The Idle Speed Control Test Case

A Simulink ©/Stateflow © implementation for the open-loop hybrid model of a 4-cylinder-in-line automotive engine in idle regime.

Andrea Balluchi [1], Luca Benvenuti [1], Tiziano Villa [1], Alberto L. Sangiovanni-Vincentelli [1, 2], Marco Zoncu [1].

[1] PARADES E.E.I.G., Rome, Italy.
[2] Dept. of EECS, University of California, Berkeley CA.

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The Idle Speed Control Problem

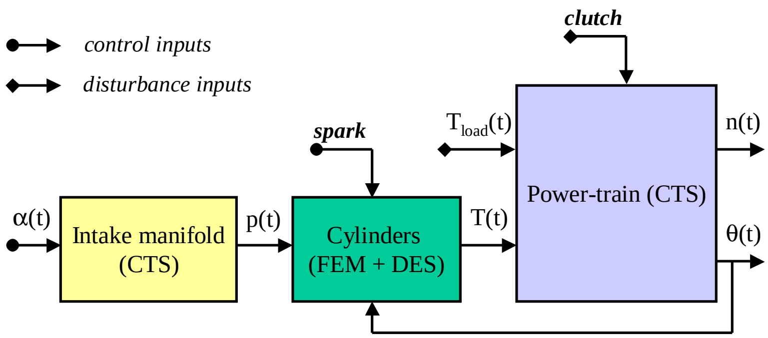
specifications:

- Maintaining the crankshaft speed within a specified range despite load torque disturbances and transmission engagements/disengagements.

constraints:

- Good combustion and emission quality;
- Acceptable NVH characteristics.

Hybrid model of the engine



Continuous dynamics

Intake manifold dynamics (linear approximation):

$$\dot{p}(t) = a_p p(t) + b_p \alpha(t)$$

Power-train dynamics:

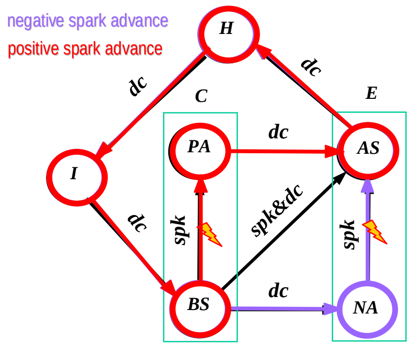
$$\dot{n}(t) = a_n n(t) + b_n (T(t) - T_L(t))$$

$$\dot{\theta}(t) = 6n(t), \quad \text{if } \theta = 180 \text{ then } \theta := 0$$

$$a_n = -Bb_n$$

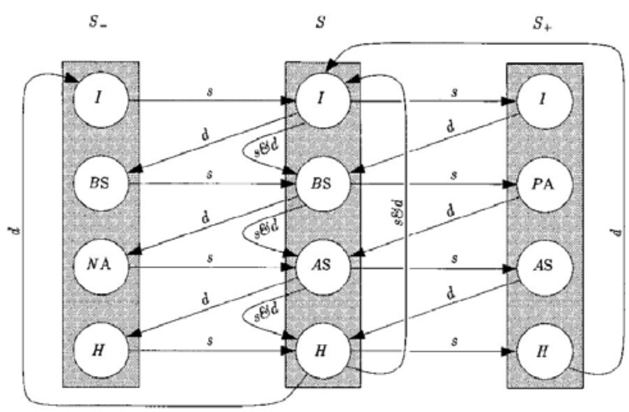
$$b_n = \begin{cases} 1/J & \textit{(clutch pressed)} \\ 1/(J+J') & \textit{(clutch released)} \end{cases}$$

Single cylinder FSM

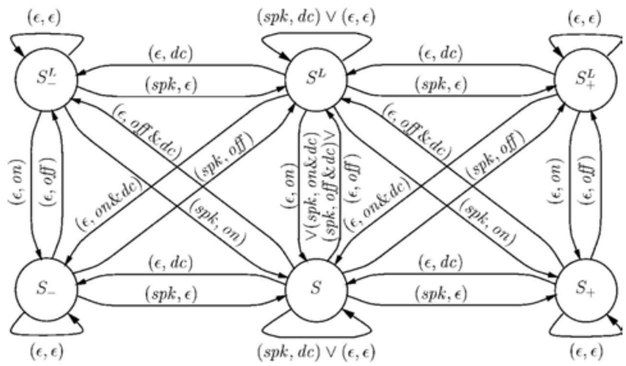


I to BS	$m := G_{mp}p + M_0$
BS to PA	$\varphi := 180 - \theta$
PA to AS	$T := T_{pot}(m)\ \eta_c(\varphi - \varphi_{opt}, m) = T_{gen}(m, \varphi)$
NA to AS	$\varphi := -\theta$ $T := T_{gen}(m, -\theta)$
AS to H	$T := 0$

4-cylinder-in-line FSM



Reduced Finite State Machine



FSM & DES transition maps

FSM reset map +
DES transition function

q	$(spk, clutch)$	$\delta\|_X$	$\delta\|_{\mathbb{R}}$
S	(ϵ, off)		
	(ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_E := m_C,\ m_C := G_{mp}p + M_0,\ T := 0$
	(spk,ϵ) (spk, off)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, off\&dc)$	$\theta := 0$	$m_C := G_{mp}p + M_0,\ T := (Gm_C + T_0)\eta(0)$
S^L	(ϵ, on)		
	(ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_E := m_C,\ m_C := G_{mp}p + M_0,\ T := 0$
	(spk,ϵ) (spk, on)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, on\&dc)$	$\theta := 0$	$m_C := G_{mp}p + M_0,\ T := (Gm_C + T_0)\eta(0)$
S_-	(ϵ, off)		
	(spk,ϵ) (spk, off)		$T := (Gm_E + T_0)\eta(-\theta)$
S^L_-	(ϵ, on)		
	(spk,ϵ) (spk, on)		$T := (Gm_E + T_0)\eta(-\theta)$
S_+	(ϵ, off)		
	(ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_C := G_{mp}p + M_0,\ T := (Gm_C + T_0)\eta(\varphi)$
S^L_+	(ϵ, on)		
	(ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_C := G_{mp}p + M_0,\ T := (Gm_C + T_0)\eta(\varphi)$

FSM guard map

q	θ	M_c^{disc}	q	θ	M_e^{disc}
S	$[0,160)$	$\{\epsilon\}$	S	$[0,180)$	$\{\epsilon, off\}$
	$[160,180]$	$\{\epsilon, spk\}$		180	$\{dc, off\&dc\}$
S^L	$[0,160)$	$\{\epsilon\}$	S^L	$[0,180)$	$\{\epsilon, on\}$
	$[160,180]$	$\{\epsilon, spk\}$		180	$\{dc, on\&dc\}$
S_+	$[0,180]$	$\{\epsilon\}$	S_-	$[0,15]$	$\{\epsilon, off\}$
S^L_+	$[0,180]$	$\{\epsilon\}$	S^L_-	$[0,15]$	$\{\epsilon, on\}$
S_-	$[0,15)$	$\{\epsilon, spk\}$	S_+	$[0,180)$	$\{\epsilon, off\}$
	15	$\{spk\}$		180	$\{dc, off\&dc\}$
S^L_-	$[0,15)$	$\{\epsilon, spk\}$	S^L_+	$[0,180)$	$\{\epsilon, on\}$
	15	$\{spk\}$		180	$\{dc, on\&dc\}$

Parameters and Set-Point Values

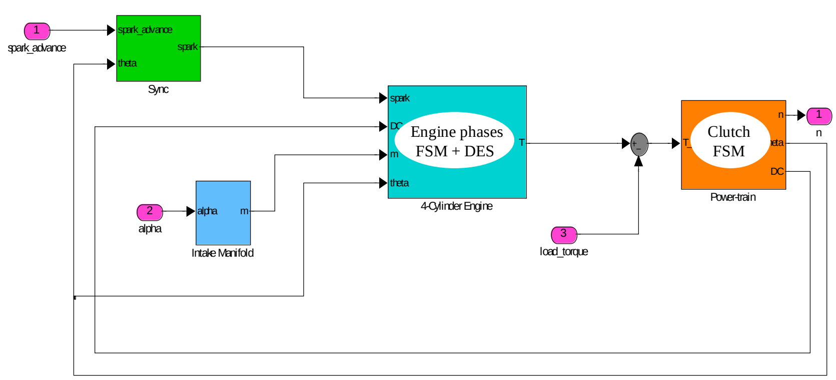
Engine parameters values

Crankshaft momentum of inertia (clutch open)	J_0	$0.9\ Kg\ m^2$
Crankshaft momentum of inertia (clutch closed)	J_c	$1.04\ Kg\ m^2$
Crankshaft viscosity coefficient	B	$0.02\ Kg\ m^2\ s$
Pumping and friction torque	T_p	$20\ Nm$
Cylinders' torque gain	G	$390000\ Nm/Kg$
Cylinders' torque offset	T_0	$-14.2\ Nm$
Spark efficiency function	$\eta(\phi)$	$\eta = 0.73 + \sqrt{0.083 + 0.005\phi}$
Manifold dynamic parameter	a_p	$-2.3\ s^{-1}$
Manifold dynamic parameter	b_p	$1538\ s^{-1}\ m^{-2}$
Compression mass/pressure gain	G_{mp}	$4.5e-9\ Kg/Pa$
Compression mass offset	M_0	$-2.08e-5\ Kg$

Set-point values of state and control variables

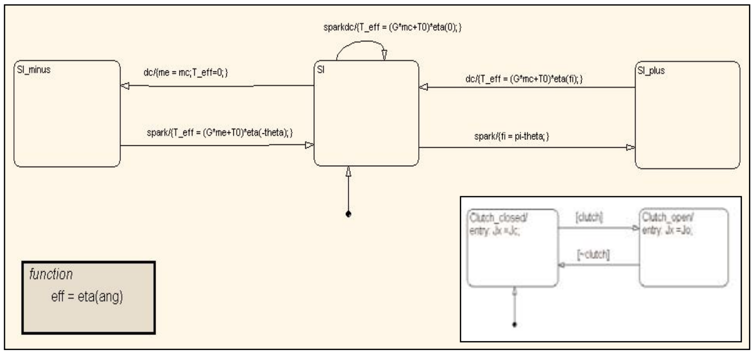
Manifold pressure	p	$2.47e4\ Pa$
Torque	T	$21.3\ Nm$
Compression mass	m_c	$9e-5\ Kg$
Expansion mass	m_e	$0\ Kg$
Spark advance	ϕ	20^0
Crankshaft speed	n_0	$800\ RPM$
Throttle angle	α	3^0
Spark advance	φ	20^0

A Simulink/Stateflow implementation



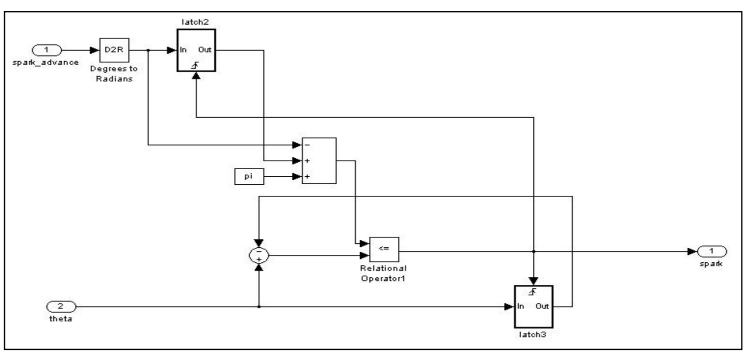
A Simulink/Stateflow implementation

FSM+DES with Stateflow:



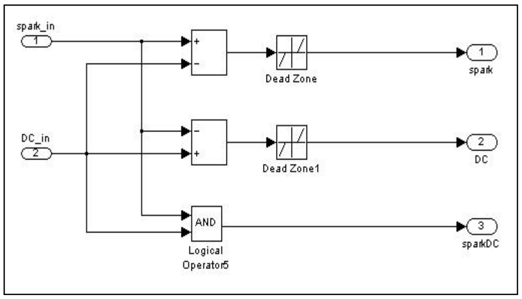
A Simulink/Stateflow implementation

Event generation: spark actuator block



A Simulink/Stateflow implementation

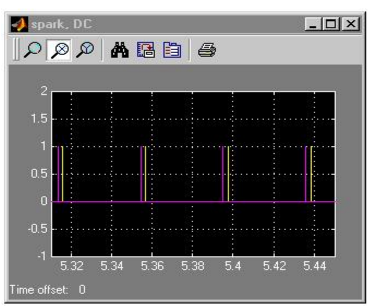
Event generation: spark&DC event generator block

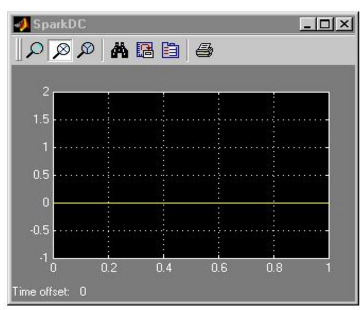


This is a 'Cylinders' block's internal abstraction, not the model of an existing device!

A Simulink/Stateflow implementation

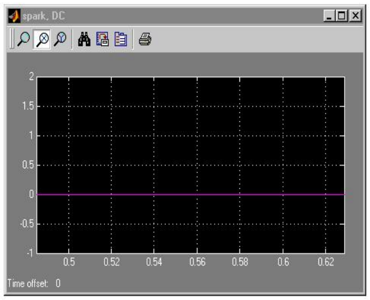
Event generation: negative spark advance

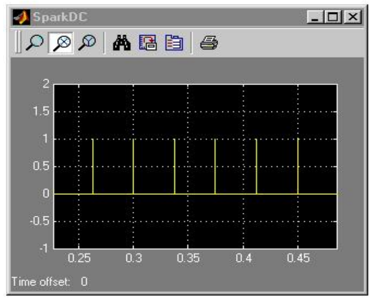




A Simulink/Stateflow implementation

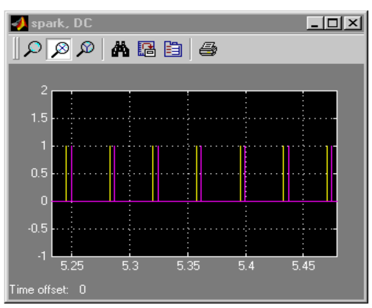
Event generation: zero spark advance

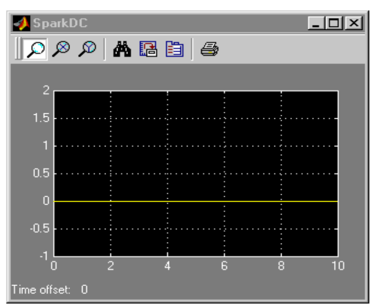




A Simulink/Stateflow implementation

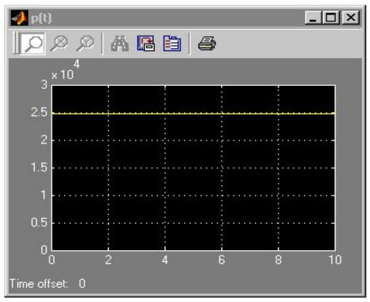
Event generation: positive spark advance

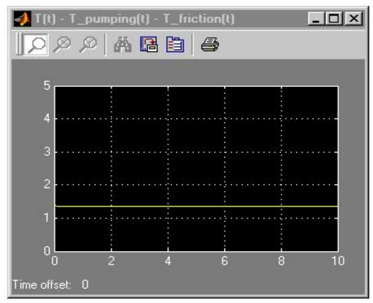




A Simulink/Stateflow implementation

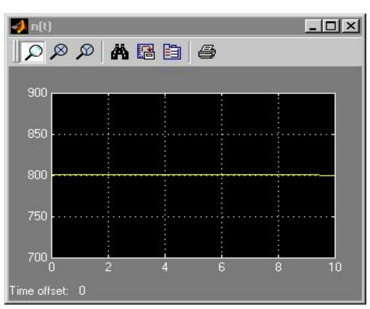
Open-loop behavior: no disturbance torque

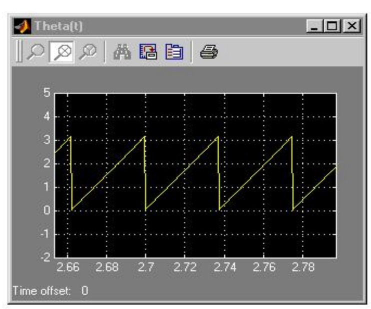




A Simulink/Stateflow implementation

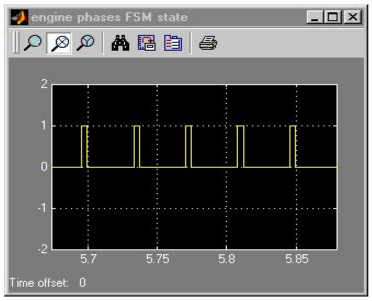
Open-loop behavior: no disturbance torque

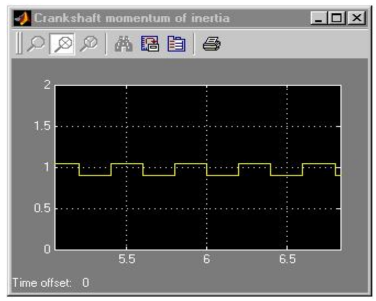




A Simulink/Stateflow implementation

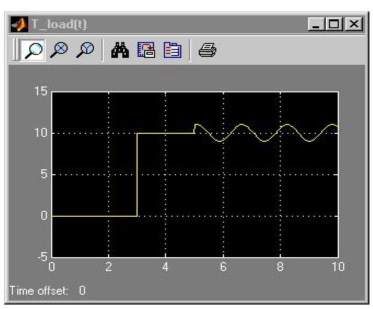
Open-loop behavior: no disturbance torque

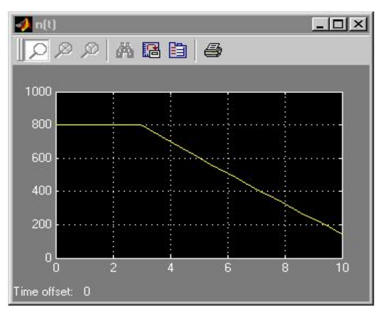




A Simulink/Stateflow implementation

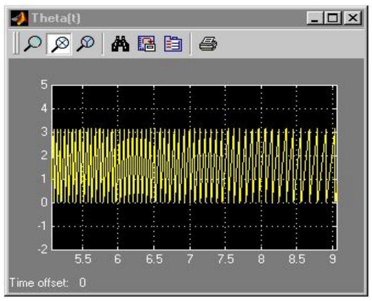
Open-loop behavior: disturbance load torque





A Simulink/Stateflow implementation

Open-loop behavior: disturbance load torque



It may be noticed how the revolution speed profile, while being strongly affected by the disturbance load torque, is almost insensitive to any variation of the crankshaft momentum of inertia due to the clutch command; the introduction of the clutch state, however, represents a first step towards a thorough hybrid model of the engine, including the gear insertion mechanism and its influence on continuous dynamics.