Jet Aircraft Propulsion

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Lecture 32
Off-Design Operation
Of Aircraft Jet Engines
• A cycle is normally designed at the maximum performance requirement (Thrust / Power and/or Efficiency) point.
• As a result once the engine is designed, much higher performance is not possible. But lower performance schedules are quite possible.
• Each of these ‘other’ operating points are known as a **off-design operating point**. The efficiency at these off-design points is always **lower** than the design point efficiency.
Thrust creation at design point operation

Forward gas load: 26288 kg
Rearward gas load: 21218 kg
Total thrust: 5070 kg

8658 kg
993 kg
15537 kg
17678 kg
1100 kg
2540 kg
1) All the above positive and negative thrust values shall change with different operating conditions.
2) All the above pressure, temperature and velocity values will change at different operating conditions.
3) Thus all aircraft engines are effectively variable cycle engines.
4) Except the take-off (Design point) operation, all other flight operations are at engine off-design operations.
The cycle nodal points \((a, 01, 02, 03, 04, 5)\) change during off-design operation of the engine.
A cycle analysis may be observed for an engine with afterburner. In this case the engine operation without afterburner would be deemed an off-design operation.
The turbofan engine uses a Fan and are often 2-spool. In addition to bypass ratio, $B$, it is necessary to specify fan pressure ratio, $\pi_{\text{fan}}$. 
Typical requirements of an Aircraft (subsonic) schedule

Take off → Engine Design Point

Climb to Cruise

F_n / F_{To} vs Mach number

Sea Level

2.0 km

4.0 km

6.0 km

8.0 km

10 km

Altitude

Aircraft stall limit
Typical requirements of an aircraft schedule

![Diagram showing typical requirements of an aircraft schedule]
Off-design component matching needed for

1) **Mass flow (normalized)** matching between the components
2) **Energy or Work** matching between the components
3) **Mechanical matching** (e.g. rpm of rotating components)
4) **Geometrical matching** of component sizes and interfaces
5) **Individual sub-component matching** of compr / Turbines for onset of instability
### Performance of Engine at various flight segments

<table>
<thead>
<tr>
<th>Flight segment</th>
<th>Engine Speed (% of $n_{\text{max}}$)</th>
<th>Thrust (% of Max)</th>
<th>SFC (% of Design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off (design)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Climb</td>
<td>98 - 95</td>
<td>95-90</td>
<td>98</td>
</tr>
<tr>
<td>Cruise</td>
<td>95 - 85</td>
<td>85-70%</td>
<td>95 - 110</td>
</tr>
</tbody>
</table>
Compressor Map

Design Point

Cruise

normalized mass flow $\frac{m \sqrt{T_{01}}}{P_{01}}$
Engine Map (two engine controls)

Variable: turbine inlet Temp.

Variable: engine speed (rpm)
Turbine Map showing Design point and the other operating points.
Design point matching of Turbine and Nozzle
Variable geometry nozzle at off-design operation
Compressor map

\[ \frac{P_{02}}{P_{01}} \]

Design point

Cruise

\[ \frac{T_{03}}{T_{01}} = \text{constant} \]

\[ \frac{m \sqrt{T_{01}}}{P_{01}} \]

Constant turbine inlet temperature on the compressor map.
Shifting of surge line by variable geometry (stagger) stators

Compressor map

compressor control at off-design operation
Next : ...

Component Matching Procedure