Design and Optimization of the 4-Stroke Opposed-Piston Sleeve Valve Engine

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Concept Overview

Opposed Piston 4-stroke

- Reciprocating sleeve valves
  - Mfg. on diesel dry-liner tooling
- Circumferential ports
  - Good breathing capacity
  - Advantageous air motion

- Low surface area
  - Long stroke – B/S ~0.42
  - Reduced heat transfer
  - Reduced knock tendency
- Stable Combustion (high turbulence)
  - Low temperature combustion system
  - Low NOx etc.
Valve stem seals isolate oil circuit from ports

Traditional metal to metal gas seal

Circumferential port allows for optimized breathing
Pinnacle Design History

Proof of Concept
250cc, b/s: 51/(60x2)
Tested: 2009-2011 (~1000 hrs)

Scooter “Alpha”
110cc, b/s 39x(46x2)
Tested: 2011-2013 (~4000 hrs)
Passed 400hr durability

Scooter “Beta”
110cc, b/s 39x(46x2)
Tested: 2014-present (~1500 hrs)
224 g/kW-hr BSFC / 35% FE gain over conventional engines
Idles stably at $\lambda=1.8+$

Multi-Cylinder Designs
1.0L 2-Cyl
Phasers
1.2L 3-Cyl
Hybrid GT-SUITE / MATLAB scheme

1. Universal platform for simulation and test data analysis
   • GT-SUITE, CONVERGE, Dyno / Test Stand – all .mat based
2. Taps PE proprietary and commercially available MATLAB tools
   • DOE generation, model fitting, opposed-piston mechanics etc.

• Auxiliary calculations
  • Crank/slider (VCR) design / kinematics
  • Balance / vibration / forces
• Parameterization / DOE Construction
• Analysis / Optimization
  • Response modeling
  • Comparison to test data
  • Comparison to CFD
• CFD boundary condition generation
1.2L 3 cyl Design

Unique VCR Scheme

- Commercially available phasers
- Conventional crank/slider mechanisms
- VCR + VVT together
Case Overview

1.2L VCR / VVT / EGR Optimization – Alpha 1 Stage

Objective:
Maximize efficiency over 10 speed / load points

Constraints / Design Questions:
Phaser stroke
Ring-to-valve clearance

DOF:
1. VCR schedule
2. Intake VVT schedule
3. Exhaust VVT schedule
4. EGR rate

Non-Standard Calculations
1. Ring-to-sleeve-valve = f(VCR, VVT)
2. Top land height (vol.) = f(VCR, VVT)
3. Effective piston motion = f(VCR)
4. Chamber wall area = f(VCR)
5. Friction model = f(VCR)
6. Sleeve gas force (post-run)
DOE with MATLAB MBC Toolbox
- Point-by-point space-filling design
- EGR circuit flow boundary honored

MATLAB scripted GT-SUITE experiment
- Prepare .par file (RPM, Load, control, piston motion etc)
- Submit to cluster & retrieve results

Data analysis in MATLAB
- Fit performance responses
- Calculate dynamic control boundaries
- Generate optimized designs (GA, gradient methods etc.)

MATLAB scripted GT-SUITE run
- Confirm response model prediction
- Optionally re-execute response and include new data
VCR Phase Requirement:

![Diagram showing optimization results for VCR Phase Requirement. The graph plots engine speed versus BMEP, with color indicating VCR Phase CA. The specific regions of interest are highlighted.]
Valve-Ring clearance with optimized VVT & VCR settings

- Efficiency advantage for late EVO (requires larger top land)
- Leveraged in-house code to estimate efficiency loss of larger top land
- Net result: improved efficiency despite crevice volume addition
VCR (Crank) Phaser Stroke Requirement

In-House Codes Used:
1. Crank phase = $f(CR)$
2. Sleeve force = $f(P, H)$

$H$ = piston height
Thanks!

Questions...
**110cc: Engine Dyno Test Data**

**Pinnacle 110cc 15:1**

- Bore/stroke: 39x(46x2)
- CR: 15:1 (fixed)
- Fixed valve events
- PFI @3bar
- ~68um SMD
- Haltermann EC-2005 (95 RON)

**Test Data**

- 2000 RPM, 2 bar BMEP
- Source: AVL 2010

**Performance Data**

- Pinnacle 110cc 15:1 2k2bar 360 [g/kW-hr]
- 224 [g/kW-hr] On a 110cc!

**Comparison**

- Fiat 0.8-L 375 g/kwhr
- Hyundai 1.0-L 375g/kwhr
- 1.0-L Ford Eco Boost
- 1.6-L Ford Eco Boost

**2000 RPM, 2 bar BMEP**

(Source: AVL 2010)

- Pinnacle 1.2-L VCR 314 [g/kW-hr]
2010 Honda Elite  Pinnacle

- 108cc (50x55)
- 11:1 CR
- Water Cooled
- Keihin EFI

- 110cc 39x(46x2)
- 15:1 CR (fixed)
- Oil Cooled
- Lean Burn
- Pinnacle EFI

Northern California Diagnostics Labs
- EPA & CARB Certified Tests (bag emissions)
- Test Cycle: WMTC Reduced
  - ARAI road load coefficients

Fixed Speed (Vehicle) Fuel Economy

WMTC Drive Cycle Fuel Economy

NCDL rider, same day, test cell, emissions, cycle, road load, etc.
Feb ’15 Customer (India) Test Results

Steady-State (road load)
- 20-45% improvement

WMTC Results (from cold)
- >30% FE Improvement
  - NOx: 2025 w/o cat
  - CO – 40% of regulation
  - HC – Not well catalyzed (needs close cat)

Acceleration (test track)
- 20% down-speeding → same 0-60 km/h

<table>
<thead>
<tr>
<th>Regulated Species</th>
<th>Pinnacle Lean Test Results</th>
<th>2015 to 2020*</th>
<th>2020* to 2025*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.46</td>
<td>1.403</td>
<td>1.14*</td>
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<tr>
<td>HC</td>
<td>1.07</td>
<td>-</td>
<td>-</td>
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<tr>
<td>NOx</td>
<td>0.17 (No Cat!)</td>
<td>0.39</td>
<td>0.225*</td>
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<tr>
<td>HC+NOx</td>
<td>1.24</td>
<td>0.79</td>
<td>0.45*</td>
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</tbody>
</table>

32% ~52 km/L

Vehicle Performance
- 68.4 km/L
- 32%