Predicting Valve Train Dynamics using Simulation with Model Validation

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Overview

• Objectives
• Validation Test Setup
• Model Build
• Model Validation
• Other Systems
• Achievements
• Q & A
Objective

- Develop and validate 2D valve train modeling methodology using GT-SUITE and motoring bench testing
- Develop a modeling methodology that can be used consistently for different valve train configurations and engine operating conditions
- Minimize model calibration and maintain accuracy

A validated model can help:
- Reduce overall development cost
  - Lead design
  - Reduce required testing
- Predict, evaluate, and improve valve train system performance
  - Design of experiments
  - Evaluate cam profiles
  - Evaluate valve spring stiffness
  - Capture dynamic valve lift
The test plan does not always consider what measurements are needed to validate the simulation. This leads to high levels of model calibration and non-repeatable model correlation.
Planning test measurements for model validation will reduce model calibration and increase the repeatability of model correlation.
Validation Test Setup

- Validation testing was completed using motoring bench testing
  - Constant engine temperature (25° C to maintain build condition)
  - Speed sweeps (0-6800 RPM)
  - High and low valve timing/lift configurations

<table>
<thead>
<tr>
<th>Crank Encoder Wheel</th>
<th>Painted Valves with Camera</th>
<th>Gap Sensor</th>
<th>Rocker Arm Strain Gauges</th>
<th>Valve Spring Strain Gauges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motoring RPM</td>
<td>Valve Lift via calibrated voltage</td>
<td>Valve Lift ≤ 1mm</td>
<td>Measured strain → tappet force</td>
<td>Measured strain → spring stress</td>
</tr>
</tbody>
</table>

Validation testing was intended to capture tappet force and valve lift over a range of engine speeds while maintaining the build condition.
Due to the engine configuration, instrumentation of multiple cylinders allows six different valve train configurations to be evaluated (Front & Rear / Intake & Exhaust / High & Low).

- **R** = Rocker Arm strain gauge
- **S** = Spring Strain Gauge
- **G** = Gap sensor
- **V** = Painted Valve
- **T** = Thermocouple

Total of 40 channels
\[ \mu_p = \mu_0 e^{\alpha p} \]

Material Properties

Part/Assy. Geometry (3D CAD)

Valve
Train
Design & Layout

2D Valve
Train Model
Model Build Overview

Material Properties

Valve Train Design & Layout

Part/Assy. Geometry (3D CAD)

Mass Properties

Kinematic VT Layout

2D Valve Train Model

\[ \mu_p = \mu_0 e^{\alpha_p} \]
The rocker stiffness was predicted independent from the valve train assembly and supporting structure. Using 3D finite element analysis (FEA) the rocker was defined as a flexible body while the cam and shaft were defined as rigid bodies.
The method used to predict rocker stiffness is consistent with GT’s rocker element definition.

- The red geometry annotations represent the 2D rocker element (as defined by GT).
- Actual rocker geometry is represented by the shaded green image.
- The rocker shaft is a fixed joint free to rotate and the roller is free to rotate and slide.
- The deflection values predicted by FEA are used to calculate the stiffness.

The equations are as follows:

$$K_{rkr} = \frac{F}{\delta} \cos \varphi$$

- $K_{rkr}$ = rocker stiffness
- $F$ = force along valve axis (load axis)
- $\delta$ = deflection along valve axis
- $\varphi$ = angle between valve axis and rocker perpendicular
Rocker components are modeled as rigid bodies. All applicable contacts are enforced. Forces are applied to rigid body reference nodes in space. All relevant boundary conditions are applied.

The rocker support stiffness was predicted independent of the rocker arm and includes all relevant supporting structure and boundary conditions. Rigid body rockers were used to load the assembly.
The boundary conditions include: bolt pretension, shaft clearances, all contact, fixed conditions at head bolts, and symmetry definitions.

- Symmetry boundary condition to cut faces
- Apply pretension loads to all relevant bolts
- Apply clearance contact to rocker shaft, cam, and journals
- Fixed boundary condition to faces of head bolt sleeves
The support stiffness prediction considered the contact footprint between the rocker to the shaft and was calculated in X & Y directions consistent with GT's coordinate system.

- Loading direction must be consistent with X and Y directions in the respective GT model.
- Predict stiffness in each direction separately.
- Apply load along an axis that is coincident with the rocker shaft (pivot) center.
- Using the rocker to load the support structure captures the contact footprint.

\[ K_i = \frac{F_i}{\delta_i} \]

- \( F_i \) = force along local axis
- \( \delta_i \) = deflection along local axis
- \( i = x, y \)
An average stiffness for the rocker and its support was calculated by measuring respective deflections at predetermined force intervals.

\[
F_i' = F_i - F_1
\]

\[
\delta_i = \text{deflection predicted by FEA}
\]

\[
\delta_i' = \text{shifted deflection predicted by FEA}
\]

\[
F_i = \text{interval force}
\]

\[
F_i' = \text{shifted interval force}
\]

\[
F_{max} = \text{maximum force}
\]

\[
i = \text{interval number}
\]

\[
K = \text{calculated stiffness (linear fit slope)}
\]

\[
N = \text{number of loading intervals (integer)}
\]
### Key Model Input Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>VT Configuration Dependencies</th>
<th>Must Have</th>
<th>Should Have</th>
<th>Could Have</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocker Stiffness</td>
<td>Basic (w/o VTEC)</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocker Stiffness</td>
<td>High Valve Timing</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocker Stiffness</td>
<td>Low Valve Timing</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Stiffness (X&amp;Y)</td>
<td>Base (w/o VTEC)</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Stiffness (X&amp;Y)</td>
<td>High Valve Timing</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Stiffness (X&amp;Y)</td>
<td>Low Valve Timing</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cam Journal Stiffness (X&amp;Y)</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Spring Stiffness</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Stiffness</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Seat Stiffness</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring Retainer Stiffness</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cam Journal Clearance</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Guide Clearance</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Lash</td>
<td>Independent</td>
<td>●</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rocker and support stiffness are dependent on operating valve train configuration and are key model inputs. Additional key model inputs include; clearances, journal stiffness, valve lash, and component mass.
Good correlation of magnitude and frequency was observed for the tappet force of the intake high rocker.
Good correlation of magnitude and closing response was observed for the valve lift of the intake high rocker.
Frequency spectrum shows resonance correlation for the intake high rocker.
Good correlation of magnitude and frequency was observed for the tappet force of the intake low rocker.
Good correlation of magnitude and closing response was observed for the valve lift of the intake low rocker.
Frequency spectrum shows resonance correlation for the intake low rocker.
The methodology used for the previously explain fixed pivot system was expanded to include a system using a hydraulic lash adjuster (HLA) at the pivot.
Engine Oil Viscosity

Barus viscosity-pressure formula:

\[ \mu_p = \mu_0 e^{\alpha P} \]

- \( \mu_p \) = dynamic viscosity (kg/m-s)
- \( \mu_0 \) = dynamic viscosity at atmospheric pressure (kg/m-s)
- \( \alpha \) = viscosity-pressure coefficient (Pa\(^{-1}\))
- \( P \) = pressure (Pa)

- Barus formula was used to calculate dynamic viscosity of oil under high pressure
- Barus formula is valid for pressures under 0.5 GPa
- \( \alpha \) is unknown and can be a function of pressure and temperature

Pressure effects on oil viscosity must be considered. For this study, the Barus formula, with a calibrated viscosity-pressure coefficient, was applied. Along with small calibration of oil aeration and leak down pressure.
# Key Model Inputs for HLA

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Must Have</th>
<th>Should Have</th>
<th>Could Have</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Temperature</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Bulk Modulus as a function of pressure and temperature</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Viscosity as a function of pressure and temperature</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLA Part Leak Down Time (per spec.)</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLA Part Leak Down Time as a function of applied load/chamber pressure</td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>HLA Starting Height</td>
<td></td>
<td></td>
<td>●</td>
</tr>
</tbody>
</table>

*All applicable inputs from a fixed pivot system must also be applied*

- Oil Bulk Modulus as a function of pressure and temperature is known
- Oil Viscosity is known for temperatures between 40 and 150° C at atmospheric pressure
- Applied Barus Formula
- $\alpha$ is unknown
- Calibration of $\alpha$ provides HLA model accuracy for all engine speeds and operating temperatures

Oil properties become a key model input for valve train systems that include a HLA. Other key inputs include; the leak down time and starting height of the HLA.
Cyclic test results were used to calibrate oil pressure-viscosity coefficient. HLA behavior correlates well for multiple leak down times (LDT) and oil temperatures (60 and 120°C). Verifying the model for LDT and temperature.
Simulation and test results diverge as engine speed increases, but correlation remains good between 1000 and 4000 RPM. This verifies the HLA model over a range of engine speeds.
Using a limited data set, the frequency of the predicted tappet force was correlated to measured strain.

Oil Temperature = 120°C
Good correlation was observed for valve lift magnitude and closing response.

Oil Temperature = 120°C
Achievement

- GT-SUITE accurately predicts dynamic responses for modeled valve train systems

- Modeling methodology validated via correlation of predicted and measured valve train system responses
  - Tappet force
  - Valve lift
  - Valve spring response

- Modeling methods are valid for multiple valve train configurations and engine operating conditions
  - High and low valve timing
  - With and without HLA
  - High and low temperature
  - High and low engine speed
Questions
Calculating Tappet Force

- Measured strain from rocker arms was used to calculate tappet force
- Slope was used to scale measured strain to calculate force

Component level testing of rocker arms was used to determine a calibration factor to convert measured strain to tappet force.
The frequency of measured spring strain and predicted spring shear stress shows good correlation in the exhaust springs for multiple engine speeds.
The frequency of measured spring strain and predicted spring shear stress shows good correlation in the intake springs for multiple engine speeds.
Good correlation of magnitude and frequency was observed for the tappet force of the basic exhaust rocker.
Good correlation of magnitude and closing response was observed for the valve lift of the basic exhaust rocker.
Frequency spectrum shows resonance correlation for the basic exhaust rocker.
Next Steps

- Use current models to support and drive design
- Increase development support
- Build confidence in model predictions
- Expand modeling capabilities
- Perform further validation