Outline

- Background
  - Model-Based Control Engineering
  - GT-POWER linearization

- Application case studies
  - Air system dynamic analysis for selection of sensor locations
  - Air system control design with multivariable control techniques
Control design challenges:
New technologies, tighter requirements, shorter development cycle
Technology trend

- Higher computation capabilities
  - More capable embedded controllers
    - Advanced controls with more complex algorithms can be applied in real-time
  - Distributed (cloud) computing platforms
    - Thousands of simulations with high-fidelity models to verify control performance can be done in a short time

- Advancement in modeling tools
  - Systematic development of plant models with different fidelities
  - Control-oriented models e.g. linear models has been added as a model option

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Model Based Controls Engineering

- Models with different fidelities are employed at different steps of control design process
- With standard PID-based control designs, focus has been on the performance verification through simulations
- Control design has been challenged with the new control requirements
- With new sensors and actuators, controls Input-Output design requires dynamic analysis before control design

➢ Need to apply advanced control techniques
  - Identify dynamic characteristics of these more complex systems
  - Synthesize high performance controller in shorter time
  - Focus on rqmts and IO selection and system design than custom control algorithm development
Modern control engineering with linear models

- Most nonlinear systems can be characterized by multiple linear models for control design.
- Dynamic characteristics of the system is done with proven theories in linear analysis.
- Mature linear control methods e.g. MPC or H-infinity available which are
  - Systematic in design and calibration (reducing development time)
  - Easily scalable to different sets of inputs and outputs (multivariable)
  - Integration of robust performance requirements in control design.

\[
\delta \dot{x} = A_i \delta x + B_i \delta u \\
\delta y = C_i \delta x + D_i \delta u
\]
Different methods to develop linear models

- **Physics-based linear models**
  - Direct linearization of the physics-based models
  - The most accurate approach
  - Need access to the governing equations

- **Data-driven linear models**
  - Developed using system identification theory
  - Input Output data is used to fit a linear model
  - Accuracy depends on quality of data, knowledge of the physics and identification approach
  - Loss of physics
  - More time consuming and expertise dependent
GT-SUITE Linearization

- Provides users with the ability to specify the model’s I/Os
  - Through Sensors and Actuators
  - Wirelessly
- “Drives” the model to the desired operating condition with
  - constant values
  - time profiles
- Launches linearization process
  - At end of case or specified time stamps
  - Results are written to ASCII files

\[
\delta x = A \cdot \delta x + B \cdot \delta u \\
\delta y = C \cdot \delta x + D \cdot \delta u
\]
Application case studies

Case study #1:
Air handling sensor location selection

Case study #2:
Air handling control system design with H-infinity and MPC

Engine Model Fidelity

- Detailed physics-based
- Mean Value/Fast Running
- Linear
- Static “map-based”
Case Study 1: Sensor Location

- The input to the air system to be controlled is VGT rack position.
- Feedback options (2 sensor locations):
  - Estimated charge flow (CF)
  - MAF sensor before compressor to measure Mass Air Flow (MAF)
- Goal is to select sensor location which is “better” for air handling control design:
  - Are there fundamental limitation imposed on achievable closed-loop control performance with any of these sensor locations.

\[ y = CF \text{ or } MAF \]
Linear model*

- Operating point
  - Engine Speed (Weng) = 1200 RPM
  - Accelerator Pedal Position: 50%
  - VGT rack position (uVGT) = 50% open
- Linearized model is a state space model with
  - 128 states
  - Input: uVGT (can add speed and fueling later)
  - Outputs: Charge Flow (CF) and Mass Air Flow (MAF)

*Linearization done by GT*
Basic pole-zero maps analysis

- Non-minimum phase (NMP) system
- The closed-loop control with charge flow feedback will be limited to lower bandwidth and consequently slower and less robust response (S Skogestad, I Postlethwaite, multivariable feedback control: analysis and design, 2nd edition)
Due to actuators saturation, the effective gain is reduced and resonance response or limit cycle behavior is expected on nonlinear system as gain is increased.
Confirmation with nonlinear model: Gain margin
Simulation with nonlinear GT model: Charge Flow as the Feedback

Loop gain = 0.1

Loop gain = 0.5 (5x)

Loop gain = 1 (10x)
Simulation with nonlinear GT model: MAF as the Feedback

Loop gain = 0.1

Loop gain = 0.5 (5x)

Loop gain = 1 (10x)
Case study 2 - MIMO control design

- **Air system is a multi-input multi output (multivariable) system**
  - Inputs or actuator commands
    - VGT position
    - EGR valve position
  - Feedback to controller (outputs)
    - Charge flow
    - EGR fraction

- **Objective**
  - Analyze the dynamics of the system
  - Design a feedback controller for this MIMO system
Model-Based control design and calibration

Engine Model

Linearization

\[
\delta x = A_i \delta x + B_i \delta u \\
\delta y = C_i \delta x + D_i \delta u
\]

Advanced Control Analysis and Synthesis

Robust Calibration Optimization

Embedded Code Generation

Model in the Loop Simulation (Requirements verification and calibration)

Control verification in rapid prototyping or ECM (HIL, Test cell, or Vehicle)
Linear model*

- Operating point
  - Engine Speed (Weng) = 1600 RPM
  - Accelerator Pedal Position: 40%
  - VGT rack position (uVGT) = 25% open

- Linearized model is a state space model with
  - 147 states
  - Input: uVGT and uEGR
  - Outputs: Charge Flow (CF) and EGR fraction

*Linearization done by GT*
Linear model analysis
Parameter varying and highly coupled dynamics

Bode Diagram - uVGT to Charge Flow

Relative Gain Array (RGA) of the linearized engine model

Large RGA Number
High Dynamic Coupling

1.6 Hz
Control Design

- **H-infinity control**
  - Readily applicable to problems involving multivariate systems with cross-coupling between channels

- **Model predictive control**
  - A real-time optimal control approach applicable to multivariable system with constraints

- **Both approaches are systematic in design and calibration**
H-infinity Control Simulation Results – Nonlinear Model

Closed-Loop Control Response of the Nonlinear Model at Engine Speed = 1600 RPM; Accelerator Position = 40 %

- EGR Fraction Reference vs EGR Fraction Response
- Charge Flow Reference vs Charge Flow Response
MPC Simulation Results – Nonlinear Model

Closed-Loop Control Response of the Nonlinear Model at Engine Speed = 1600 RPM; Accelerator Position = 40%

- EGR Fraction Reference and Response
- Charge Flow Reference and Response
- uVGT Feedforward and Feedback (final command)
- uEGR Feedforward and Feedback (final command)
Summary

- Need
  Accurate and fast linear model development of engine and powertrain system using the current platforms being used to develop plant models

- Solution
  Direct physics-based linearization of the models developed in GT-SUITE

- Alternative approach
  System identification approach where linear models are fitted to input-output simulated data

- Benefits
  GT-SUITE direct linearization provides faster path to more accurate physics-based model of the system enabling more effective application of advanced controls methods in automotive systems

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