Lost Motion Compression Relief Brake Design and Optimization using GT-Suite

GT-User Conference, Nov 5, 2012, Birmingham, MI, U.S.A
Brad Lynch, Cummins Inc
Presentation Overview

- Objective
- Background
- Technology Review
- Challenges Associated with Lost-motion
- Modeling Approach
- Results and ALD Benefits
- Conclusions
Project Objective

- Design a low cost lost-motion compression relief brake for a new engine platform
- Today I am presenting the methodology I developed during the course of the project
  - Hopefully generate some conversation on the topic and collect feedback as well!
Background

- Why add an additional retarder?
  - Retarders reduce wear on the cab and trailer brakes therefore lowering operating costs
  - They also provide drivers with additional stopping power during descents

- Why a compression relief brake?
  - Excellent performance
    - In some cases, modern designs can absorb more power than the engine produces (Jacobs 2-stroke braking system)
    - Most designs now require traction control to modulate brake activation
  - Potential for highly integrated designs
    - Integrated approaches minimize the cost add of a brake to the engine BOM
    - Nearly zero net weight increase in comparison with driveline retarders
  - Many engine manufacturers are implementing variable valve timing for performance and economy reasons but compression relief braking can be achieved with VVT at low costs
Compression Relief Brake Function

- In its simplest form, compression relief braking is achieved by turning off fueling and opening the exhaust valve during the compression stroke.
- The diagram below illustrates the difference between the pumping loops for firing and braking – note the work input required to maintain the braking loop.
- If the valve was not opened then the gas would act like a spring, returning the work done during compression.

Exhaust Valve is opened during compression stroke.
## Compression Relief Brake Technology

<table>
<thead>
<tr>
<th>Legacy</th>
<th>Mature</th>
<th>State of the Art</th>
</tr>
</thead>
<tbody>
<tr>
<td>The “Slab-brake” makes use of valve motion at an adjacent cylinder to open the exhaust valve near TDC firing</td>
<td>“Integrated brakes” make use of a dedicated cam lobe and rocker arm for braking</td>
<td>“Two stroke brakes” make use of fully variable valve actuation to create a compression relief event every complete rotation of the engine</td>
</tr>
<tr>
<td>“Lost-motion brakes” have a special exhaust lever and cam which carry out normal exhaust function as well as braking</td>
<td>“Reset brakes” release the hydraulic pressure at peak brake lift and allow the exhaust valve to close based on the fluid dynamics in the brake instead of cam actuation</td>
<td></td>
</tr>
</tbody>
</table>

Focus of today’s presentation
What is Lost-Motion?

- It is predetermined motion which is hidden from the follower, in this case it is hidden by a large amount of lash
  - This motion can be “Found” based on system inputs
- The example below shows a cam profile and two different states of valve lash
  - State 1 is engine firing, in this case there is so much lash that the follower only sees the main exhaust lift event and the engine runs normally
  - State 2 is braking, in this case the lash has been removed from the system and now all of the motion prescribed by the cam profile is seen by the follower, the engine starts braking
Part Terminology

- Rocker Lever or Rocker Arm
- Master Piston
- Roller Pin
- Roller
Lost-Motion and Reset Brake Challenges

- **Valvetrain dynamics**
  - The valvetrain must be designed to control the motion of the cam follower during the lost motion events
    - Since there is a large amount of lash the rocker arm must be stabilized during engine operation
    - A single cam lobe is now used to control braking and normal engine operation; brake failure will leave the operator stranded
  - Added mass of the exhaust rocker arm due to the integrated brake functionality must be controlled

- **Oil circuit design**
  - Customers desire a responsive brake – this requires an oil circuit which readily meets the demands of the brake
  - A reset brake design empties and fills the master piston every engine cycle
    - This requires thorough analysis and optimization of the hydraulic circuit
Modeling Approach

- The design process begins with a GT-Power performance model and a mechanical-hydraulic model of the engine brake system.
- These two models are then combined to form a “Coupled” Mechanical/Hydraulic brake performance model.
- The predicted cylinder pressures from this model are fed into a model of the entire brake system including the engine oil circuit (Use your judgment on drawing the system’s boundaries).

![Diagram of design process](Image)
Engine Performance Model

- This model starts life as your program’s model for estimating combustion, performance, and emissions
- That model is then converted to a braking model by turning off combustion, removing fuelling parts and controls, adding a variable orifice to simulate an exhaust throttle, etc

- Uses of this model
  - Without predictive combustion or any mechanical or hydraulic circuits this model will be relatively fast running
  - Effective for evaluating different technologies: bleeder brake versus compression relief
  - Can be used to create tech profile targets on brake performance and mechanical limits
  - **Best Practice**: Use DOEs on brake event timing, peak lift, force on valve due to $\Delta P$ across it, addition of other valve events, etc to limit your design space

- Limitations of this model
  - Without modeling the valvetrain dynamics any estimates on the force required to open the valve will be **estimates**
  - Actual valve event lift will differ from input to model due to hydraulic (and mechanical) compliance throughout the engine brake system
EXAMPLE: Engine Performance Modeling

- Run a DOE on:
  - Brake event opening, closing, and peak lift
  - Exhaust air recirculation event opening, closing, and peak lift
  - Exhaust throttle or VGT position
  - Use engine speed as an operating parameter

- Optimization Options
  - Our engine doesn’t make use of VVT or VVA so the cam lobe design is fixed across the engine speed range
  - The exhaust throttle position can be varied as a function of engine speed
  - Limit the brake event peak lift based on piston pockets or other physical constraints
  - Limit $\Delta P$ across valve to limit loads on valvetrain
  - Maximize for power and set speed weighting based on customer requirements
Single Cylinder Model of Brake Mechanics and Hydraulics

- This model is generally created from scratch
- Contains all of the mechanical and hydraulic aspects of the brake but no performance parts

Uses for this model
- Initial development of valvetrain kinematics
- Optimization of lost-motion dynamics, roller design, and ball and socket design
- Sensitivity study on component tolerancing (i.e., roller pin oil film characteristics)
- Initial design of the oil supply circuit

Limitations of this model
- This model is fed a static cylinder pressure trace to determine the valvetrain kinetics but there is no feedback loop to alter the cylinder pressure based on the resulting valve motion
- One could incorporate a simple simulation of cylinder pressure based on intake and exhaust manifold pressures
- 1D modeling of oil circuit should be calibrated to CFD on design
  - Experimental data would be better! At this point it may not be available…
Coupled Mech/Hyd Performance Model

- This model is the integration of the single cylinder mech/hyd model into the engine performance model
  - Cylinder and exhaust port pressures are passed to the mech/hyd model, resulting valve motion is returned to the performance model
  - Valve lift is phased to other cylinders in performance model

- Uses for this model
  - Detailed cam design
  - Design of reset features and oil circuit

- Limitations of this model
  - Significantly longer run times than either model on their own
  - Convergence – Depending on the conditions of the model, oscillating/divergent conditions can be reached
    - Relaxation techniques may need to be implemented to reduce the gain in the feedback loop
Coupled Mech/Hyd Performance Model

Single cylinder Mech/Hyd model

Mechanical – Hydraulic Interaction

Lift is phased to the proper timing

Lift signals actuate valves in engine model

To Engine Model

Model relaxation – limits the lift profile change phased to cylinders 2-6 per cycle
EXAMPLE: Cam Design with Coupled Mech/Hyd Model

- Challenge
  - Manage cam contact force generated during braking

- One Solution
  - Run a sweep of different brake event designs and expected timing variation
  - Collect the resulting cam contact force
  - Design the cam to limit the potential Hertz stress
    - The maximum Hertz stress is a function of the force at the contact, the materials in contact, and the geometry of the two bodies
    - For this problem let's assume that our force is dictated by a desired performance level and our materials are set based on a corporate standard
    - Let's also assume that we have already optimized the basic roller design
    - This leaves control of cam geometry, specifically the radius of curvature, for managing the high loads
    - Calculation of radius of curvature and Hertz stress are outside the scope of this presentation but [4] and [5] are excellent references
EXAMPLE: Cam Design with Coupled Mech/Hyd Model (Cont.)

- Continued Solution
  - A constraint is set on Hertz stress
    - Typically based on a company’s past experience
  - If this constraint is violated during the solution process our tool stops chasing its current goal (This could be targeting a certain jerk, acceleration, RadC) and begins solving for radius of curvature based on the Hertz stress constraint
    - The forces collected from the sensitivity study are used as input to the stress calculation
  - The cam acceleration is calculated from this radius of curvature and the state variables for velocity and lift

- The designer will be rewarded with a profile robust to timing error
  - Cam acceleration profile will likely appear odd to the seasoned designer
Mech/Hyd Model of Complete Brake System

- This model is an expansion of the single cylinder model
  - The size of the model depends on the brake design
  - No performance modeling – cylinder pressure traces are imported
  - A portion of the engine’s oil circuit is modeled
    - Care should be taken to determine how much of the system needs to be modeled

- Uses for this model
  - Detailed design and tuning of oil circuit
    - Is the oil supply to the brake sufficient? Is a pressure regulator needed?
  - Assessing cylinder to cylinder interactions and variation
    - Cyl 1 and 2 and Cyl 5 and 6 are 240 deg out of phase but Cyl 3 and 4 are 360 deg out

- Limitations
  - 1D model should be calibrated to experimental data
    - CFD results are appropriate until experimental data is available
  - Extremely long solution times
    - This is especially true if the initial state is not well understood. Rely on previous models!
  - No feedback loop to cylinder pressures
    - Valve lift results from this model should be run in the performance model
    - The resulting cylinder pressures can then be brought back in for validation
Results

- **Rapid Design Cycle**
  - Initial design = 4 months
  - Running brake @ 11 months after start of design
    - This could have been considerably faster but we are working with a new supplier (Never made a brake or rocker lever before)
  - Design improvements ready @ 14 months after SOD

- **Initial performance within 7% of nominal target**
  - Target achieved through minor timing changes of existing HW
Conclusions

- GT-Suite software enables very rapid development of mechanical/hydraulic systems, specifically engine brakes

- Depending on brake type and design, a significant portion of the ALD efforts should be targeted at the oil circuit
  - Especially true of reset brake types
  - 1D model should be calibrated to CFD at first but should be followed up with calibration to experimental data as soon as it is available
Thank You

- To Prof. Robert Norton for your inspiration, focus on fundamentals, and open door
- To Rick Gustafson at Cummins for guidance, mentoring, and “Ah-ha” moments
- To James Kersey at Gamma Technologies for your help and guidance with my modeling questions
  - And to everyone at GT for developing such great tools
- To the audience for your time and attention
  - Hopefully my slides were not too dense!
Citations


