Preliminary design of twin-cylinder engines for hybrid electric vehicle applications

Yannick Louvigny
Ltas - Automotive engineering
University of Liège
Introduction
Project background

- Growing industrial interest for small ICE (with 2 or 3 cylinders) for urban or hybrid vehicles
- Support to the prototyping of a twin-cylinder engine by BTD
- Research efforts in non-accurate methods for the design of unusual engine configurations
  - Preliminary design tools
  - Calculation based on multibody systems simulation
Topics of the study

• Determining general ICE requirements for a HEV applications

• Developing simplified models of four different twin-cylinder engine configurations
  - Calculating inertia forces and moments in the engines
  - Balancing the engines

• Comparison of the different engine configurations (from a HEV applications point of view)
Methods
ICE requirements for HEV

- Working at full load most of the time
- Rapid and reliable start
- As light as possible
- Compact and easy to pack in the vehicle
- High overall efficiency and low fuel consumption
- Not expensive

=> Twin-cylinder engine

- But small engines show some balancing problems
### Engine configurations

<table>
<thead>
<tr>
<th></th>
<th>In-phase</th>
<th>Out-of-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-line</strong></td>
<td><img src="image1" alt="In-line diagram" /></td>
<td><img src="image2" alt="Out-of-phase diagram" /></td>
</tr>
<tr>
<td><strong>Boxer</strong></td>
<td><img src="image3" alt="Boxer diagram" /></td>
<td><img src="image4" alt="Boxer diagram" /></td>
</tr>
</tbody>
</table>

**Preliminary design of twin-cylinder engines for HEV applications**

**Methods**

**Results**

**Conclusion**
Simulation steps

- Calculation of inertia forces and moments with respect to the crankshaft angle for the different engine configurations (based on simplified models)
- Balancing the engine using crankshaft counterweights and balancing shaft(s) (first or second order)
- Introducing the gas pressure effect in the simulation
- Comparison between the twin-cylinder engines and an equivalent four-cylinder engine (reference level for inertia forces and moments)
Simplified models

- Calculation of inertia forces produced by pistons motion

\[ F_x = r \cdot \omega^2 \cdot [m_r \cdot \cos \theta + m_o \cdot (\cos \theta + A_2 \cdot \cos 2\theta + A_4 \cdot \cos 4\theta + A_6 \cdot \cos 6\theta + ...)] \]

\[ F_y = r \cdot \omega^2 \cdot m_r \cdot \sin \theta \]

\[ m_r = m_1 + \frac{2}{3} \cdot m_2 \]

\[ m_o = m_3 + \frac{1}{3} \cdot m_2 \]

\[ F_{res} = \sqrt{F_x^2 + F_y^2} \]
Balancing systems

- Optimization of the crankshaft counterweight
- Adding first or second order balance shafts

Normal balance shaft (inertia forces)

Double balance shaft (inertia moments)
Results
Inertia forces and moments

- In-phase in-line twin-cylinder engine

Forces (N)

Moments (Nm)

fobs: first order balance shaft(s) (rotating at the crankshaft speed)
sobs: second order balance shaft(s) (rotating at twice the crankshaft speed)
Inertia forces and moments

• Out-of-phase in-line twin-cylinder engine

Forces (N)

Moments (Nm)

25000
20000
15000
10000
5000
0

0
440
880
1320
1760
2200

original data  opti. crank  2 fobs  1 fobs  2 sobs  1 fobs  1 fobs  2 sobs  1 fobs  2 sobs

Fres,\text{max} Mres,\text{max}

fobs: first order balance shaft(s) (rotating at the crankshaft speed)
sobs: second order balance shaft(s) (rotating at twice the crankshaft speed)
Inertia forces and moments

• Out-of-phase boxer twin-cylinder engine

`fobs`: first order balance shaft(s) (rotating at the crankshaft speed)
`sobs`: second order balance shaft(s) (rotating at twice the crankshaft speed)
Inertia forces and moments

- In-phase boxer twin-cylinder engine

**Graph: Inertia forces and moments**

- **Forces (N)**
  - 0
  - 440
  - 880
  - 1320
  - 1760
  - 2200

- **Moments (Nm)**
  - 0
  - 440
  - 880
  - 1320
  - 1760
  - 2200

**Legend:**
- **Fres,max**
- **Mres,max**

**Annotations:**
- fobs: first order balance shaft(s) (rotating at the crankshaft speed)
- sobs: second order balance shaft(s) (rotating at twice the crankshaft speed)
Comparison

- Comparison between the twin-cylinder engines and an equivalent four-cylinder engine (reference level)

![Graph showing comparison between twin-cylinder engines and an equivalent four-cylinder engine.]

**Legend**
- fobs: first order balance shaft(s) (rotating at the crankshaft speed)
- sobs: second order balance shaft(s) (rotating at twice the crankshaft speed)
Gas pressure

- Gas pressure inside one cylinder (various rotation speed)

- No effect of the gas pressure on the force transmitted to the engine mounts
Gas pressure

- Variation of torque inside an in-phase engine (boxer or in-line) rotating at 4000 rpm

- Variation of torque inside an out-of-phase engine (boxer or in-line) rotating at 4000 rpm
Conclusion
Each configuration of engine has its own characteristics in term of inertia forces and moments. These loads can be reduced by addition of counterweights or balance shafts.

<table>
<thead>
<tr>
<th></th>
<th>First order forces</th>
<th>High order forces</th>
<th>First order moments</th>
<th>High order moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-line, in-phase</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>In-line, out-of-phase</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Boxer, in-phase</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Boxer, out-of-phase</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Conclusion

• Twin-cylinder engines offer interesting prospects thanks to their
  - small size
  - low weight
  - low cost

• Among them, the in-phase boxer engine is promising because
  - its inertia forces are naturally balanced
  - It has a small height (it allows an easy packaging in the vehicle)
Perspectives

• Improve multibody simulations of engine dynamics
• Stress analysis of engine parts
• Design and fabrication of a twin-cylinder prototype engine (BTD)
Thank you for your attention