the number of crankshaft revolutions per cycle (2 for a four-stroke engine, 1 for a two-stroke engine). The volumetric efficiency is one of the quantities that cannot be measured directly and is identified from tests [3]. In a model-based

controller the air charge is computed within each cycle by a dynamic model of the manifold and not read from a look-up table [6].

Worked example (generic). A four-stroke engine of $V_d = 0.5$ L at $N = 6{,}000$ rpm, $p_m = 80$ kPa, $T_m = 310$ K and assumed $\eta_v = 0.85$ has an air density of $80{,}000/(287 \times 310) = 0.899$ kg/m³ and a flow $\dot{m}_{cyl} = 0.85 \times 0.899 \times 0.5 \times 10^{-3} \times 6000/(60 \times 2) = 0.0191$ kg/s, that is 3.82×10^{-4} kg of air per cycle (calculated here).

2.2 Fuel path

Stoichiometric fuel. The stoichiometric air-fuel ratio of a gasoline-ethanol blend is $AFR_s = 9\,e_m + 14.6\,(1 - e_m)$, with e_m the ethanol mass fraction [4]; for gasoline, $AFR_s = 14.6$. The relative air-fuel ratio is $\lambda = AFR / AFR_s$ (dimensionless). The base fuel mass per cycle is the air mass per cycle divided by AFR_s.

Worked example (continued). The air mass of 3.82×10^{-4} kg per cycle requires $3.82 \times 10^{-4}/14.6 = 26.2$ mg of fuel per cycle, a fuel flow of 1.31 g/s (4.7 kg/h) at 50 cycles per second (calculated here). With an assumed injector static flow of 3.0 g/s, the pulse width is $26.2/3000$ s ≈ 8.7 ms, which is 44 % of the 20 ms cycle.

Fuel film. In port injection a part of the injected fuel is deposited on the port walls and the back of the intake valve and enters the cylinder later; this causes a divergence between the injected and the inducted fuel, and the fuel dynamics are slower than the air dynamics [6]. The first-order model of Aquino describes the film with two parameters [6]:

$$\frac{df}{dt} = x\,\frac{i}{T} - \frac{f}{\tau}, \qquad \frac{c}{T} = (1 - x)\,\frac{i}{T} + \frac{f}{\tau}$$

where f is the film mass (kg), i the injected mass per cycle (kg), c the mass inducted per cycle (kg), T the engine period (s), x the fraction of the injected fuel that enters the film (dimensionless) and τ the time constant of the fuel leaving the film (s) [6]. In transfer-function form for a step in injected fuel, the delivered fuel follows $WW(s) = [1 + (1 - x)\tau s]/(\tau s + 1)$ [5], so that a fraction $1 - x$ arrives at once and the remainder with the time constant τ.

Worked example (transient). At steady state $df/dt = 0$ gives $f = x\,i_0\tau/T$, so the film releases $x\,i_0$ per cycle. If the load steps up so that the injected fuel rises from i_0 to $i_1 = 1.5\,i_0$ (fuel sized for the new air charge), the first cycle after the step delivers $c_1 = (1 - x)\,i_1 + x\,i_0$, that is $c_1/i_1 = (1 - x) + x\,i_0/i_1$. With $x = 0.30$ (a reference value reported in [6] for wall temperatures of 72–85 °C) this ratio is $0.70 + 0.30/1.5 = 0.90$, a mixture 10 % lean ($\lambda = 1/0.9 = 1.11$) in the first cycle, relaxing toward $\lambda = 1$ with time constant τ (calculated here). The reference film parameters in [6] ranged from $x = 0.33$, $\tau = 0.51$ at 54 °C to $x = 0.30$, $\tau = 0.39$ at 85 °C (units of τ as in the source), consistent with the report that the film is more stable at higher temperature.

2.3 Control structure and delay

A conventional structure combines a feedforward base fuel $F_b = \hat{A}\,(F/A)_d$ computed from the estimated air charge $\hat{A}$ and the desired fuel-air ratio $(F/A)_d$, with a multiplicative proportional-integral correction C, so that the commanded fuel is $u = (1 + C)F_b$ [5]. The multiplicative form scales the feedback fuel with the base fuel, which improves compensation during transients when the operating point changes [5]. The feedback signal is the relative air-fuel ratio measured by an exhaust-gas oxygen sensor, compared with the desired $\lambda = 1$ [4].

The total delay is the sum of the time from the injection calculation to the formation of exhaust gas and the time for the exhaust gas to reach the sensor; the sensor is modelled as a first-order lag in series with a pure delay, $S(s) = Ke^{-\delta s}/(\tau_u s + 1)$, and the delay is a key factor limiting the bandwidth of the air-fuel ratio feedback loop [5]. A pure delay δ adds a phase lag $\omega\delta$ (rad) at angular frequency ω (rad/s). If the phase lag from the delay alone is to stay below $\pi/4$ at the crossover frequency, then $\omega_c \le \pi/(4\delta)$; for an assumed $\delta = 0.1$ s this gives $\omega_c \le 7.9$ rad/s (1.25 Hz) (calculated here). Faster mixture corrections must therefore come from the feedforward path, which depends on the quality of the air-charge estimate and of the film compensation; the reviewed sources list inaccuracies of these two models and ageing of the oxygen sensor as the main sources of plant uncertainty [5].

2.4 Altitude

At constant composition the air mass per cycle is proportional to air density. In the International Standard Atmosphere, the density at 3,000 m is 0.742 of the sea-level value (calculated here from the standard temperature lapse rate). An engine whose fuel is not compensated for density, at wide-open throttle at 3,000 m, would therefore operate with the air-fuel ratio of the sea-level calibration scaled by 0.742: $AFR \approx 14.6 \times 0.742 = 10.8$, that is $\lambda = 0.74$ (rich), in the absence of feedback. A speed-density estimate based on measured pressure and temperature, as in Section 2.1, corrects the base fuel for density; feedback from the oxygen sensor corrects the residual error.

3. Design and calibration methods

3.1 Model-based versus map-based fuel control

Conventional controllers use stored maps of the fuel-film parameters, which have limited accuracy especially in transients; adaptive and model-based alternatives replace the maps with an engine model that runs on the ECU [6]. Cipollone et al. identified the two film parameters online from the injected and inducted fuel mass of two successive cycles, using an air-dynamics model for the inducted air, and validated the procedure on a single-cylinder research engine with port injection by comparing the identified values with reference values mapped for that engine [6]. They report that the parameter x agreed satisfactorily with the reference values, that τ varied much more at low engine speed, and that

τ became more stable at higher speed [6]. The result is a model-to-reference comparison on a single research engine under part-load throttle ramps.

3.2 Adaptive control of the delayed loop

Yildiz et al. considered two adaptive designs for the inner loop, one with feedforward adaptation and one adding feedback adaptation by an adaptive Posicast controller, which is an adaptive counterpart of the Smith predictor, and compared them with a baseline feedforward-plus-PI controller in simulation and in vehicle experiments [5]. The design problem they state is the combination of a variable time delay, uncertain plant behaviour and disturbances such as air-charge estimation errors [5]. The abstract and introduction do not give numerical performance gains, so none are cited here.

3.3 Fuel models for different fuels

The fuel-film behaviour depends on the fuel. Ahn et al. proposed a physics-based puddle model for gasoline-ethanol blends, with a droplet-evaporation model run off-line to generate the wall-impacting factors and a cycle-based single-puddle model that can run on-line, and formulated a transient fuel compensator from it; the validation is against limited experimental data [4]. The relevance to small-engine controllers is that a calibration made for one fuel needs verification when the fuel changes [4].

3.4 Engine models for control design

Mean value engine models are widely used for control because of their flexibility, performance and low computing cost; they represent the overall result of intake, exhaust and combustion without describing them explicitly [3]. Palma et al. built a multi-cylinder model by analogy with electrical circuits and compared mean outputs (pressure, temperature, mass flow, torque) with measurements at 1,500 and 5,500 rpm at wide-open throttle on a four-stroke automotive engine; the paper reports the comparison graphically and notes that the approximation underlying the electrical analogy is less accurate at the higher speed [3]. No numerical error values are available from the extracted text.

4. Parameters and typical ranges

Parameter	Reported value or range	Type	Source
Stoichiometric air-fuel ratio, gasoline / ethanol	14.6 / 9	Model constant	[4]
Fraction of injected fuel entering the film, x	0.30–0.33 (wall temperature 54–85 °C)	Reference values mapped for a research engine	[6]
Film time constant, τ	0.39–0.51 (same conditions; unit as in source)	Reference values mapped for a research engine	[6]
Film mass in a cold engine (coolant 30 °C) relative to a hot engine (80 °C)	about 4 times	Reported in literature cited by [6]	[6]
Port-injection supply pressure	2.5–3.0 bar	Typical value stated	[6]
Choked-flow critical pressure ratio ($\gamma = 1.4$)	0.528	Calculated	Section 2.1
Relative air density at 3,000 m (ISA)	0.742	Calculated	Section 2.4
Delay-limited crossover frequency for 45° delay lag, $\delta = 0.1$ s	7.9 rad/s	Calculated	Section 2.3
Sensor failure modes simulated in a test programme	scale-factor change, bias, drift, noise	Test method	[2]
Hard / soft sensor failure	out-of-range or large instantaneous bias / small bias or slowly accumulating drift	Definition	[2]

5. Failure modes, testing and qualification

5.1 Sensor failures and analytical redundancy

A NASA programme on turbofan engine control reports that engine sensors are the least reliable of the control-system components and that some type of sensor redundancy is required to achieve adequate control-system reliability [2]. One type is analytical redundancy, in which a mathematical model generates redundant information that is compared with measurements to detect failures [2]. The algorithm described has three elements: hard-failure detection and isolation, soft-failure detection and isolation, and an accommodation filter. Hard failures are defined as out-of-range or large bias errors that occur in-

stantaneously in the sensed values; soft failures are small bias errors or drift errors that accumulate relatively slowly with time [2]. The test bed simulated four sensor failure modes: scale-factor change, bias, drift and noise [2]. The performance of the accommodation filter and of the detection logic depends strongly on the model of the engine, and detection thresholds were initially based on standard deviations of the residuals [2]. The report describes the algorithm on a full-scale turbofan engine with a multi-processor controller; the relevance to piston engines is the principle that the air-charge and fuel models of Section 2 can serve as analytical redundancy for a manifold-pressure or oxygen sensor, which the sources reviewed do not demonstrate.

5.2 Regulatory requirements for engine control systems

Title 14 CFR § 33.28 applies to any system or device that is part of the engine type design, controls, limits or monitors engine operation and is necessary for continued airworthiness of the engine [1]. Its main requirements are:

- **Function and limits** (b): substantiation by test, analysis or both that the control keeps the engine within approved operating limits over changing atmospheric conditions in the declared envelope, allows modulation of power with adequate sensitivity and does not create unacceptable oscillations; the system functionality must not be adversely affected by declared environmental conditions, including electromagnetic interference, high-intensity radiated fields and lightning [1].
- **Control transitions** (c): when a fault changes the control mode, the channel or the system, the engine must not exceed limits or experience unacceptable power changes, and a means must alert the crew where required [1].
- **Failures** (d)–(e): the rate of loss of thrust or power control events must be consistent with the safety objective of the application; in the full-up configuration the system must be single-fault tolerant for electrical and electronic failures with respect to those events; single failures must not result in a hazardous engine effect; and a system safety assessment must identify the faults and their predicted frequency [1].
- **Protection** (f): electronic overspeed protection must include a means of testing at least once per start/stop cycle [1].
- **Software and programmable logic** (g), (m): software and programmable logic devices must be developed by a method approved by the authority, consistent with the criticality of the function [1].
- **Aircraft-supplied data and electrical power** (h)–(i): single failures leading to loss or corruption of aircraft-supplied data must not result in a hazardous engine effect and must be detected and accommodated; loss, malfunction or interruption of aircraft-supplied electrical power must not cause a hazardous effect; the need for aircraft power and its voltage limits must be declared; and the system must resume normal operation when power returns to the declared limits [1].
- **Air pressure signals and shutdown** (j), (l): blockage or leakage of signal lines must be considered in the safety assessment, and means must be provided for shutting down the engine rapidly [1].

The regulation applies to engines certified under its part; whether a given small unmanned-aircraft engine falls under it, under another certification basis or under none depends on the applicable authority and category, which was not reviewed. The requirements are nevertheless a precise statement of the failure behaviour expected of an electronic engine control in aviation, and the design questions they raise are independent of the engine size.

5.3 Testing evidence

The sources reviewed show the following kinds of evidence: dynamic test-bench tests of a single-cylinder engine with fast air-fuel analysis and wide-band oxygen measurement [6]; in-vehicle experiments of control algorithms [5]; comparison of model outputs with measurements at two operating points [3]; and failure-injection tests with a simulator of sensor failure modes and a real-time engine simulation [2]. The regulation requires substantiation of the control functions by test, analysis or both [1]. None of the sources defines a calibration or test procedure for a small unmanned-aircraft engine.

6. Open problems and limitations

1. **Engine type.** The air-path and fuel-film models reviewed come from four-stroke automotive and research engines [3][5][6]. Two-stroke engines have scavenging and trapping effects not represented in the mean value models cited; the open literature accessible for this review does not report validated ECU models for them.
2. **Parameter variability.** The film time constant τ varies strongly at low speed and with temperature, and was identified with satisfactory agreement for x but not for τ in the single-engine study [6].
3. **Delay-limited feedback.** Feedback bandwidth is bounded by the delay from injection to sensor [5], so the quality of transient control depends on the feedforward models; their uncertainty is not quantified in the sources for small engines.
4. **Sensor-failure methods.** Analytical redundancy has been demonstrated on a turbofan engine with a multi-processor controller [2]; implementations for low-cost piston-engine controllers are not reported in the sources reviewed.
5. **Regulatory transfer.** The reviewed regulation is written for certified engines [1]; the applicable safety objective and means of compliance for engines of unmanned aircraft depend on the certification basis, which is not covered here.
6. **Altitude and fuel effects.** The altitude example uses standard-atmosphere relations and ignores temperature, humidity and exhaust-restriction effects; fuel composition affects the stoichiometric ratio and the film [4].

7. Conclusions

- The air flow of a port-injected engine can be computed from manifold pressure, temperature and speed by a speed-density relation, with throttle flow modelled as compressible orifice flow with a critical pressure ratio of 0.528 for $\gamma = 1.4$ [3]; for a generic 0.5 L engine at 6,000 rpm this gives about 0.019 kg/s of air and 26 mg of fuel per cycle (calculated).
- Fuel deposited in the port wall film produces transient mixture errors; with a film fraction of 0.30, a 50 % step in load produces a first-cycle lean excursion of about 10 % (calculated from the model of [6]).
- Feedback from the exhaust oxygen sensor is limited in bandwidth by the delay between injection and sensing [5]; for a 0.1 s delay the crossover frequency is bounded by about 1.25 Hz for a 45° delay lag (calculated), so transient accuracy relies on feedforward models.
- Without density compensation, a sea-level fuel calibration at 3,000 m in the standard atmosphere would produce $\lambda \approx 0.74$ (calculated); speed-density estimation with oxygen-sensor trim addresses this.
- Sensor failures can be detected and accommodated by analytical redundancy, whose performance depends strongly on the engine model [2].
- 14 CFR 33.28 states the failure, transition, software, protection and power-supply behaviour required of an electronic engine control in aviation [1]; no source reviewed provides validated models, test procedures or flight data for small unmanned-aircraft engines.

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