Compressor Flow Instabilities at Low Mass Flow Rates

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Centrifugal Compressor Flow Instabilities

Engine downsizing and turbocharging to maintain the same maximum power output
- to control emissions & improve fuel economy
**Investigated compressor: GT40**

- **Problem:** Instabilities at low mass flow rates which limit the compressor range of operation
- **Ported Shroud** solution used to extend this range

<table>
<thead>
<tr>
<th>Turbo compatibility</th>
<th>Heavy truck engine</th>
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<tbody>
<tr>
<td>Power range</td>
<td>400 to 850 kW</td>
</tr>
<tr>
<td>Number of blades</td>
<td>10 full blades</td>
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<tr>
<td>Exducer diameter</td>
<td>88 mm</td>
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<tr>
<td>TRIM</td>
<td>56</td>
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<tr>
<td>Diffuser area ratio</td>
<td>0.57</td>
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</tbody>
</table>

Ported shroud compressor supported by four unequally spaced ribs

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CCGEx at the Royal Institute of Technology (KTH) • [www.ccgex.kth.se](http://www.ccgex.kth.se)
Experimentally investigated compressor at UC

Closed ported Shroud: Stable operating condition (0.28kg/s); LES vs. experiments

Design Condition, 64k rpm; In-plane velocity magnitudes (m/s)

Fair agreement with experimental data


Experimental data provided by Dr. Gutmark and his team at Univ. of Cincinnati (UC)

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Experimentally investigated compressor at UC

Stable Operating Condition (0.28kg/s); LES vs. experiments

- Design Condition; 64k rpm; Time-averaged pressure data on the diffuser’s backplate (kPa)

- Possible causes for differences: case set-up simplifications (e.g. back-plate gap not included); the unavoidable mismatched w.r.t. Boundary Conditions

- Stable condition: uniform tangential velocity distribution with indication of some activity in the ported shroud; flow goes relatively smoothly into the compressor.
- Surge condition (0.050kg/s): Large tangential velocities; strong swirling flow motion sustained by the swirling reversed flow at the shroud.

Single point Fourier Spectra

- Tonality at 43 Hz, 1\textsuperscript{st} surge cycle harmonic, blade passing frequency and rotating order
- Broadband: mid-frequency range
- Narrowband: 250~600 Hz (peak at 0.5 RO)
- RO - rotating order of the shaft
- BPF - blade passing frequency

Sundström, Semlitsch & Mihaescu, SAE Paper: 01-2856, 2014
Extracting acoustic information

- SPL amplitude amplifies towards surge
- Broadbanded features around 0.5RO and 3RO, in agreement with other observations, e.g. Evans D. and Ward A., SAE2005-01-2485; Teng C. and Homco S., SAE2009-01-2053

Which are the developed flow structures responsible for the frequencies observed? How do they look like?

- Fourier transform; surface spectra analysis
- Proper Orthogonal Decomposition (POD)
- Dynamic Mode Decomposition (DMD)
Unstable ← Stable

Surface spectra: pressure fluctuation (RMS), unstable (Case A)


How do these modes evolve in space and time and how energetic they are?
Flow modes @ Case A /surge condition

- Quantification of flow instabilities observed
- Dynamic Mode Decomposition at surge (velocity)

Propagation wave speed ~ 340 m/s (reference point $z = -0.2$)

- Waves propagate upstream (negative slope)
- Longer wave length/period disturbances for unstable conditions

$R(r_i, \Delta t) = \frac{< p'(x_i, t)p'(x_i + r_i, t + \Delta t)>}{\sqrt{(p'^2(x_i, t))\sqrt{(p'^2(x_i + r_i, t + \Delta t))}}}$

**Upstream acoustic domain:**

**Space-time correlations based on pressure**

Outlook

- Is there a similarity in mechanism for surge at different operating conditions? (compressor speed & mass flow/volume flow)
- How does the rotor-system inertia affects instabilities?
- How does the upstream and downstream flow perturbations impact the onset of instabilities?
- How does the compressor installation (piping system & volume) influence surge?
- How one can avoid / control unwanted phenomena?
Acknowledgements

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"Charging for the future"

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