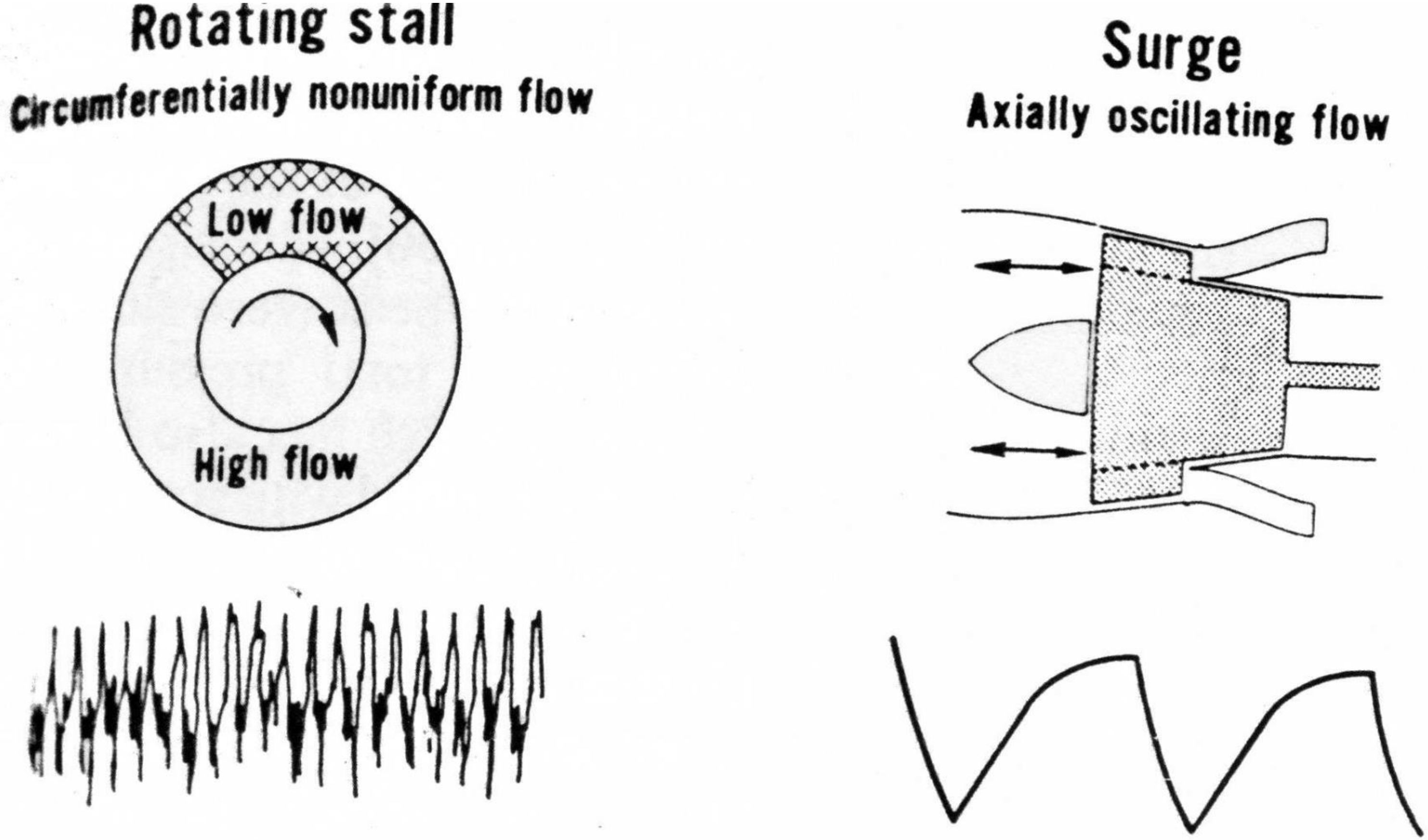
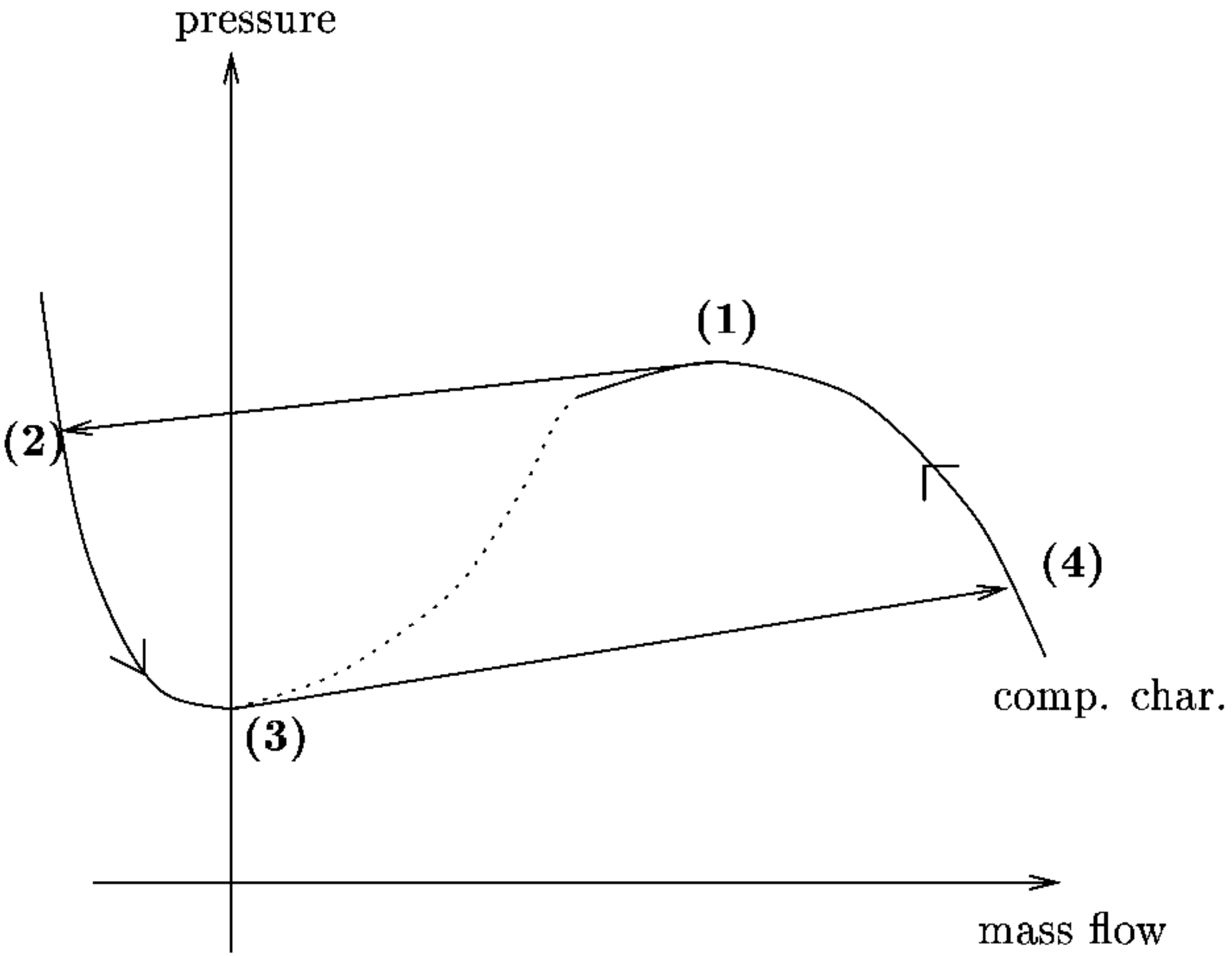
- Recap: Lecture 13: 5th September 2015, 1030-1200 hrs.
  - Stall
    - Blade stall
    - Rotating stall
      - Mechanism
      - Effects of rotating stall
      - Stall inception mechanisms
  - Surge
    - Causes and effects of surge



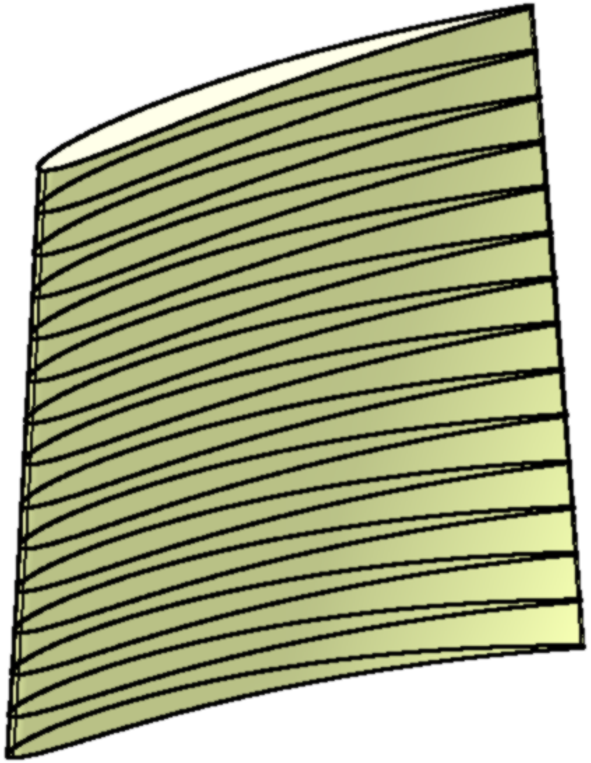
Rotating stall and surge

- Surge is sometimes classified as follows.
  - **Mild surge:**
    - Pressure fluctuations are small and reverse flow does not occur.
  - **Classic surge:**
    - Oscillations are larger and at lower frequency than mild surge. No flow reversal takes place.
  - **Modified surge:**
    - It is a mixture of rotating stall and classic surge. The entire flow fluctuates in axial direction and it is unsteady and non-axisymmetric.
  - **Deep surge:**
    - It is a severe version of classic surge with flow reversal. It is highly undesirable as it causes mechanical damage. Flow is unsteady but axisymmetric. It oscillates back and forth at the compressor stage.

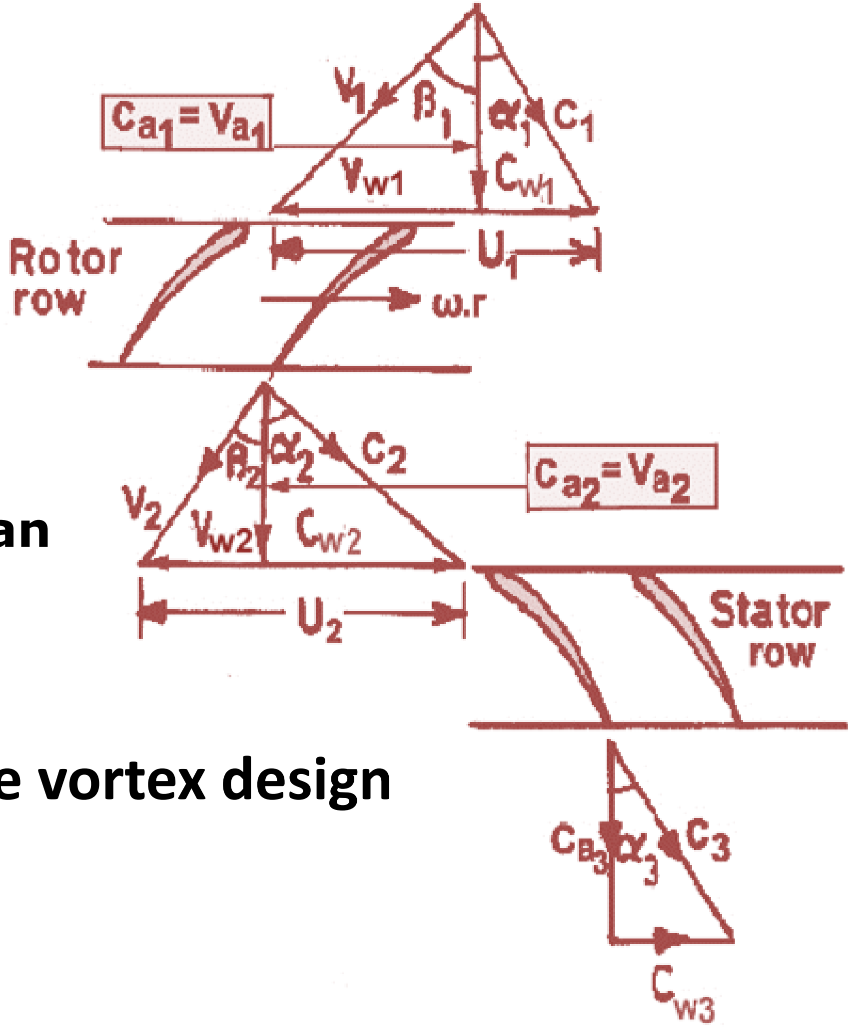


Deep surge phenomenon

Aerodynamic Design of Axial Compressor
Blade design Procedure



INDIVIDUAL STAGE DESIGN METHOD



Ideal Work Required

$$W_{th} = (C_{w1} - C_{w2})\; U_m$$

$$C_{wm} = \frac{C_{w1} + C_{w2}}{2}$$ **At Mean**

$$C_{wm}.r = const$$ **For free vortex design**

$$C_{w,1\text{-}r} = C_{w,1m} \cdot \left(\frac{r_m}{r} \right)$$

INDIVIUAL STAGE DESIGN METHOD

$$C_{1-r} = \sqrt{\left(C_{a,1r}^{2} + C_{w,1r}^{2}\right)}$$ Absolute Velocity

$$\alpha_{1,r} = \sin^{-1}\left(\frac{C_{w.1r}}{C_{1,r}}\right) = \cos^{-1}\left(\frac{C_{a,1r}}{C_{1,r}}\right)$$ Absolute Angle

$$U_{1,r} = U_{1,m} \cdot \left(\frac{r_1}{r_m}\right)$$ Blade Speed

$$\beta_{1,r} = \tan^{-1}\left(\frac{\left(U_{1,r} - C_{w,1r}\right)}{C_{a,1r}}\right)$$ Relative Angle

$$V_{1,r} = \left(\frac{C_{1,a}}{\cos\beta_{1,r}} \right)$$ Relative Velocity

$$U_{2,r} = U_{2,m} \cdot \left(\frac{r_2}{r_{2,m}} \right)$$ **If, d_m = constant, $U_{1,m} = U_{2,m}$**

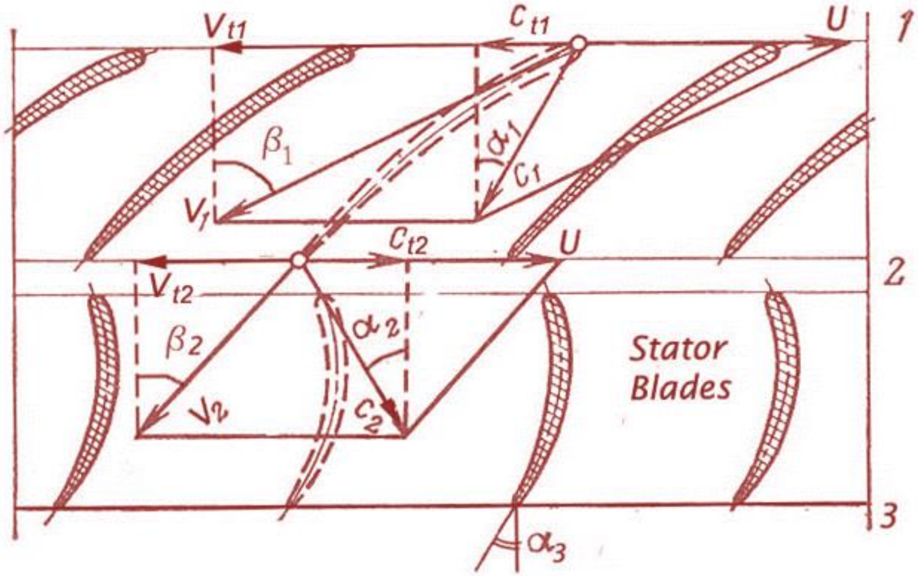
$$C_{w,2r} = C_{w,2m} \cdot \left(\frac{r_{2m}}{r} \right)$$

Check

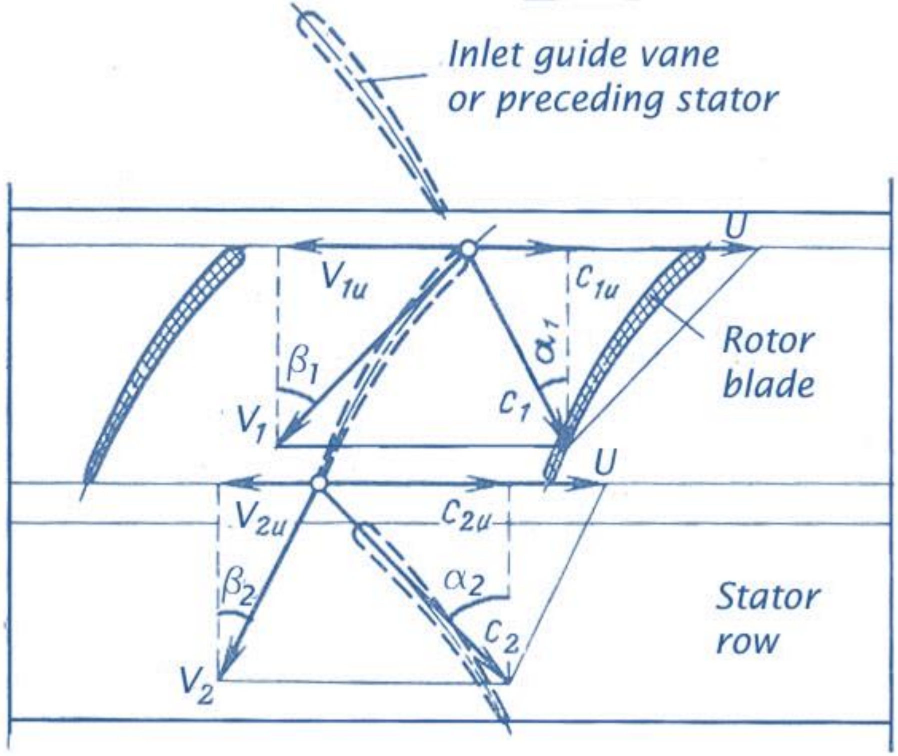
Degree of Reaction, Rx should never be zero anywhere on the rotor blade

INDIVIUAL STAGE DESIGN METHOD

Degree of Reaction



100% reaction blade



50% reaction blade

$$C_{a,2r} = C_{a,m} = const$$

or assume a value for

$c_{a1} . \rho_1 / c_{a2} . \rho_2 \approx 1.0$

$V_2 < V_1 \longrightarrow$ **Generally accepted**

$V_2 = V_1 \longrightarrow$ **Rarely Used**

$V_2 > V_1 \longrightarrow$ **transonic fan design – possibility**

$$\boxed{\alpha_{2,r} = \tan^{-1}\left(\frac{C_{w,2r}}{C_{a,2r}}\right)}$$

$$\boxed{\beta_{2,r} = \tan^{-1}\left(\frac{\left(U_{2,r} - C_{w,2r}\right)}{C_{a,2r}}\right)}$$

$$\Delta\beta = \beta_{2,r} - \beta_{1,r}$$

INDIVIUAL STAGE DESIGN METHOD

$$V_{2,r} = \left(\frac{C_{a,2r}}{\cos\beta_{2,r}} \right)$$

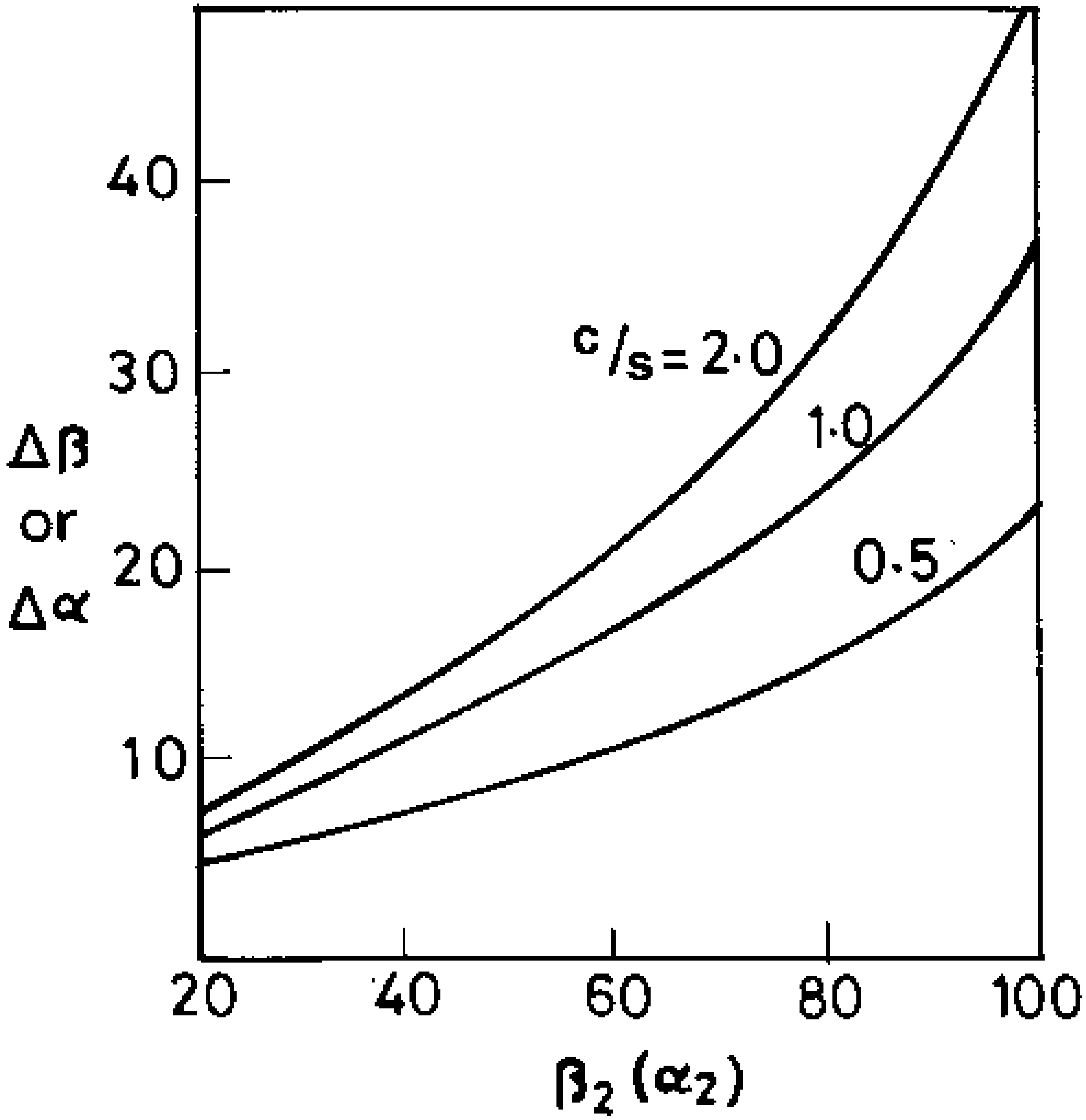
$$\Delta\beta = \beta_{2,r} - \beta_{1,r}$$ → Flow Turning Angle

Provide angle of incidence, *i*, at design point

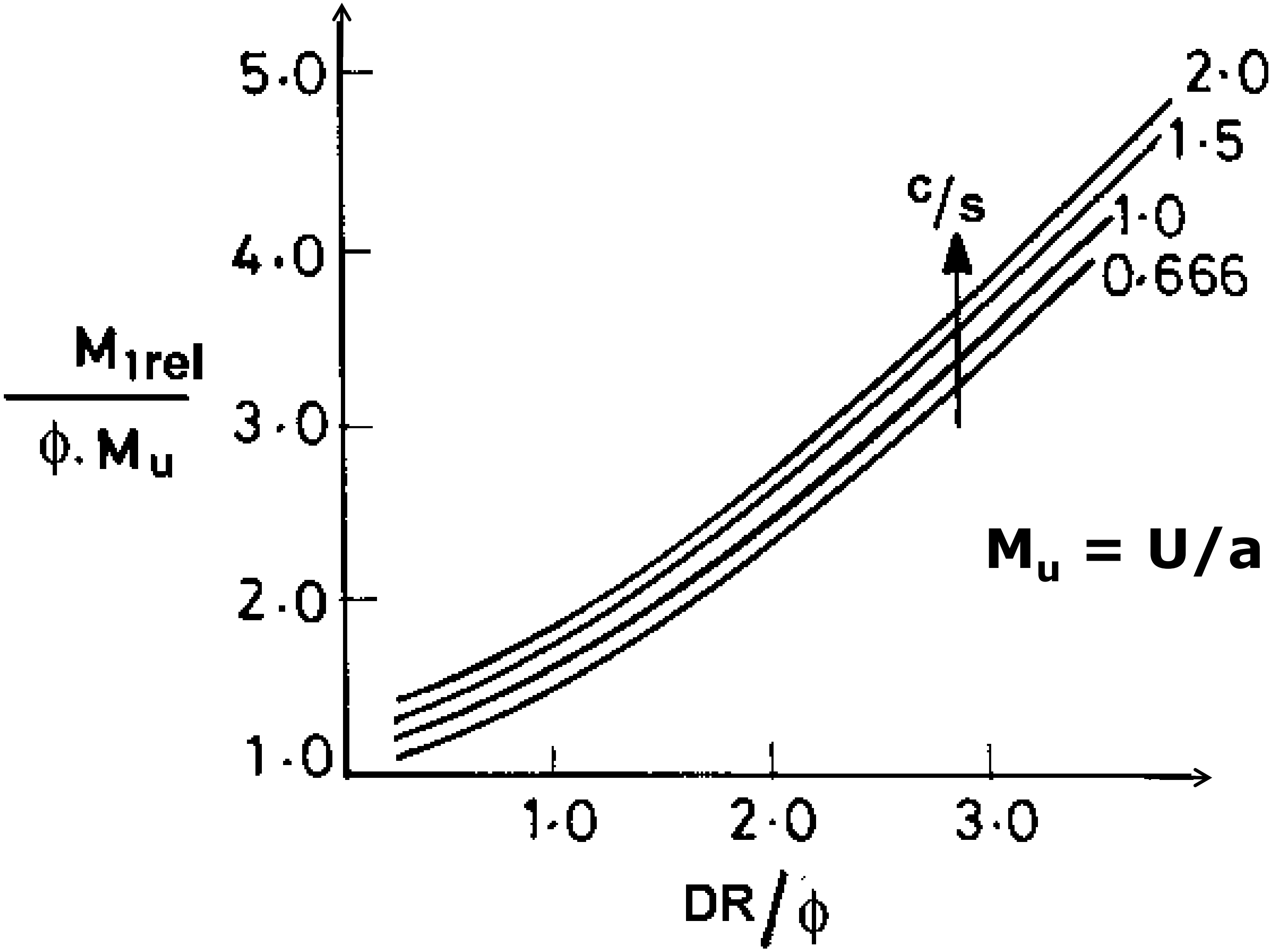
Usually, $i_{tip} = -(1^o \text{ to } 2^o)$ **and**

$i_{root} = +(1^o \text{ to } 2^o)$

Choose solidity of the blade section



c/s = σ, solidity


5.0
4.0
3.0
2.0
1.0
$\frac{M_{1rel}}{\phi . M_u}$
c/s
2·0
1·5
1·0
0·666
$M_u = U/a$
1·0
2·0
3·0
DR/φ

INDIVIUAL STAGE DESIGN METHOD

$$\beta'_{1,r} = \beta_{1,r} + i_r$$

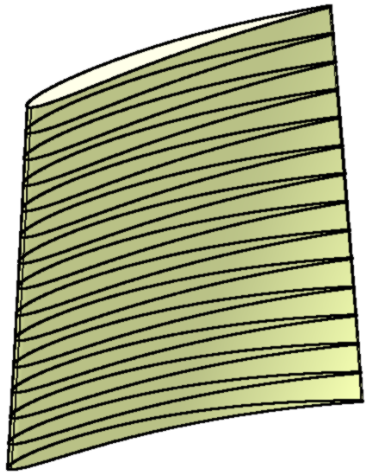
$$\beta'_{2,r} = \beta_{2,r} - \delta^{\bullet}_r$$

(Carter's deviation – valid at design point)

At any radius

Deviation, $\delta^{\bullet}_r = \beta'_{2,r} - \beta_{2,r} = m_r . \theta . \sqrt{\frac{s}{c}}$

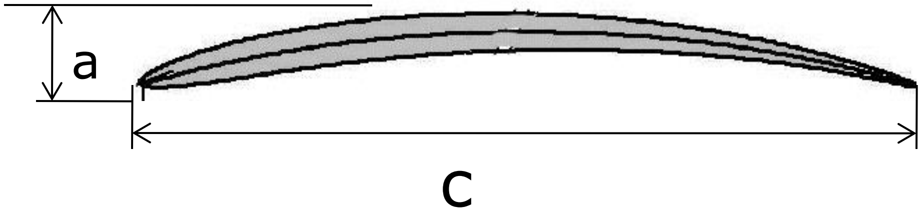
Blade camber angle at any blade element



$$\theta_r = \beta'_{2,r} - \beta'_{1,r} = \frac{\Delta\beta - i_r}{1 + m_r\sqrt{\frac{s}{c}}}$$

Where,

$$m = 0.23\left(2 * \frac{a_i}{c_i}\right)^2 + 0.1\left(\frac{90^{\circ} - \beta_{2,r}}{50}\right)$$



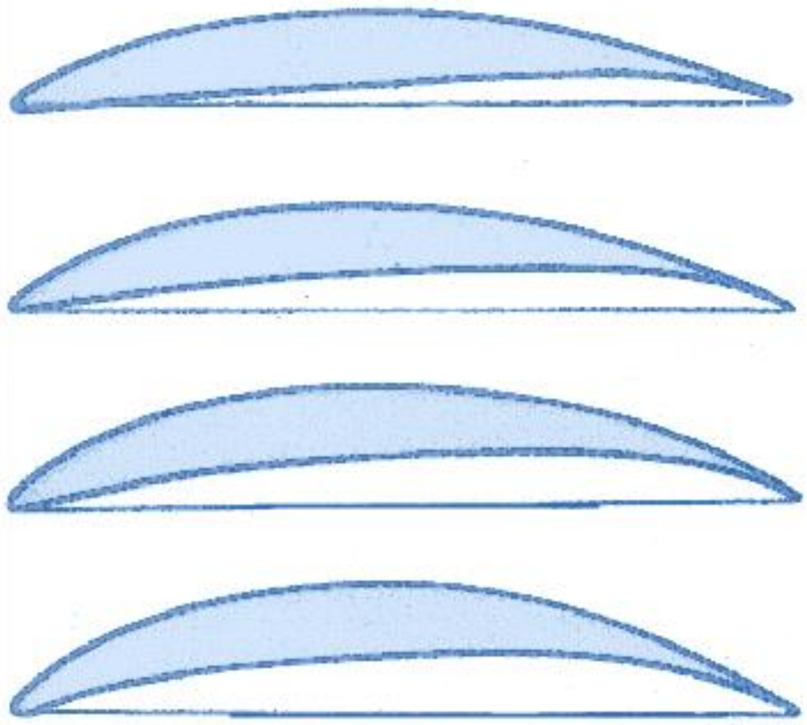
$$\frac{a_i}{c_i} = 0.4 \ \text{to} \ 0.5$$

1. Degree of reaction varies along the radius depending on the law of profile and its values change from 0 to 0.2 at the root to 0.8 to 1 at the tip.
2. There are certain other parameters that affect the dynamics of the flow. These geometrical parameters are:-

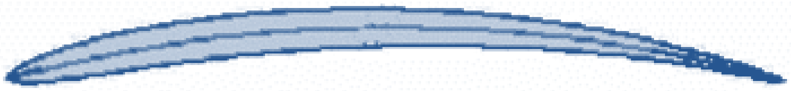
Degree of divergence,	**θ_D**
Flow turning angle,	**$\Delta\beta$**
Blade solidity,	**c/s**

These three are connected by

$$\theta_D = \frac{180}{\pi}\frac{c}{h_c} \times \frac{\cos\left(\beta_1 + \Delta\beta\right) - \cos\beta_1}{c/s}$$



NACA 65 - series

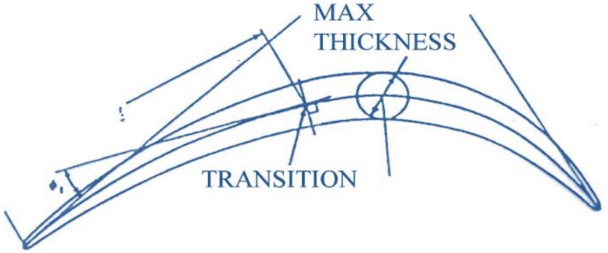


C4 Airfoil

CONTROLLED DIFFUSION AIRFOIL (CDA)

NACA 65 SERIES AIRFOIL

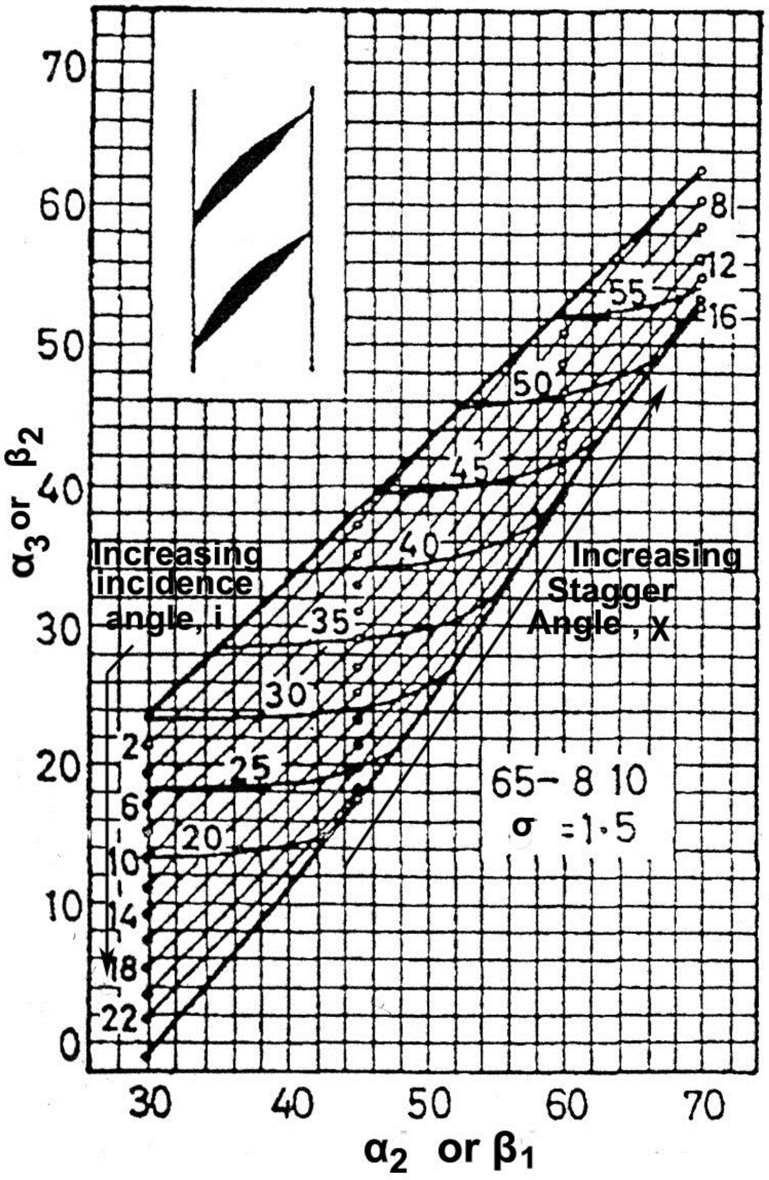
DOUBLE CIRCULAR ARC AIRFOIL (DCA)



MCA

MCA

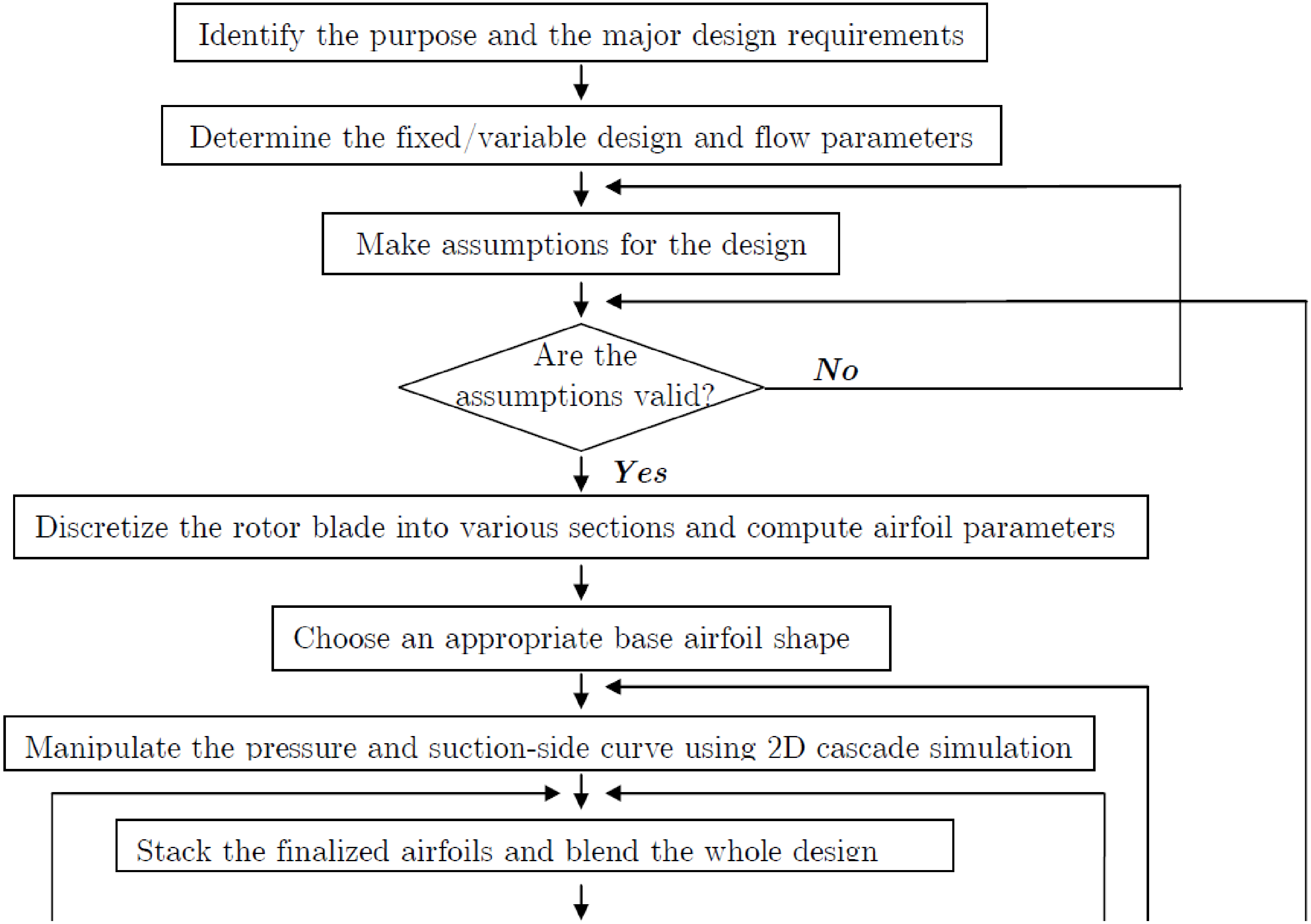
S-TYPE



65-Series Airfoil Data in percentage chord

	Camber definition for $C_{L_0} = 1$		NACA 65-010
x	y_c	dy_c/dx	$\pm y_t$
0	0	-------	0
.5	.250	0.42120	.772
.75	.350	.38875	.932
1.25	.535	.34770	1.169
2.5	.930	.29155	1.574
5.0	1.580	.23430	2.177
7.5	2.120	.19995	2.647
10	2.585	.17485	3.040
15	3.365	.13805	3.666
20	3.980	.11030	4.143
25	4.475	.08745	4.503
30	4.860	.06745	4.760
35	5.150	.04925	4.924
40	5.355	.03225	4.996
45	5.475	.01595	4.963
50	5.515	0	4.812
55	5.475	−.01595	4.530
60	5.355	−.03225	4.146
65	5.150	−.04925	3.682
70	4.860	−.06745	3.156
75	4.475	−.08745	2.584
80	3.980	−.11030	1.987
85	3.365	−.13805	1.385
90	2.585	−.17485	.810
95	1.580	−.23430	.306
100	0	-------	0
		LE rad.	.687

Design Procedure



Identify the purpose and the major design requirements

Determine the fixed/variable design and flow parameters

Make assumptions for the design

Are the assumptions valid?

No

Yes

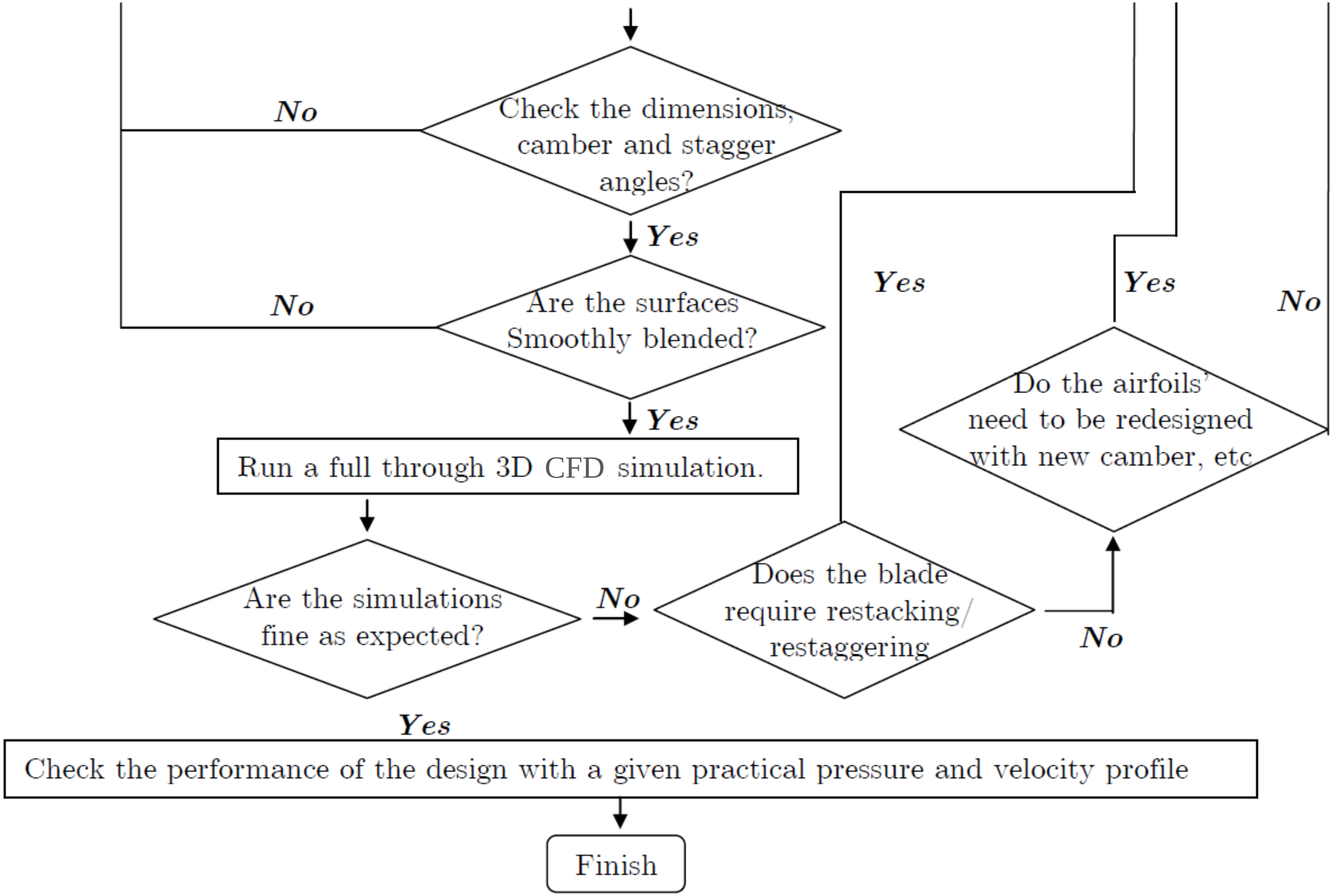
Discretize the rotor blade into various sections and compute airfoil parameters

Choose an appropriate base airfoil shape

Manipulate the pressure and suction-side curve using 2D cascade simulation

Stack the finalized airfoils and blend the whole design

Design Procedure cont…



No

Check the dimensions, camber and stagger angles?

Yes

No

Are the surfaces Smoothly blended?

Yes

Run a full through 3D CFD simulation.

Are the simulations fine as expected?

No

Does the blade require restacking/ restaggering

No

Do the airfoils' need to be redesigned with new camber, etc

Yes

Yes

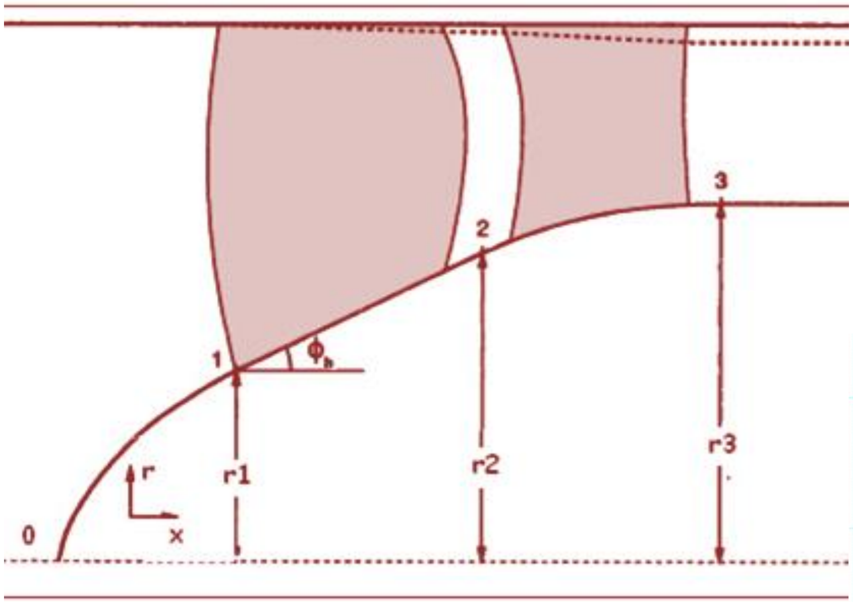
No

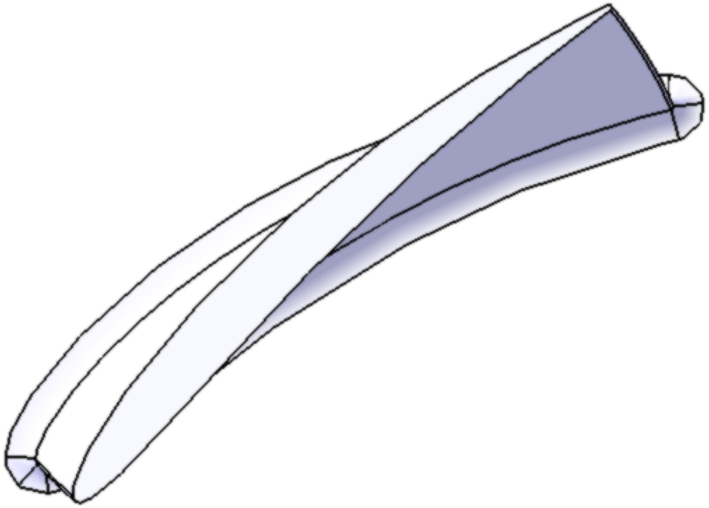
Yes

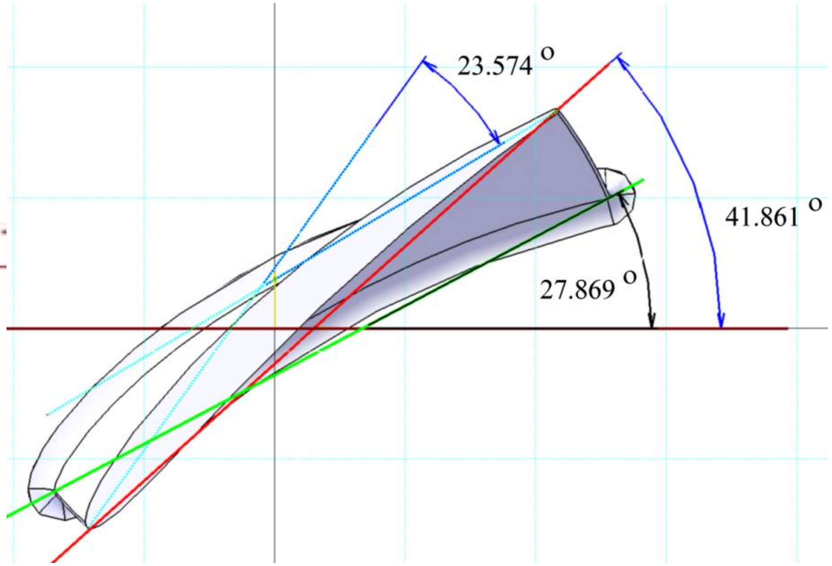
Check the performance of the design with a given practical pressure and velocity profile

Finish

3-D Blade Shapes



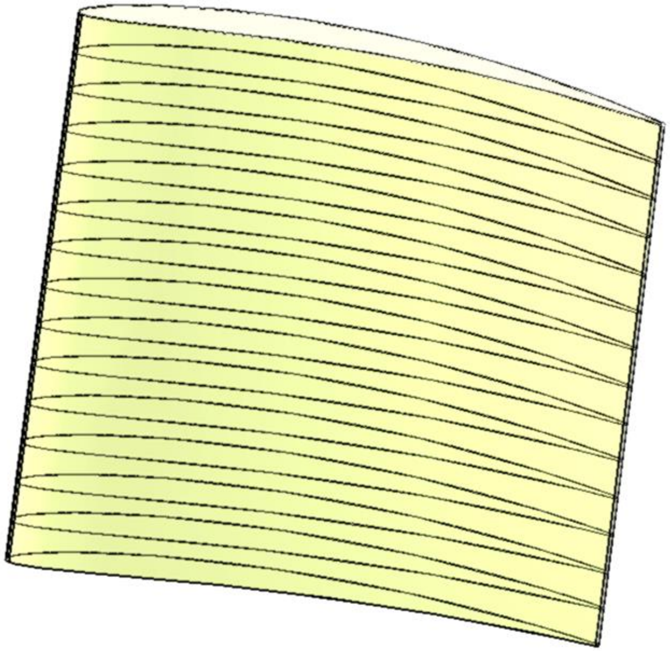




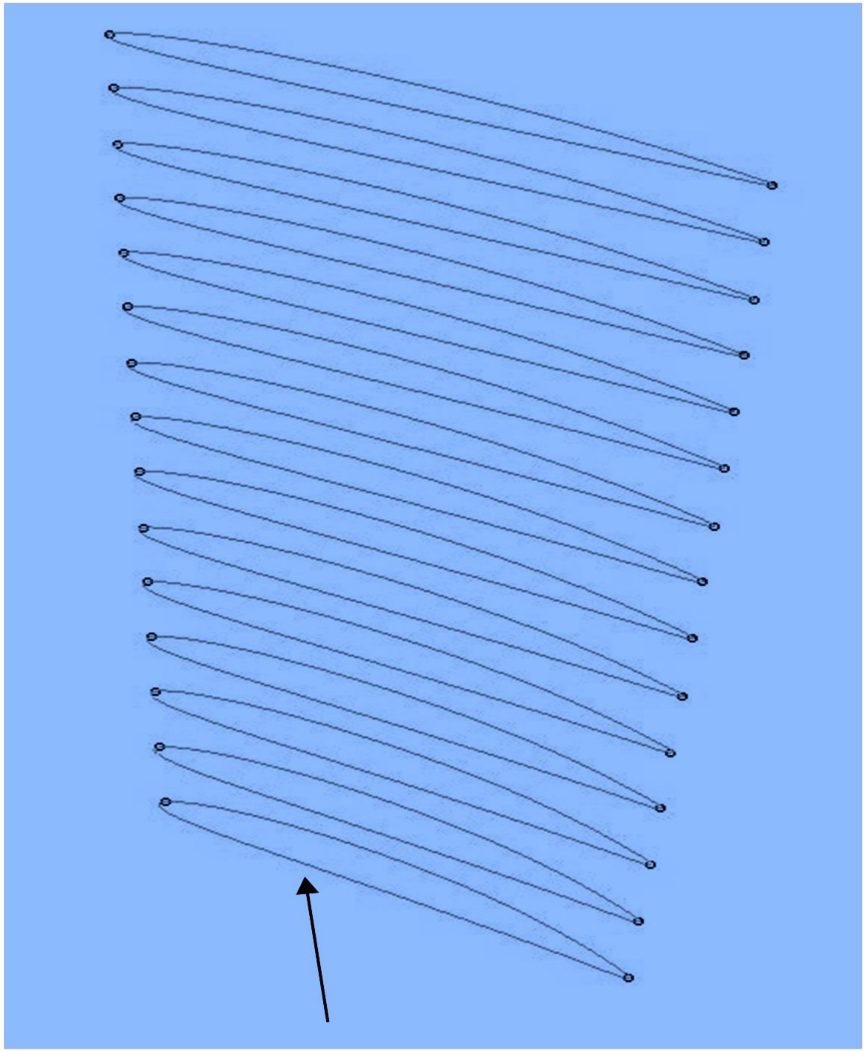
Follow similar step-by-step procedure for STATOR blade design by building up airfoil sections from hub to tip to match with the ROTOR blade design.

Stage design is completed after the rotor-matched stator design is completed.

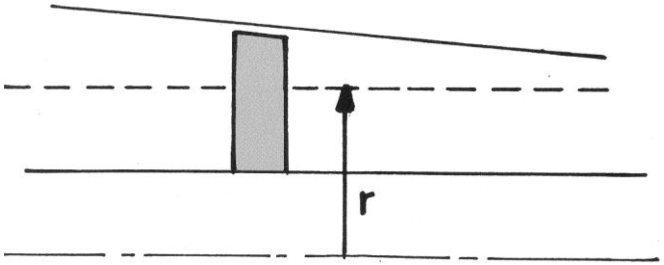
Modern Blade designers have started using 3-D airfoils which are set on cylindrical coordinates, even as they are radially stacked.



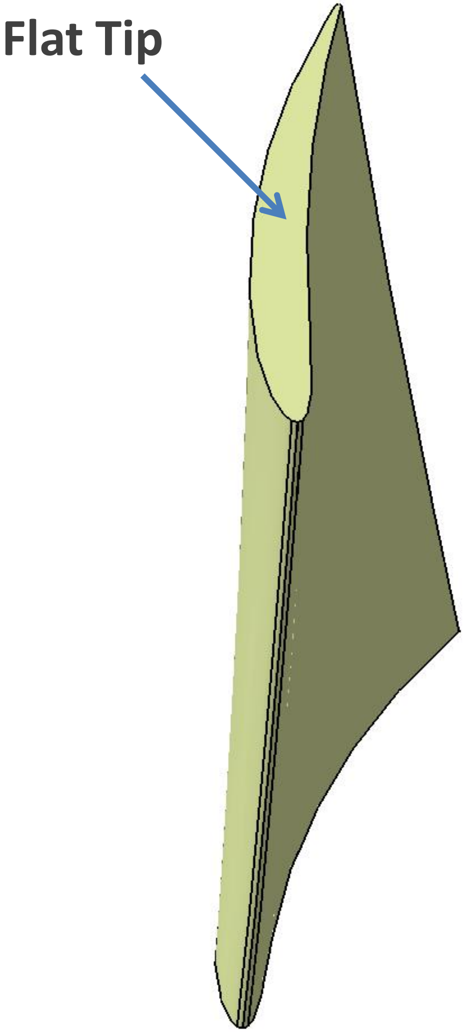
- Standard axial compressor rotor blade design is done with a vortex law as guiding principle
- Such designs normally use airfoils picked from cascade data available with the designers
- Normally produce a twisted blade and a flat tip
- These designs often have strong secondary flow characteristics , in spite of applying radial equilibrium condition for blade design.



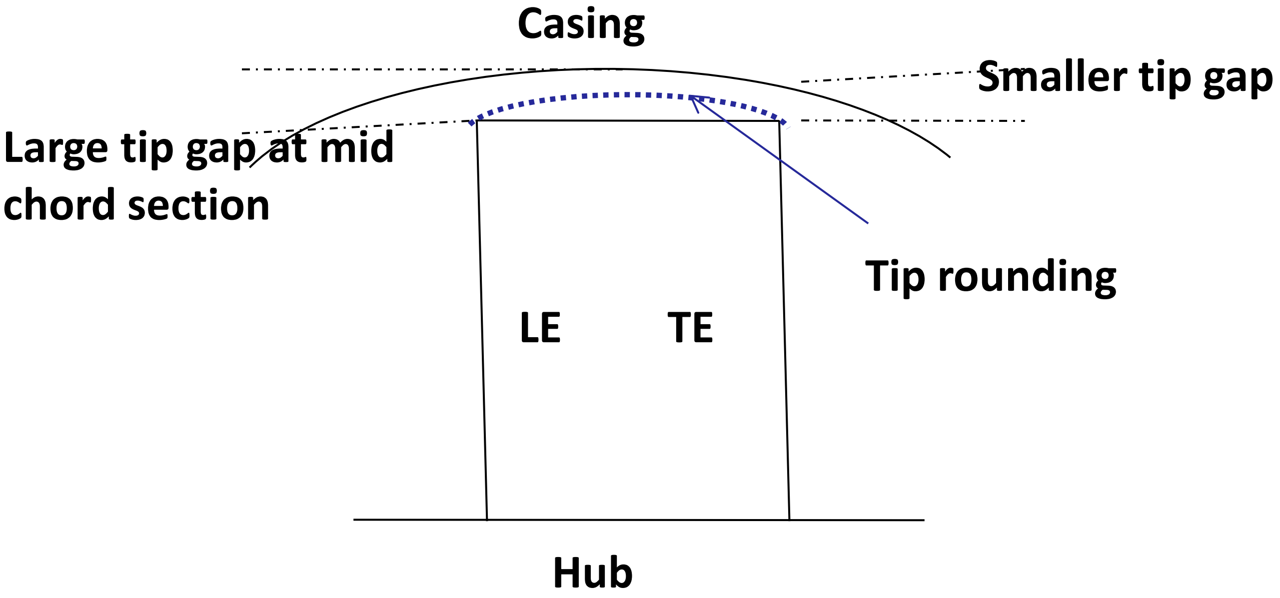
Airfoil profiles



- Airfoils at various radial stations are arranged in a manner such that the airfoils are at constant radius (from LE to TE).
- The CGs of the airfoils are in a radial locus



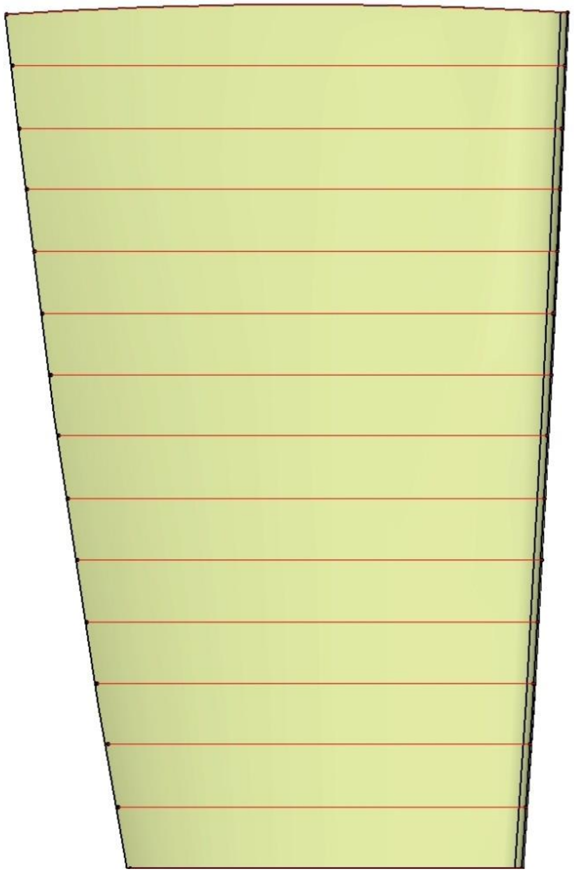
- Such designs normally produce a flat airfoil tip
- The entire L.E is linear or in a smooth line
- The blade T.E by design is normally a smooth non-linear line



- A flat tip creates a divergent-convergent tip gap (from LE to TE) which is meridionally arranged as per tip-airfoil stagger.

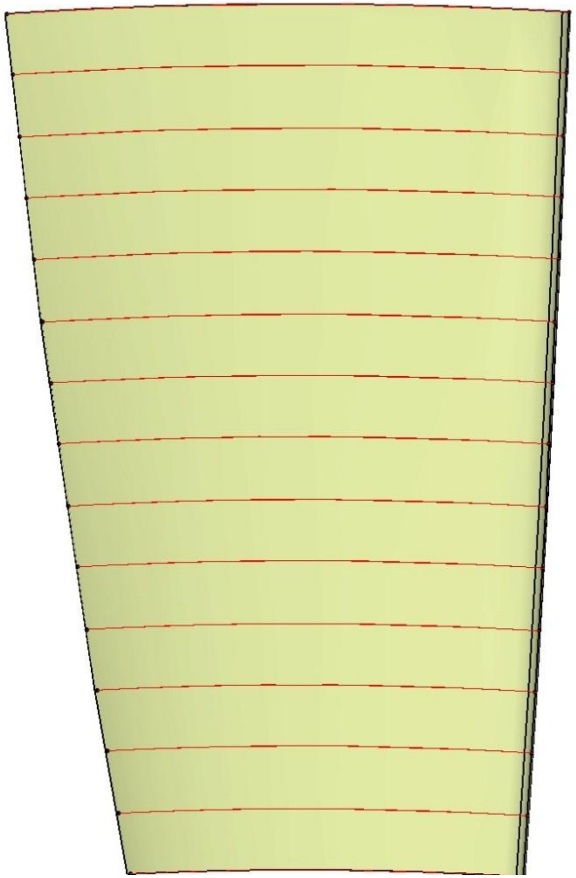
- To ensure a constant tip gap along tip airfoil needs to be arranged in a 3-D surface.

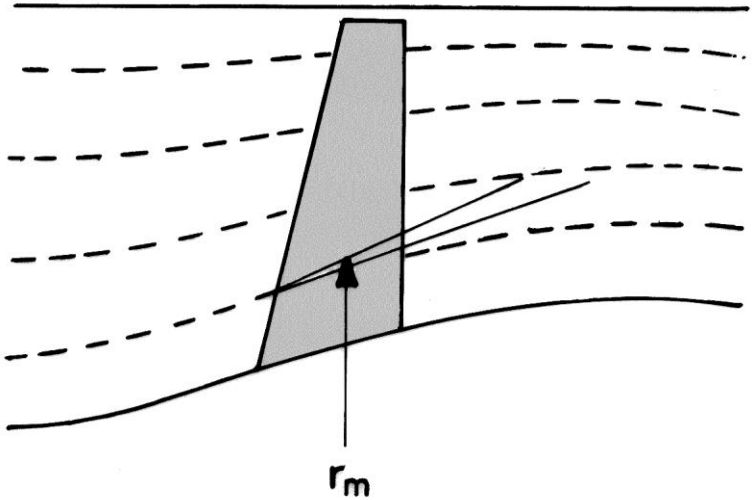
3D airfoil at tip section



During this tip rounding all the other airfoils along the blade length may be held in their flat constant radius meridional planes

3D airfoils at all sections

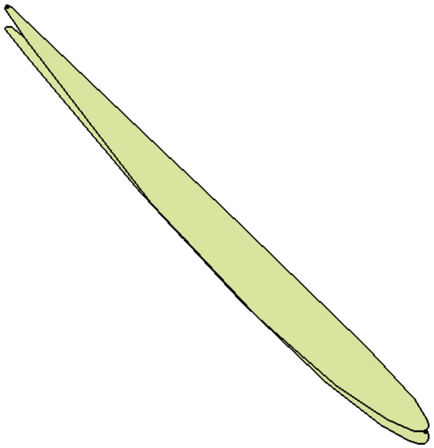




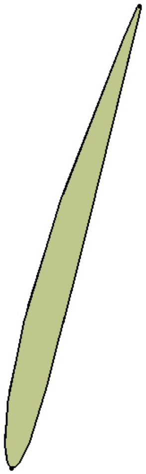
- Each of the airfoils at various blade lengths is set on a curved meridional plane

3D Airfoil

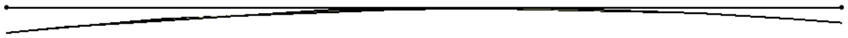
Isometric View



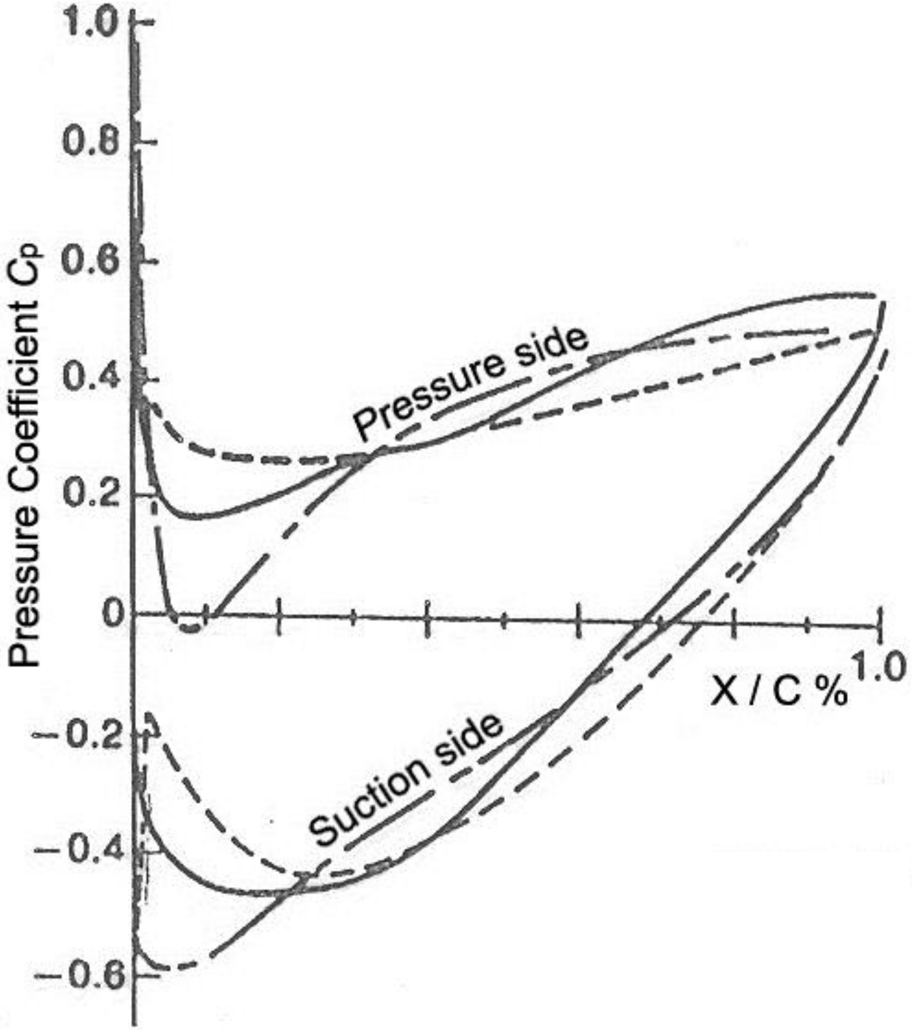
Top View



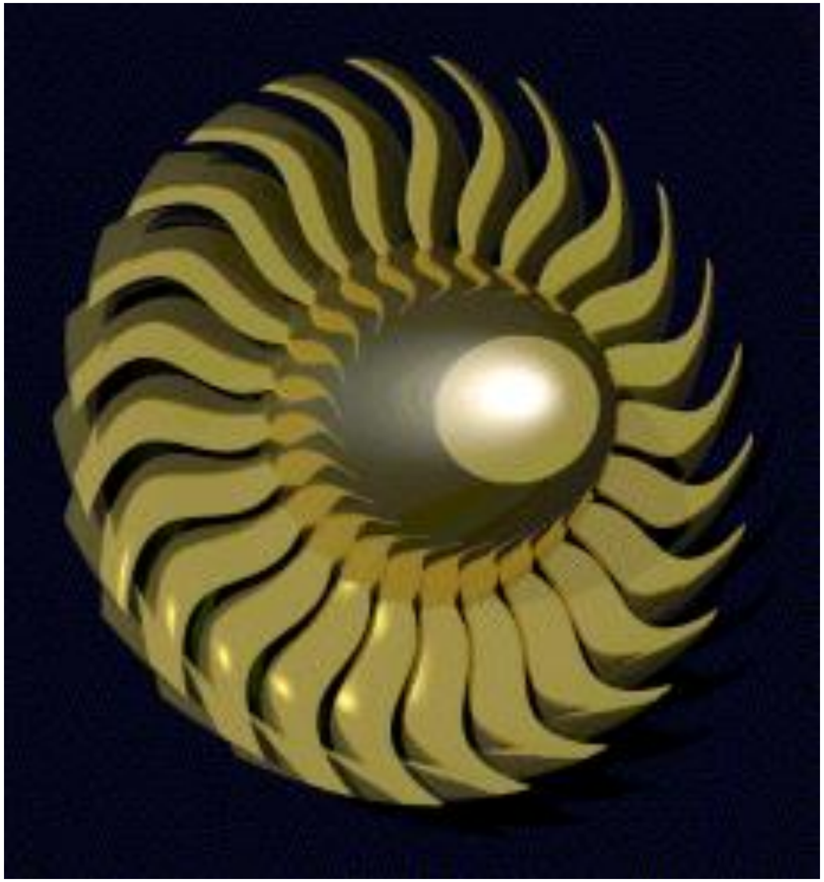
Axial View



Circumferential View



- Cp distribution of a standard airfoil shall change when it is set on a meridional plane and in cylindrical coordinate system
- Restoration of the original Cp distribution shall require the original airfoil shape to be altered



Fan rotor row of a typical commercial aircraft engine