Automated Cam Design for Optimal Performance

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Current Optimization Approach

- Too many manual operations and handoffs
- Extremely inefficient and time-consuming
- The iterative loop often ends abruptly because of approaching manufacturing deadlines
Integrated Approach (Proposed)

Automate in modeFRONTIER

- Fix shape or size
- Perturb other variables Create a DOE
- DFMA and Dynamic Limits
- Contact stresses Case hardened depth
- All limits met?
  - Yes
  - No
    - Discard
- GT power
  - Minimize BSFC
  - Maximize Vol. Eff
  - Satisfying DFMA, ESW and performance constraints
- All targets met?
  - Yes
  - No
    - Discard

- Awareness of what to expect
- All overlook the whole process and collaborate ideas
- Improves overall understanding of cam design

Optimized profiles To choose from

Exchange ideas and pick the best design for durability, reliability and performance
Integrated Approach (Proposed Final)

Automate in modeFRONTIER

- Perturb other variables Create a DOE
- Fix shape or size

DFMA and Dynamic Limits
- Contact stresses Case hardened depth

All limits met?
- Yes
- No

All targets met?
- Yes
- No

Minimize BSFC, Maximize Vol. Eff Satisfying DFMA, ESW and performance constraints

Keep

Awareness of what to expect
All overlook the whole process and collaborate ideas
Improves overall understanding of cam design

Optimized profiles To choose from
Exchange ideas and pick the best design for durability, reliability and performance
Objective Statement

Improve the cam design and performance optimization process by integrating both design and performance models together, and reduce the process time, while maintaining our historical design and durability standards.
Customer Selection Matrix

Customer Description

<table>
<thead>
<tr>
<th>Function</th>
<th>Light Duty</th>
<th>Mid-Range</th>
<th>Heavy Duty</th>
<th>Power Systems</th>
<th>R&amp;T</th>
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<tr>
<td>Analysis</td>
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<td>Design</td>
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A total of 17 people
Discussion guide

1. How would you have approached the cam design optimization problem currently? If you’d change 5 things in our current process, what would they be?

2. What are your expectations from cam profile design and optimization studies? Are there any additional bottlenecks other than the 5 you mentioned above that are hindering to meeting your expectations?

3. Which sections of a cam profile are crucial in cam design with regards to durability and which ones to performance outputs? Where should we focus our attention on?

4. What other parameters of the valve train model other than the cam profile would be significant in affecting the cam design and engine performance?

5. How would you explore the design space when the program doesn’t have clear bounds/constraints or when you would want to do an entitlement study and come up with the best cam design for a certain program? What do we need to fix first to properly layout the objectives and constraints to this optimization problem? And what would are they for you?

6. What are the practical difficulties you faced with regards to time, efforts, and tool capabilities?

7. Which of the current ESW limits you think need to be revised in order open up our design space a bit more?

8. Is there anything else I am missing that would be a significant contributor to this project? Is there anyone else you would like me to interview?
Key questions

Performance studies or Cam Designs
It is often unclear whether the performance engineer should give the designer the profile they want, or vice versa. **Which goes first?**

GT or modeFRONTIER or something else
If both Performance and Valve train dynamics models can be integrated in GT, **why do we need modeFRONTIER? When to use what?**

Intake and/or Exhaust
Are the intake and exhaust cam events to be optimized **separately or together? If separate, does the order matter?**
Typical Inputs and Outputs

**Manufacturability**

**Inputs:** Cam Profile or Valve Profile (kinematic)
**Outputs:** Linear roller follower lift, and its first three derivatives.

**Durability**

**Inputs:** Dynamic valve train model containing all the geometry information, cylinder and port pressures, inertia and stiffness of all parts in the valve-train, operating speed range
**Outputs:** Valve to piston clearance, No-follow Speed, Valve-seating velocity, Contact Stresses

**Reliability**

**Inputs:** Dynamic Valve Profile at speed of interest, GT power model.
**Outputs:** Thermal Efficiency, Fuel Consumption, Volumetric Efficiency, among many others.

**Performance**

**Inputs:** Dynamic Valve Profile at speed of interest, GT power model.
**Outputs:** Thermal Efficiency, Fuel Consumption, Volumetric Efficiency, among many others.
Overview of the Cam design process

Manufacturing Limits

Dynamic Limits

Contact stresses

Cam Design

GT VT Design
- Peak Lift
- Peak Velocity
- Peak Acceleration
- Peak Jerk
- Min. Positive Radius of Curvature
- Min. Negative radius of curvature

GT ISE Valvetrain
- Valve to piston clearance
- Valve seating velocity
- No-follow speed

Contact
- Max. Center stress
- Cam shaft case hardened depth
- Edge stresses in case of misalignment
What’s in and what’s out?

Out of scope

- Creation or calibration of GT mechanical or performance models
- Non-polynomial cam design methods
- Contact stress evaluation
- Valve to piston interference
- Other valve-train or system design inputs
- Challenging ESW limits
- Brake cams, and fuel pump cams
GT Models

Kinematic Model

Dynamic Model

Engine Performance Model

No follow speed

Non-negative Valve Lift
Integrated Workflow

Parametrized Cam Profile

Inputs

DOE/Optimizer → GT Kinematics → GT Dynamics → GT Engine Performance

Outputs

Valve Opening angle

Design targets and objectives

Other Inputs?
Overall Process

Preparation of GT models for Automation
- GT Kinematic Model
- GT Dynamic Model
- GT Performance Model

Editing modeFRONTIER workflow template
- Call for a scoping meeting and review the inputs, constraints and optimization goals and methods
- Browse to the right models and introspection
- DOE and Optimizer settings, and Run the workflow

HPC Setup, Post-Processing and Decision making
- Modifying the workflow to run on grid
- Verify file associations, inputs and outputs to each nodes
- Modifying the batch run files
- Securing the compute nodes, and launching the parallel runs
- Post Process results and call in a meeting for discussing the results and making decisions
Focus of this example study

- Valve train design already exists, only camshaft is to be changed for improved performance benefits.
- Criteria considered for this study: Manufacturability (Lift and its 3 derivatives), No follow speed, and Valve seating velocity.
- Contact stress (including the crown profiles) evaluation slows down the workflow at least by 15 times per design—best left out until the end. Other alternatives are to get the functional relationship between the center stress, force and the radii and use that. But out of scope for this study. Used Hertz Stresses in this study.
- Objective is to improve Brake Thermal Efficiency (BTE).
- Not to discard designs, but to understand the right directions towards best performance while maintaining durability/reliability standards.
“It took me about 19 working days full time for both intake and exhaust valve lifts. This was with something already existing, there was a bunch of back and forth with Tim Shipp so this is just not my time but also Tim’s time. The final output was phased valve profiles with 0.1% improvement in BTE.”

“What’s worse is, after all that effort Darren mentioned, after designing and finalizing the cams, the manufacturer said we won’t be able to deliver the cams on time with the agreed upon radius of curvature. We had to start over again, almost from scratch”
Integrated workflow

- Uniform Latin Hypercube (ULH) Sampling method for DOE (32 samples)
- Non-dominated Sorting Genetic Algorithm II (NSGA) for optimization (15000 total designs)
- Hertz Stresses are used instead of Contact Stress
Review of the workflow schematic

Inputs
- DOE/Optimizer
- Parametrized Cam Profile
- GT Kinematics
- GT Dynamics

Outputs
- Valve Opening angle
- Design targets and objectives
- GT Engine Performance

Other Inputs?
- Exit
Proposed Methodology

• Not changing the intake profile from the baseline model but just changing the exhaust profile.

• This also can be changed to fixing the exhaust first and changing the intake only, if for certain programs this is important.

• Maximizing BTE is the only objective for this program, but there could be more than one objective. Just need to be watchful of the size of the problem.

• The idea is to use one of the best profiles from this exhaust workflow and use it in the intake workflow and optimize only for intake then.
Exhaust Optimization

• Parallel Queue 256 cores (8 Nodes) – 23152 Total Design evaluations
• 64 concurrent designs with 128 GT Databases. 8 GT jobs per node.
• Took 48 hours total – 482 designs per hour on an average!!
Intake with best Exhaust

- Only change Intake. But both EVO and IVO changed
- Parallel Queue 256 cores (8 Nodes) – 15000 Total Design evaluations
- 64 concurrent designs with 128 GT Databases. 8 GT jobs per node.
- Took 55 hours total – 272 designs per hour on an average!!
Summary, Conclusions and Future work

The key benefits of the new process are:

- **Improved Technical Productivity**: reduced process time from more than 4 weeks to less than 1 week (subject to user experience levels and maturity level of the program) - for not one design, but for a database of feasible designs. Also, about 70% of this time in the new process is computer time NOT employee time.

- **Better understanding**: The integrated and automated process enables us to start looking at the problem in a better way understanding the cause and effect in both design and performance worlds – a unified process to find a durable, reliable valve train that gives the best performance!

- **Data management**: Thousands of designs in a very organized and structured folder setup, and excellent data visualization and control enables us make well-informed, better decisions faster.

- **Portability and Neutrality**: Once set-up, this process can be very easily modified to fit the needs of different engine programs and valve train types, provided the constituting GT models are available. Also, designer, analyst or a CPE engineer can run the workflow and meet with the rest of the team regularly for review.
Summary, Conclusions and Future work

- This new process is to supplement the existing design process and not to replace it. It is recommended that once a few good designs are chosen, all the limits are verified according to the current (old) process.

- Even the feasible profiles generated by this automated process do not always necessarily look “typical” or “conventional”, but they do meet the prescribed constraints and performance goals or targets. It is left up to the team to decide how to approach this - fine-tune, assess risks and compromises.

- Other possible methods of optimization could be explored in future. One of these depicted in the next slide involves multilevel optimization workflows, where first a performance level optimization is done. The best profile(s) of this level could be used as a reference or ‘desired’ profile(s) for the next level. In this level, the ‘error’ between the desired and generated profile could be minimized subject to the durability and manufacturing targets.
modeFRONTIER Workflow 2

Valve Events Phasing and Scaling

DOE/Optimizer

GT Engine Performance

Design targets and objectives

Reference Pareto Designs/Optimal Cams

Parametrized Cam Profile

Inputs

GT Kinematics

GT Dynamics

Outputs

Minimize Error with reference designs!

Multilevel Workflows

Design targets and objectives

Design targets and objectives