Axial Flow High Pressure Turbine Design

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Acknowledgement:

This course material is based partly on the lecture series of Dr. Mark Taylor (RRplc) and Dr. Neil Harvey from 2003 & 2005.

Melbourne (U.K.), February 2008

Outline

Introduction
Basic Mech. Design Considerations
Mean line design, Velocity Triangles
2D Blade design
3D Design, Blade stacking
Summary

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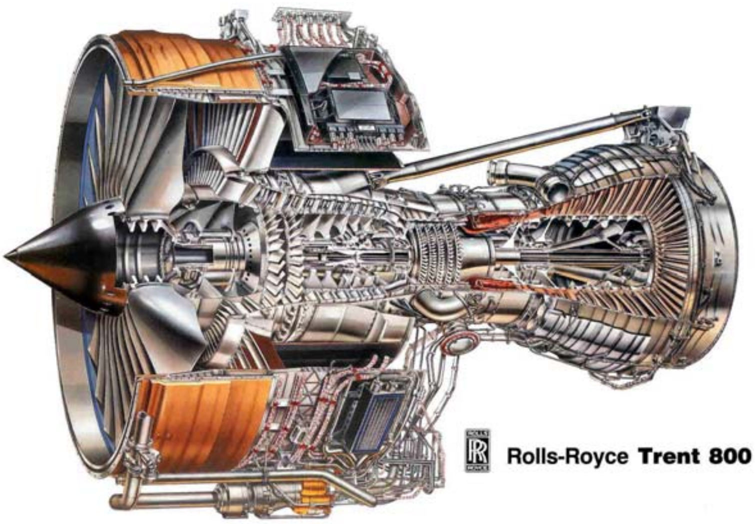
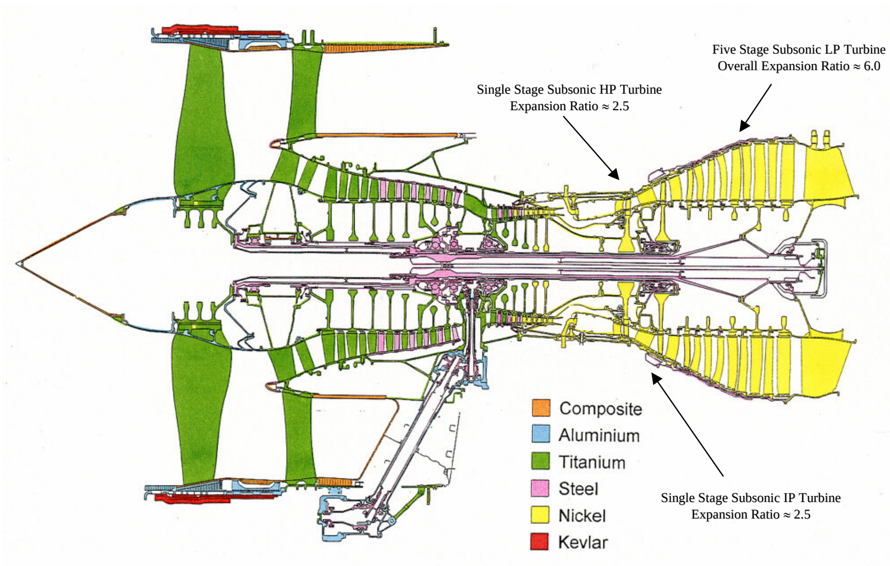
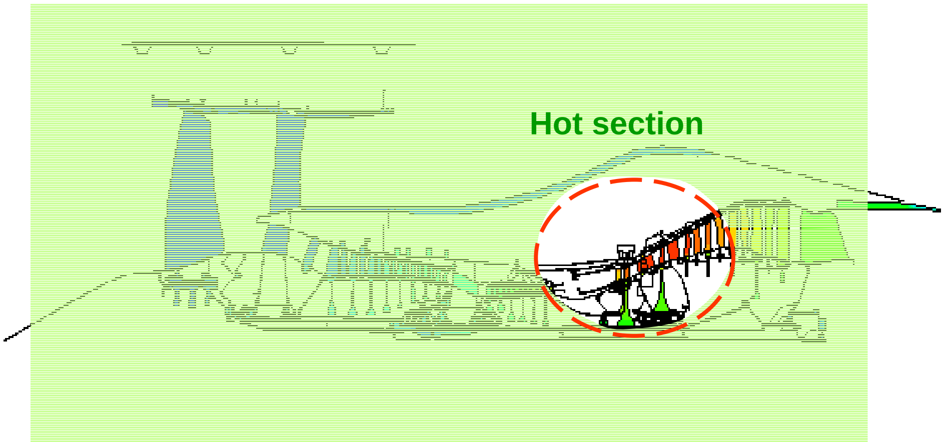


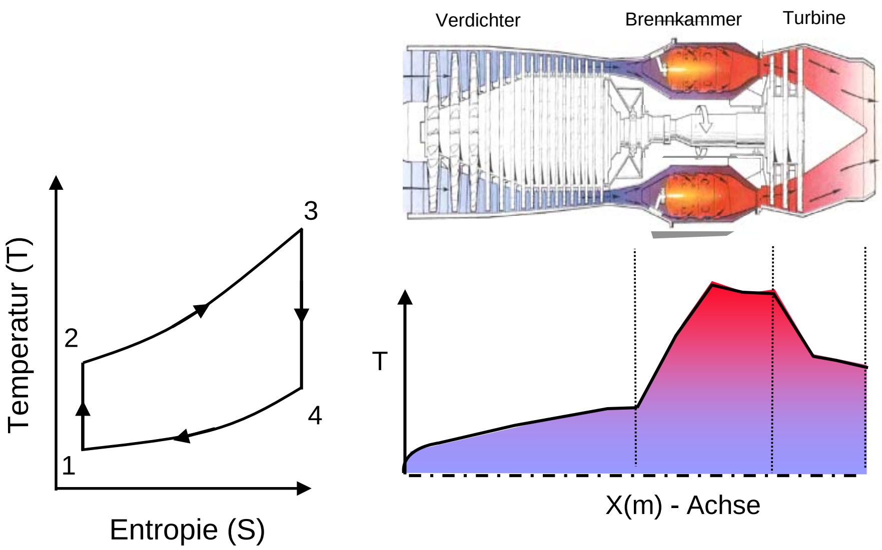
Introduction
RR High Bypass Turbofan



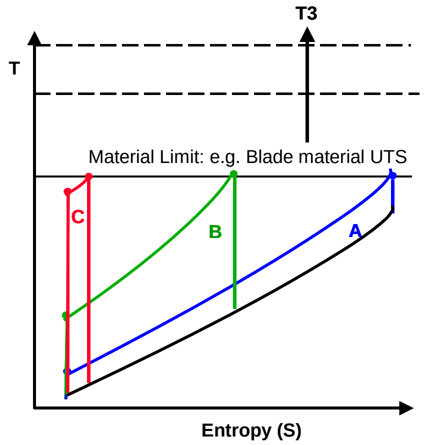
Introduction
Primary GasPath Flow Regimes

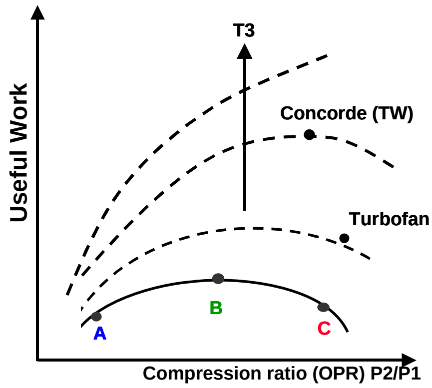


Joule (Brayton) Process: Temperature

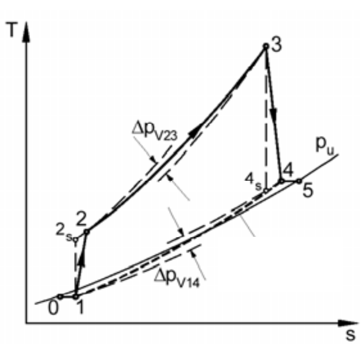


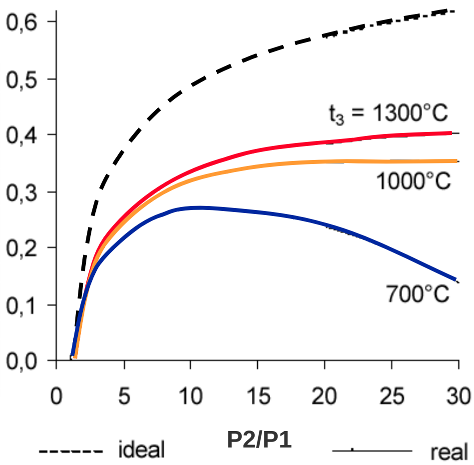
The Cycle (…a turbine engineers view)





‚Real' Gas turbine – Cycle (Efficiency)





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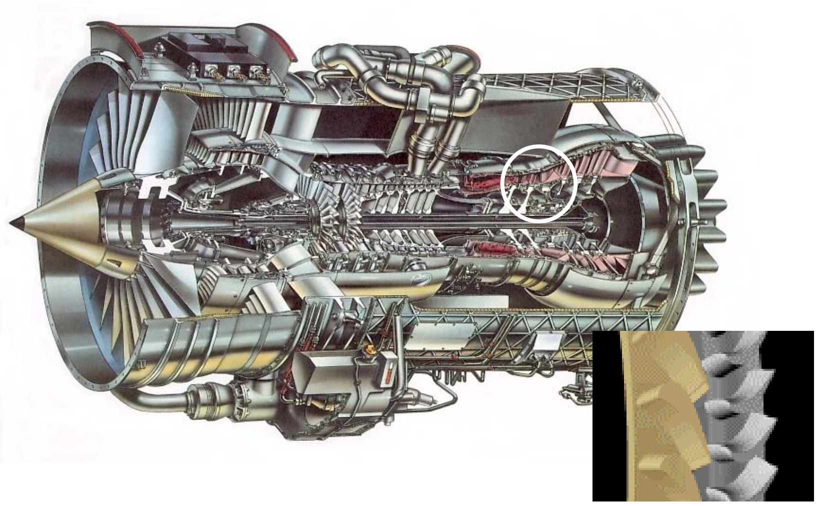

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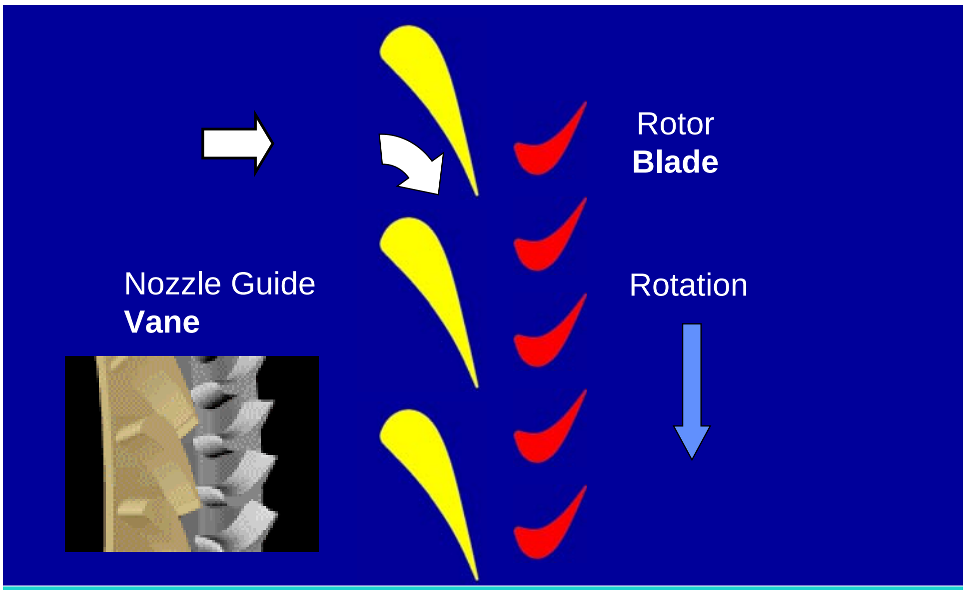
Turbine Stage



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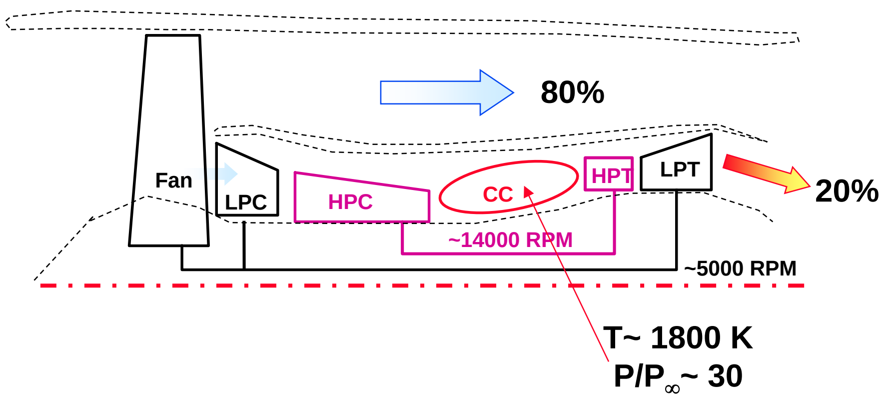
General Architecture

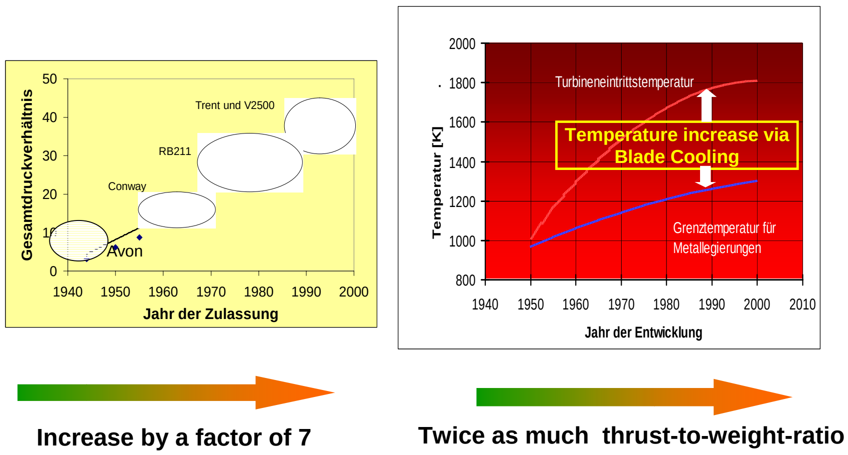
Two-Shaft Engine



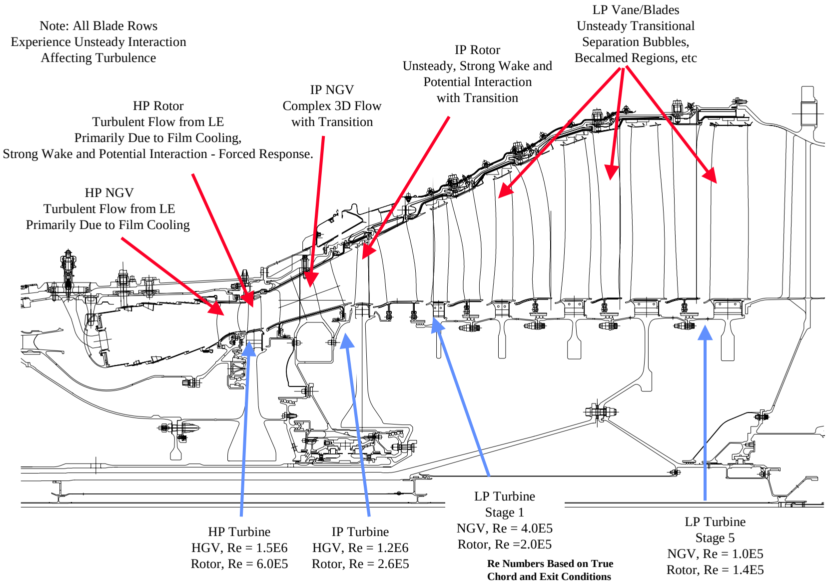
Trends in modern Jet engines

Overall Pressure Ratio

Turbine Inlet temperatures



Introduction
Primary GasPath Flow Regimes



Introduction
Some Interesting Facts about HP Turbines

The High Pressure (HP) turbine in the Trent 500 engine (Airbus 340-500/600) produces 49,000 HP (36.5MW) at take-off.

This is equivalent to the take-off power of 25 Spitfire aircraft - Merlin/Griffin engine (2000 HP).

One turbine rotor blade (70 in a T500 set) produces 700 HP which is the power output of a F1 car engine.

The gas temperature within the HP turbine is 700 degrees hotter than the melting point of the blade material.

The cooling load of the HP turbine will boil a domestic kettle in 0.05sec.

The HP turbine blade is subjected to a gravitational load of 60,000g at take-off.

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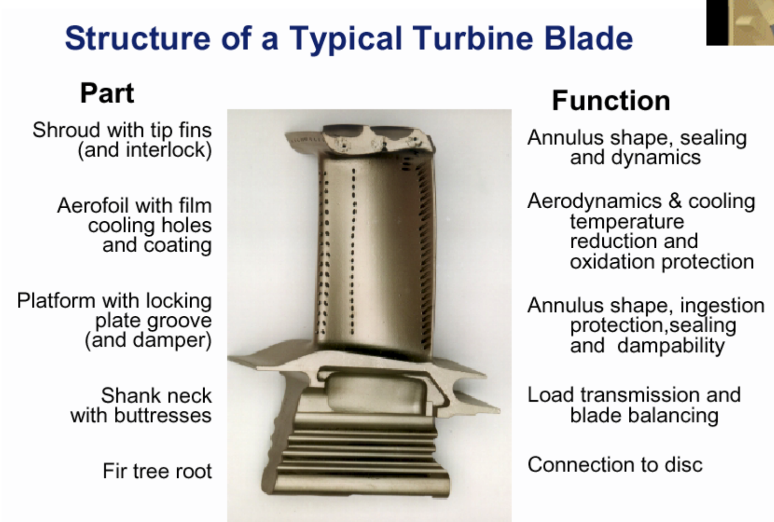
Turbine Blade



Turbine Blade

Loading on a Typical Turbine Blade

Mechanical loading

Tensile CF load

CF off-set bending moment

Pre-twist torsional moment

Gas bending moment

Cyclic loading

Dynamic loading

Thermal loading

High metal temperature

Local peak temperature

Large thermal gradient

Transient overshoot

Cyclic thermal loading

Stress concentration due to geometrical features

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Turbine Blade

Damage on a typical Turbine Blade

Erosion of coating

Oxidation of substrate

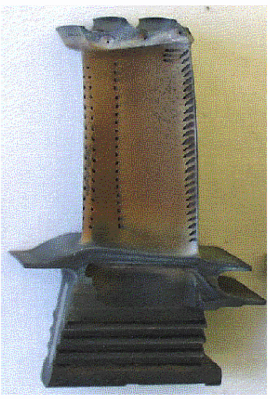
High Cycle Fatigue (HCF)

Low Cycle Fatigue (LCF)

Creep

Combined damage (CFI)

Thermal-Mechanical Fatigue (TMF, TGMF)



Tip fin rubbing

Shroud curling due to creep

Hot spot at LE & TE

Creep growth of aerofoil

Platform rubbing with static components

FOD on the aerofoil

Cracking on root fir tree

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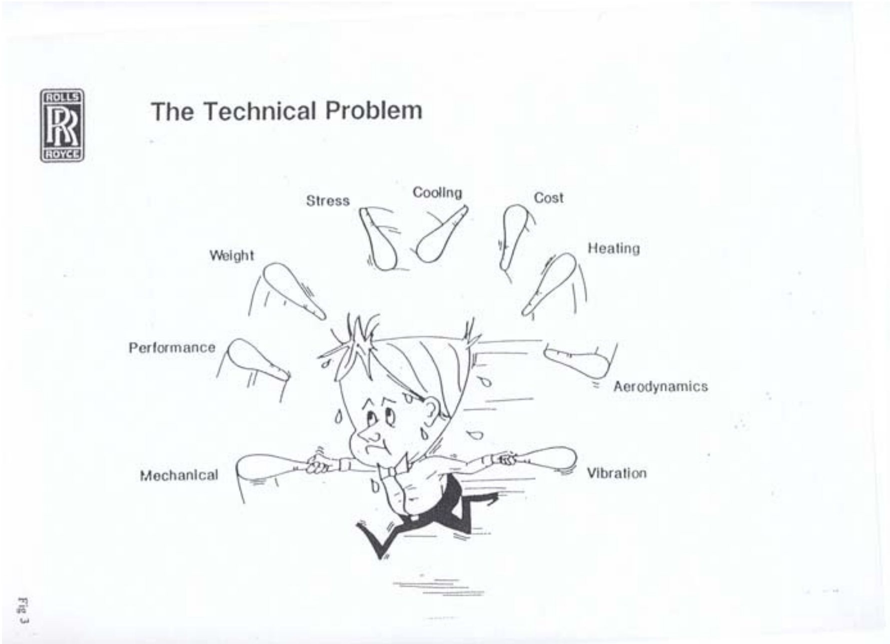

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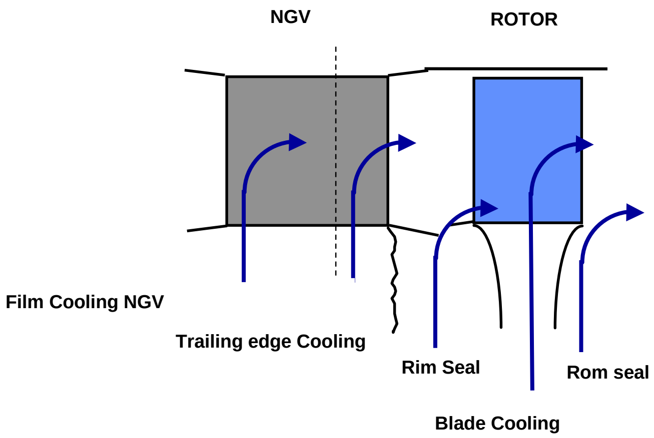
Turbine Cooling



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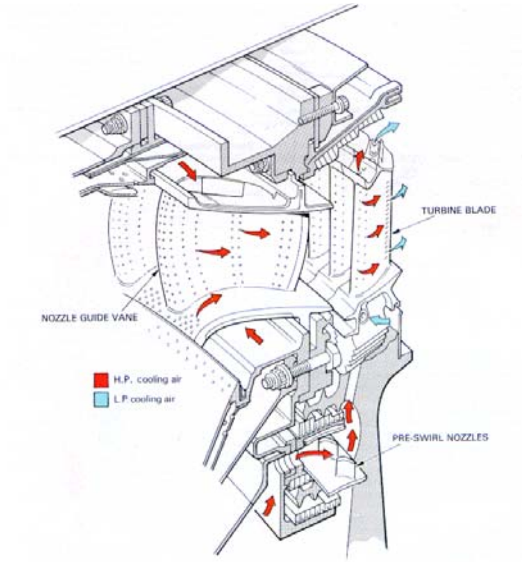
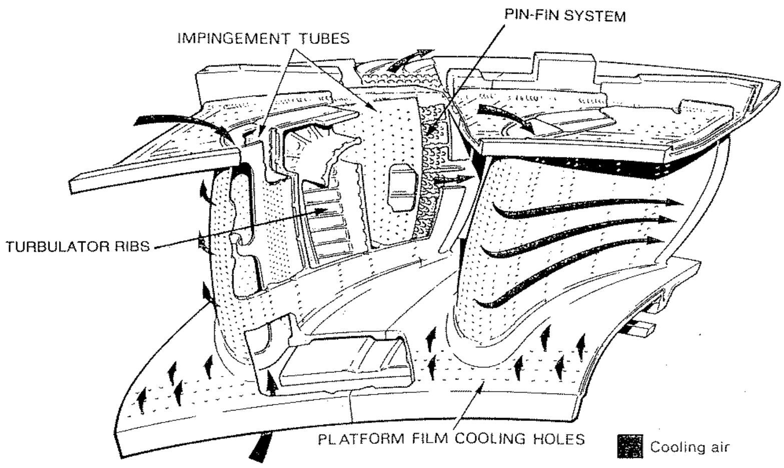
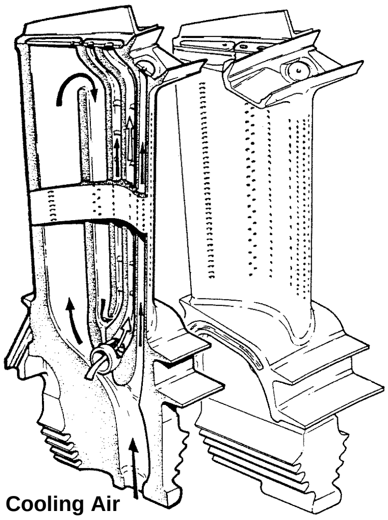
Turbine Secondary Air System (Cooling)



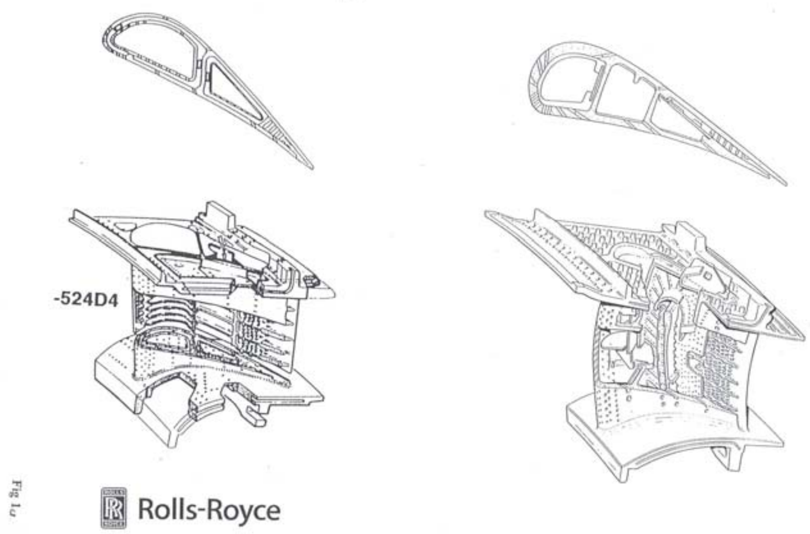
Cooling System of a Rolls-Royce High Pressure Turbine Nozzle Guide Vane

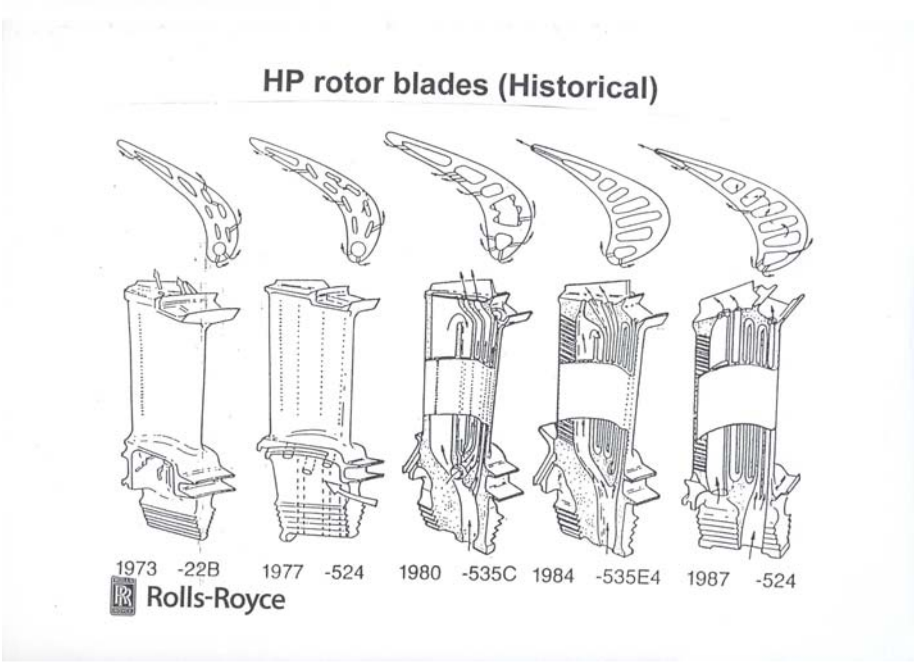


Cooling System of a Rolls-Royce High Pressure Turbine Rotor Blade

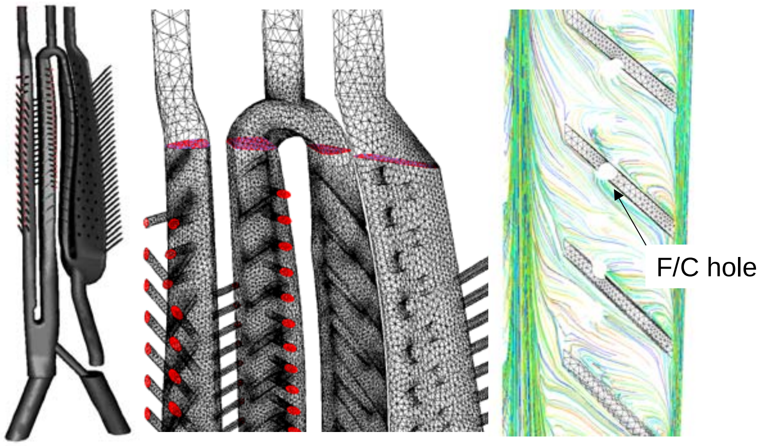


Typical HP NGV's

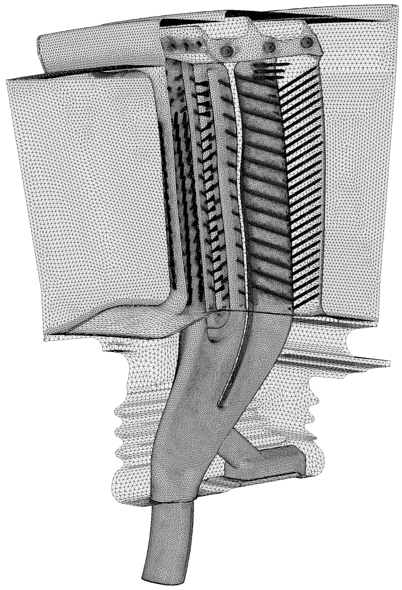




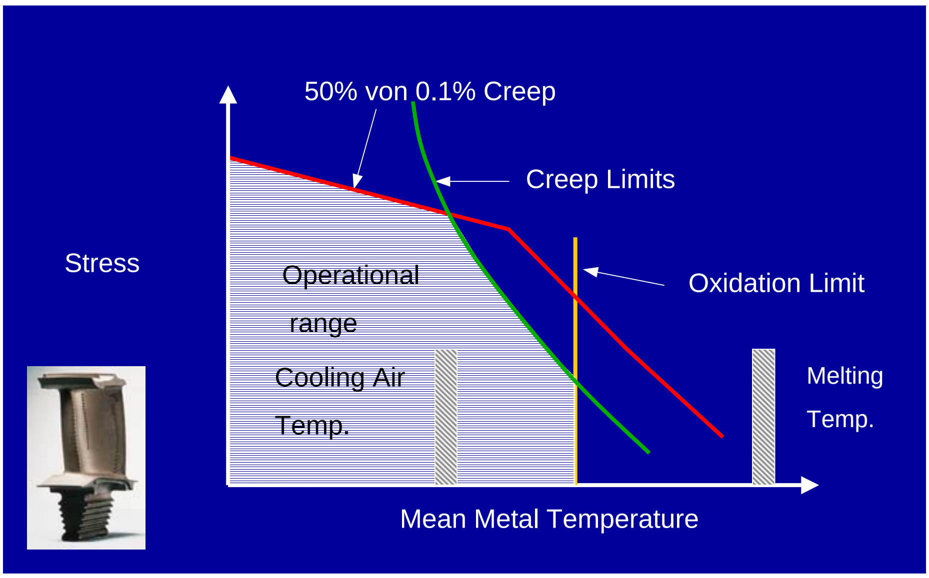
3D Computational Fluid Dynamics



3D Computational Fluid Dynamics



Blade – Mechanical Design Limits



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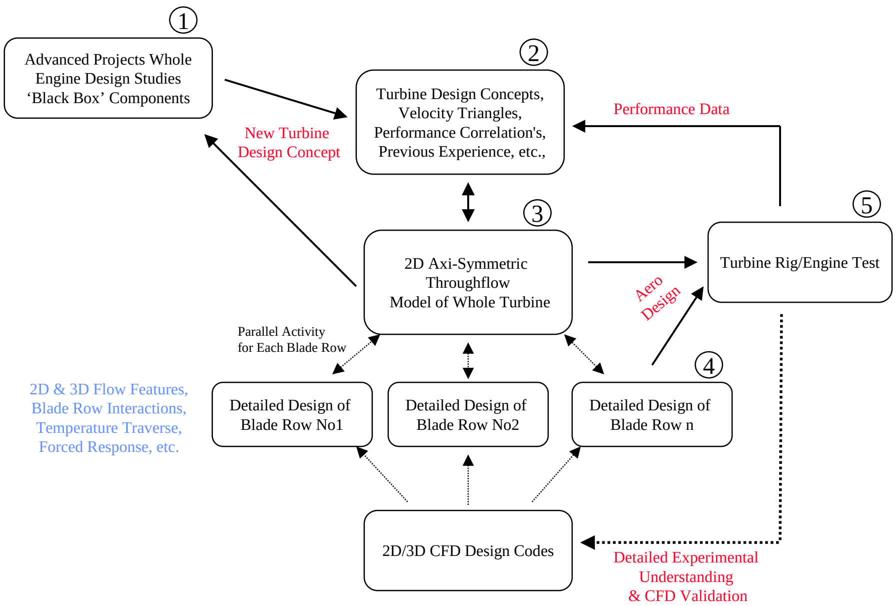
Introduction

How Do We Undertake an Aerodynamic Design?



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Aerodynamic Design Process Overview

Preliminary Annulus Design

- Velocity Triangle, Basic Rules, Efficiency Charts,
- One-Dimensional Mean Line Methods,

Preliminary Annulus/Vortex Design

- Two-Dimensional Throughflow & Correlations,

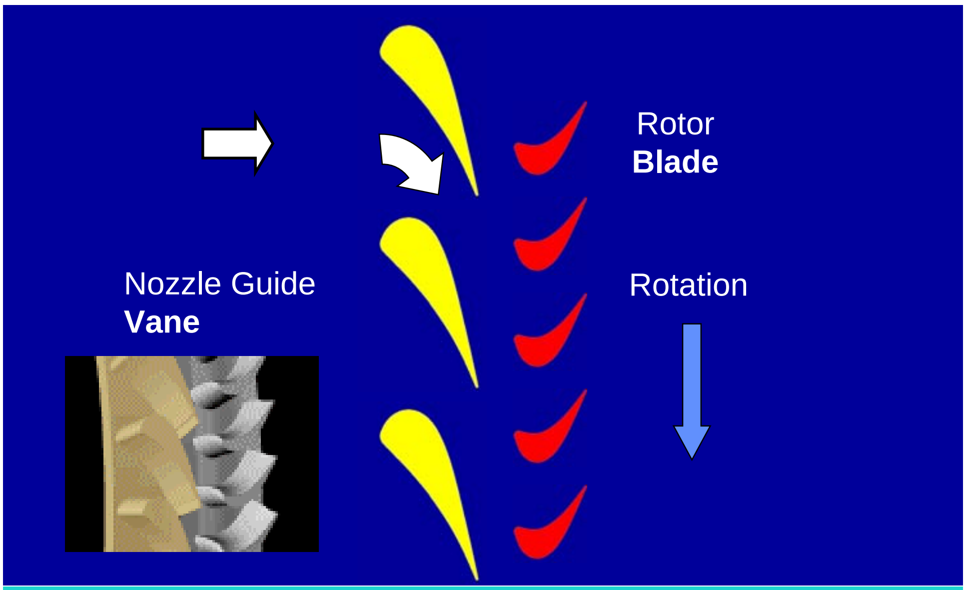
2D Aerofoil Design

- Design of a Passage,
- Prescribed Velocity Distribution - Inverse Design,

3D Aerofoil Design

- Aerofoil Stacking,
- Contoured Endwalls.

Turbine Stage



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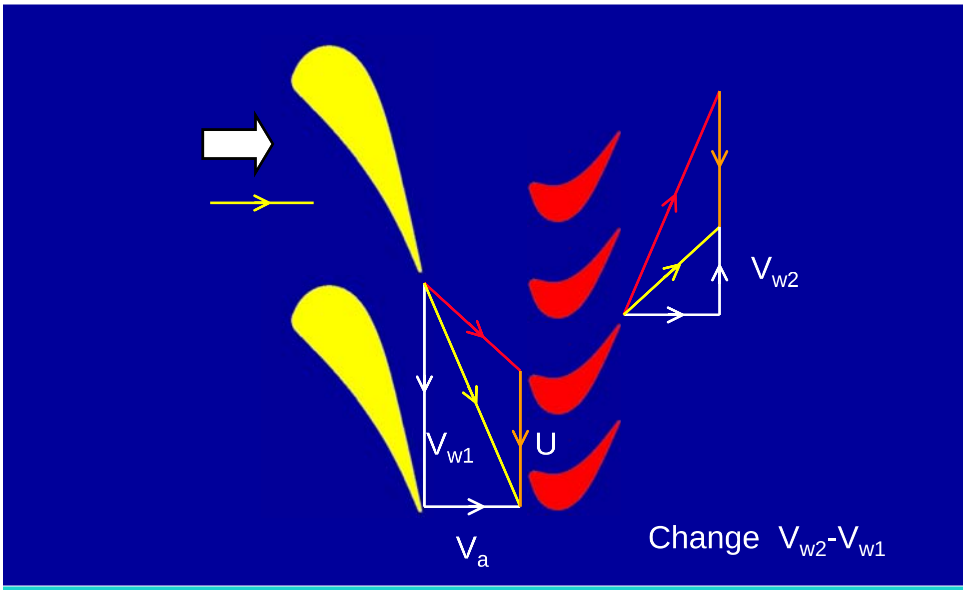
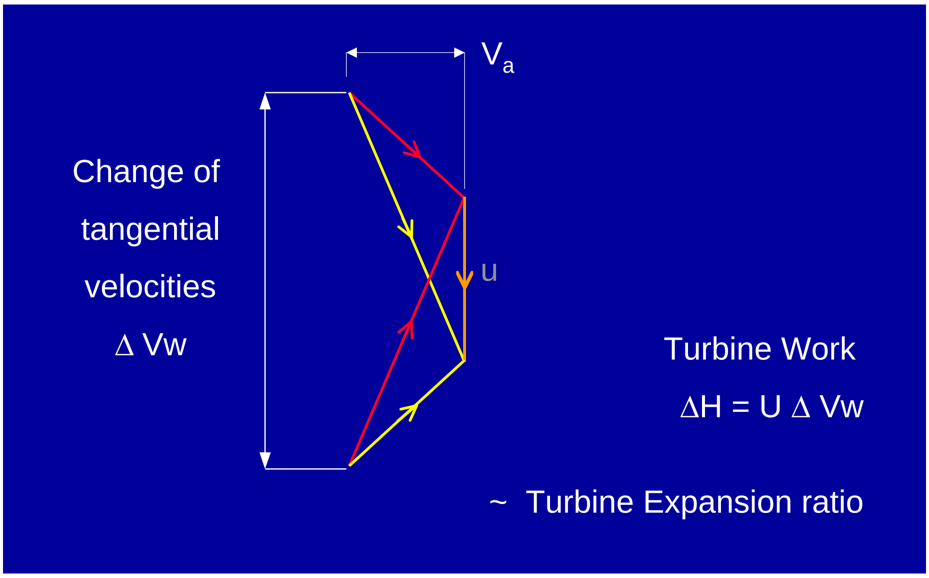
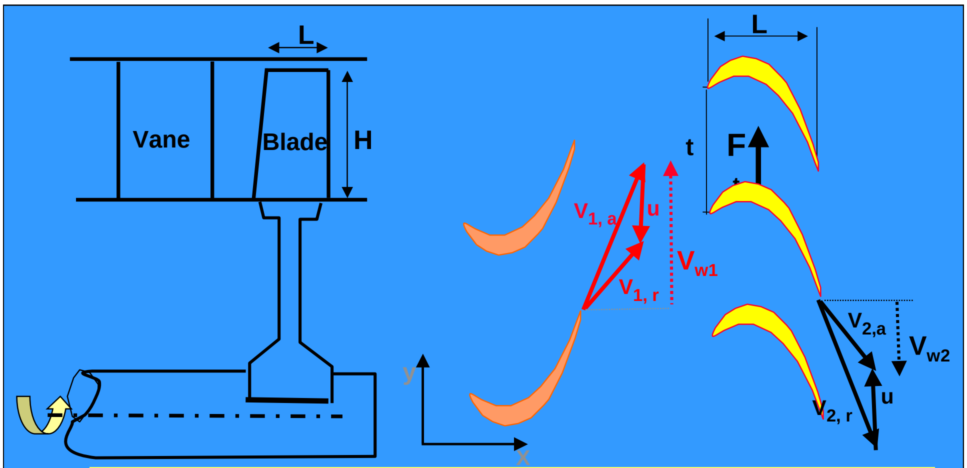
Turbine Velocity Triangle



Velocity Triangle



Turbine - Force – Blade Loading

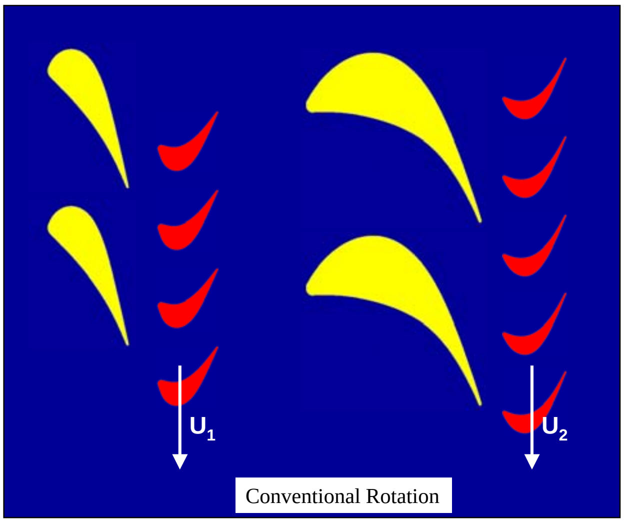


Power: $P = M \cdot \Omega = \text{Torque} \cdot \text{Rotation}$

Torque Moment : $M = \dot{m} \cdot (V_{w1} - V_{w2}) \cdot R = NOB \cdot F_t \cdot R$

Tangential Force : $F_t = (p_{PS} - p_{SS}) \cdot H \cdot L$

Introduction
Types of Turbines - Conventional Rotation

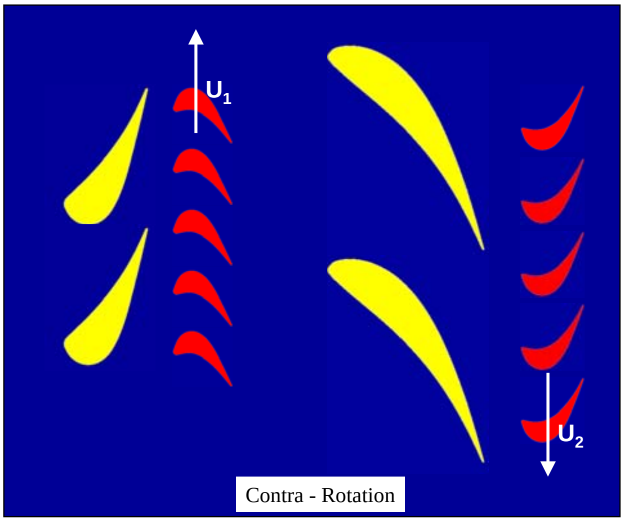


Industry standard design RR, P&W, GE, etc.,

Use in the RB211's, Trent Series, EJ200, etc,

Vanes turn and accelerate flow for next blade row.

Introduction
Types of Turbines - Reverse Rotation



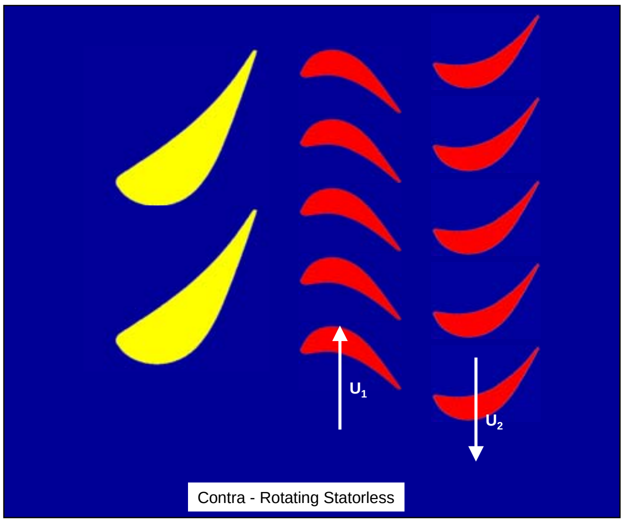
Innovative technique to reduced the turning in the second vane (90 ⇒ 40 degrees).

Resulting in a significant reduction in the secondary loss, and hence improvement in stage efficiency.

RR demonstrated technique on cold flow rig, and have now designed a reverse-rotation IP turbine for the T900 (Airbus A380 - first engine run March 2003).

Although reverse-rotation means that the exit flow from the first rotor is in the correct sense for the second rotor, the second vane is still required to achieve the required whirl velocity for the second rotor, i.e., comparable work on the 1st and 2nd stages.

Introduction
Types of Turbines - Contra-Rotating Statorless



Removal of 2nd vane, resulting in improved efficiency (maybe through reduced cooling), reduced cost & weight.

Technique used in military turbines, RR XJ99 lift fan, F120/136 JSF engines (GE & PW).

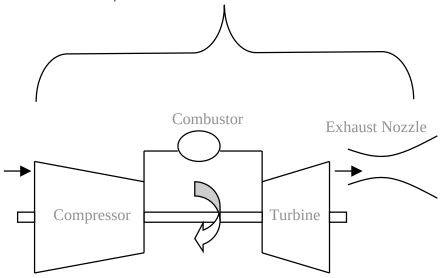
Possible future RR turbine design for civil aircraft. Limitation of this type of turbine is that the work produced by first rotor is around 2 to 3 times greater that that of the second (at conventional shaft speeds).

First rotor exit whirl velocity is limited by exit Mach number ⇒ supersonic design and high reaction.

Introduction
Factors Influencing Turbine Efficiency

Engine Thermodynamic Cycle Improvements,

- Increase Inlet Total Pressure and Temperature (PR),
- Reduced Core Inlet Capacity (Increased Bypass Ratio),
- Increased Specific Work on Core Turbines,
- Cooling and Leakage Flows Have Greater Effect,
- Mechanical Features Do Not Scale - Seals, Bearings, Shafts, etc.



Turbine Efficiency Improvements Resulting From

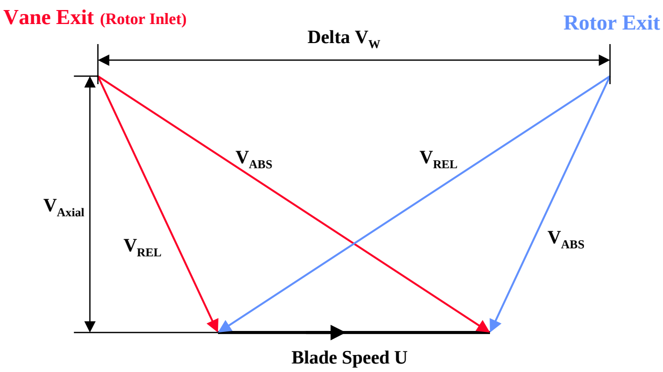
Improved Aerodynamic Component Efficiencies (η_{row})

- Secondary Flows - Reverse Rotation, Contoured Endwalls,
- Improved Cooling Design,
- Reduced Leakage Flows,
- Improved Trailing Edge Designs and Thinner Trailing Edges,

Improved Mechanical and Manufacturing Technologies,

- Disk Technology Limits Blade Speed $U_{B\ mean}$ - Mach Number,
- Blade/Disc Stress Limits Annulus Area (AN^2) - Axial Mach Number
- Casting Technology (Yield) Limits Trailing Edge Size,
- Tip Clearance Control (Shroudless Rotor) - Efficiency Improvements Available from Increased $U_{B\ mean}$, Reduced No Off, etc., Offset by Tip Leakage Increase,
- Seal Leakage Proportionally Greater - Mechanical Features Do Not Scale,
- Casting Technology Limits Cooling Hole Size and Internal Feed Geometry - Reduced Cooling Effectiveness

Preliminary - Annulus Design
Velocity Triangles, Basic Rules and Efficiency Charts
Velocity Triangles



Velocity Triangle

Preliminary - Annulus Design

Velocity Triangles, Basic Rules and Efficiency Charts

Turbine Design Parameters

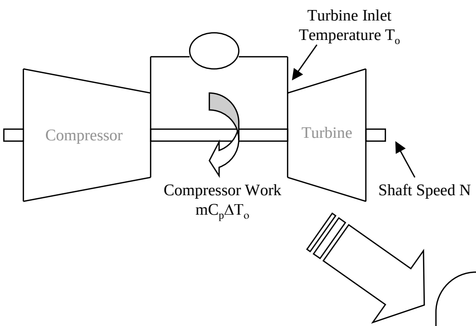
$\dfrac{C_P \Delta T_o}{T_o}$	Specific Work
$\dfrac{N}{\sqrt{T_o}}$ & $\dfrac{U}{\sqrt{T_o}}$	Engine & Turbine Non-Dimensional Speeds
$\dfrac{\Delta H}{U^2}$	Stage Loading
$\dfrac{V_A}{U}$	Flow Coefficient (Flow Function)
$\dfrac{m\sqrt{T_o}}{P_o}$	Inlet Capacity
$\dfrac{t_2 - t_3}{T_{o1} - t_3}$	Stage Reaction

where, Cp specific heat at constant pressure $Jkg^{-1}K^{-1}$, P_o total pressure kPa, T_o total temperature K, t static temperature K, N rotational speed rpm, U blade velocity ms^{-1}, H specific enthalpy $Jkg^{-1}K^{-1}$, Va axial velocity ms^{-1}, m mass flow rate kgs^{-1}.

Preliminary - Annulus Design

Velocity Triangles, Basic Rules and Efficiency Charts

Cycle Requirements



Fixed Specific Work, $\dfrac{C_P \Delta T_o}{T_o}$

Inlet Capacity & $\dfrac{m\sqrt{T_o}}{P_o}$

Engine Non-Dimensional Speed $\dfrac{N}{\sqrt{T_o}}$

Preliminary - Annulus Design
Velocity Triangles, Basic Rules and Efficiency Charts
Work Equation

$$\text{Work Done By Turbine}_{\text{(assuming cont radius)}} = \text{m U } \Delta V_W$$
$$\text{Energy Extracted From Fluid } = m\Delta H = mC_P\Delta T_o$$

As the work done by the turbine equals the energy extracted from the fluid, combining the above equations and simplifying;

$$\frac{\Delta H}{U^2} = \frac{\Delta V_W}{U} \qquad \frac{\Delta H}{U^2} = \frac{\Delta V_W}{U}$$

From the above equation it is clear that stage loading is the width of the velocity triangles to the length of the base. Note: For fixed flow coefficient (Va/U), high stage loading leads to high turning in both the vane and the blade.

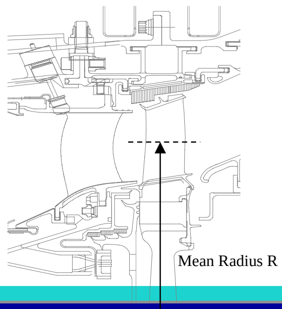
Dividing the above equation by U^2 and multiplying through by, $(\sqrt{T_o})^2$, gives;

Preliminary - Annulus Design
Velocity Triangles, Basic Rules and Efficiency Charts
Work Equation

$$\frac{\Delta H}{U^2} = \frac{C_P \Delta T_o}{T_o} \Big/ \left(\frac{U}{\sqrt{T_o}} \right)^2$$

Hence, the stage loading is equal to the specific work divided by the square of turbine non-dimensional blade speed.

As the Advanced Projects Department (preliminary cycle design) will not have set the mean diameter, the mean blade speed U is still free to be adjusted by the turbine designer.



$$U = \frac{2\pi N}{60} * \text{Mean Radius}$$

Stage Loading

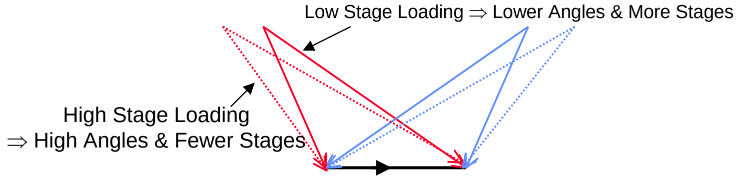
The stage loading $\frac{\Delta H}{U^2}$ of the turbine can now be set with an appropriate mean diameter. Typical stage loading are;

HP turbine	**1.5 - 2.0**
IP turbine	**1.5 - 2.0**
LP turbine	**2.0 - 3.0**

Note: As stage loading is proportional to the width of the triangles to the length of the base, i.e., $\frac{\Delta H}{U^2} = \frac{\Delta V_W}{U}$

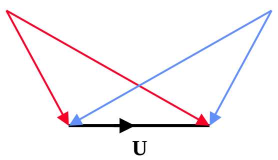
High stage loading leads to higher turning and an increase in Mach Number, however there is more work per stage, which can lead to fewer stages.

Low stage loading leads to lower turning and a decrease in Mach Number, however you are not getting the best out of the turbine.

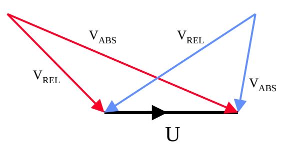


Reaction

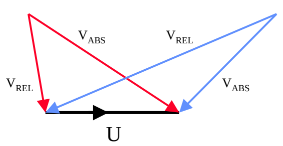
As 2-D loss is approximately proportional to the square of Mach number, from the velocity triangles you might expect that minimum loss will occur when the triangles are symmetrical (assuming Vane η_{row} = Rotor η_{row}).



This is the condition of 50% reaction, i.e., the same expansion over the vane as the rotor. As reaction is the amount of expansion over the rotor, low reaction (< 50%) leads to increased expansion over the nozzle and reduced expansion over the rotor and visa-versa.



Low Reaction



High Reaction

Preliminary - Annulus Design

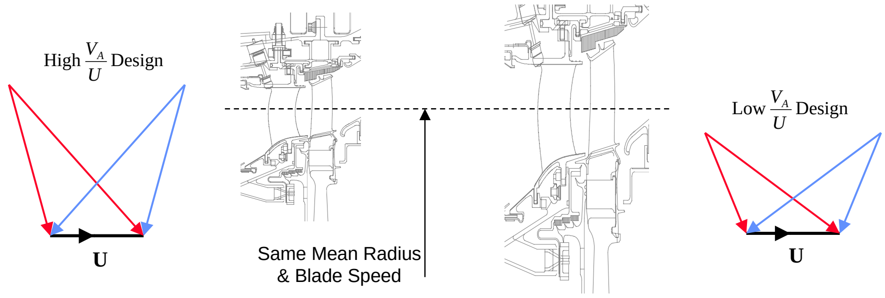
Velocity Triangles, Basic Rules and Efficiency Charts

Reaction and Flow Coefficient

For a conventional HP turbine it is common practice to use 45% reaction as this leads to reduced relative total temperature (and pressure) in the rotor ($T_{OR} = T_O + \frac{1}{2C_p}\left(V_{rel}^2 - V_{abs}^2\right)$, V_{abs} reduces more than V_{rel}), reduced inlet angles to the following nozzle (less turning) and reduced bearing loads. This is a compromise and will not necessary lead to the best design.

Flow Coefficient $\frac{V_A}{U}$, is the height of the velocity triangles to the length of the base.

Once this parameter is selected the velocity triangles are effectively 'locked up'. As the mean diameter is fixed, changing V_A adjusts the height of the annulus, and hence the hub and case diameters (hub/tip ratio).



Preliminary - Annulus Design

Velocity Triangles, Basic Rules and Efficiency Charts

High Flow Coefficient (Va/U)

Increased $\frac{V_A}{U}$, leads to increased Mach Numbers, reduced exit angles and turning in both the vane and rotor, and a smaller annulus height. This will result in increased aerofoil chord and/or numbers off (increased trailing edge loss) to achieve the required work (sail area) and increased cost.

In addition the aspect ratio of the aerofoils will be reduced, resulting in increased secondary loss. However, the turbine is smaller and lighter and the blade stress will be reduced (i.e., AN^2 will reduce).

As the hub diameter will increase, there is the potential for more leakage loss due to the increased area of the seals. At the casing the overall result depends on two opposing effects, as the area of the seals is reduced there is the potential for reduced leakage, however, assuming the tip gap is fixed, the tip gap to height ratio of the rotor will increase, providing the potential for increased tip leakage flow per unit area.

Due to the size and weight constraints of military aircraft, and the fact that efficiency (thrust/weight is the main design target) and cost are not as high priority, many military turbine are high Va/U designs.

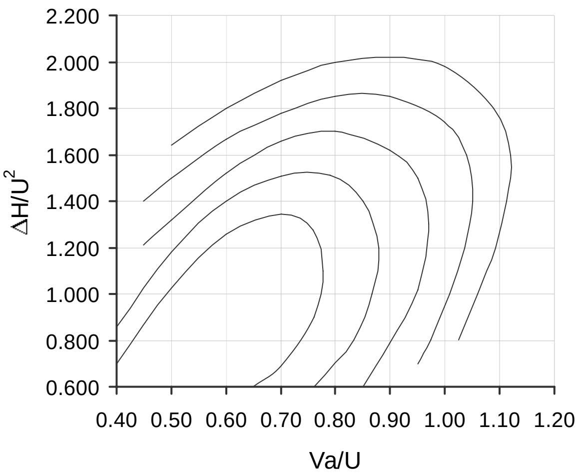
Typical values for flow coefficients;

HP turbine	**0.4 - 0.6**
IP turbine	**0.4 - 0.6**

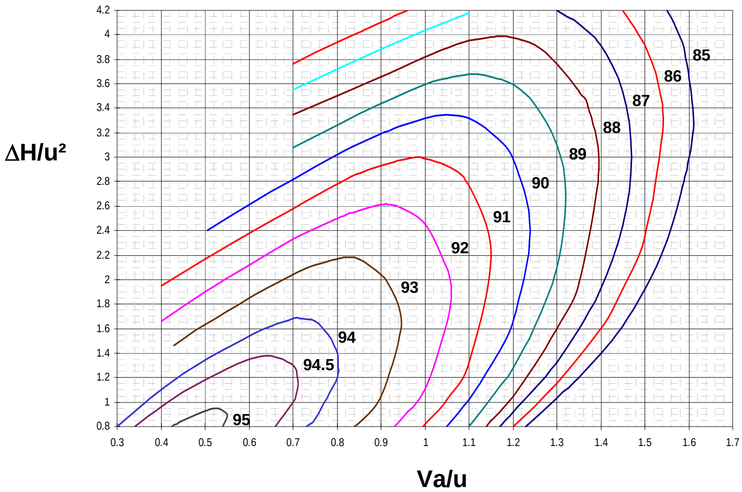
Smith or Swindell Chart

Plot shows efficiency as a function of stage loading ($\Delta H/U^2$) and flow(Va/U)

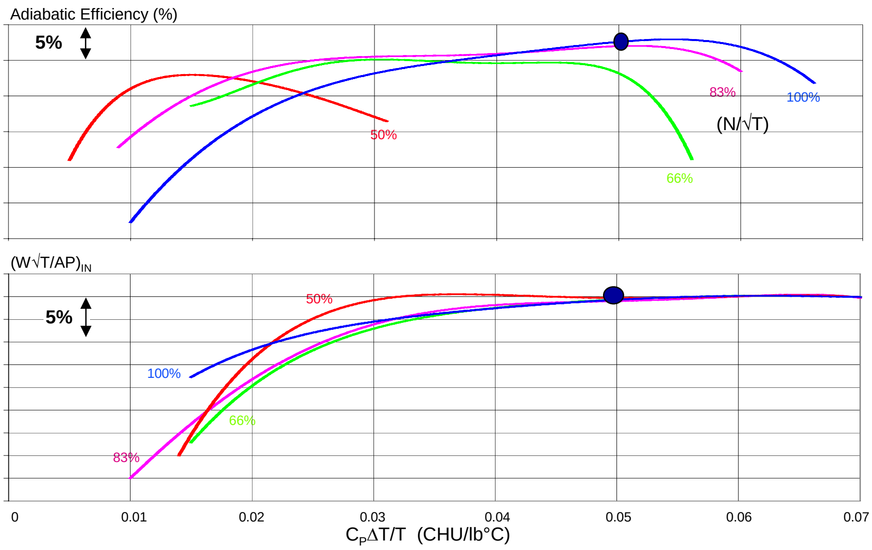
Shows efficiency of uncooled turbine



Turbine Smith Chart



Turbine Characteristic: Efficiency and Flow(Capacity)



Preliminary - Annulus Design

One-Dimensional Mean Line Methods

Row Efficiency and Pressure Loss Coefficient

The next level of preliminary design is based on the application of one-dimensional mean line methods. These methods use simple bulk values of pressure, temperature, Mach numbers, etc., to represent the flow within a turbine and are usually linked to some form of simple efficiency correlation.

Using a combination of one-dimensional mean line methods, simple assumptions and the stage efficiency equation, important understanding can be gained into how the turbine design parameters ($Cp\Delta T_o/T_o$, $U/T_o^{0.5}$, Va/U, etc.,) influence both the design and the overall efficiency of a turbine.

Consider the following Equations;

$$\text{Row Efficiency } \eta_{row} \text{ (Kinetic Energy Loss)} = \frac{Actual\ Kinetic}{Max\ Kinetic} = \frac{T_{Oex}-t_{ex}}{T_{Oex}-t'_{ex}} = \frac{\frac{\gamma-1}{2}M_{ex}^2}{1+\frac{\gamma-1}{2}M_{ex}^2-\left(1-\frac{\Delta P_o}{P_{oIN}}\right)^{\frac{\gamma-1}{\gamma}}}$$

$$\varsigma = \text{Pressure Loss Coefficient} = \left(1-\frac{P_{o2}}{P_{o1}}\right) = \frac{\Delta P_o}{P_{o1}} = \frac{\Delta P_o}{P_{oIN}}$$

where, at exit of blade row - T_{oex} total temperature, t_{ex} static temperature, t_{ex} isentropic static temperature, Mn_{ex} Mach Number, P_{oIN} Inlet total pressure, ΔP_o Total pressure change over blade row.

Preliminary - Annulus Design
One-Dimensional Mean Line Methods

Stage Efficiency

Relating these parameters to stage efficiency;

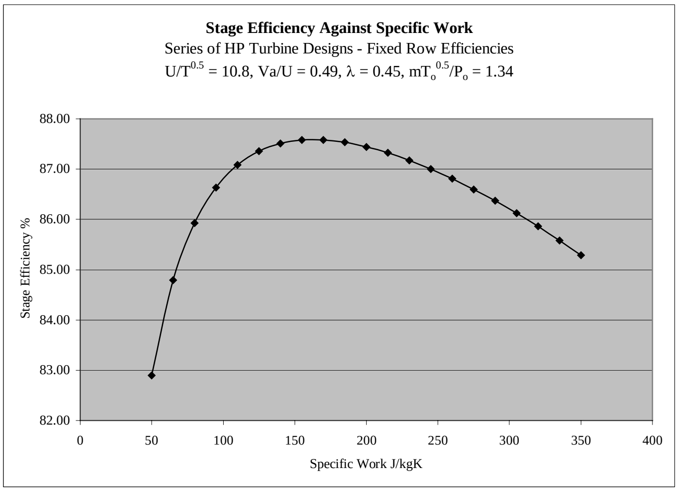
$$\eta_{stage} = \frac{T_{O\,(ngv\,in)} - T_{O\,(rotor\,exit)}}{T_{O\,(ngv\,in)} - T^{ideal}_{O\,(rotor\,exit)}} = \frac{T_{O\,(ngv\,in)} - T_{O\,(rotor\,exit)}}{T_{O\,(ngv\,in)} - T_{O\,(rotor\,exit)}\left[1-\frac{\gamma-1}{2}M^2_{NGVex}\left(\frac{1}{\eta_{row\,NGV}}-1\right)\right]\left[1-\frac{\gamma-1}{2}M^2_{Rotorex}\left(\frac{1}{\eta_{row\,Rotor}}-1\right)\right]}$$

$$\eta_{stage} = \frac{T_{O\,(ngv\,in)} - T_{O\,(rotor\,exit)}}{T_{O\,(ngv\,in)} - T_{O\,(rotor\,exit)}\left[\left(1-\frac{\Delta P_{oNGV}}{P_{oIN\,NGV}}\right)^{\frac{\gamma-1}{\gamma}}\left(1-\frac{\Delta P_{oRotor}}{P_{oIN\,Rotor}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where, total temperatures are in the absolute frame of reference, and exit Mach numbers and total pressures are relative to a particular blade row, i.e., vane Mn are absolute frame, rotor Mach numbers are relative frame, etc.

Preliminary - Annulus Design
One-Dimensional Mean Line Methods

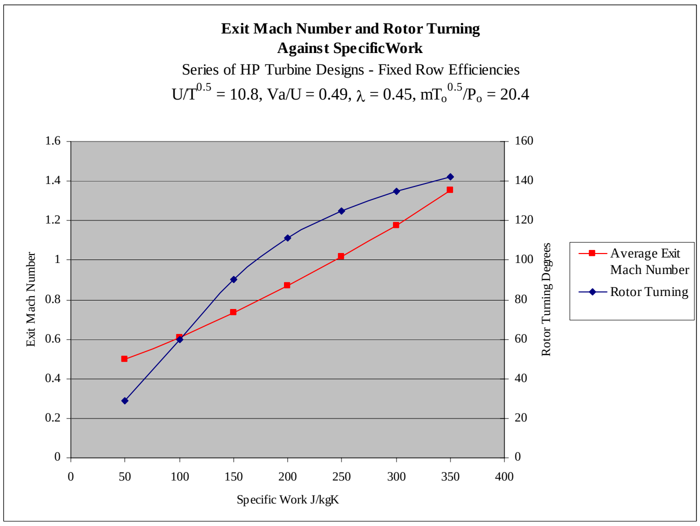
Stage Efficiency Against Specific Work



Preliminary - Annulus Design

One-Dimensional Mean Line Methods

Stage Efficiency Against Specific Work



Preliminary - Annulus Design

One-Dimensional Mean Line Methods

Stage Efficiency Against Specific Work – Effect of $U/T^{0.5}$

Figure 13a shows the effect that the turbine non-dimensional speed $U/T_o^{0.5}$ has on the shape and level of efficiency profile. It is clear from the plot that reducing the non-dimensional speed results in a reduction in the peak value of efficiency and a shift in this peak to a lower value of specific work, and visa-versa for an increase in non-dimensional speed.

Consider the relationship;

$$\frac{\Delta H}{U^2} = \frac{\Delta V_w}{U} = \frac{C_P \Delta T_o}{T_o} \Big/ \left(\frac{U}{\sqrt{T_o}}\right)$$

Two important conclusions can be drawn from this result,

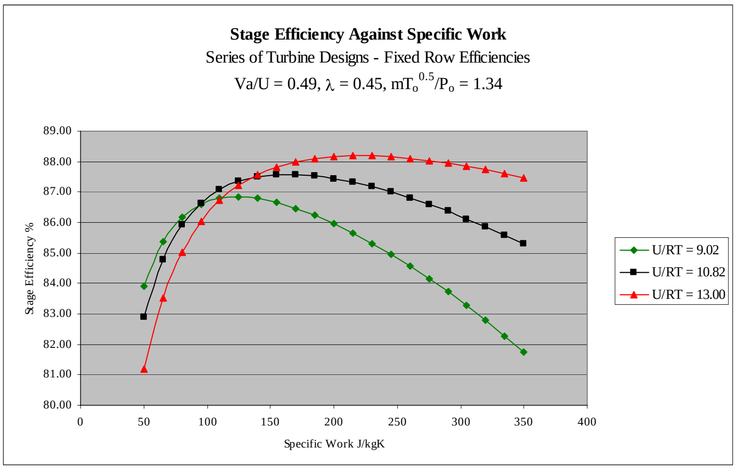
(i) At a given specific work, increasing the non-dimensional speed results in a reduction in the stage loading and ratio of $\Delta V_w/U$ (the width of the velocity triangle to its base – U increased, T_o fixed), which leads to a reduction in the blade row exit Mach numbers, figure 13b, and subsequent increase in the stage efficiency, i.e., the efficiency of a turbine (fixed aerodynamic technology) can be further improved if is non-dimensional speed is increased above current mechanical technology levels,

Preliminary - Annulus Design
One-Dimensional Mean Line Methods
Stage Efficiency Against Specific Work – Effect of $U/T^{0.5}$

(ii) As a consequence of these reduced Mach numbers (resulting from increased U), it is possible to operate a turbine at higher values of specific work whilst achieving comparable values of stage efficiency, i.e., the probability of designing an efficient high work turbine is significantly improved if the design incorporates a high values of $U/T_o^{0.5}$.

Overall these results show that turbine non-dimensional speed has a significant effect on the Mach numbers within a turbine and hence the stage efficiency.

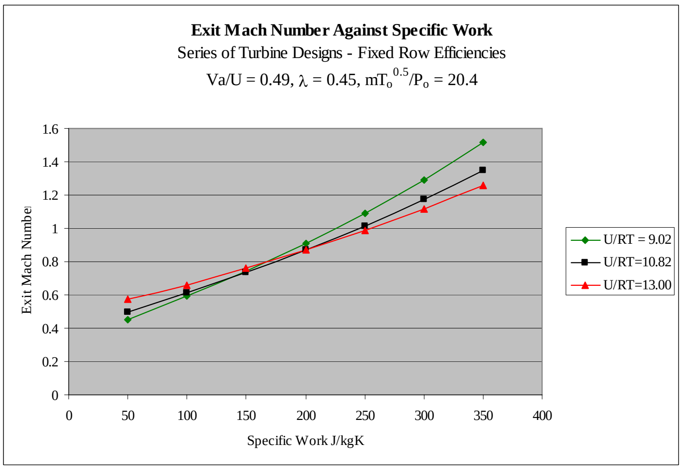
Preliminary - Annulus Design
One-Dimensional Mean Line Methods
Stage Efficiency Against Specific Work – Effect of $U/T^{0.5}$



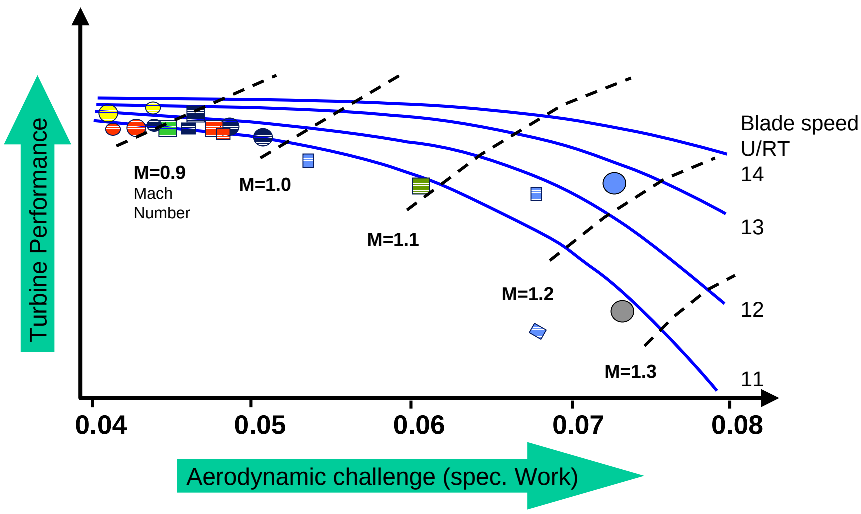
Preliminary - Annulus Design

One-Dimensional Mean Line Methods

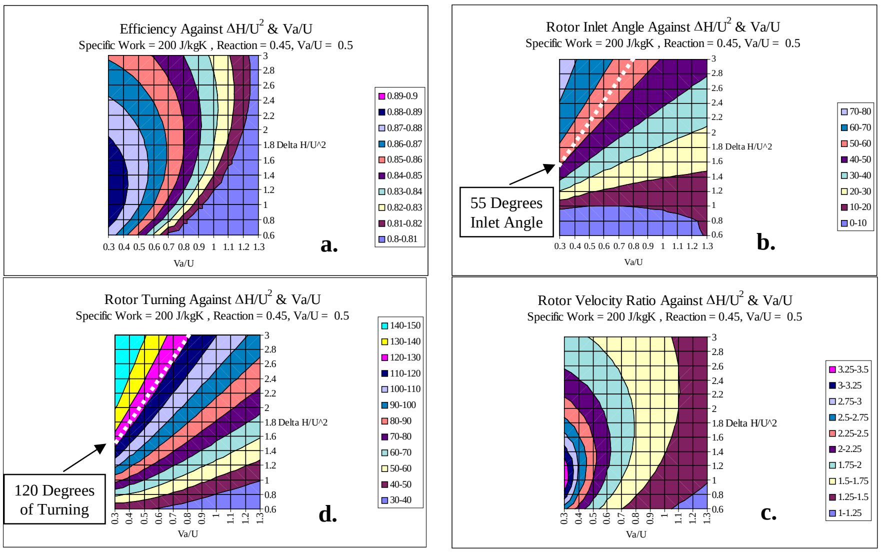
Stage Efficiency Against Specific Work – Effect of $U/T^{0.5}$



Some real turbines plotted as a function of speed

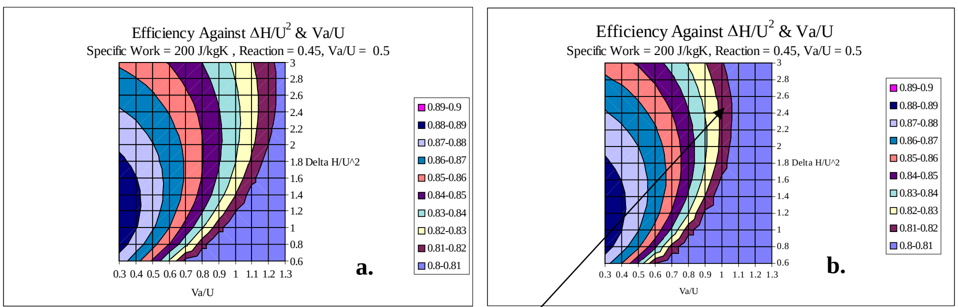


Preliminary - Annulus Design
One-Dimensional Mean Line Methods
Efficiency Chart Understanding - Fixed Row Efficiencies



Preliminary - Annulus Design
One-Dimensional Mean Line Methods
Efficiency Chart Understanding – Row Efficiency = f(Exit Mn)

Row Efficiency – f(Exit Mn) Does Not Significantly Alter Shape of Plot



Fixed Row Efficiency

Reduced Efficiency at High ΔH/U² and Va/U

Row Efficiency = f(Exit Mn)

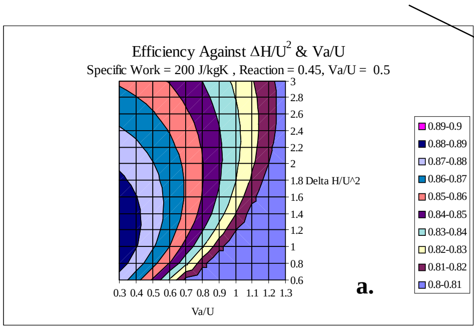
Preliminary - Annulus Design

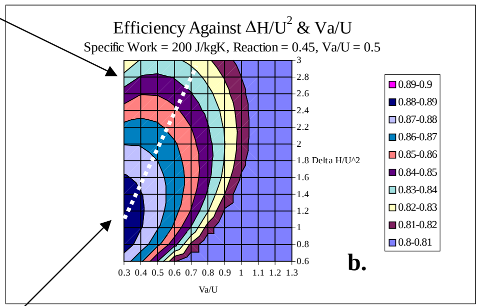
One-Dimensional Mean Line Methods

Efficiency Chart Understanding – Row Efficiency = f(Exit Mn, Secondary Loss)

Introduction of Secondary Loss Correlation Leads to a Reduction in Efficiency at Low Va/U, High $\Delta H/U^2$.

Secondary Loss = f(C_L, AR, Turning, VR), Analysis Shows for HP Style Turbine Turning is the Dominant Factor, i.e., +120 degrees.





Fixed Row Efficiency

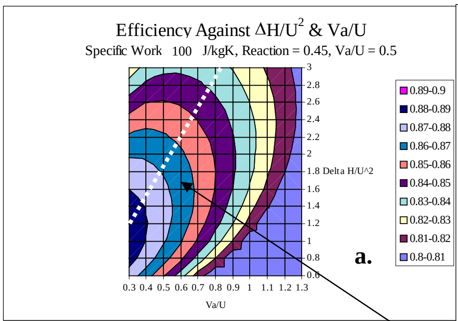
Row Efficiency = f(Exit Mn, Secondary Loss)

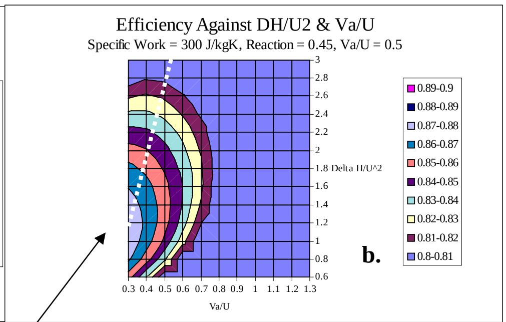
Inclusion of Secondary Loss Correlation Leads to Efficiency Ridge.

Preliminary - Annulus Design

One-Dimensional Mean Line Methods

Efficiency Chart Understanding – Row Efficiency = f(Exit Mn, Secondary Loss)





Specific Work = 100 J/kgK

Specific Work = 300 J/kgK

Change in Specific Works Result in Both a Efficiency Level and Ridge Location Change.

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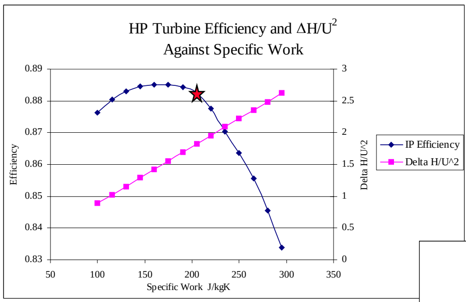
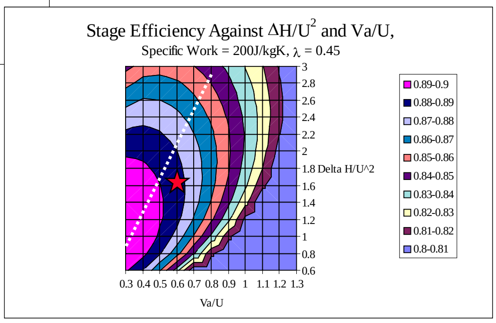
Preliminary - Annulus Design
One-Dimension Mean Line Methods - Worked Example
1-D Optimisation





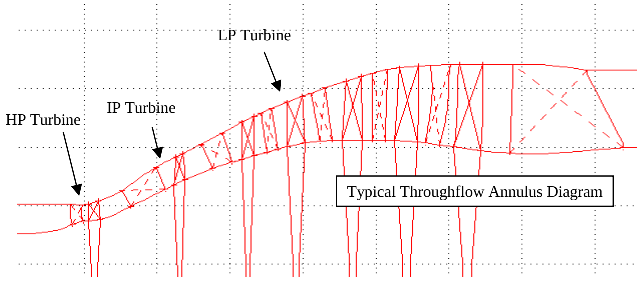
Preliminary – Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Introduction

Up until this point in the design we have utilised the basic relationships and simple models to undertake the first stage in the preliminary design. This process mainly relied on the understanding and previous experience that the turbine design has of what is possible aerodynamically, and how these aerodynamic requirements relate to the mechanical, stress, cooling and weight requirements of the turbine and whole engine.

This is a key stage in the design process, as decisions taken now will fix the main architecture of the turbine(s).

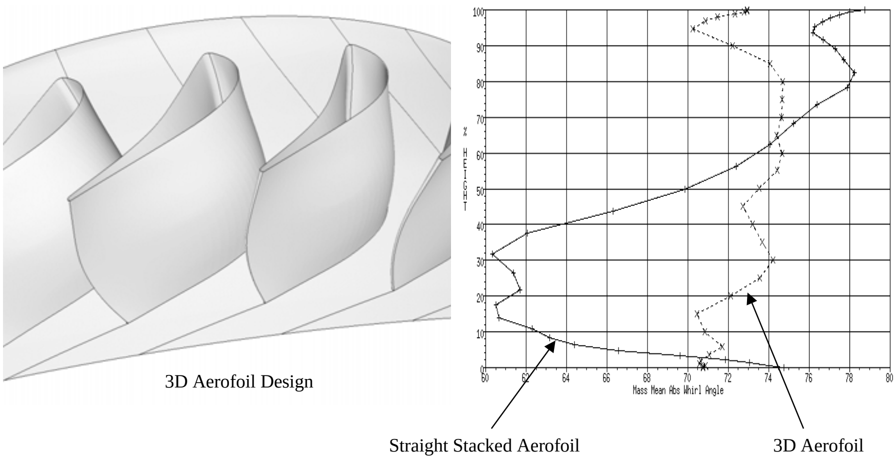
Before finalising these decisions the designer must develop a more complex model of the turbine. Within Rolls-Royce turbines this is done by developing a 2-D axi-symmetric throughflow model, which represent the desired flow conditions throughout the turbines. Utilising this model along with the Rolls-Royce turbine performance correlation's, the designer is able to optimise the requirements of the aerodynamic design, against those of the mechanical, stress and cooling designers.

Preliminary – Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Utilisation of New Concepts



In order to develop this model the designer must decide on what aerodynamic conditions he wants to achieve in each of the blade rows. It is at this point that he must decide if there are new detailed aerodynamic concepts which he wants to utilise, i.e., a rig test has shown that a particular exit angle profile - vortex (resulting from a new aerofoil shape) improves the efficiency, figures 20a & b, 3-D CFD has predicted that a particular distance between two adjacent aerofoils maybe beneficial to reduce blade row interaction, figures 21a, b & c (forced response and reduced unsteady loss), etc.

Preliminary - Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Utilisation of New Concepts - Improved Mass Distribution Leading to Improved Efficiency



Preliminary - Annulus/Vortex Design

Two-Dimensional Throughflow Methods

Target Gaspath Model

The designer can then combine these new ideas along with previously measured (or predicted) data on angle profile deviations, efficiency profiles, coolant and tip leakage flows, etc, to develop the target gaspath throughflow model.

In addition, the Rolls-Royce turbine efficiency correlations allow an initial number of aerofoils to selected, however, this usually is not the final numbers as mechanical, cooling and cost have a strong influence on aerofoil numbers.

By developing this model the designer can verify (in a 2-D representation) if the required design concept, i.e., turbine type, specific work, stage loading, numbers off, etc, are feasible, and if not what parameters must be change to achieve (utilising the RR efficiency correlation's and other evidence to numerate) the required overall aerodynamic specification.

This model represents the target gaspath flowfield against which each of the individual blade rows are to be designed (to match), and allows the detailed aerodynamics of each blade row to be designed independently and in parallel.

Once each blade row has been designed (2-D and 3-D CFD), the results are fed back into the target gaspath throughflow model (angle deviations, loss profiles, etc.). A new target gaspath throughflow model is generated and the process is repeated until an acceptable aerodynamic design of the whole turbine is achieved.

Preliminary - Annulus/Vortex Design

Two-Dimensional Throughflow Methods

Efficiency Correlations

The Rolls-Royce turbine efficiency correlations are a mixture of physical models, measured exchange rates and correlations. They have been developed over many years and are based on an extensive experimental database (high-speed turbine rig tests). They provide a pre-profile estimation of the stage efficiency of a particular turbine design, and are used extensively in the aerodynamic bid process (2-D throughflow $\Rightarrow$ flow conditions $\Rightarrow$ correlation - row efficiencies $\Rightarrow$ stage efficiency). The main factors considered are;

Secondary Loss - Lift Coefficient $\left(\frac{\text{Force per Blade}}{\text{Height} * \text{Chord} * (P_o - P)}\right)$, Aspect Ratio $\left(\frac{\text{Blade Height}}{\text{Blade Chord}}\right)$, Aerofoil Turning, and Velocity Ratio.

Trailing Edge Loss - Exit Mach No, Trailing Edge Thickness, Boundary Layer Thickness.

Profile Loss - Lift Distribution (see fig.22a), Lift Coefficient, Blade Area.

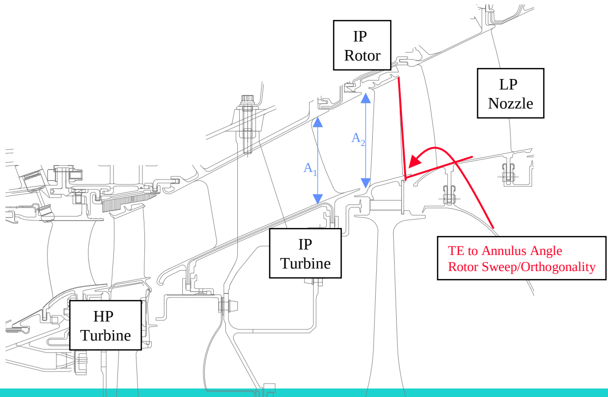
Over Tip Leakage Loss - Shrouded/Shroudless (see fig.22b), Height of Tip Gap, Tip Lift Coefficient.

Preliminary - Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Efficiency Correlations

Disk Windage Loss - Modified Buckingham Correlation.

Wetted Area Loss - Hub and Casing Endwall Mach No, Endwall Areas.

Annulus and Stacking Loss - Area Ratio (Diffusion), Annulus Hade, Orthogonality, fig.23.



Preliminary - Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Efficiency Correlations

Cooling Exchange Rates - Experimental measured exchange rates for a series of different cooling flows which, reflect the change in turbine efficiency as a percentage of coolant flow. As these exchange rates are very dependant on the location at which the flow enters the annulus great care must be taken when applying them in a design and bid process (range 0.1% to 1% change in efficiency for 1% change in coolant flow).

Leakage Exchange Rates - As above - platform, blade root seals, over tip leakage, etc.

Pumping Losses - The energy required to pump the coolant and leakage flows from a source to the point where it enters the annulus.

Measured to Bid - A term which attempts to capture the previous difference recorded in the biding process of a similar type of turbine design.

Preliminary - Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Efficiency Correlations

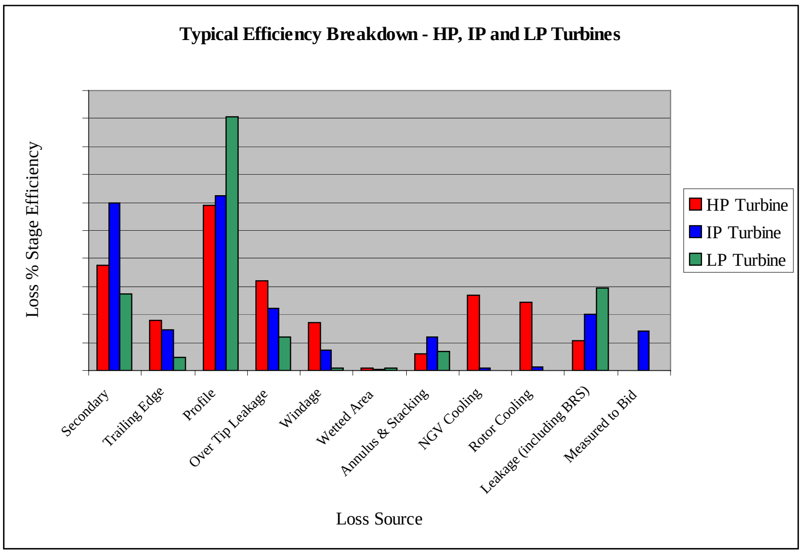
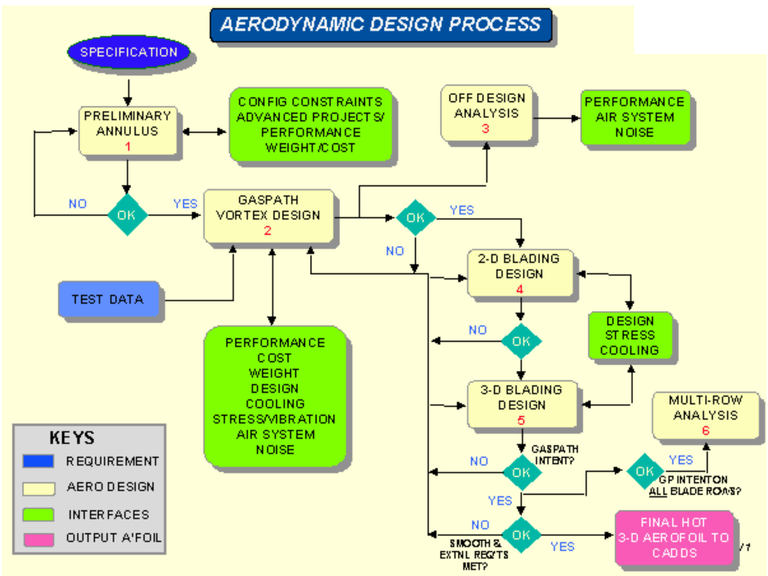


Figure 24

Preliminary - Annulus/Vortex Design
Summary of Aerodynamic Design Process



Outline

- Introduction
- Basic Mech. Design Considerations
- Mean line design, Velocity Triangles
- 2D Blade design
- 3D Design, Blade stacking
- Summary

2-D Blading Design
Introduction
Control Volume Analysis

The primary function of 2-D blading is to satisfy the flow condition calculated from the throughflow model, i.e., inlet and exit flow angles and Mach numbers. As an estimation of the loss within the blade row will have been input to the throughflow model, it is important that this loss is also taken into account when designing the 2-D aerofoil sections. It is usual to specify the loss as a function up to and downstream of the aerodynamic throat, in order that the aerofoil is designed with the correct inlet flow capacity ($mT_o^{0.5}/P_o$) and exit angle.

Consider the following;

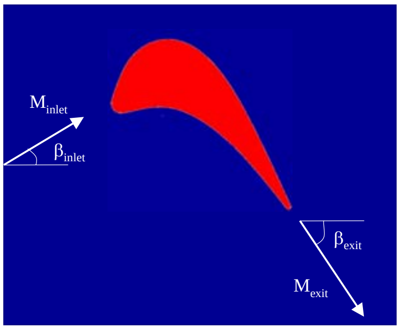
If we use the continuity equation on a control surface which stretches from a plane "infinitely far" ahead of an aerofoil cascade to a plane "infinitely far" behind the aerofoil cascade (homogeneous entry and exit flow), the exit flow angle can be calculated from the other flow parameters

$$\rho_{\text{inlet}} V_{\text{inlet}} S \cos\beta_{\text{inlet}} = \rho_{\text{exit}} V_{\text{exit}} S \cos\beta_{\text{exit}}$$

With the assumption that the flow between inlet and exit exchanges no energy with the aerofoil, the fluid behaves like an idea gas, and that density and temperature ratios are a function of Mach number, the above equation can be written in the following form;

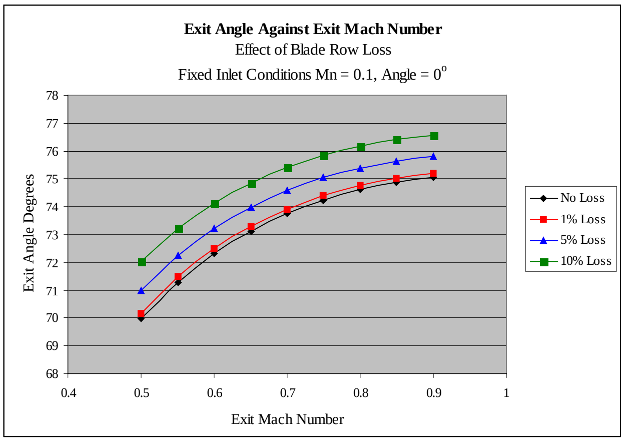
2-D Blading Design
Introduction
Control Volume Analysis

$$\cos\beta_{exit} = \cos\beta_{inlet}\frac{M_{inlet}\left(1+\frac{\gamma-1}{2}M_{inlet}^2\right)^{\frac{1+\gamma}{2(1-\gamma)}}}{M_{exit}\left(1+\frac{\gamma-1}{2}M_{exit}^2\right)^{\frac{1+\gamma}{2(1-\gamma)}}}\left(\frac{P_{Oinlet}}{P_{Oexit}}\right)$$



2-D Blading Design
Introduction
Control Volume Analysis

Utilising the above equation the variation of exit angle can be calculated for a range of loss levels and over a range of exit Mach numbers, for fixed inlet conditions, i.e., $M_{inlet} = 0.15$, $\beta_{inlet} = 0^o$.



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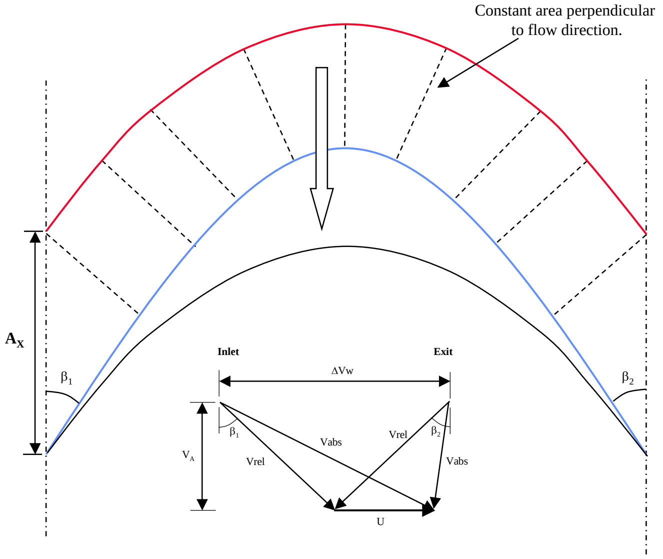
2-D Blading Design
Design of a Passage
Impulse Blading

Impulse Blade

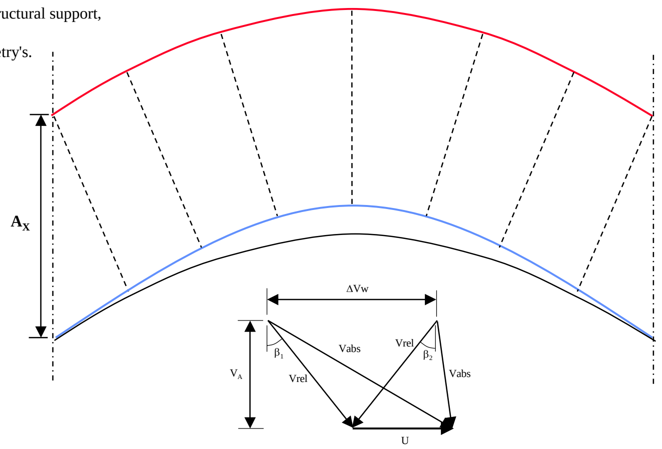
- Zero reaction, i.e., no expansion over rotor,
- Constant flow area,
- Constant bulk velocity,
- Varying axial velocity.



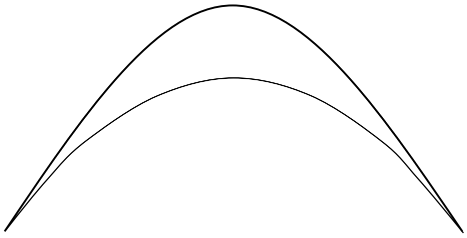
2-D Blading Design
Design of a Passage
Impulse Blading - Effect of Aerofoil Turning

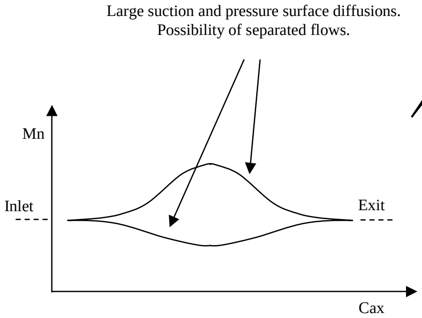
Reduced turning leads to a thinner aerofoil

- Limits diameter of service pipes,
- Reduced XS area for structural support,
- Difficult cooling geometry's.



2-D Blading Design
Design of a Passage
Impulse Blading - Limitations





- Large suction and pressure surface diffusions,
- Flow separation(s) leading to increased loss, enhanced heat transfer at re-attachment points,
- Diffusion on suction surface limits amount of available lift, i.e., low lift coefficient leads to high number of aerofoils and/or blade chord,

Consider: Inlet and exit relative Mn = 0.6, max diffusion level = 35%, therefore peak Mn ≈ 0.8.

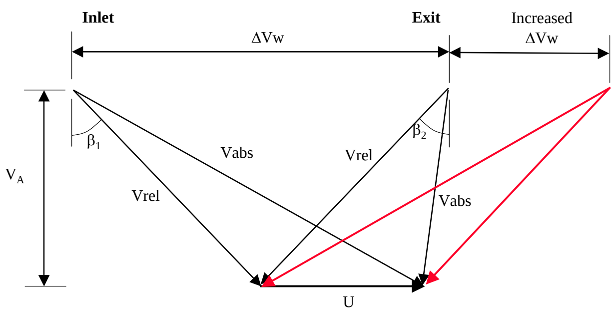
$\Delta p/D = (p_{\text{end of diffusion}} - p_{\text{start of diffusion}})/(P_o - p)_{\text{start of diffusion}}$

2-D Blading Design
Design of a Passage
Impulse Blading - Limitations

As the change in whirl velocity (ΔV_W) and hence turbine power (mU ΔV_W) is limited by the constraint that no expansion can take place over the rotor (Mn relative inlet = Mn relative exit) the specific power (per kg mass flow) available from an impulse turbine will always be lower then an equivalent reaction design with equal relative exit Mach numbers on both the vane and rotor.

In addition, the requirement to do all of the expansion over the nozzle leads to high inlet angle to the rotor, which tends to increase the levels of pressure surface diffusion previously highlighted.

These limitations along with the difficulties previously outlined (separations, low lift coefficient, etc) means that most modern gas turbine designs are based on reaction styles of turbine blading.



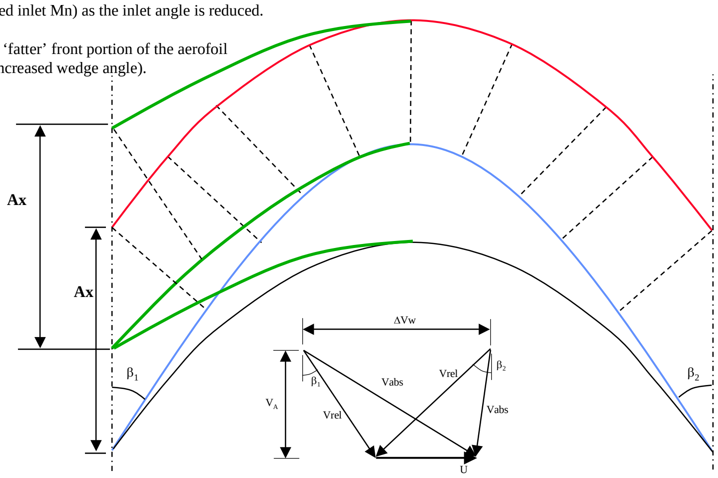
2-D Blading Design

Design of a Passage

Reaction Blading - Reduced Inlet Angle

At constant axial velocity (and hence axial area), it is clear from the diagram that there is a corresponding flow area increase (reduced inlet Mn) as the inlet angle is reduced.

This leads to a 'fatter' front portion of the aerofoil (increased wedge angle).

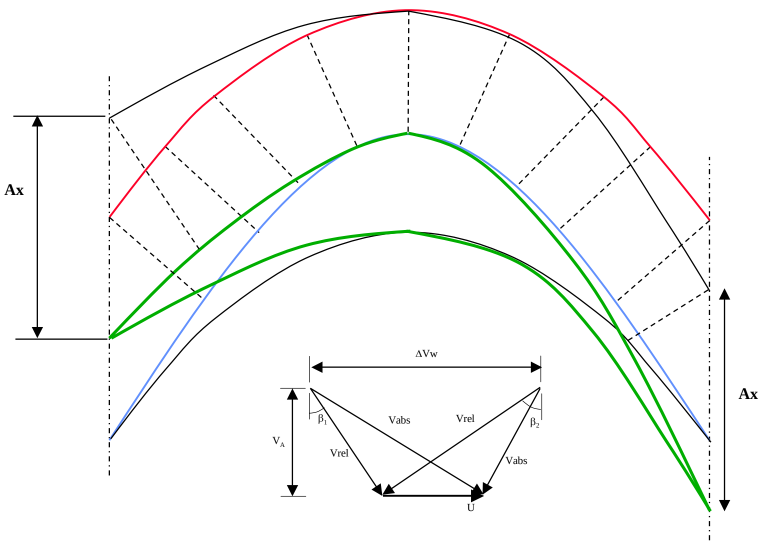


However, as ΔVw has been reduced by the reduction in inlet angle, the exit angle must be increased to restore the work.

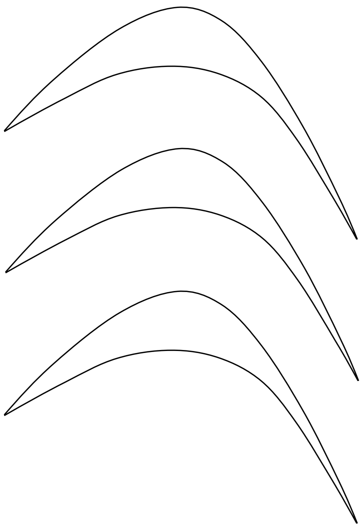
2-D Blading Design

Design of a Passage

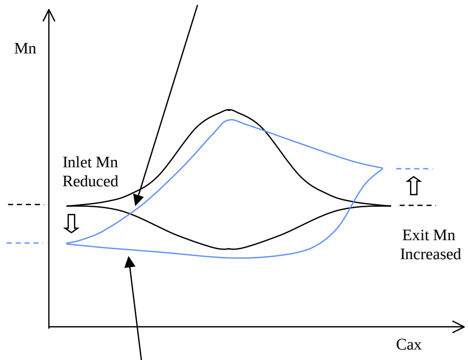
Reaction Blading - Increased Exit Angle



2-D Blading Design
Design of a Passage
Reaction Blading

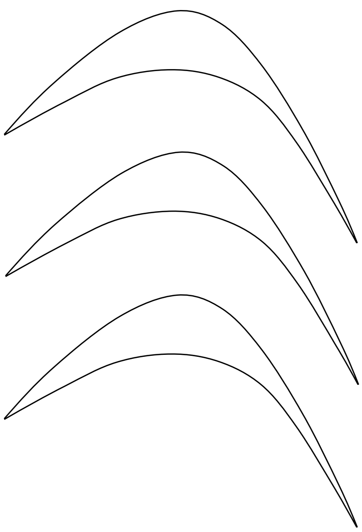


'Fatter' front portion of aerofoil leads to increased convex curvature and blockage on front half of the suction surface and hence a more rapid rise in the suction surface Mach number.



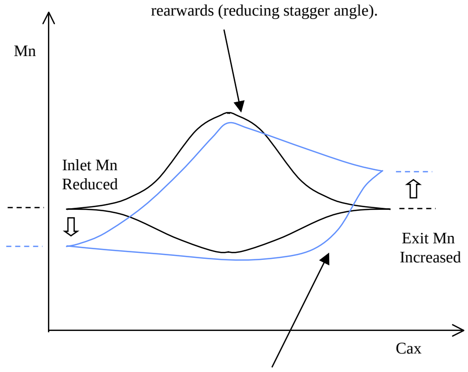
'Fatter' front portion reduces concave curvature on pressure surface which leads to reduced pressure surface diffusion.

2-D Blading Design
Design of a Passage
Reaction Blading - Aft Loading



Aerofoil remains forward loaded as the location of peak suction (peak suction surface Mach number) has not altered.

Suction surface diffusion can be significantly reduced by 'aft' loading the aerofoil, i.e., moving the location of peak suction rearwards (reducing stagger angle).



Formation of a convergent passage and increased trailing edge wedge angle leads to increased acceleration on rear part of pressure surface.

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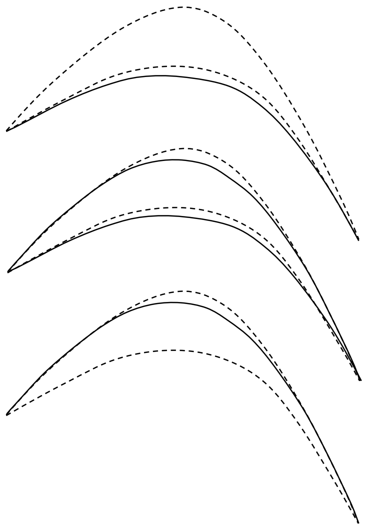
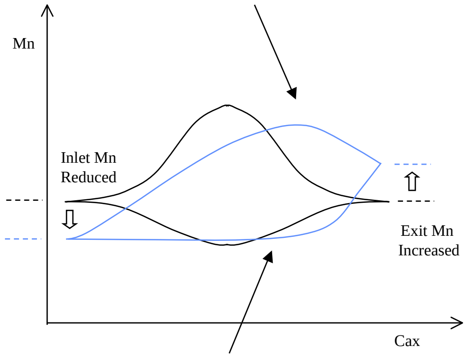
2-D Blading Design
Design of a Passage
Reaction Blading - Aft Loading

Suction surface curvature modified to move peak suction rearwards, i.e., Mach number distribution change due to both curvature and blockage.

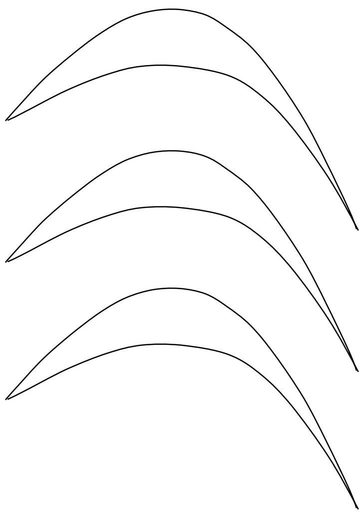
Aerofoil has clearly defined geometric throat at or close to peak suction.

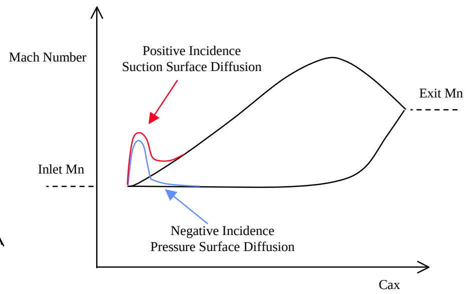




Aerofoil X-sectional area reduction maybe undesirable, hence pressure surface concave curvature can be reduced to restore X-sectional area and eliminate pressure surface diffusion (blockage and curvature changes on pressure surface have weaker effect as Mach numbers are lower).

2-D Blading Design
Design of a Passage
Reaction Blading - Incidence





Small wedge angle at leading edge of aerofoil gives little incidence tolerance, i.e., suction and pressure surface spikes and diffusions.

As aerofoil will be subjected to incidence variation from upstream blade row (potential interaction, wakes, secondary flows, etc), careful design of the leading edge must be undertaken to minimise the loss associated with these forms of unsteady interaction loss.

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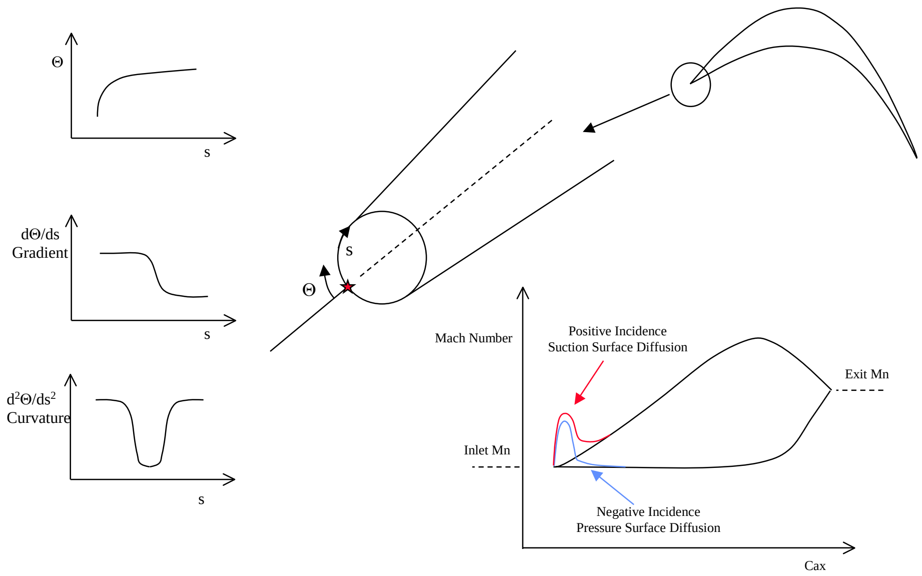
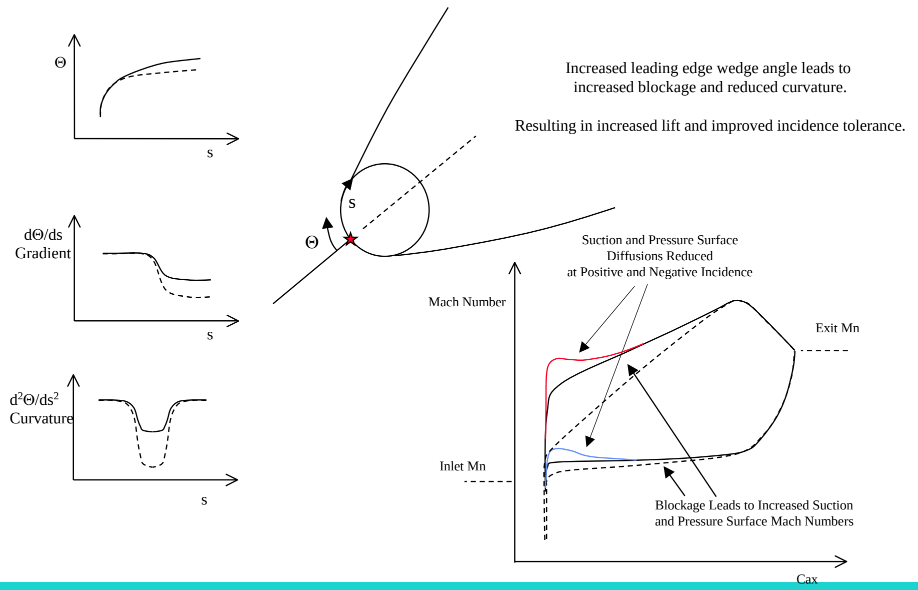
2-D Blading Design
Design of a Passage
Reaction Blading - Small Wedge Angle



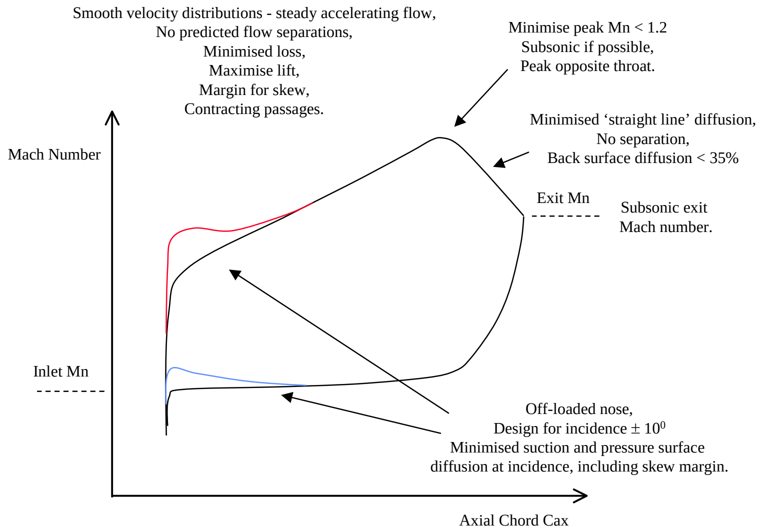
2-D Blading Design
Design of a Passage
Reaction Blading - Large Wedge Angle



2-D Blading Design

Design of a Passage

Reaction Blading - Design Objectives



2-D Blading Design

Design of a Passage

Prescribed Velocity Distribution - Inverse Design

Although as the previous slides have show, a good understanding can be gained into how the geometric shape of a passage (curvature and blockage) influence an aerofoil Mach number distribution, it is more convenient to design an aerofoil to meet a desired lift distribution.

Within Rolls-Royce turbines this is undertaken using an inverse design technique known as Prescribed Velocity Distribution (PVD), i.e., a desired velocity distribution is chose and the resulting geometry to meet this requirement is automatically generated, i.e., figures 29a & b.

Although this is a more convenient method by which to design a row of aerofoil, the designer must still understand the simple rules developed earlier, if he is to design an aerofoil which also meet the many mechanical and cooling requirements.

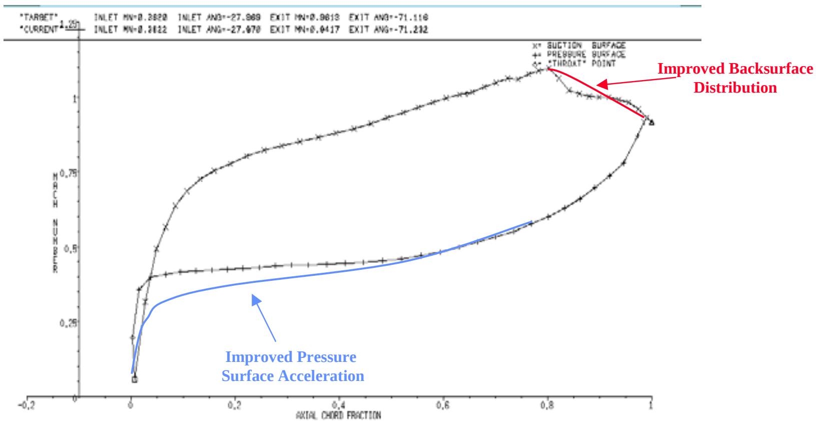
For example, the wedge angle at the leading edge of a HP turbine is significantly greater than is required aerodynamically. The thickness requirement is predominantly there in order that there is enough physical space to accommodate the complex cooling arrangement within the leading edge, figure 29c.

2-D Blading Design

Design of a Passage

Prescribed Velocity Distribution - Inverse Design

Figure 29a highlights the type of modifications to the velocity distributions, which can be easily undertaken using a prescribed velocity distribution method.

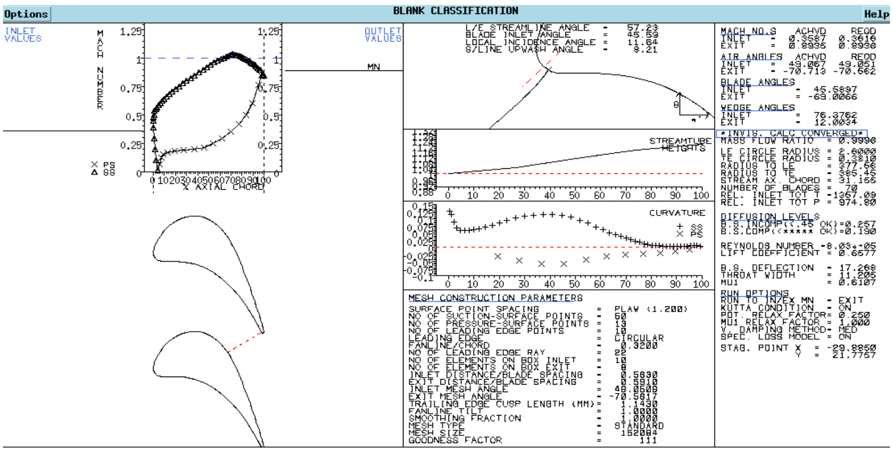


2-D Blading Design

Design of a Passage

Prescribed Velocity Distribution - Inverse Design

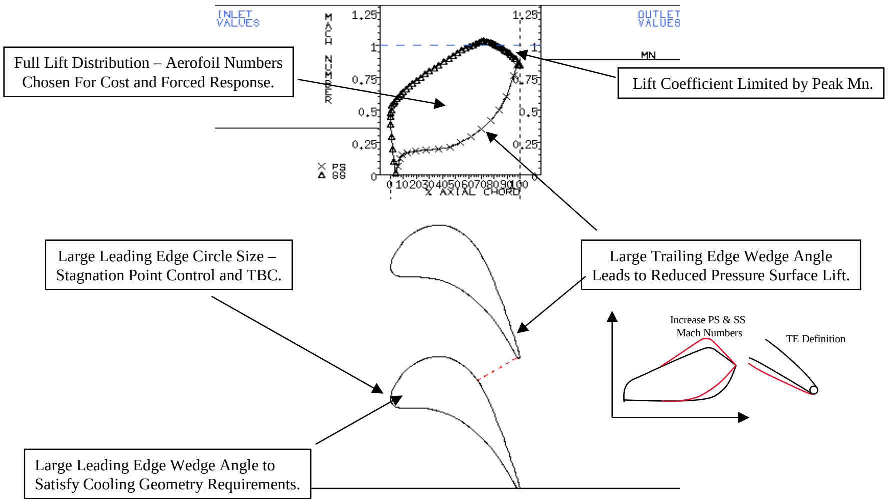
Based on the rules presented in figure 28l (and particular lift style) 2-D aerofoil profiles are designed at a number of spanwise locations. A typical final summary of the 2-D aerofoil parameters is given below.



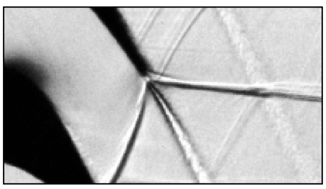
2-D Blading Design

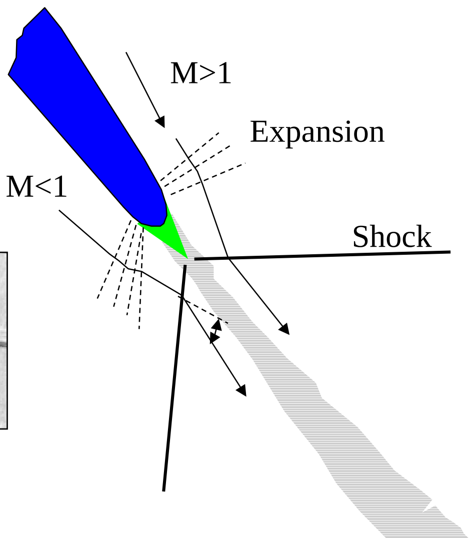
Design of a Passage

HP Vane and Rotor 2-D Design



Transonic HPTs

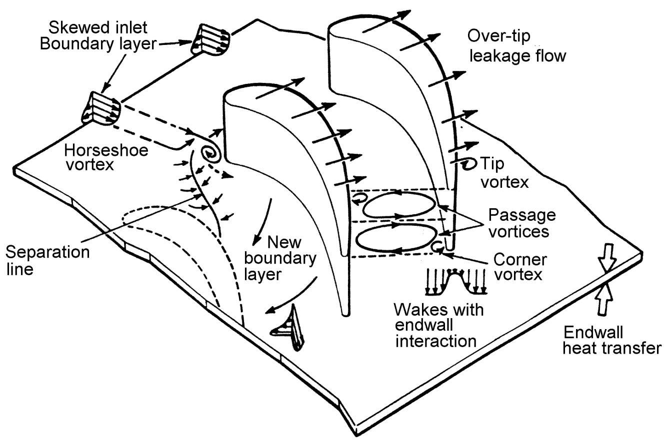




Outline

Introduction
Basic Mech. Design Considerations
Mean line design, Velocity Triangles
2D Blade design
3D Design, Blade stacking
Summary

3-D Blading Design
Introduction
Turbine Blade 3D Flow Phenomena



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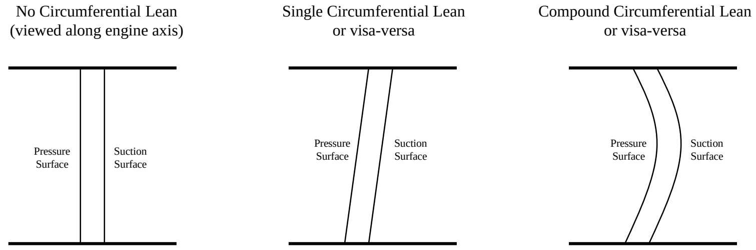
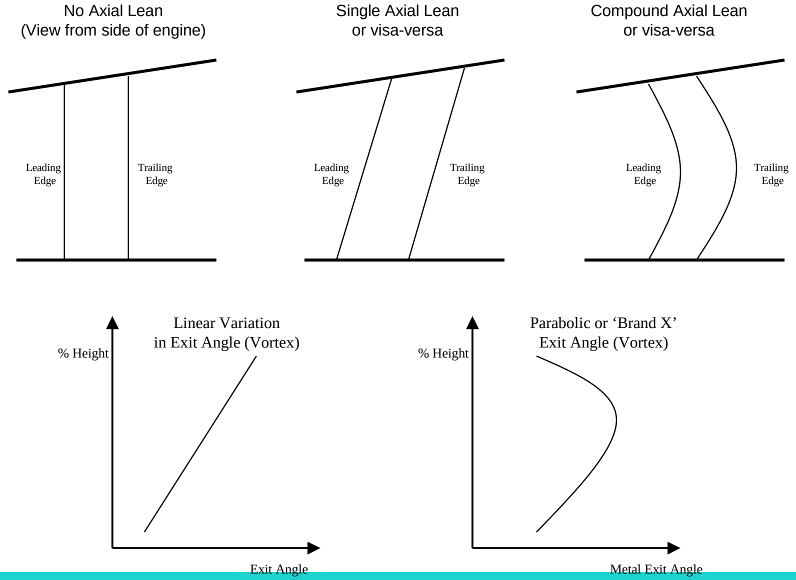
3-D Blading Design
Aerofoil Stacking and Vortex

The 3-D design process is based around the concept that 2-D sections can be ‘stacked’ in space to achieve the target gaspath throughflow conditions. There are effectively 3 main stacking concepts available to the designer, circumferential lean (single or compound), axial lean (single or compound) and exit angle distribution (linear or Brand X).



3-D Blading Design
Aerofoil Stacking and Vortex



3-D Blading Design
Aerofoil Stacking and Vortex
Compound Lean

Each of these stacking concepts have different effects on the flow field, for example consider the effect of compound lean (convex pressure surface, concave suction surface).

Increased Static Pressure in the Endwall Regions

↓

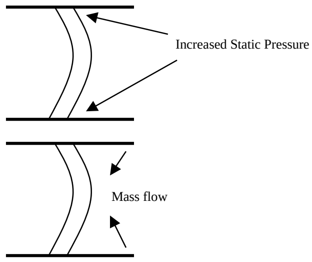
Mass Flow Within Passage Moves from Endwalls to Mid-Height

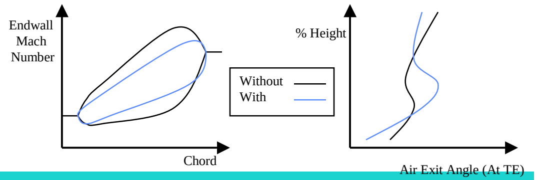
↓

Less Turning at Endwalls (reduced lift)
More Turning Mid-Height (increase lift)

↓

Loss α $V^3_{endwalls}$
Endwall Loss Reduced
Overall Loss ?





3-D Blading Design
Aerofoil Stacking and Vortex
Brand X

Both of the exit angle (vortex) concepts have different effect on the flow field, for example consider the effect of Brand X (reduced exit angles at endwalls, increased exit angles at mid-height).

Reduce Angles at Endwalls
Increase Angle At Mid-Height

↓

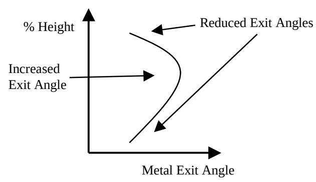
Exit Mass Flow Moves from Mid-Height to the Endwall Regions

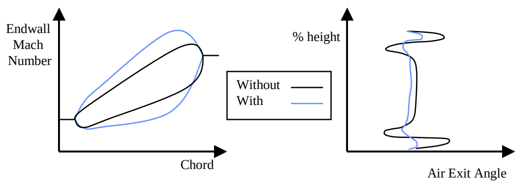
↓

More Turning at Endwalls (increased lift)
Reduced Turning Mid-Height (reduced lift)

↓

More Uniform Distribution of Massflow into Following Blade Row
Improved Stage Efficiency





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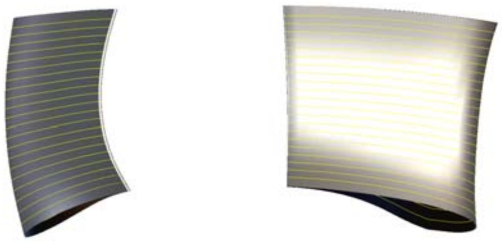
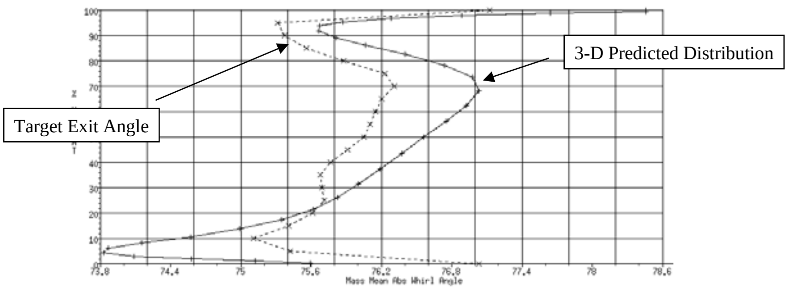
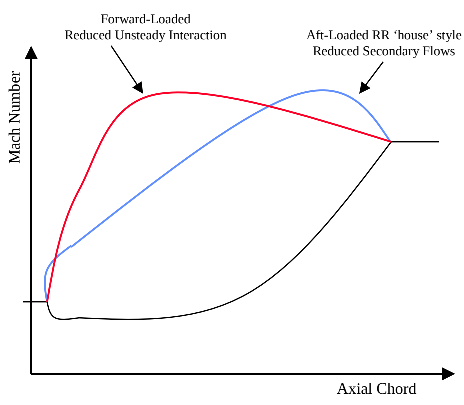
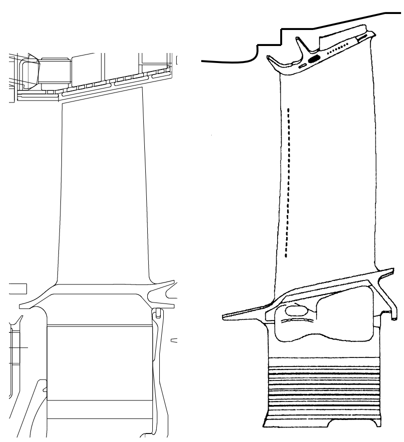
3-D Blading Design
Aerofoil Stacking and Vortex
Vane 3-D Stack and Vortex





Preliminary - Annulus/Vortex Design
Two-Dimensional Throughflow Methods
Efficiency Correlations





Shroudless Shrouded

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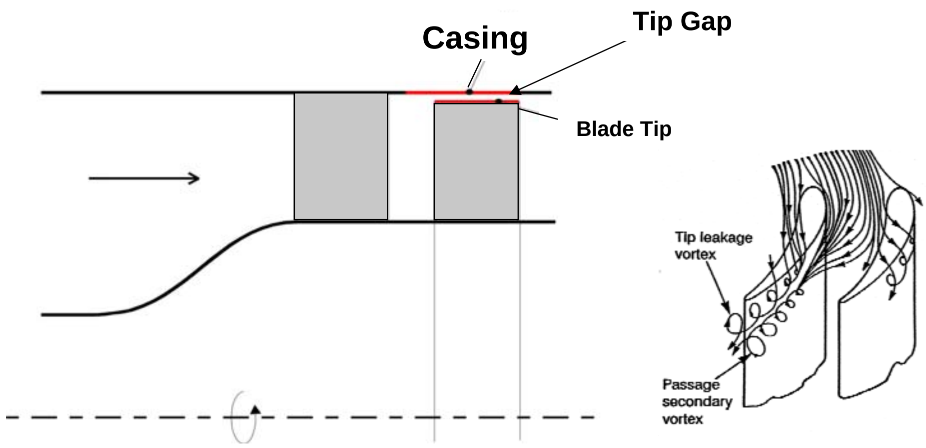
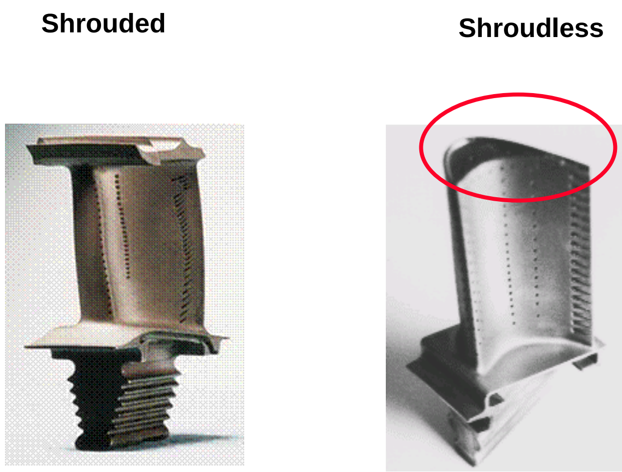
Over tip leakage loss



Turbine Blade Tip Style

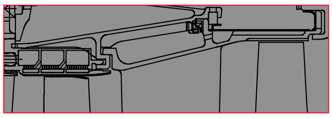


Tip clearance effects

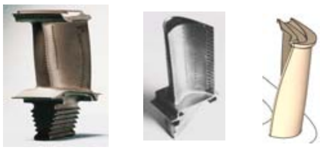
Beside profile loss, sec. flow losses and mixing losses the main contribution is **<u>overtip leakage loss</u>**. <u>(about a third)</u>

Overtip leakage loss = clearance x exchange rate

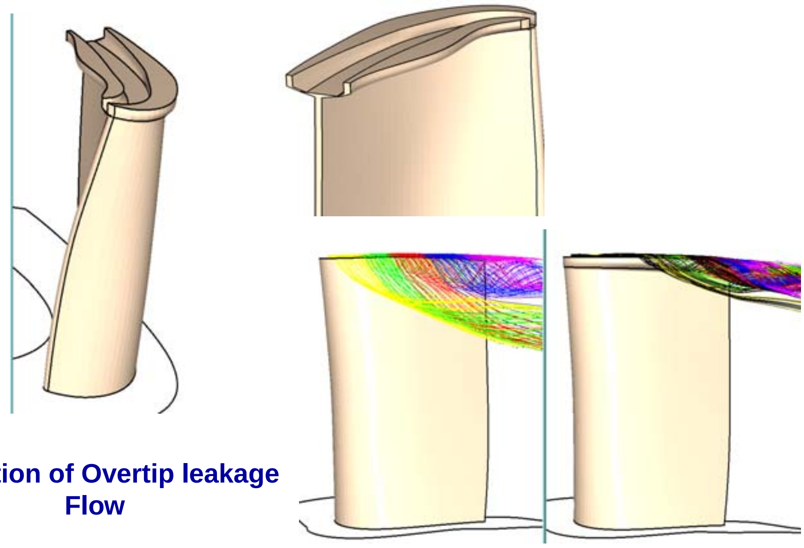
clearance ➔ T/C control concept



exchange rate ➔ Blade tip style

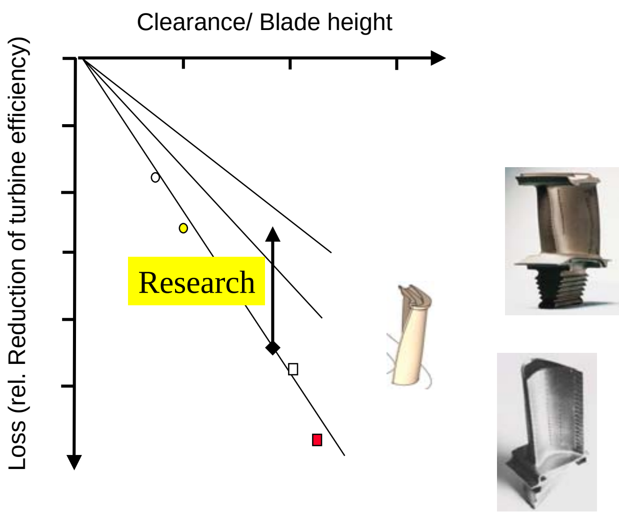


Winglet Design

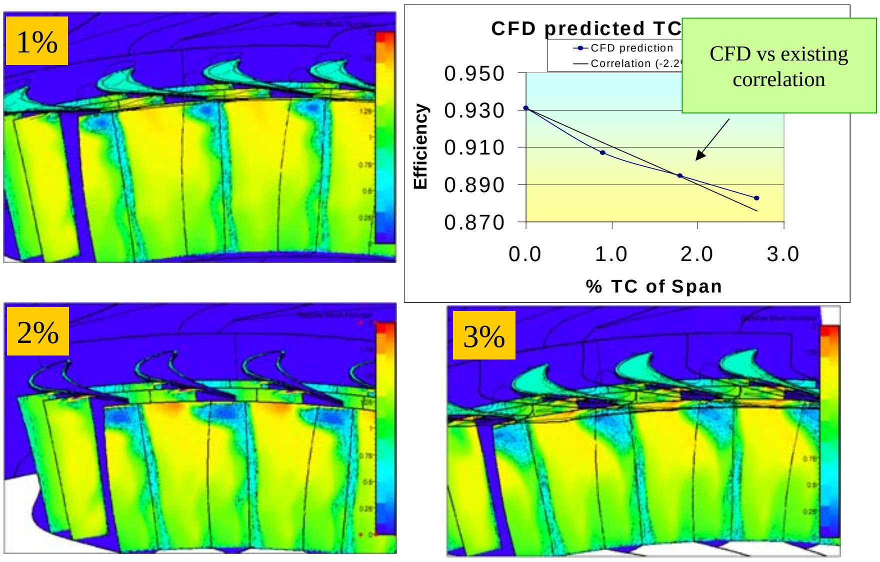


Reduction of Overtip leakage Flow

„exchange rate“ – a matter of detailed tip design



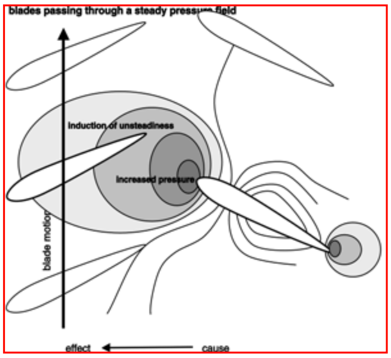
CFD ?



Unsteady Interaction in Turbomachines

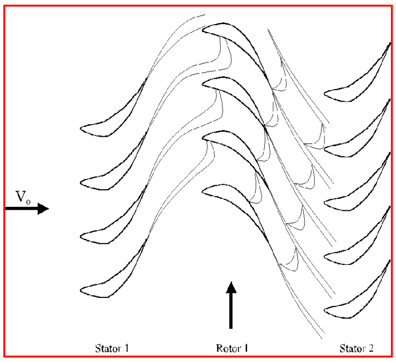
- **Potential Field**

Example: HPT

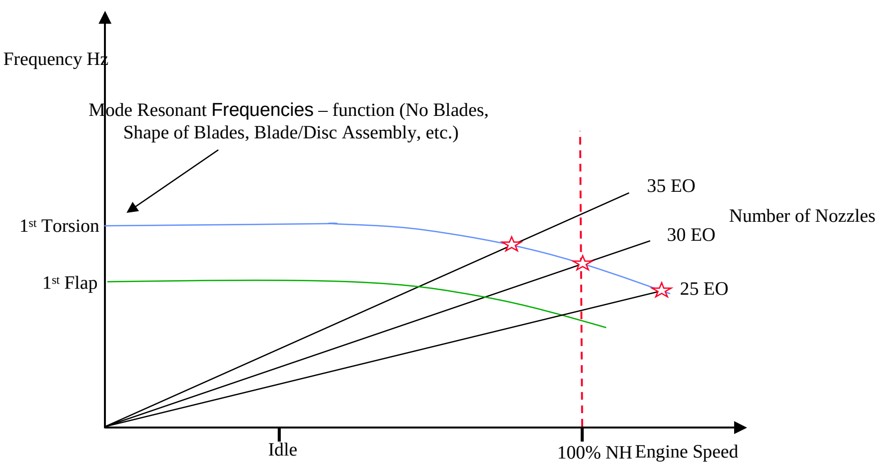


- **Viscous interaction (Wake/Boundary layer)**

Example: LPT



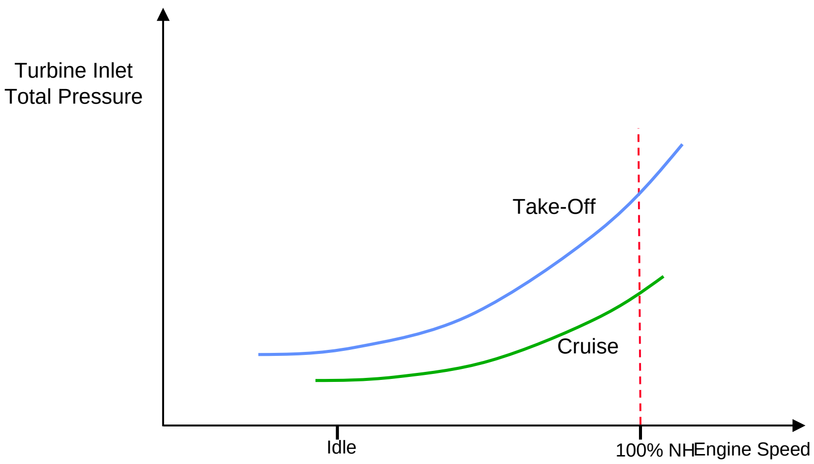
3-D Blading Design
Aerofoil Stacking and Vortex
Forced Response – Campbell Diagram



3-D Blading Design

Aerofoil Stacking and Vortex

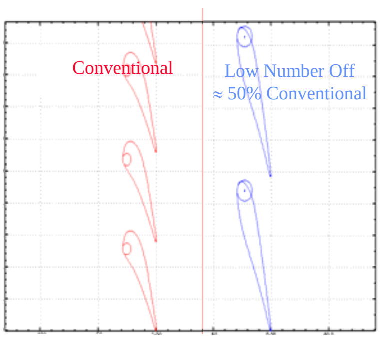
Forced Response – Turbine Inlet Pressure



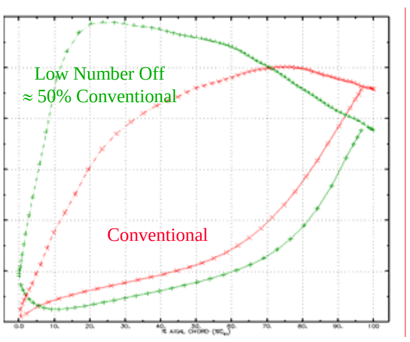
3-D Blading Design

Aerofoil Stacking and Vortex

Forced Response – Lift Styles

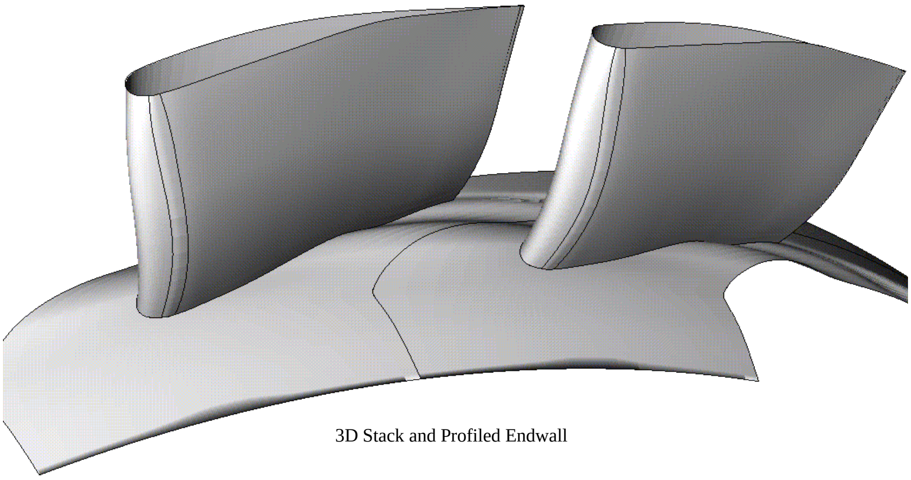


Mid-Height NGV section



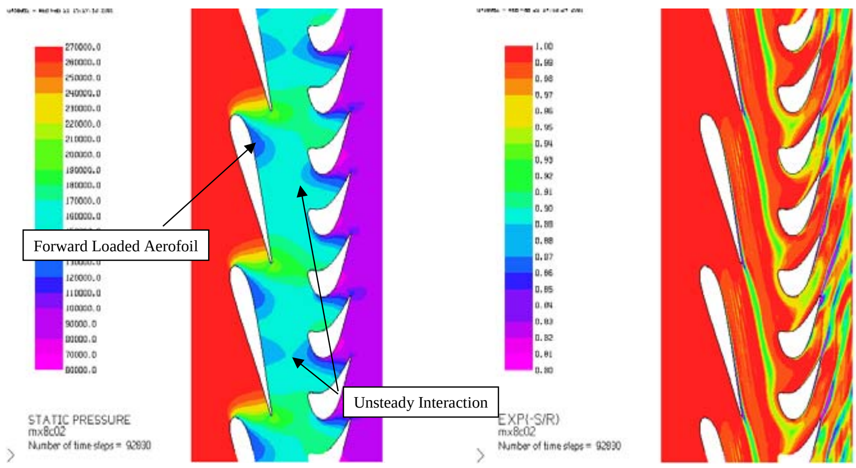
Mid-Height Lift Plot

3-D Blading Design
Aerofoil Stacking and Vortex
Forced Response – Stack and Profiled Endwalls



3D Stack and Profiled Endwall

3-D Blading Design
Aerofoil Stacking and Vortex
Forced Response – Unsteady CFD Predictions



Static Pressure — Entropy

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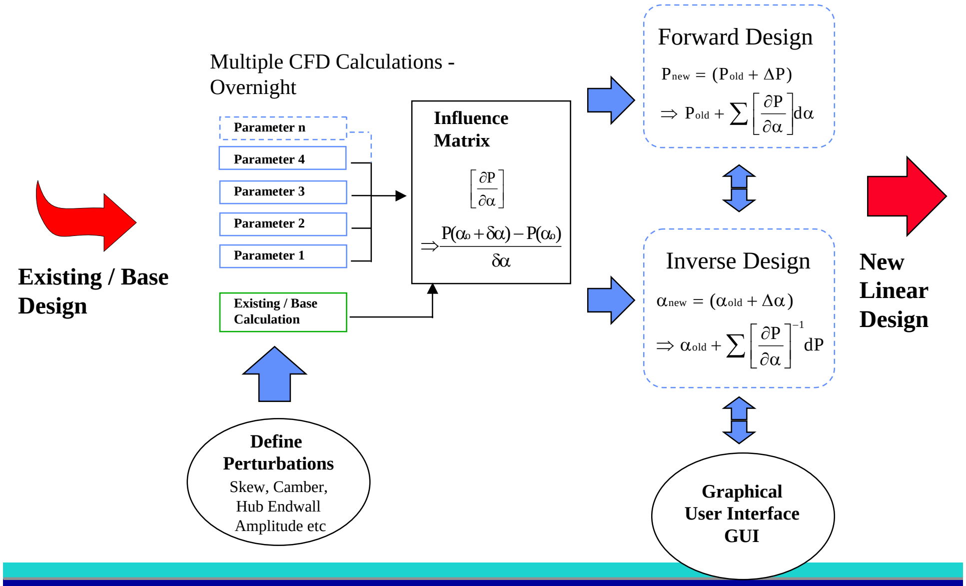
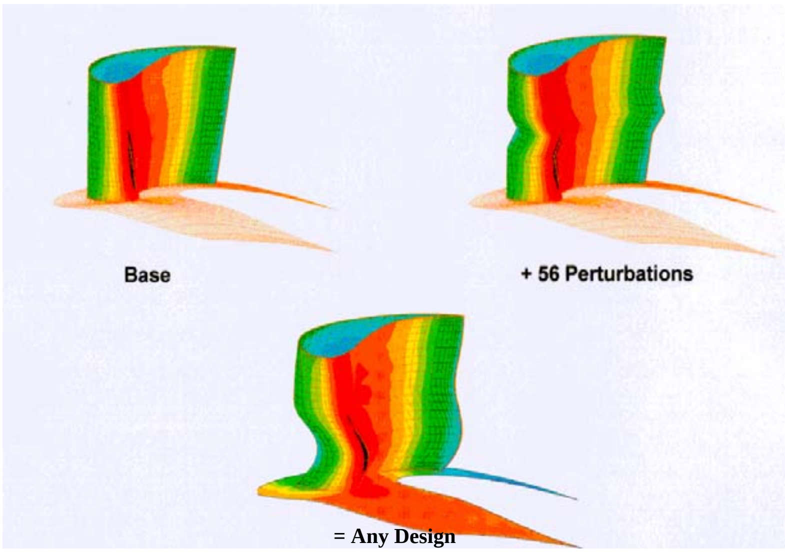
3-D Blading Design
Aerofoil Stacking and Vortex
FAITH Design System



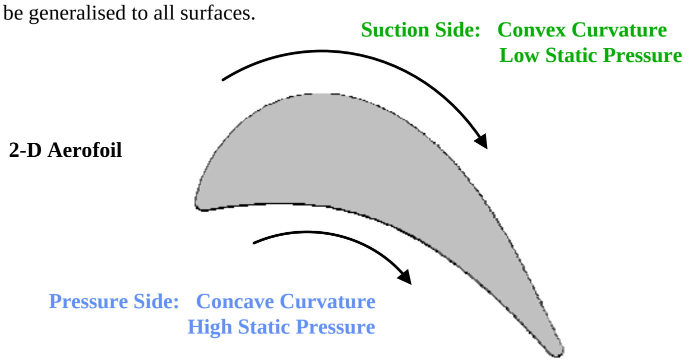
3-D Blading Design
Aerofoil Stacking and Vortex
FAITH Design System



Fundamentals: Streamline Curvature

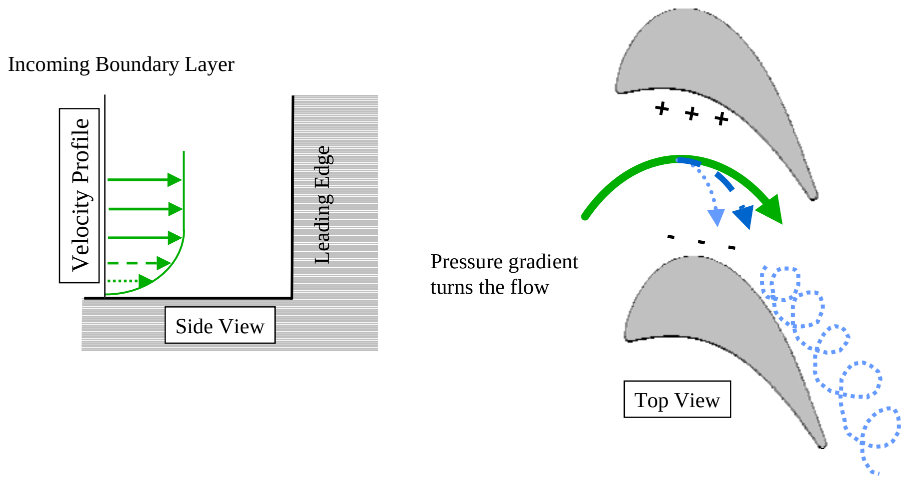
Static pressure is controlled through surface curvature,

This principle can be generalised to all surfaces.



3-D Blading Design
Contoured Endwalls
Fundamentals

Secondary flows are generated as the low momentum fluid in the boundary layer is over turned.



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3-D Blading Design
Contoured Endwalls
Fundamentals

Use local endwall surface curvature to:-

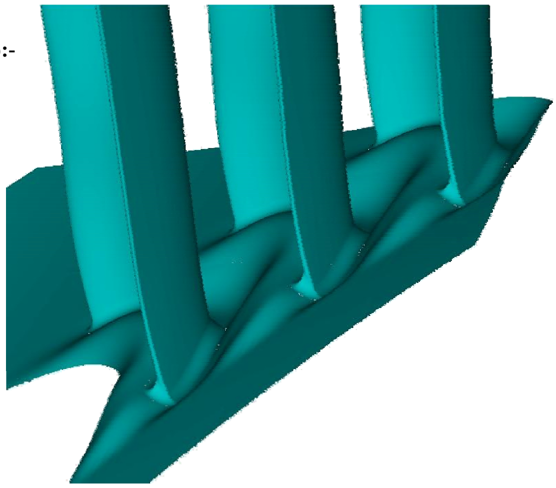
Change the Static Pressure

↓

Reduce the Over Turning

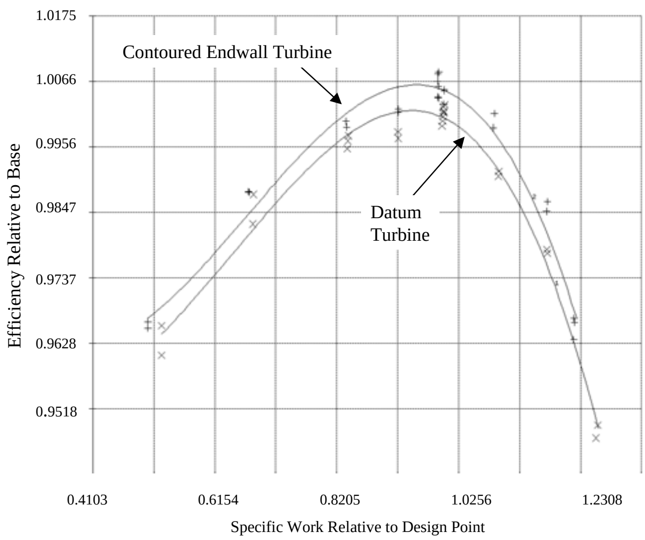
↓

Reduce the Secondary Loss



3-D Blading Design
Contoured Endwalls
HP Turbine - Experimental Results

Design Point
$\Delta\eta = +0.59\%$



Outline

Introduction

Basic Mech. Design Considerations

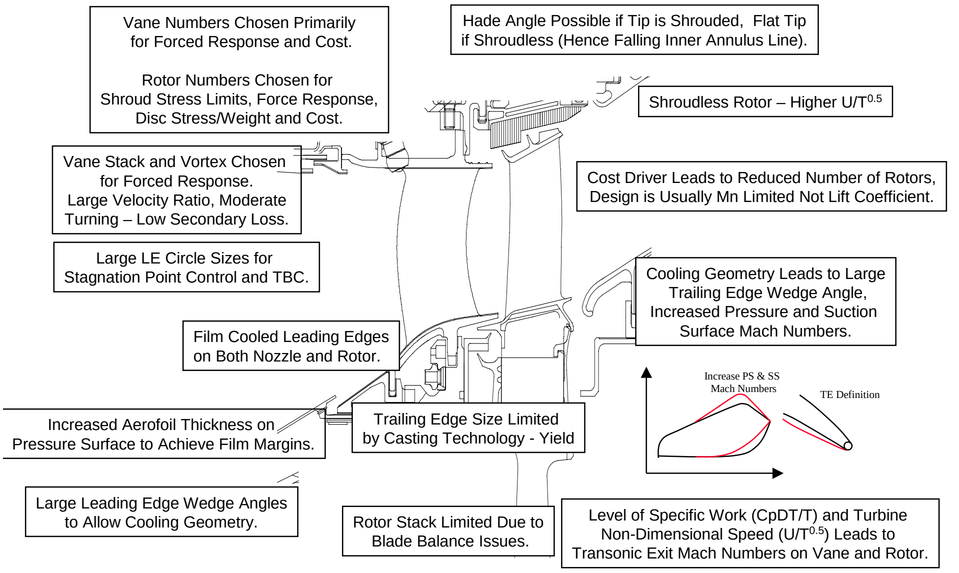
Mean line design, Velocity Triangles

2D Blade design

3D Design, Blade stacking

Summary

3-D Blading Design
Conclusion
Design Considerations



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Conclusions

The aerodynamic Design of HP Turbines is dominated by the multidisciplinary requirements and mechanical design constraints

In principle, in the early stages of te design, very important decisions are taken, which will govern all following design phases

The advent of 3D multirow CFD with capabilities far beyond those just a decade ago allows for more complex modelling and thus realistic assessment of the goodness of a particular design, especially with all complex 3D flow regimes present in the CFD.

3-D CFD and rig testing offers the potential to aid the designer to significantly reduce the steady secondary loss within a turbine. This is believed to be equivalent to a 1% reduction in SFC for a large turbofan engine,

An improved understanding of Unsteady interaction, real geometry impacts, secondary air/main gas path interaction, turbulence, will help us to optimise the aerodynamic and cooling performance of turbines

The optimisation of turbines so far has been achieved in the absence of complex turbulence models and detailed modelling – thus, future progress is still possible

Thank You

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