System Identification and Model Predictive Control of SI Engine in Idling Mode using Mathworks Tools

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Agenda

- Introduction
- MPC Overview
- Case Study – MPC
  - Work Flow and Virtual Set up
  - System Identification of engine model for idle mode
  - Plant Model Validation
  - Controller Synthesis
  - MIL results
- Benefits
- Future Scope
A stable and fuel efficient idle running of automotive engines has been crucial part of engine management system for OEMs and Tier-1s.

Low rpm idling: Trade off between fuel consumption, stability and disturbance performance.

Prevalent ISC scenario
- EMS' address ISC using variants of PI/PID/FF/compensators
- Use of maps/LUTs for idle air requirement and idling load compensation
- No / indirect use of model for idle behavior for the tuning of the controller

Proposed scenario
- Use of simplified, linear discrete state space model in idling
- Receding Horizon Model Predictive Control
- Inherently stable, constrained optimal control with improved tracking and disturbance rejection performance
MPC Overview: What, Why?

MPC = Model + Prediction + Correction (Control)

A Model of the Process (Plant) is used to Predict the future evolution of the process and control signal is computed to minimize the deviation of the predicted output from the target by exercising the correction at every time interval.

- Established and proven beneficial in the process control domain
- Potential to leverage it for automotive with the advent and abundance of high capacity, faster processors
- A constrained MPC algorithm holds promise to achieve stable and tighter idle speed control
MPC: How?

1a. At time instant $k$, construct and solve the optimal control problem to minimize the error between the target and predicted output over finite prediction steps, $m$.

1b. Deploy only the first element of the solution vector, i.e., the control move for $k+1$... (RHC)

2. At time $k+1$ read the output feedback and repeat the step 1...

Mathematical Expression:

$$\text{Minimize } J(u^M) = \sum_{j=1}^{P} \left| e_{k+j}^y \right|^q + \left| \Delta u_{k+j} \right|^q_S$$

Structure of Model Predictive Control

Desired Output \[\xrightarrow{+} \] Controller \[\xrightarrow{-} \] Process \[\xrightarrow{+} \] Process Output

Model \[\xrightarrow{-} \] Predicted Error

Diagram:

- Past
- Future
- Error
- Predicted
- Desired

- History
- Input Profile

- $k$
- $k+1$
- $P$
- $Q$
- $S$
- $e$
- $\Delta u$
- $y$
- $\sum$
- $\| \cdot \|^q$
- $\| \cdot \|_S$
MPC: How?

Objective function: \[ J = \sum_{i=0}^{m} (y_{set}(k+i) - y_p(k+i))^2 + \lambda \sum_{i=0}^{l-1} U(k+i)^2 \]

Error term Penalty on control moves

Constraints:
\[ u_{\text{min}} \leq u(k+j) \leq u_{\text{max}} \quad ; j = 0 \text{ to } l-1 \]
\[ U_l \leq U(k+j) \leq U_u \quad ; i = 0 \text{ to } l-1 \]
\[ y_l \leq y_p(k+j) \leq y_u \quad ; j = 1 \text{ to } m \]

Tuning
- Prediction horizon
- Control horizon
- Penalty factors on control moves
- Weights on output variables
- Hard / soft Constraints on inputs and outputs
- Constraints on rate of change of inputs
Case Study: Idle Speed Control of 2.9L V6 SI engine

- **MPC based ISC**


  ![Graph](image)

- Lower the idle rpm, lesser is the fuel consumption
- However, the tradeoff is with stable running, disturbance rejection performance and tracking performance

Fuel consumption for idle running at 750 and 1000 rpm idling of enDYNA* simulator

* enDYNA is engine simulator from Tesis-Dynaware.
Case Study: Work Flow and Virtual Set up

- enDYNA engine simulator for system identification of model during idling
- MISO model with throttle opening and spark advance as inputs and rpm as output
- Step response and PRBS excitation
- IDENT tool for transfer function identification
- Linear discrete (Ts = 10ms) MISO state space model from SISO TFs (throttle and spark advance as inputs and rpm as output)
- Controller synthesis using MPC Toolbox
- Closed Loop simulation with MPC controller
Case Study: SysID – Step response

Throttle step response

SysID using IDENT toolbox

ΔThrottle/Δrpm TF output comparison

Δspk/Δrpm TF output comparison
Case Study: SysID – PRBS response

PRBS signal applied to SA in open loop with constant throttle

Assuming throttle/rpm and spk/rpm relationships as linear, a combined MISO state space model is obtained.

Comparison of the outputs by PRBS SS model and enDYNA

Measured and simulated model output
Comparison of the outputs of state space $\Delta / \Delta$ models (Step Response) and enDYNA

Controller was constructed using the step response model as the predictive model for MPC
Using the MPC toolbox, MPC object was created.

Plant Model directly imported from IDENT session.
Case Study: Controller Synthesis

Tuning: Horizons

Tuning: Constraints on inputs and output
Case Study: Controller Synthesis

- Pre-closed loop simulation
- Simple and straightforward tuning iterations
Case Study: MIL closed loop validation

**Default EMS**

- **AccPedalPos [0_1]**
- **CrankSpd [rad/s]**
- **EngineAirMFlow [kg/s]**
- **Intended lambda**
- **BatteryVolt [V]**
- **FuelPres [Pa]**
- **ManifoldPres [Pa]**

**Drive EMS**

- **MPC controller**
  - for bumpless transfer
  - feedback setpoint
  - 0.1514 throttle_bias
  - 0.1514 throttleBias
  - 0.1514 throttleBias

**Idle**

- **rpm**
- **rpm Bias**
- **rpm Setpoint Bias**

**Base Idle Speed**

- 750 / 9.5493
Engine cranked by electric motor, target idle speed 750 rpm regulated by default PID control loop

The MPC controller switched on after matching the initial conditions for the bump-less transfer.

The idle set point ramped from 750 rpm to 850 rpm @100rpm/s

The idle set point ramped down from 850 rpm to 750 rpm @100rpm/s

The step load of 25Nm applied as disturbance @ 750 rpm (hostile) idle rpm, removed in 1 or 2 seconds

The scenario applied for predictive model that included additional integral state
The controller may not be optimally tuned for $K_P$, $K_I$, $K_D$

Under-damped behavior at set point change and disturbance

Marginal improvement after conducting Simulink response optimization
Case Study: Closed Loop Simulation Results

- (a) Fuel cut for reaching the limit
- (b) PI controller's regulation action
- (c) Switch over to MPC (bumpless)
- (d) steady state at new setpoint
- (e) setpoint restored
- (f) disturbance applied
- (g) disturbance applied

Time Scale (sec)
Case Study: Addition of Integral Element for Disturbance Rejection

1. Feedback
2. Setpoint

Discrete-Time Integrator

Linear MPC

MPC Controller

Integration setpoint

rpm_Integration_setpoint

Time Scale (sec)

(a) Fuel cut for reaching the limit
(b) PI controller's regulation action
(c) Switch over to MPC (bumpless)
(d) Reference ramp applied to setpoint
(e) Steady state at new setpoint
(f) Setpoint restored
(g) Disturbance applied
(h) Disturbance applied

set point
rpm
Benefits and Future Scope

Benefits

- The approach
  - Stable low rpm idling saving fuel
  - Improved performance for idle loads such as AC, PS, lighting
  - Constraints imposition

- The tools
  - GUI based Time effective and simplified system identification using IDENT
  - GUI based simple and time effective controller synthesis
  - Seamless interface between the tools

Future Scope

- Real Time overheads calculations to include MPC-ISC in the EMS
- HiL validation on RCP ECU and virtual tuning/calibration
- Modeling disturbance for rejection performance / improving the integral action for tracking performance
- Explore fast MPC on embedded hardware for automotive applications