Turbine and Compressor Design

Eric Myers
Daniel Mammolito

Overview

- History of gas turbine engines
- Modern Gas turbine engine
- Types of turbines and basics of design
- Types of compressors and basics of design
- Design of axial compressors
- Multistage axial compressor
- Axial compressor Design example

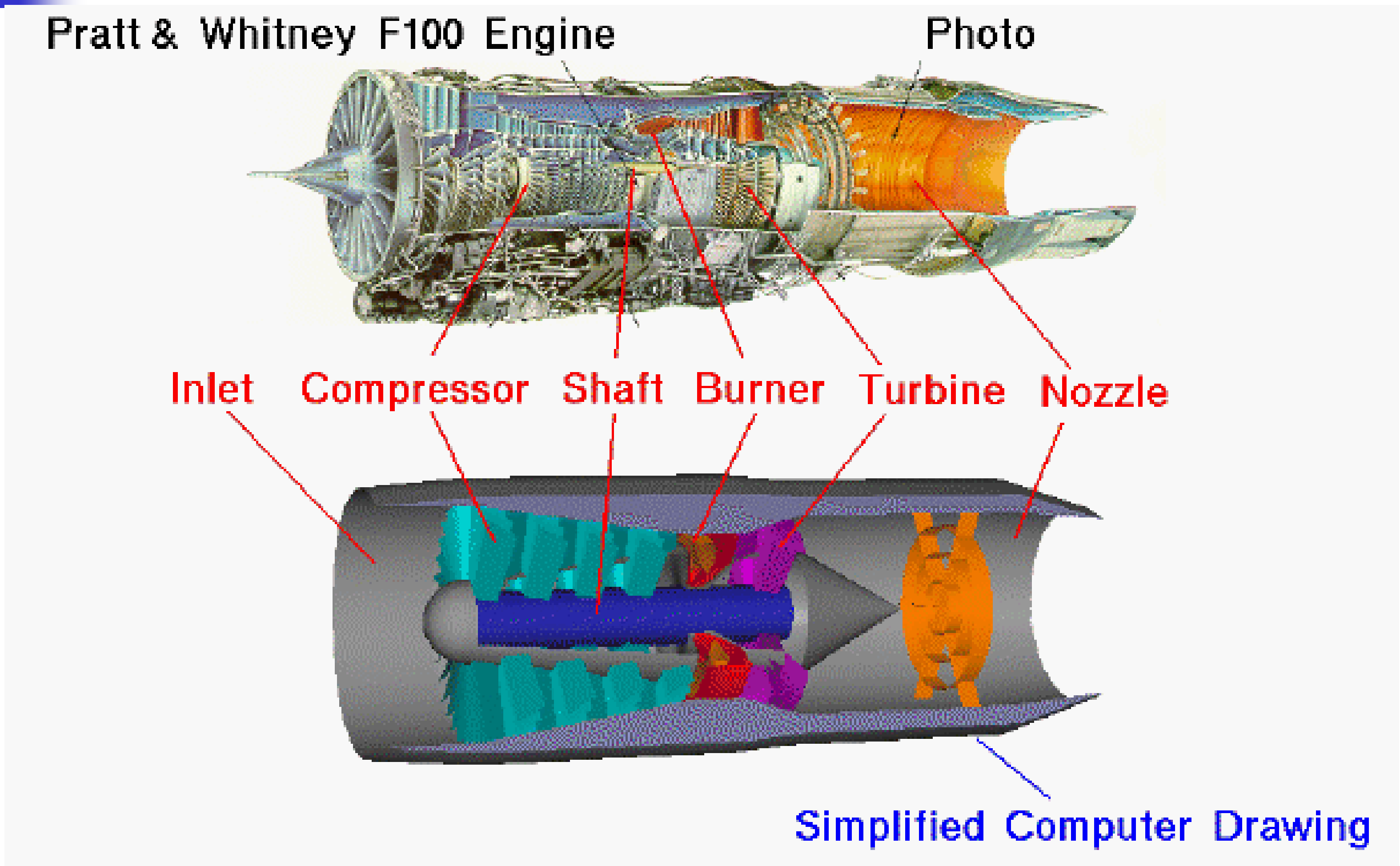
History of gas turbine engines

- 1903 first gas turbine was built; had three cylinders; multistage compressor combustion chamber; impulse turbine
- 1903 Stolze Aegidus Elling of Norway, built successful gas turbine engine that had 80% efficiency for both the turbine and compressor and could withstand inlet temperatures up to 400 C

History of Gas turbine engine

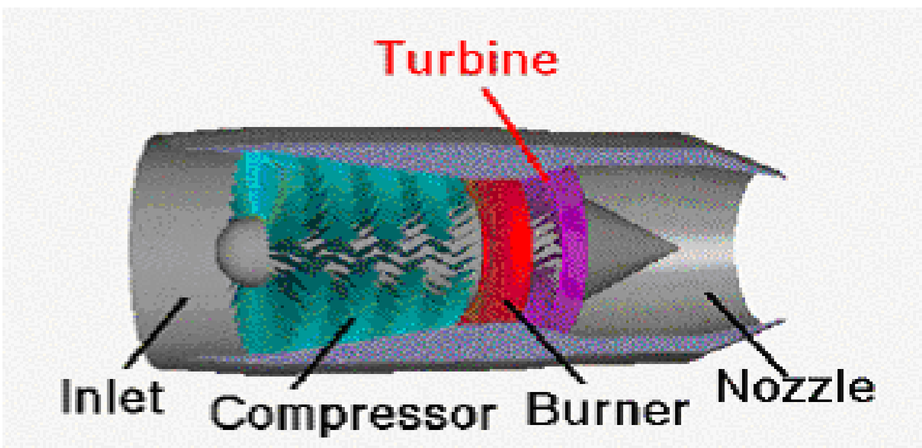
- 1930’s Sir Frank Whittle headed a group at the Royal Aircraft Establishment whose goal was to produce an efficient gas turbine engine for jet propulsion
- Their first successful jet took flight May 15 1941
- Dr Hans P. von Ohain had similar progress in Germany which led to the first ever flight of a jet aircraft on August 27, 1939

Modern Gas turbine engine



Turbines

- Consists of rotating members (rotors) and stationary members (stators)
- 2 types: radial flow and axial flow
- Axial flow turbines are most common in gas turbine engines



Turbines

- The purpose of a turbine is to extract energy from the hot flow and turn the compressor
- Stators redirect the flow back parallel with the axis
- Generally have multiple stages. A single turbine stage can drive several compressor stages.

Turbines

Turbine Pressure Ratio (TPR)

$$TPR := \frac{p_{T5}}{P_{T4}} \qquad TPR := \left(\frac{T_5}{T_4}\right)^{\frac{\gamma}{\gamma-1}}$$

Turbine Work (TW)

$$TW := h_{T4} - h_{T5} \qquad TW := \eta_t \cdot c_p \cdot T_4 \cdot \left(1 - TPR^{\frac{\gamma-1}{\gamma}}\right)$$

Where 4 – turbine entrance

5 – turbine exit

Turbine Compressor Matching

- Ideally, the compressor work is equal to the turbine work
- Since the turbine drives the compressor, the TPR (turbine pressure ratio) is related to and is a function of the CPR (compressor pressure ratio)

$$TPR^{\gamma-1/\gamma} = 1 - \frac{T_{t2}}{\eta_c(\eta_t)(T_{t4})} * (CPR^{\gamma-1/\gamma} - 1)$$

Turbine Environment

- Because the turbine is located behind the combustor, it experiences extremely high temperatures. Oftentimes, such temperatures are more than 1000 F.
- Special materials are needed to withstand such temperatures or the blades can be actively cooled.

Turbine Material Limits

Material	**Temperature**
Aluminum	500 F
Titanium alloys	800 F
Polymer matrix composites	450 – 500 F
Nickel-based alloys	1000 – 1200 F
Ceramic matrix composites	2200 – 2400 F

Turbine Cooling Methods

- Convection cooling:air flows outward from the base of the blade to the end through internal airways within the blade
- Impingement cooling:air is brought radially through a center core of the blade, turned normal to the radial direction, and passed through a series of holes

Cooling Methods (cont’d.)

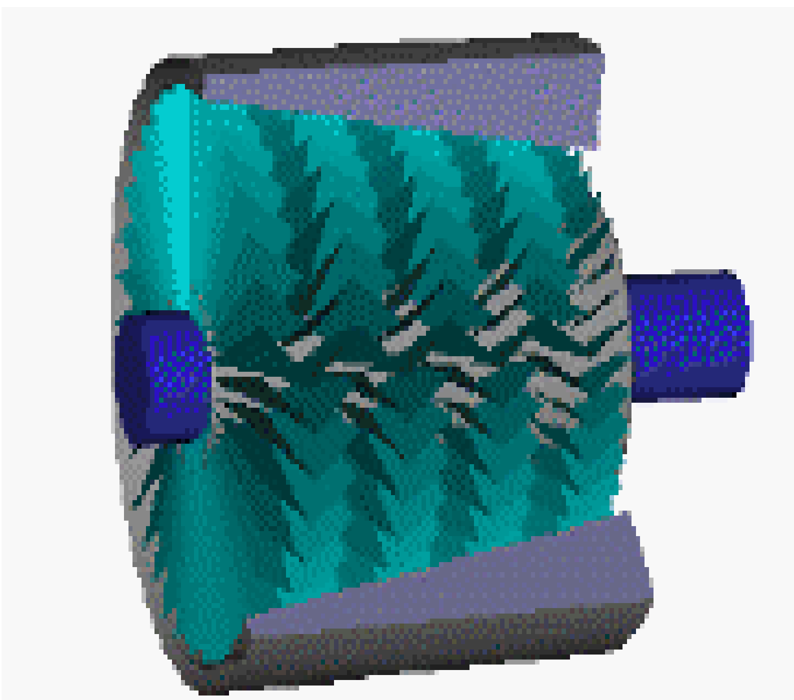
- Film cooling:protects the surface from the hot fluid by injecting cool air into the boundary layer which provides a protective, cooling film on the surface.
- Transpiration cooling:involves the use of a porous material through which cooling air is forced into the boundary layer to form an insulating film.

Types of Compressors

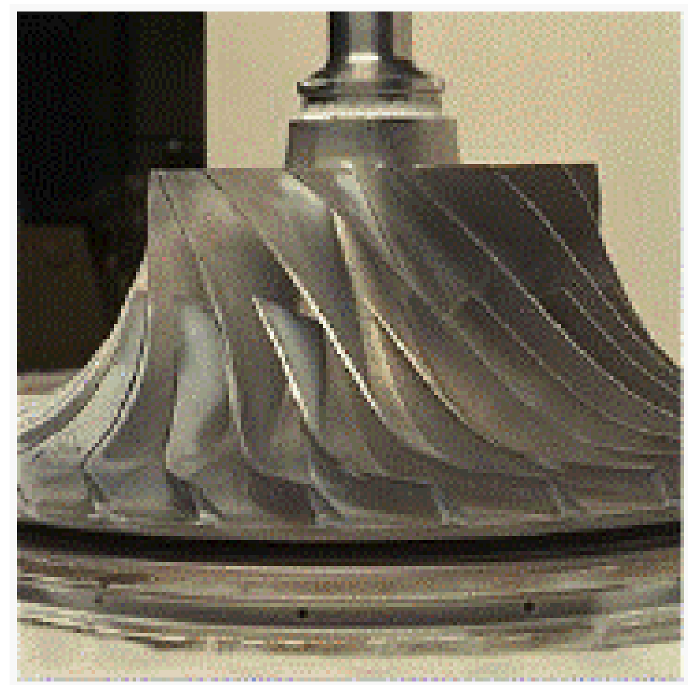
- Axial Compressors
  - Fluid flow is parallel to axis of rotation
  - Used in modern aircraft
  - Have several stages to increase compressor pressure ratio
  - Used in modern gas turbine engines
- Centrifugal Compressor
  - Fluid flow is perpendicular to the axis of rotation
  - Used in first jet turbine engines
  - Have a larger CPR per stage

Types of compressors

- Axial



- Centrifugal



Centrifugal Compressors

Advantages

- Larger CPR per stage
- Simple and rugged
- Shorter in length

Disadvantages

- Cannot be used in stages

Axial Compressors

Advantages

- High peak efficiency
- Small frontal area for given airflow
- Multistaging allows for increase in CPR

Disadvantages

- High weight
- High manufacturing costs
- High starting power requirements

Basic Design of Axial Compressor

- The axial compressor produces small increases in pressure per stage
- Each stage consists of first a revolving rotor followed by a stationary stator
- The rotor gives the energy to the fluid flow
- The stator increases pressure and keeps the flow from spiraling around the axis

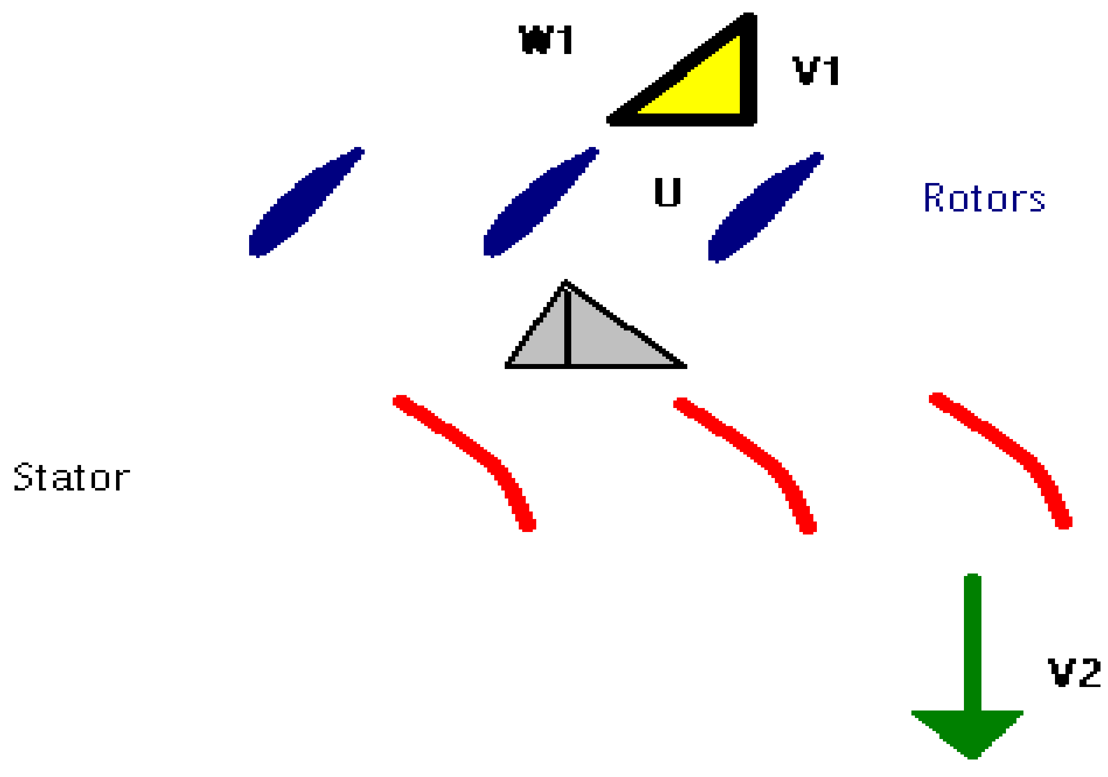
Basic Design of Axial Compressor

- Fluid enters compressor where the blades are longer and exits where blades are shorter, opposite of the turbine
- Must be designed in such a way as to prevent stall
- Use of velocity diagrams will determine blades angles

Multistage axial compressors

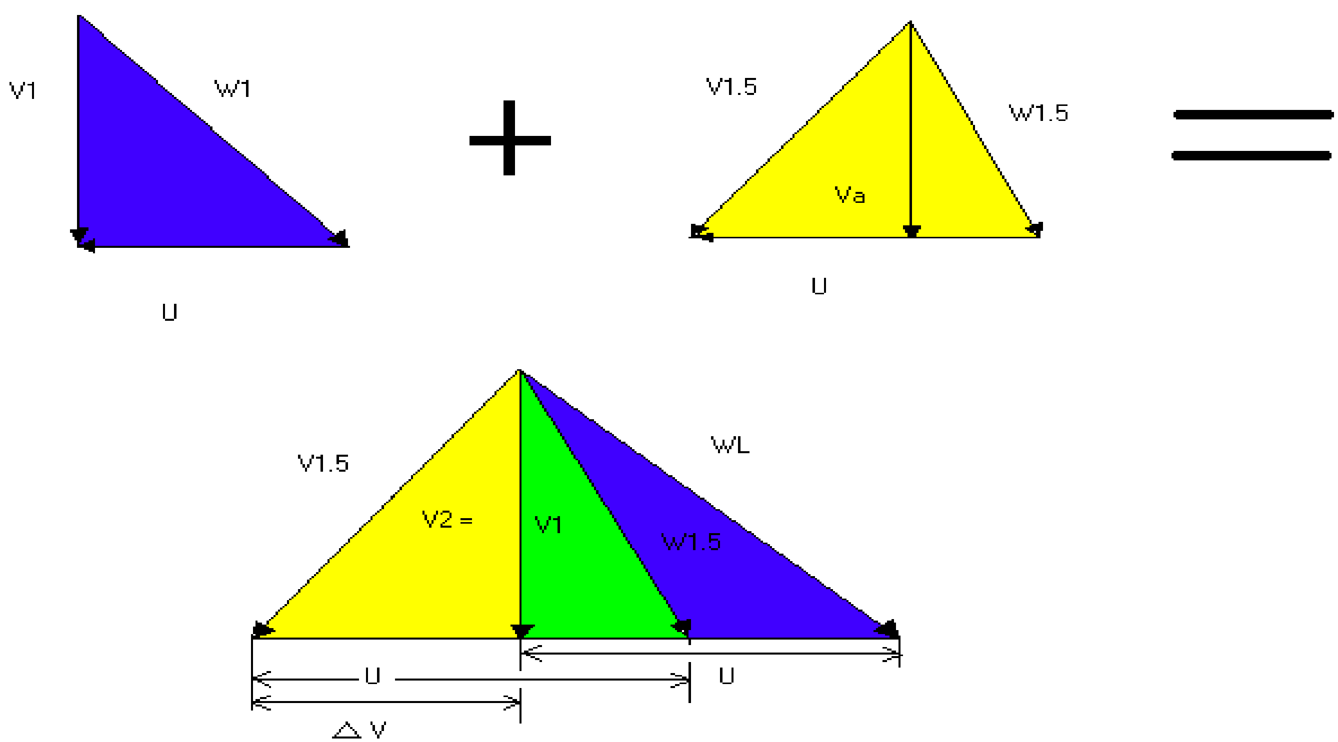
- Multistage axial flow compressors will produce much larger CPR then single stage compressors
- Largest pressure ratio is in first stage
- To calculate the average pressure ratio needed per stage for a set pressure ratio
- $ASPR = PR_{total}^{1/n}$
- Where n is the number of stages needed

Compressor design: Using Velocity Diagrams



Compressor design: Using Velocity Diagrams

- This velocity diagram can be simplified from two triangles into one triangle



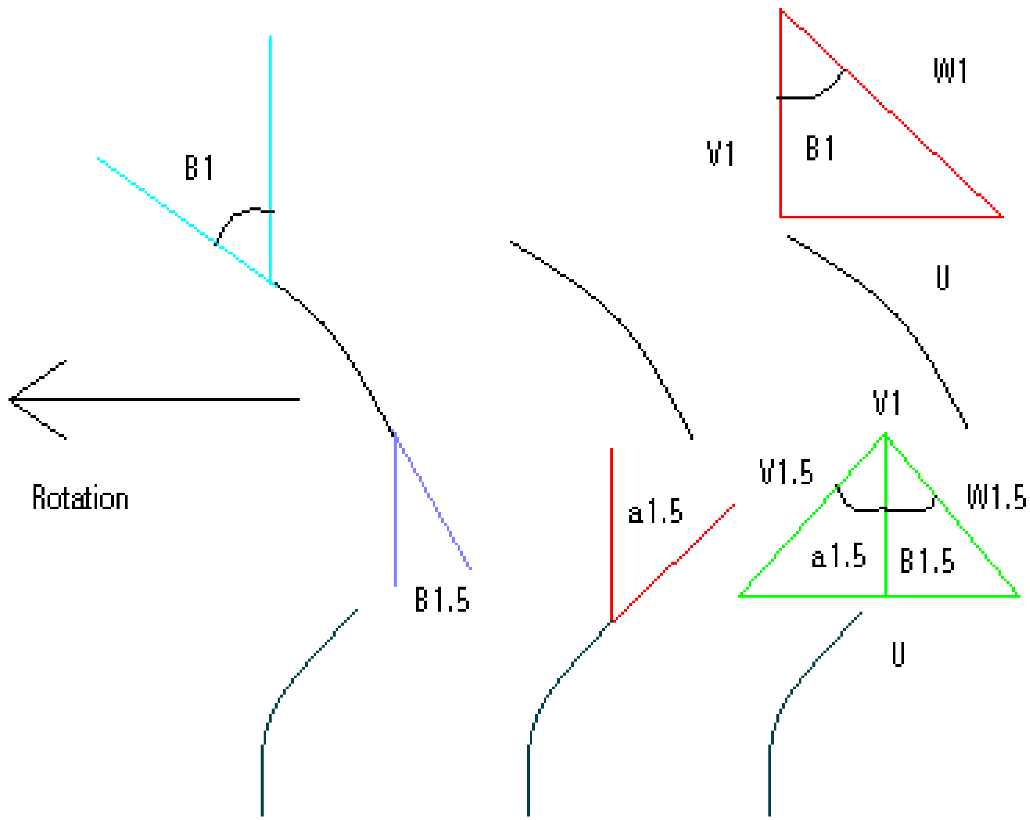
Compressor design: Using Velocity Diagrams

- Velocity diagram shows single stage of axial compressor
- $V=W+U$
- Where:
  - V is the inlet velocity
  - W is the relative velocity of the flow to the rotor blade
  - U is the velocity of the rotor in m/s
  - $U=r\omega$
  - Where r is the representative radius halfway in between the tip and the hub and ω is in rad/sec

Compressor Design: example

- Assume:
- P_{in}=101.3 kPa T_{in}=288K
- V_{in}=170.0 m/s
- Rotor has D_{tip}=66.0 cm and D_{hub}=45.7
- Rotor speed of 8000 rpm
  - Construct velocity diagrams
  - Calculate the stage pressure ratio

Compressor Design: example



Compressor design: Creating a velocity diagram

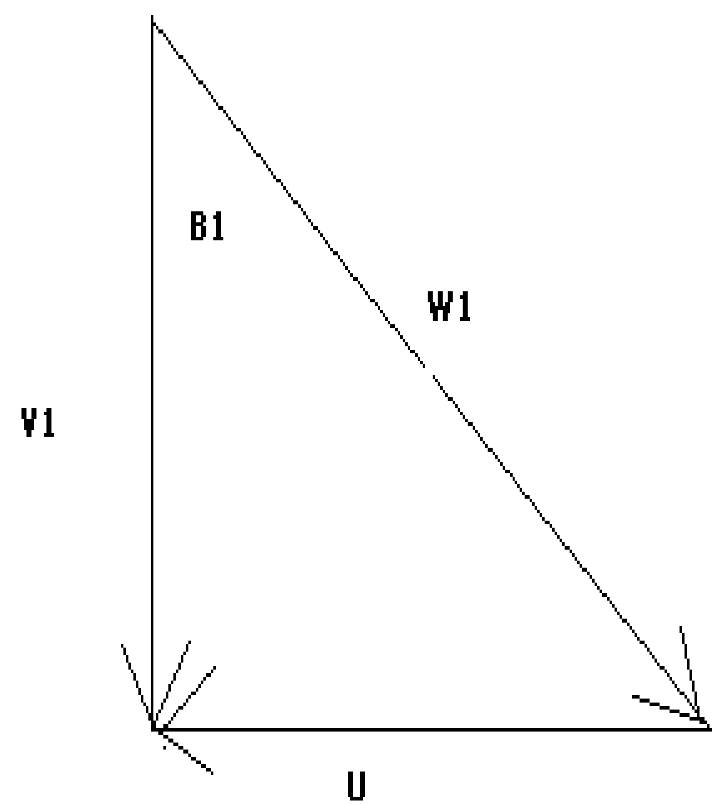
$$U = r\omega$$

$$U = \frac{1}{2}\left(\frac{.457 + .66}{2}\right)\left(\frac{2\pi}{60}\right)(8000)$$

$$U = 233.9\frac{m}{s}$$

$$W_x = -U$$

$$W_x = -233.9\frac{m}{s}$$



Compressor design: Creating a velocity diagram

$$\beta_1 = \tan^{-1}\left(\frac{W_x}{V_1}\right)$$

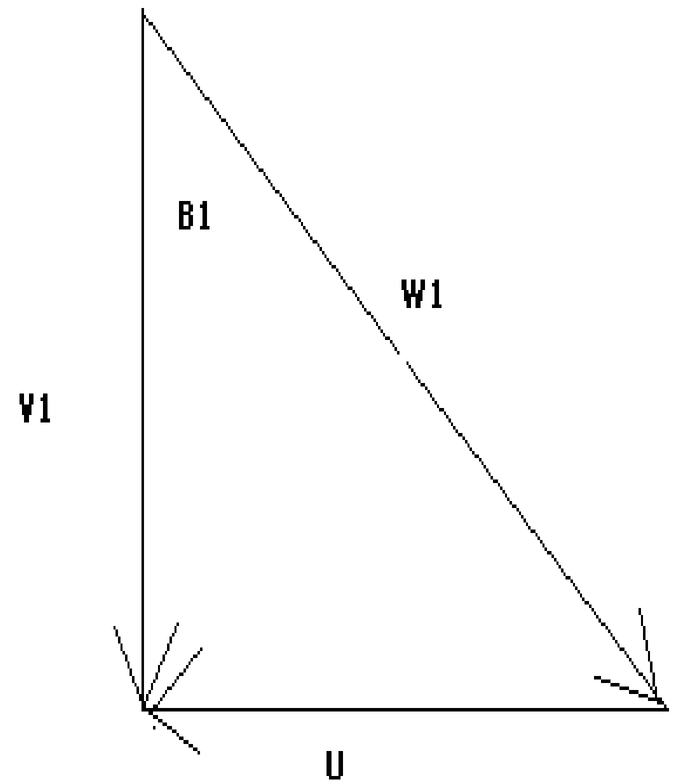
$$\beta_1 = \tan^{-1}\left(\frac{-233.9}{170.0}\right)$$

$$\beta_1 = -54.0 \deg$$

$$W_1 = \sqrt{W_x^2 + V_1^2}$$

$$W_1 = \sqrt{(-233.9)^2 + 170.0^2}$$

$$W_1 = 289.2 \frac{m}{s}$$



Compressor design: Creating a velocity diagram

$$\beta_{1.5} = \beta_1 + \theta$$

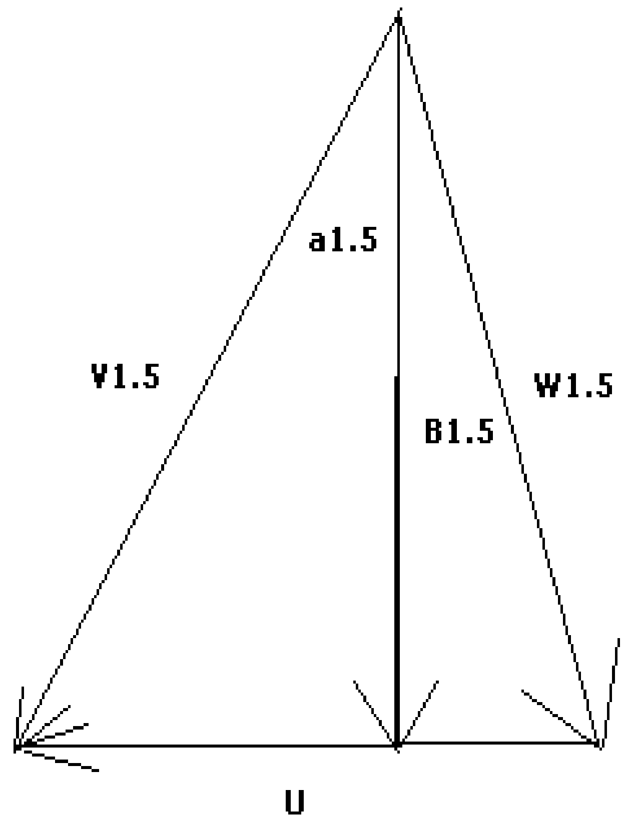
$$\beta_{1.5} = -54.0 + 15$$

$$\beta_{1.5} = -39.0 \text{ deg}$$

$$V_a = 170.0 \frac{m}{s}$$

$$W_{1.5} = \frac{V_a}{\cos(\beta_{1.5})}$$

$$W_{1.5} = 137.7 \frac{m}{s}$$



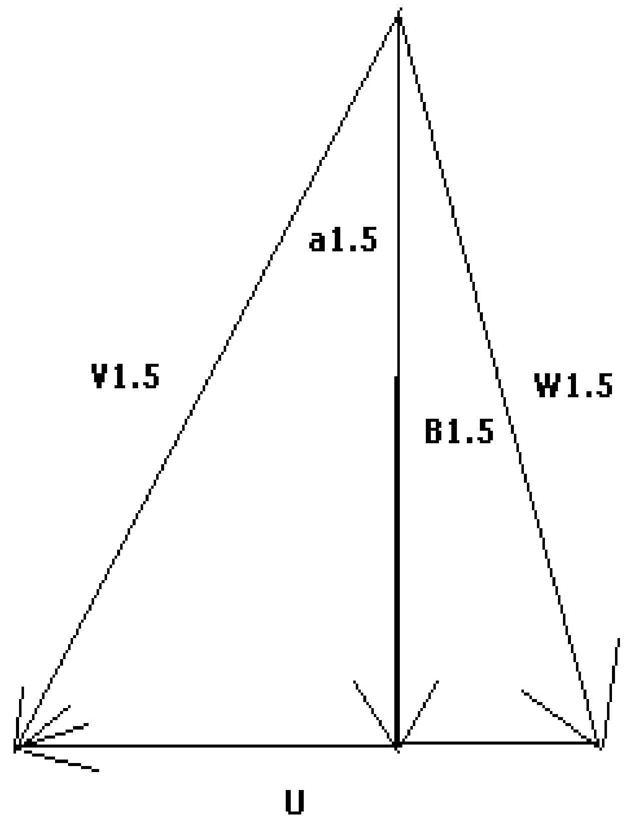
Compressor design: Creating a velocity diagram

$$W_{u1.5} = V_a \tan(\beta_{1.5})$$

$$W_{u1.5} = -137.7 \frac{m}{s}$$

$$V_{u1.5} = U + W_{u1.5}$$

$$V_{u1.5} = 96.2 \frac{m}{s}$$



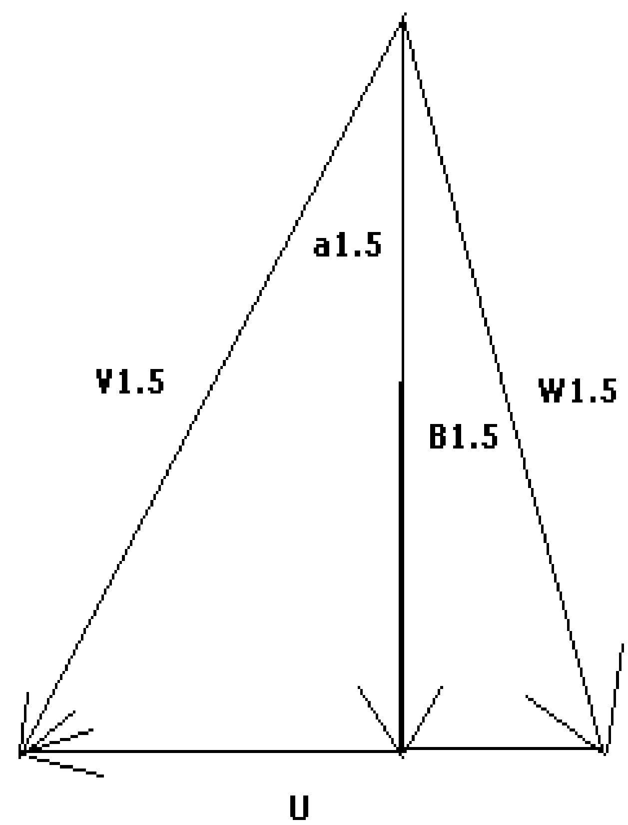
Compressor design: Creating a velocity diagram

$$\alpha_{1.5} = \tan^{-1}\left(\frac{V_{u1.5}}{V_a}\right)$$

$$\alpha_{1.5} = 29.5 \deg$$

$$V_{1.5} = \frac{V_a}{\cos(\alpha_{1.5})}$$

$$V_{1.5} = 195.3 \frac{m}{s}$$



Velocity Diagram Explanation

- Velocity Diagram gives blade camber line angle and inlet (β_1) and outlet ($\beta_{1.5}$)
- Turning angle of the blade is the change in the inlet and outlet angles of the blade
- The line of attack for the stator is represented by $\alpha_{1.5}$

Compressor Design: Determining Pressure Ratio

- To find the compressor pressure ratio we assume that we have an adiabatic, reversible process where:

$$\frac{P_{o1.5}}{P_{o1}} = \left(\frac{T_{o1.5}}{T_{o1}}\right)^{\frac{k}{k-1}}$$

- To use this relationship we must first find the temperatures

Compressor Design: Determining Pressure Ratio

- T_{o1} is the easier of the two temperatures to find. It is dependent on the inlet velocity and temperature of the fluid.

$$T_{o1} = T_1 + \frac{V_1^2}{2C_p}$$

$$T_{o1} = 288 + \frac{170^2}{2(1000)(1.004)}$$

$$T_{o1} = 324.8K$$

Compressor Design: Determining Pressure Ratio

- $T_{o1.5}$ is more difficult to calculate because it is dependent on the compressor work which you must find first.
- Work of the compressor is the power divided by the mass flow rate. Where power is the torque multiplied by ω.

$$_1w_2 = \frac{T\omega}{m}$$

Compressor Design: Determining Pressure Ratio

$$m = \rho_1 \cdot A_1 \cdot V_1 = \frac{P_1 m_{air}}{RT_1} \left(\frac{\pi D_{hub}{}^2 + \pi D_{tip}{}^2}{4} \right)(V_1)$$

$$m = 37.10 kg / s$$

$$T_{shaft} = m \cdot \left(\frac{D_{hub} + D_{tip}}{4} \right) \cdot \left(V_{u1} - V_{u1.5} \right)$$

$$T_{shaft} = 37.10 \cdot \left(\frac{.457 + .66}{4} \right) \cdot \left(0 - 96.2 \right) = -996.6 Nm$$

$$power = T \cdot \omega = -996.6 \frac{8000 \cdot 2\pi}{60 \cdot 1000} = -834.9 kW$$

Compressor Design: Determining Pressure Ratio

$$_{1}w_{2} = \frac{-834.9}{37.10} = -22.5$$

- The work done by a compressor will always be negative, the opposite is always true for a turbine

Compressor Design: Determining Pressure Ratio

- Now we are ready to find $T_{o1.5}$ and our stage pressure ratio

$$T_{o1.5} = T_{o1} - \frac{{}_1 w_2}{C_p} = 302.4 - \frac{-22.5}{1.004}$$

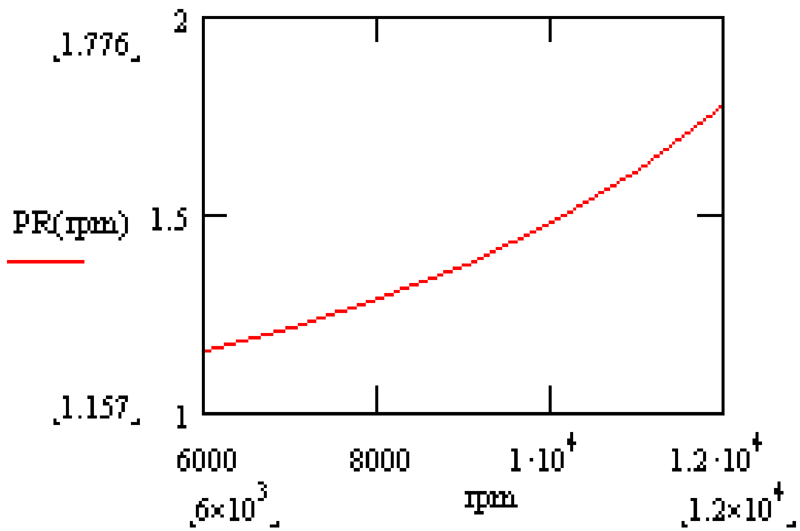
$$T_{o1.5} = 324.8K$$

$$PR = \left(\frac{324.8}{302.4}\right)^{\frac{1.4}{1.4-1}}$$

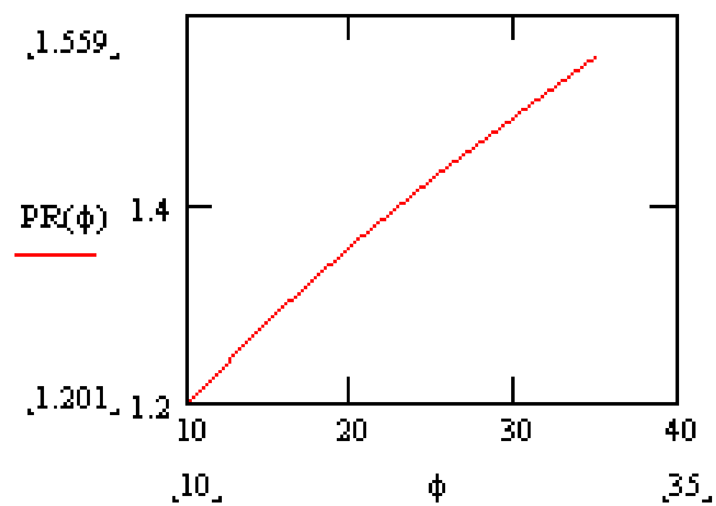
$$PR = 1.284$$

Compressor Design Graphs

- PR as a function of rotational speed
- PR as a function of turning angle



Pressure Ratio as a function of RPM



Any Questions???