Development of a Novel Transient-Pulsating Flow Rig for Engine Air System Research using GT-SUITE

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http://www.imperial.ac.uk/turbochargers/facilities/tasr/
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1. Introduction: Background

• Road transport in the EU accounts for around 20% of all CO₂ emissions

• Transition to hybrid- or full-electric powertrains in pass-car / light-duty vehicles continues…

• …but much more difficult for heavy-duty applications – not as well-suited to electrification
  ▪ CO₂ from heavy-duty vehicles increased 36% between 1990–2010¹; continues to grow

• While the powertrain mix is changing, the internal combustion engine is currently the most numerous prime mover, and will be around in some form for many decades

• So the consensus² is that we must continue striving for thermal efficiency improvements, to reduce CO₂ emissions across all modes of transport

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1. Introduction: Project

High Performance Engine Air System (EAS) Project

• Objective: *This project will design and develop a highly responsive and efficient Engine Air System that will enable engine downsizing and alternative engine operating strategies with their associated fuel efficiency gains*

• Commissioned as part of the Energy Technologies Institute (ETI)’s Heavy Duty Vehicle Efficiency (HDVE) Programme

• Collaboration between Caterpillar Inc., Imperial College London, Honeywell Transportation Systems

• Demo engine is a 7-litre heavy-duty industrial diesel engine, built in the UK
  ▪ Numerous different applications and duty cycles
  ▪ **Two-stage air system** – two fixed geometry turbos in series

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1. Introduction: *Objectives*

Imperial’s primary role: **Air system test rig design and development**

The essential requirement of the Transient Air System Rig is:

*To enable the performance (efficiency and *transient* response) of multi-stage engine air system concepts to be evaluated experimentally*

**Transient** – meaning at the timescale of engine acceleration (e.g., due to a load change), typically in order of a few seconds

**Pulse, pulse flow, pulsating flow** – meaning at the timescale of pulses in the exhaust manifold caused by the opening and closing of the valves

- Order of $10^{1–2}$ Hz
- e.g., 6-cylinder engine running at 1200 rpm corresponds to $\frac{6 \times 1200}{2 \times 60} = 60$ Hz
2. Methodology: Requirements gathering & concept downselection

Requirements – be able to:

- Test air systems for a wide range of engine sizes and speeds, both heavy- and light-duty
  - Drives requirements for high flow, fast response, and high pulse frequency
- Replicate exhaust pulse shape throughout an engine transient event
  - Drives requirement to be able to control pulse amplitude and frequency, transiently

Concept downselection – various concepts assessed, e.g.,

- Actual engine (fired or motored)
- Pressure plenum + actual engine cylinder head
- Pressure plenum + pulse generator (chopper/rotary valve)

**Pressure plenum + camless valve train**

- Only the “pressure plenum + camless valvetrain” concept provides the flexibility to cover different engine sizes and speeds, with capability to transiently control pulse amplitude and frequency

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**Lotus Active Valve Train (AVT™)**

Lotus AVT is a camless valve train system, permitting independent control of valve lift profiles, enabling pressure pulse frequency, amplitude and shape to be adjusted as desired.
2. Methodology: Proposed rig layout

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2. Methodology: GT-SUITE rig model

- Simulink interface block
- TASR (pressure plenum + camless valvetrain)
- Exhaust manifold
- Air system (turbochargers and interstage ducts)
- Tailpipe geometry

Lotus AVT sub-model
Lift profile modulation
2. Methodology: Scale factor

Key question

- *Would proposed rig concept be able to recreate exhaust pressure pulses of the correct amplitude?*
  - …given that the max plenum pressure would be much lower than in an engine cylinder head at EVO
  - …how closely could the pulse shape be matched?

Scale factor approach

- Use Simulink controls to compress lift duration
  - define a simple *Scale Factor (SF)* referenced to the real engine lift profile duration
- Use GT-SUITE rig model to simulate effect of different SF values on HP turbine inlet pressure
  - Only duration was scaled; no changes to profile shape
3. Results: *HP turbine inlet pressure*

- Plot shows sweep of instantaneous HP turbine inlet pressure as a function of $SF$, in equal intervals of 0.05

- $SF$ modulation strongly affects mean pressure and amplitude, as well as the resultant pulse shape

- As $SF$ decreases:
  - Mean pressure *decreases*
  - Pulse amplitude *increases*

- In this example, best match is around $SF \sim 0.4$
3. Results: *HP turbine inlet pressure*

- Scale factor modulation achieved the following results, in steady-state and transient operation.

**Instantaneous HP turbine inlet pressure**
- Engine reference pulse
- GT-SUITE rig model predicted pulse

**Steady state** (i.e., constant engine speed)

**Transient** (load step)

- GT-SUITE simulations provided confidence that the proposed rig concept could work...
- ...allowing us to proceed with the detailed design, manufacturing and commissioning...
3. Results: **TASR design summary**

**TASR, the Transient Air System Rig**

- Transients created by a fast-acting pressure regulating valve → imposes ramps in mean flow entering plenum, to imitate vehicle-level events

- Pulses generated by Lotus AVT (Active Valve Train) system (6 electrohydraulic poppet valve actuators) + corresponding mounting plates, exhaust ports, valves and seats, installed on top of plenum

- Modular design philosophy allows different cylinder spacing with minimal part changes; simple plenum design can be adjusted for volume, or internal features added
4. Conclusions

Conclusions

- GT-SUITE was used early on in development of TASR
  - Proof-of-concept rig model provided confidence that required air system inlet BCs can be recreated experimentally
- Simulated effect of Scale Factor on valve lift duration
  - SF allows desired pressure pulse amplitude (and shape) to be recreated, but using plenum pressures lower than would be seen in a real engine at EVO
- TASR has since been successfully built and commissioned
  - Recreates both transient and pulsating gas dynamics entering the engine air system
  - Air system performance can be measured in engine-realistic conditions, without recourse to expensive and time consuming engine testing!
Acknowledgements

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Thanks for your attention!