Jet Aircraft Propulsion

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Lecture 34

Engine
Component Matching
and
Sizing

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Core-engine or Gas-generator matching

1) Select Rotational speed, N , $\mathbf{N/\sqrt{T_{01}}}$, $\mathbf{N/\sqrt{T_{03}}}$
2) Select a compr. pressure ratio , $\boldsymbol{\pi_{0C} = P_{02}/P_{01}}$
3) Obtain mass flow parameter $\dfrac{\dot{m}_{air}\sqrt{T_{01}}}{P_{01}}$
4) The compressor specific work is :

$$\overline{W}_c = \frac{C_{p\text{-}air}\Delta T_{012}}{\eta_c} = \frac{C_{p\text{-}air}T_{01}}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} - 1\right]$$

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5) Obtain Compressor Turbine matching from :

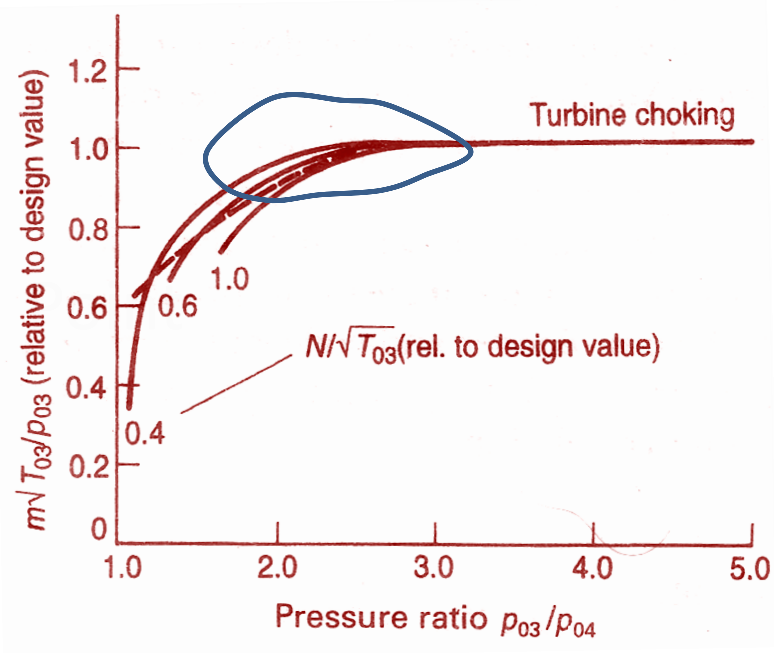
$$\dot{m}_C.\overline{W}_C = \dot{m}_T.\overline{W}_T.\eta_{mech}$$

For which, you need P_{03} / P_{04} to compute:

$$\overline{W}_T = \eta_T.C_{p-gas}\Delta T_{034} = \eta_T C_{p-gas} T_{03}\left[1 - \frac{1}{\left(\frac{P_{03}}{P_{04}}\right)^{\frac{\gamma_{gas}-1}{\gamma_{gas}}}}\right]$$

6) Select (Guess?) P_{03} / P_{04}

7) Obtain turbine mass flow parameter: $\dfrac{\dot{m}_{gas}\sqrt{T_{03}}}{P_{03}}$



8) Assume the turbine Op as shown in fig.

9) Turbine mass flow

$$\dot{m}_T = \dot{m}_c.(1+f-b)$$

10) T_{03}/T_{01} is found by mass flow balance:

$$\left(\frac{\dot{m}_{gas}\sqrt{T_{03}}.P_{01}}{\dot{m}_{air}\sqrt{T_{01}}.P_{03}}.\frac{P_{02}}{P_{01}}.\frac{P_{03}}{P_{02}}.\frac{\dot{m}_{air}}{\dot{m}_{gas}}\right)^2 = \left(\frac{T_{03}}{T_{01}}\right)$$

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11) From work done balance of the gas generator find out another value of T_{03}

$$\left(\frac{T_{03}}{T_{01}}\right)'' = \frac{\dot{m}_{air}.Cp-air}{\dot{m}_{gas}.Cp-gas.\eta_c.\eta_T} \cdot \frac{\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}}-1\right]}{\left[1-\frac{1}{\left(P_{03}/P_{04}\right)^{\gamma_{gas}-1/\gamma_{gas}}}\right]}$$

12) The two values of T_{03}/ T_{01} may not match. That means the original guess(?) of P_{03}/ P_{04} does not provide a equilibrium operating point. The steps (6) to (11) need to be iterated till convergence.

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Matching of the Power Turbine

Power turbine related parameters are :

P_{04}/P_a ; $N/\sqrt{T_{04}}$; η_{PT}; $\dfrac{\dot{m}_{gas}\sqrt{T_{04}}}{P_{04}}$;

The mass flow parameter

$$\frac{\dot{m}_{gas}\sqrt{T_{04}}}{P_{04}} = \frac{\dot{m}_{gas}\sqrt{T_{03}}}{P_{03}} \cdot \frac{P_{03}}{P_{04}} \cdot \sqrt{\frac{T_{04}}{T_{03}}}$$

Pressure ratio across the power turbine is

$$\frac{P_{04}}{P_a} = \frac{P_{04}}{P_{03}} \cdot \frac{P_{03}}{P_{02}} \cdot \frac{P_{02}}{P_{01}} \cdot \frac{P_{01}}{P_a}$$

Assuming, $P_{05}=P_{01}$
And, $P_5=P_a$

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Procedure :

1) Select a normalize speed line on the compressor map
2) Select a point on this speed line – as the operating point
3) Follow the procedure given for Gas generator to match this point with the main turbine
4) Compute power turbine pressure ratio from the equation :

$$\frac{P_{04}}{P_a} = \frac{P_{04}}{P_{03}} \cdot \frac{P_{03}}{P_{02}} \cdot \frac{P_{02}}{P_{01}} \cdot \frac{P_{01}}{P_a}$$

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5) Determine the mass flow parameter from the free turbine map

6) Compare this mass flow parameter with the computed value of

$$\frac{\dot{m}_{gas}\sqrt{T_{04}}}{P_{04}} = \frac{\dot{m}_{gas}\sqrt{T_{03}}}{P_{03}} \cdot \frac{P_{03}}{P_{04}} \cdot \sqrt{\frac{T_{04}}{T_{03}}}$$

7) If the two mass flow parameters do not agree, repeat the procedure till convergence is achieved.

8) Repeat this procedure for the other speed lines

9) The matched points on each speed line may be joined to obtain the matched operating line.

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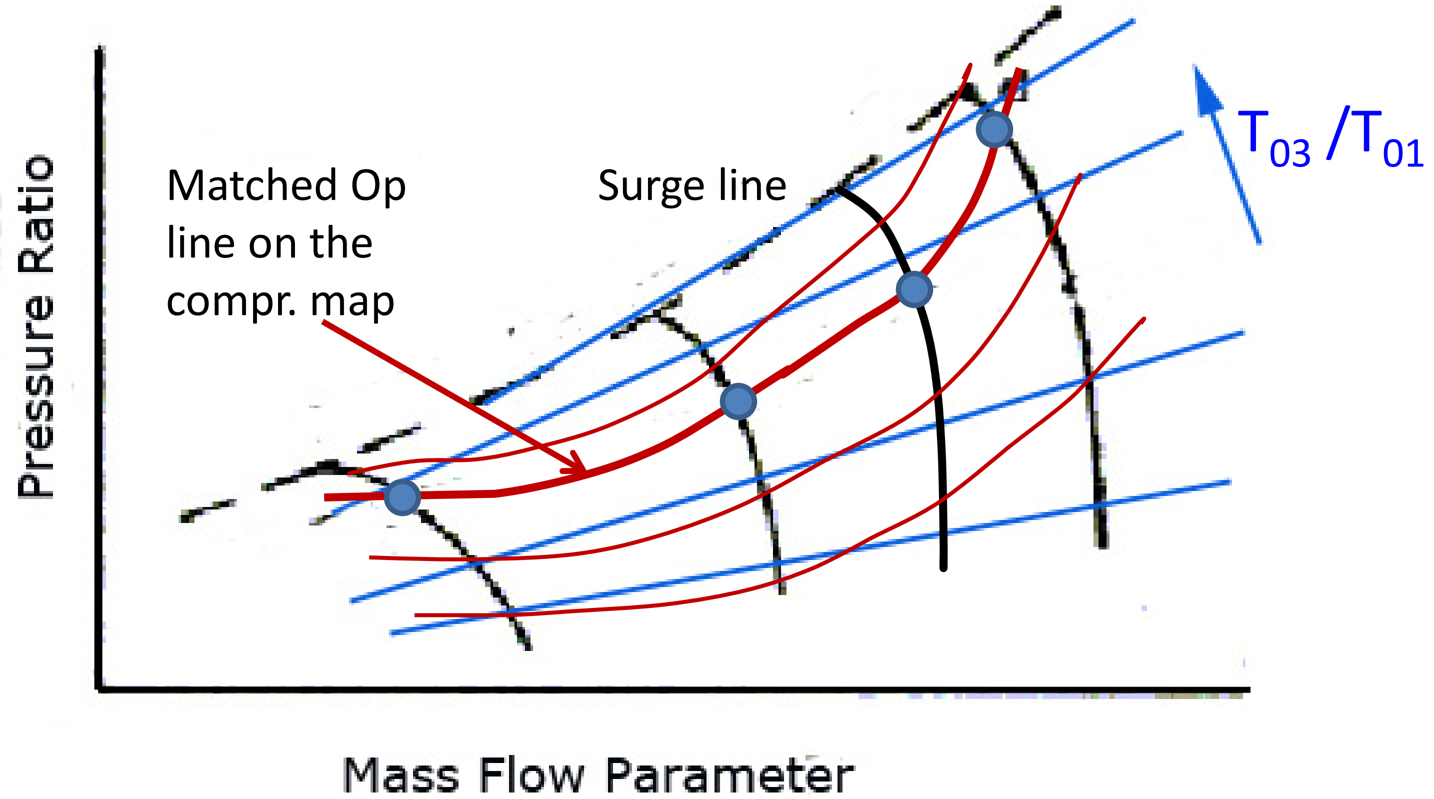
Compressor map showing matching with power turbine



The power generated by the power turbine may be computed from

$$P_T = \dot{m}_4 . C_{p\text{-}gas} \Delta T_{045} = \eta_{PT} . \dot{m}_4 . C_{p\text{-}gas} T_{04} . \left[1 - \left(\frac{1}{P_{04}/P_a} \right)^{\frac{\gamma_{gas}-1}{\gamma_{gas}}} \right]$$

Mass flow rate through the turbine may be computed from :

$$\left[\frac{\dot{m}_{gas}\sqrt{T_{04}}}{P_{04}} \right]_{matched} . \left[\frac{P_{04}}{\sqrt{T_{04}}} \right]_{actual} = \dot{m}_{gas\text{-}actual}$$

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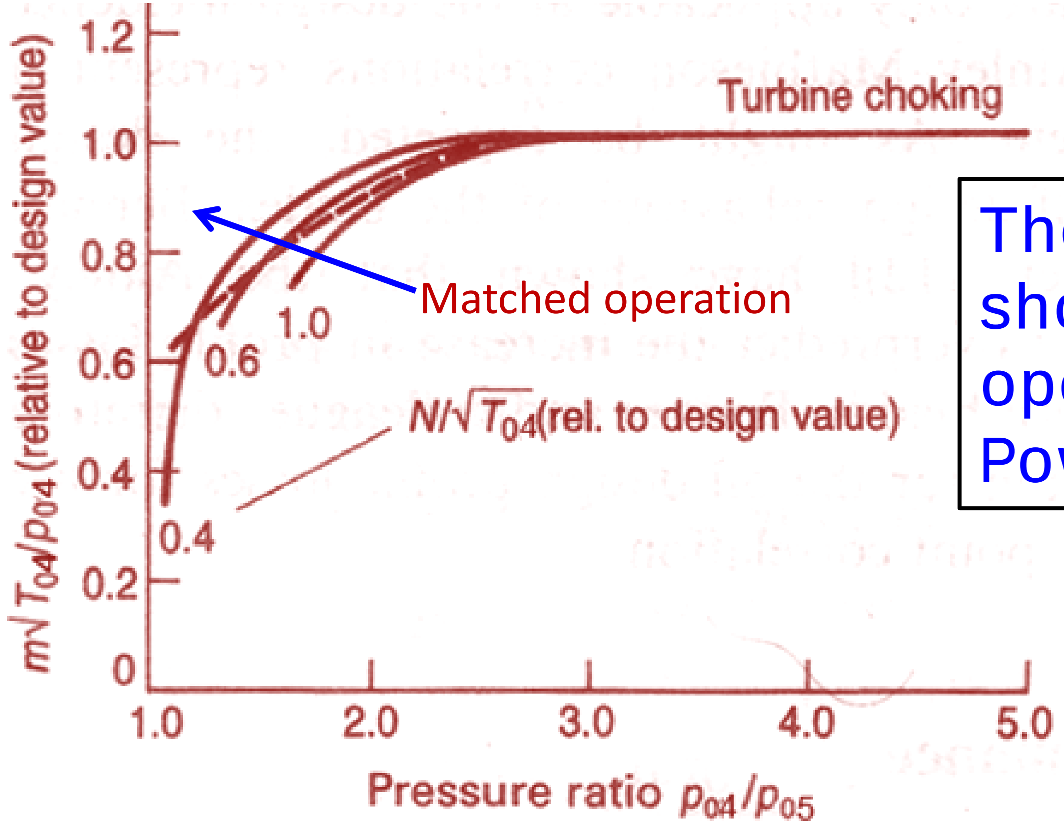
- The gas generator (core) turbine and the power turbine represent two turbines in series
- If the free turbine is choked – the core turbine will be constrained to operate at a fixed design point.



The dotted line shows matched operation on the Power Turbine map

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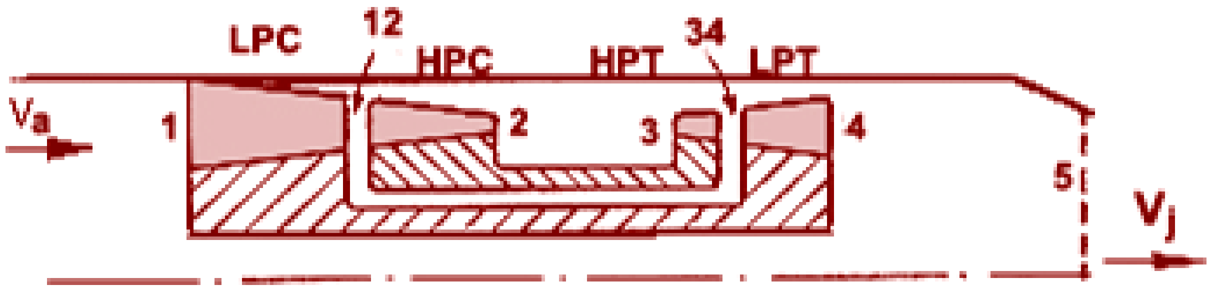
Off-Design Matching of Turbojet Engine

$$\dot{m}_C . \overline{W}_C = \dot{m}_T . \overline{W}_T . \eta_{mech}$$

(a) Single spool turbojet engine : Matching spool : Compr-Turbine



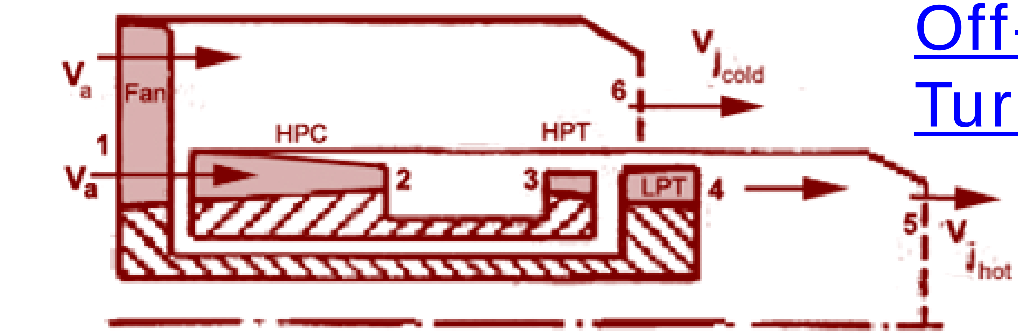
(b) Two spool turbojet engine : Matching spool-1 : LPC-LPT

Matching spool-2 : HPC-HPT

$$\dot{m}_{LPC} . \overline{W}_{LPC} = \dot{m}_{LPT} . \overline{W}_{LPT} . \eta_{mech-LP}$$

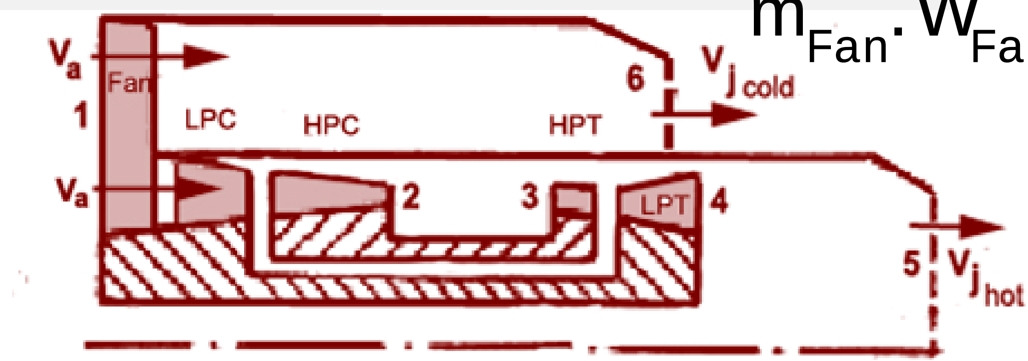
$$\dot{m}_{HPC} . \overline{W}_{HPC} = \dot{m}_{HPT} . \overline{W}_{HPT} . \eta_{mech-HP}$$

Off-design Matching of Turbo-prop, turbo-fan



c) 2-spool engine matching- spool1 - Fan + LPT, spool2- HPC + HPT

$$\dot{m}_{Fan}.\overline{W}_{Fan} = \dot{m}_{LPT}.\overline{W}_{LPT}.\eta_{mech-FT}$$



d) 2-spool engine matching - spool 1 - Fan + LPC + LPT, spool 2 - HPC + HPT

$$\dot{m}_{Fan}.\overline{W}_{Fan} + \dot{m}_{LPC}.\overline{W}_{LPC} = \dot{m}_{LPT}.\overline{W}_{LPT}.\eta_{mech-F-LPC-T}$$

$$\dot{m}_{HPC}.\overline{W}_{HPC} = \dot{m}_{HPT}.\overline{W}_{HPT}.\eta_{mech-HP}$$

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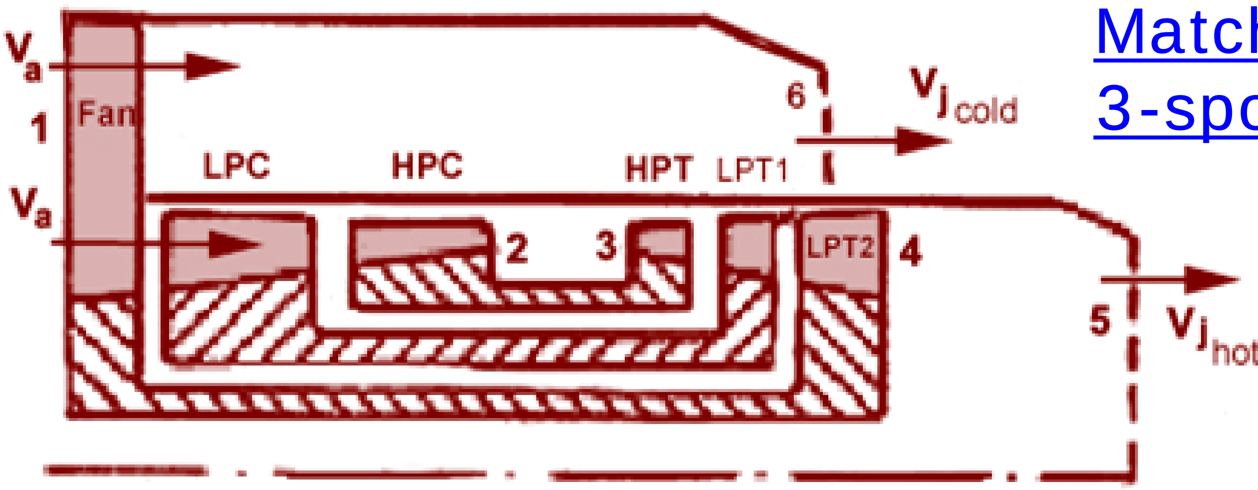
Matching of a 3-spool Engine



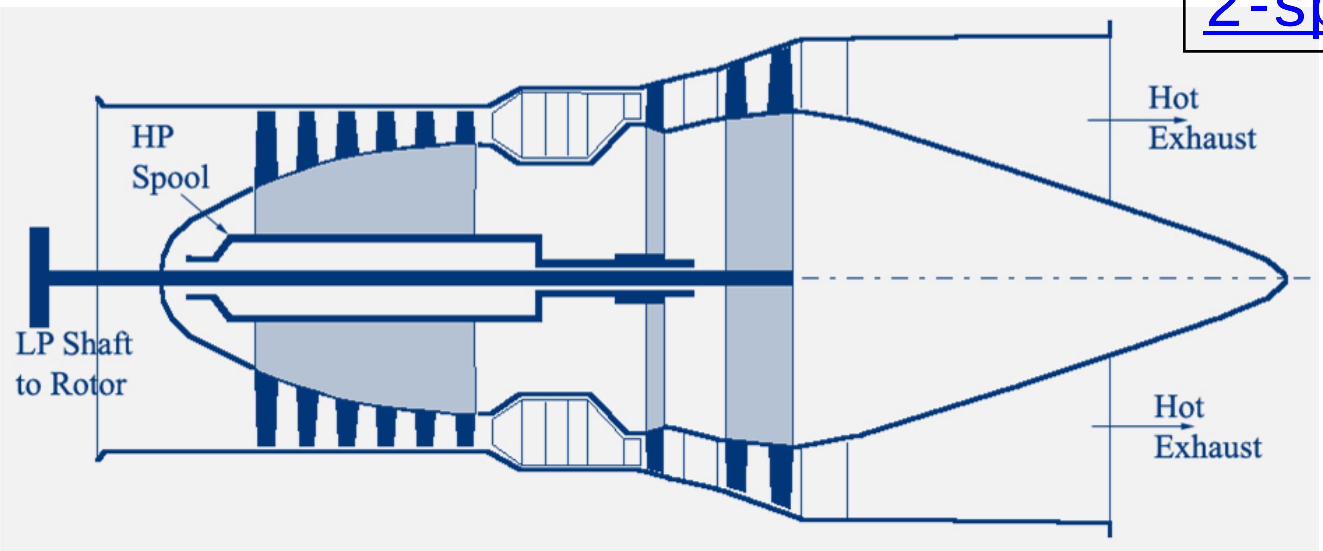
e) 3-spool engine matching - spool1 - Fan + LPT2, spool 2 - LPC + LPT1 , spool 3 - HPC + HPT

$$\dot{m}_{Fan}.\overline{W}_{Fan} = \dot{m}_{LPT2}.\overline{W}_{LPT2}.\eta_{mech-F-T}$$

$$\dot{m}_{LPC}.\overline{W}_{LPC} = \dot{m}_{LPT1}.\overline{W}_{LPT1}.\eta_{mech-LPC-T}$$

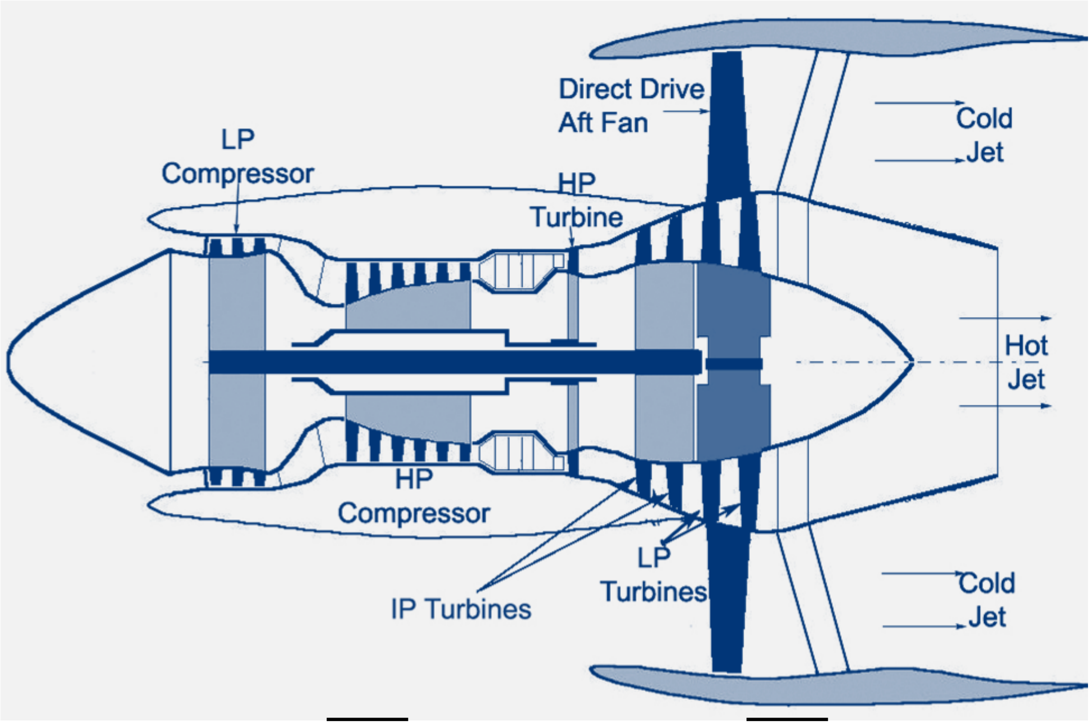
$$\dot{m}_{HPC}.\overline{W}_{HPC} = \dot{m}_{HPT}.\overline{W}_{HPT}.\eta_{mech-HP}$$

A turbo-prop or turbo-shaft 2-spool engine



$$\dot{m}_{HPC}.\overline{W}_{HPC} = \dot{m}_{HPT}.\overline{W}_{HPT}.\eta_{mech-HP}$$

$$\dot{m}_{Rotor}.\overline{W}_{Rotor} = \dot{m}_{LPT}.\overline{W}_{LPT}.\eta_{mech-Rotor-T}$$



An aft-fan engine

$$\dot{m}_{LPC}.\overline{W}_{LPC} = \dot{m}_{IPT}.\overline{W}_{IPT}.\eta_{mech-LPC-IPT}$$

$$\dot{m}_{HPC}.\overline{W}_{HPC} = \dot{m}_{HPT}.\overline{W}_{HPT}.\eta_{mech-HP}$$

$$\dot{m}_{Aft-Fan}.\overline{W}_{Aft-Fan} = \dot{m}_{LPT2}.\overline{W}_{LPT2}$$

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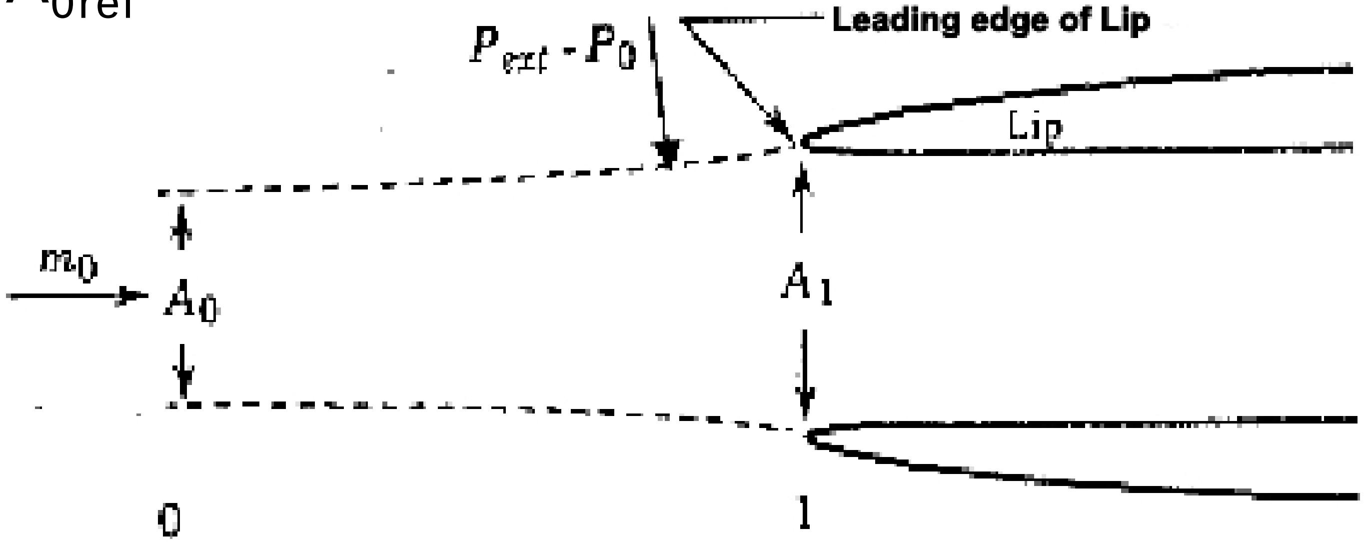
Sizing the Inlet Area (A_1)

Engine size is not fixed at the end of component design process; the initial inlet area (A_1) is connected to the free stream area of engine design air flow at its design point (A_{0ref}), giving a required value of A_1/A_{0ref}.

When the engine is resized the new inlet capture area (A_1) can be determined directly because both the sizing frpm flight conditions and the ratio A_1/A_{0ref} are constant.

The engine airflow is accelerated from the free stream Mach No. (M_0) to capture Mach No. (M_1). In order to prevent choking of the inlet, the inlet capture area (A_1) must be slightly larger than the area for choking, $A_1^* = A_0^*$.

In addition to sizing the inlet for $M_1 = 0.8$ or less to allow for boundary layer displacement, a safety margin of 4-5% is provided for any aerodynamic effects that affect the flow downstream of inlet . Therefore sizing A_1 for $M_1=0.8$, plus a 1.04 safety factor gives $A_1 = 1.04(A_1/A_1^*)_{M1=0.8} = 1.04(A_1/A_0^*)$ or, $(A_0^*/A_{ref}^*)_{M1=0.8}$ $A_0^* = (1.04)(1.038)(1.07\ A_{0ref}^*) = 1.16\ A_{0ref}$



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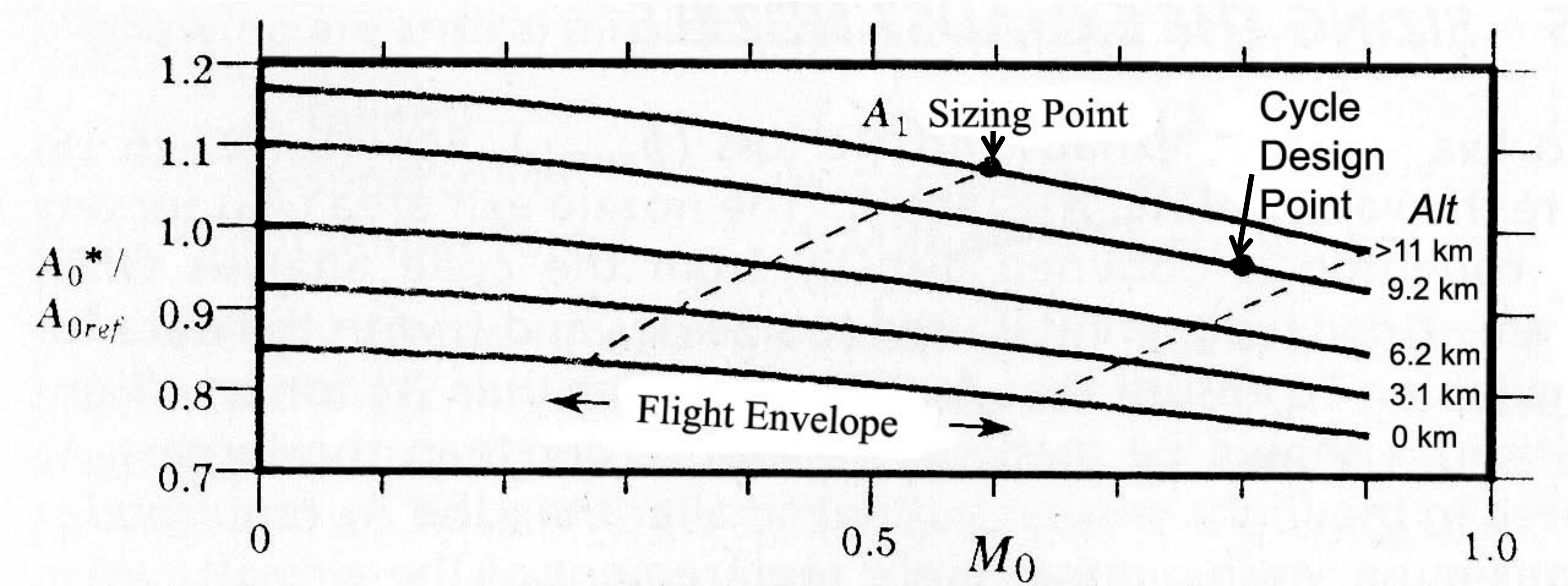
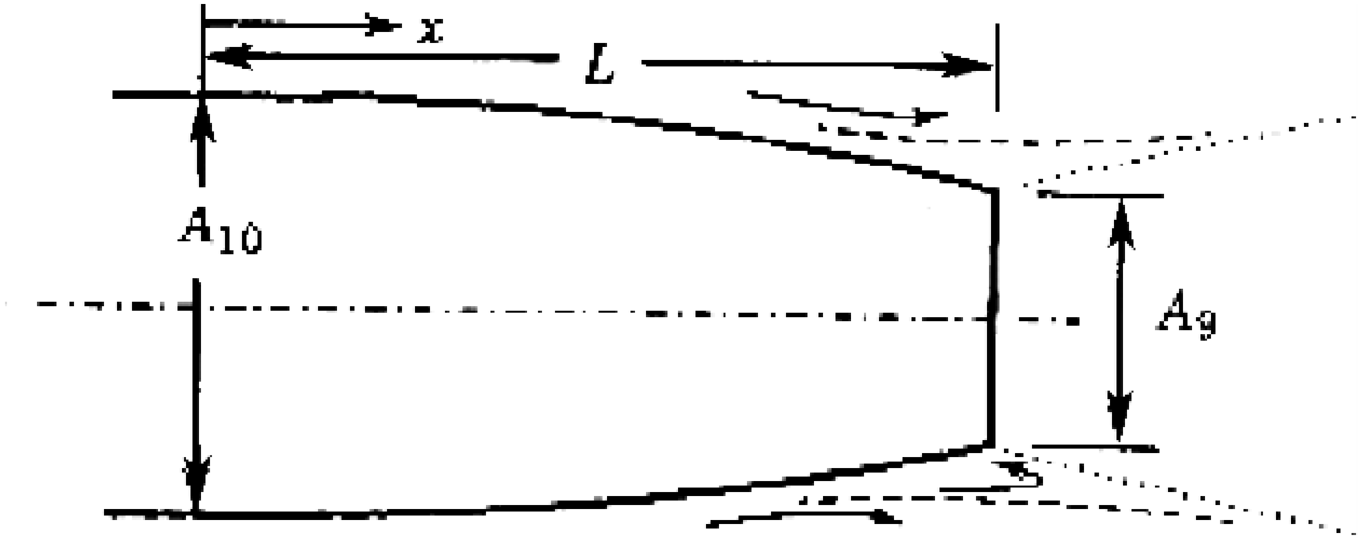

1.2
1.1
1.0
0.9
0.8
0.7
A_0^* / A_{0ref}
A_1 Sizing Point
Cycle Design Point
Alt
>11 km
9.2 km
6.2 km
3.1 km
0 km
Flight Envelope
0
0.5
M_0
1.0

Sizing the Exhaust Nozzle



To ensure that A_{10} is not smaller than A_9 for any flight condition, it should be made somewhat larger than largest A_9 required in the flight mission but not smaller than the A_9 required for maximum Mach No. flight requirement. With A_9 and A_{10} fixed, the choice of nozzle length (L) can be based on the diameters of nozzle.

Next Class :

Installed Performance of Engine

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