# Turbine Aerodynamics

## Aircraft Engine Turbomachinery
## Project Report

**Serkan Burak Örs***

*orss19@itu.edu.tr

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# 1 Turbine Aerodynamics

We have chosen to use constant axial veloci adiabatic, selected Mach number, mean-line turbine stage design.

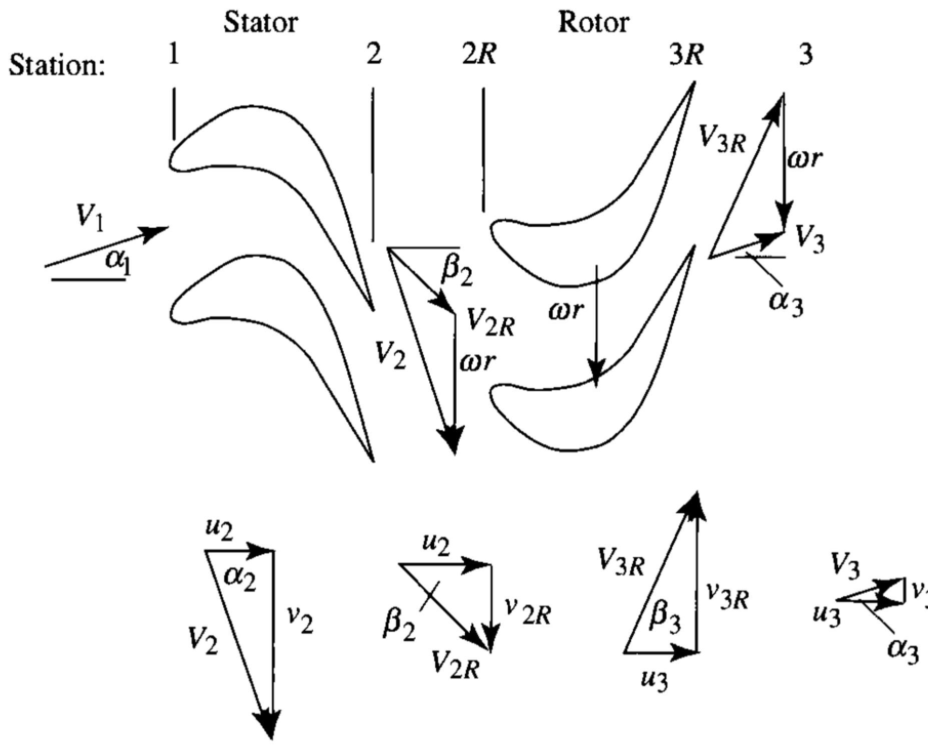


Figure 1: Typical turbine stage and velocity diagrams

## 1.1 Assumptions

1. $M_2$ and $M_{3R}$ are given.
2. Two-dimensional flow (that is, no property variation or velocity component normal to the flow).
3. Constant axial velocity ($u_l = u_2 = u_3$).
4. Constant mean radius.
5. Adiabatic flow in the stator and rotor.
6. Calorically perfect gas with known $\gamma_t$ and $R_t$.

## 1.2 Design Method

The design of turbines is different from that of compressors for a number of reasons, including the following:

1. The engine cycle performance models of this textbook require that the turbine stage entrance stator (a.k.a. inlet guide vane or nozzle) be choked and all other stator and rotor airfoil rows be unchoked.
2. The density of the working fluid changes dramatically, so that compressibility or Mach number effects must be included.
3. The turbine generates rather than absorbs power.
4. High inlet temperatures require that heat transfer and cooling be considered.
5. There are no wide-ranging rules for choosing turbine flow and airfoil geometries, such as the compressor diffusion factor.

Because of compressibility effects, the rotor degree of reaction $^{\circ}R_t$ has a definition that is more suitable to turbines. For calorically perfect gases, it can be defined as:

$$^{\circ}R_t = \frac{h_2 - h_3}{h_t1 - h_t3} = \frac{T_2 - T_3}{T_{t1} - T_{t3}} \tag{1}$$

And we can define dimensionless rotor speed $\omega r$ as:

$$\Omega = \frac{\omega r}{V'} \tag{2}$$

where $V' = \sqrt{g_c c_{pt} T_{t1}}$
We can define design steps as:
**1) Total velocity at station 2:**

$$\frac{V_2}{V'} = \sqrt{\frac{(\gamma_t - 1)\, M_2^2}{1 + \frac{(\gamma_t - 1)\, M_2^2}{2}}} \tag{3}$$

**2) Stage axial velocity:**

$$\frac{u}{V'} = \frac{V_2}{V'} cos\alpha_2 \tag{4}$$

**3) Tangential velocity at station 2:**

$$\frac{\vartheta_2}{V'} = \frac{V_2}{V'} sin\alpha_2 \tag{5}$$

**4) Rotor relative tangential velocity at station 2:**

$$\frac{\vartheta_{2R}}{V'} = \frac{\vartheta_2}{V'} = \Omega \tag{6}$$

**5) Rotor relative flow angle at station 2:**

$$tan\beta_2 = \frac{\vartheta_{2R}/V'}{u/V'} \tag{7}$$

**6) Rotor relative total temperature:**

$$\frac{T_{t2R}}{T_{t1}} = 1 + \Omega^2 \left( \frac{1}{2} - \frac{\vartheta_2/V'}{\Omega} \right) \tag{8}$$

**7) Rotor relative flow angle at station 3:**

$$tan\beta_3 = \sqrt{\frac{T_{t2R/T_{t1}}}{u^2/V'^2} \frac{(\gamma_t - 1)\, M_{3R}^2}{1 + \frac{(\gamma_t - 1)\, M_{3R}^2}{2}}} \tag{9}$$

**8) Rotor flow turning angle:**

$$\beta_2 + \beta_3 \tag{10}$$

**9) Tangential velocity at station 3:**

$$\frac{\vartheta_3}{V'} = \frac{u}{V'} tan\beta_3 - \Omega \tag{11}$$

**10) Stage exit flow angle:**

$$tan\alpha_3 = \frac{\vartheta_3/V'}{u/V'} \tag{12}$$

**11) Static temperature at station 3:**

$$\frac{T_3}{T_{t1}} = \frac{T_{t2R}/T_{t1}}{1 + \frac{(\gamma_t - 1)\, M_{3R}^2}{2}} \tag{13}$$

**12) Stage temperature ratio:**

$$\tau_{ts} = \frac{T_{t3}}{T_{t1}} = \frac{T_3}{T_{t1}} + \frac{u^2}{V'^2} \frac{1 + tan^2\alpha_3}{2} \tag{14}$$

**13) Rotor degree of reaction:**

$$^\circ R_t = \frac{\vartheta_{3R}^2 - \vartheta_{32R}^2}{2\,(1 - \tau_{ts})\, V'^2} = \frac{sec^2\beta_3 - sec^2\beta_2}{sec^2\beta_3 - sec^2\beta_3 + sec^2\beta_2 - 1} \tag{15}$$

**14) Rotor solidity based on axial chord $c_x$:**

$$\sigma_{xr} = \frac{s}{c_x} = \frac{2cos^2\beta_3\,(tan\beta_2 + tan\beta_3)}{Z} \tag{16}$$

General design principles of turbine design are:

- We must consider two different types of stages
  - Stator where flow is choked. This consideration can be suitable for first stage of turbine.
  - Stator where flow is unchoked This consideration can be suitable for other than first stage of turbine.
- For increasing values of $M_{3R}$, stage performance also increse. But we need to apply a safety factor in order to prevent flow to choke in rotor. Practically it can be chosen as 0.9.
- The open literature strongly suggests that the best performance is obtained when
  - $60deg < \alpha_2 < 75deg$
  - $0.2 < \Omega < 0.3$

## 1.3 Airfoil Geometry

The necessary nomenclature for this step is shown in figure[2] with the inlet flow angle shown at other than the design point.

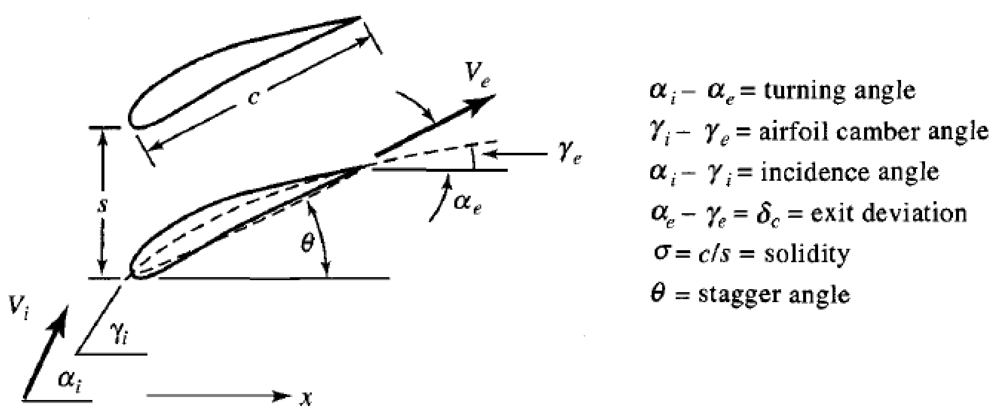


Figure 2: Cascade airfoil nomenclature

**Carter rule:** Carter's rule for turbines can be determined as:

$$\delta_t = \frac{\gamma_1 - \gamma_2}{8\sqrt{\sigma}} \tag{1}$$

It is a useful method for determining the metal angles $\gamma_l$ and $\gamma_2$ at the design point is to take $\gamma_l = \alpha_l$. With solving Carter's rule $\gamma_2 = \alpha_2 - \delta_t$ can be computed. Equation[1] can be manipulated as:

$$\delta_t = \frac{\alpha_1 - \alpha_2}{8\sqrt{\sigma} - 1} \tag{2}$$

# 2 Design Considerations

## 2.1 Design Point

For beginning the design. the parameters below are determined from several calculations and references.

- $\tau_{tH} = 1.9676$
- $\pi_{tH} = 42.451364$
- $\eta_{tH} = 0.87195$
- $P_{t4,1} = 258,499$ psia
- $T_{t4,1} = 3162,29°R$
- $\gamma_t = 1.3$
- $g_c c_{pt} = 7378 \frac{ft^2}{s^2 -^{\circ} R}$
- $R_t = 53.0 \frac{ft - lbf}{lbm -^{\circ} R}$

## 2.2 Design Choices

### 2.2.1 Flow Path

The flow paths for the turbomachinery components have been evaluated using three different design approaches: constant mean diameter, constant outer diameter and constant inner diameter. Constant outer diameter turbines are used when the minimum number of stages is required, and these are commonly found in aircraft engines. Hence, we used constant outer flow path in our design.

### 2.2.2 Inlet Guide Vanes

Inlet guide vanes (IGV) are commonly used after th last turbine stage. They have two purposes; first one is to adjust to Mach number of the flow, the second one is to divert the flow angle for the nozzle inlet. Hence we decided to use IGV in our design

### 2.2.3 Material Selection

We decided to use ceramic matrix compoenet in turbine blades due to figure[**??**].
Among ceramic matrix components, we have chosen SiC/LAS as material. Properties of SiC/LAS are obtained from figure[3] (Kaw A., 2006)[4]

Typical Mechanical Properties of Some Ceramic Matrix Composites

| Property | Units | SiC/LAS | SiC/CAS | Steel | Aluminum |
|---|---|---|---|---|---|
| *System of units: USCS* | | | | | |
| Specific gravity | — | 2.1 | 2.5 | 7.8 | 2.6 |
| Young's modulus | Msi | 13 | 17.55 | 30.0 | 10.0 |
| Ultimate tensile strength | ksi | 72 | 58.0 | 94.0 | 34.0 |
| Coefficient of thermal expansion | µin./in./°F | 2 | 2.5 | 6.5 | 12.8 |
| *System of units: SI* | | | | | |
| Specific gravity | — | 2.1 | 2.5 | 7.8 | 2.6 |
| Young's modulus | GPa | 89.63 | 121 | 206.8 | 68.95 |
| Ultimate tensile strength | MPa | 496.4 | 400 | 648.1 | 234.4 |
| Coefficient of thermal expansion | µm/m/°C | 3.6 | 4.5 | 11.7 | 23 |

Figure 3: Properties an comparison of ceramic matrix composites

#### 2.2.4 Turbine Type Choice

**Zero reaction turbine,** from the definition of reaction, if the reaction is selected as zero for the case of constant axial velocity, then

- $h_3 = h_2$
- $tan\beta_3 = \beta_2$ therefore,
- $\beta_3 = \beta_2$
- $V_{3R} = V_{2R}$

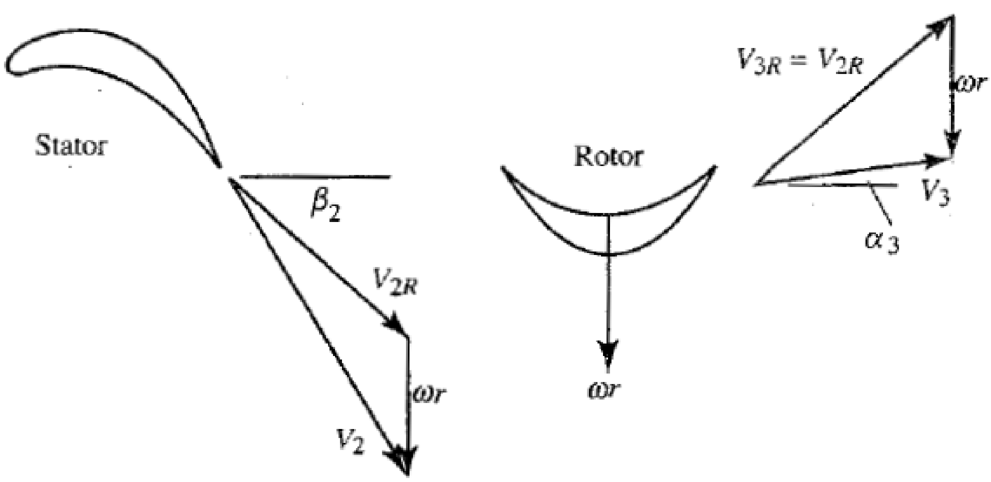


Figure 4: Zero-reaction turbine stage velocity diagram

The stage loading coefficient for the impulse stage with constant axial velocity is

$$\psi = 2\left(\Phi tan\alpha_2 - 1\right) = 2\Phi tan\beta_2 \quad (1)$$

We desire a $\alpha_2$ to be large. But this leads to large $V_2$ and large $V_{2R}$, which lead to large losses. So a $\alpha_2$ is generally limited to less than 70°
Also, if $\alpha_3 = 0$(no exit swirl), then $tan\alpha_2 = 2\omega r/u_2$ and

$$\psi = 2 \text{ no exit swirl} \quad (2)$$

Thus we see that the rotor speed $\omega r$ is proportional to $\sqrt{\Delta h_t}$. If the resultant blade speed is too high, we must go to a multistage turbine.
**Fifty percent reaction turbine,** if there is equal enthalpy drop across rotor and stator, then $R_t = 0.5$ and the velocity triangles are symmetrical, as shown in figure[5]

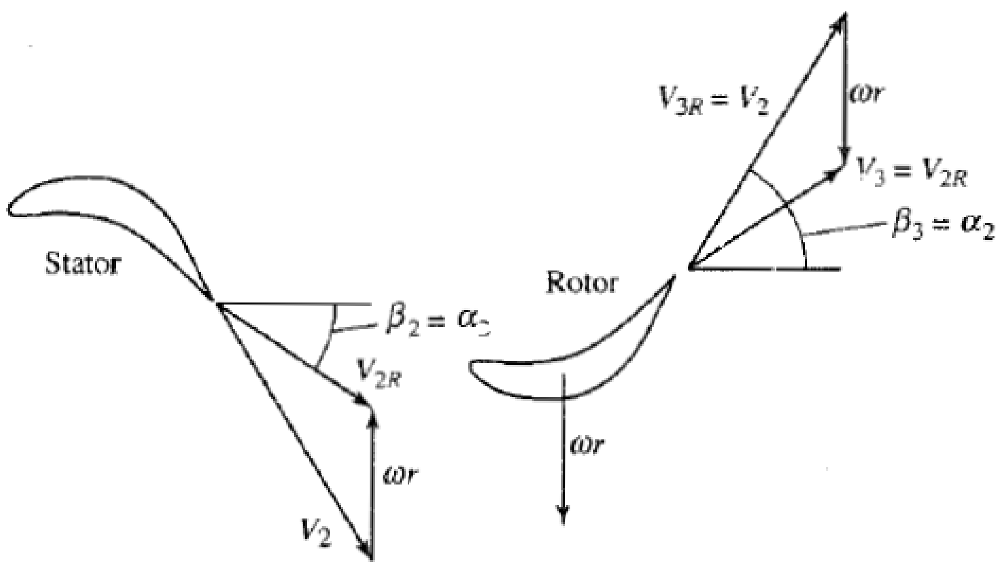


Figure 5: Fifty percent reaction turbine stage velocity diagram

then, $\alpha_2 = \beta_3$, $\alpha_3 = \beta_2$, and

$$tan\beta_3 - tan\beta_2 = tan\alpha_2 - tan\alpha_3 = \frac{\omega r}{u_2} = \frac{1}{\Phi} \quad (3)$$

The stage loading coefficient for fifty percent reaction turbine with constant axial velocity is

$$\psi = \frac{\Delta \nu}{\omega r} = 2\Phi tan\alpha_2 - 1 = 2\Phi tan\beta_3 - 1 \quad (4)$$

Again, $\alpha_2$ should be high but is limited to less than 70°. For zero exit swirl

$$tan\beta_3 = tan\alpha_2 = \frac{\omega r}{u}; \beta_2 = 0; \psi = 0 \quad (5)$$

Thus, for the same $\omega r$ and $V_3 = 0$, the work per unit mass from a zero-reaction turbine is twice that from the 50 percent reaction turbine.

**Choice conclusion:** We have chosen 0.5 reaction turbine type, in order to distribute loads equally on both rotor and stator.

# 3 High Pressure Turbine(HPT) Design

Environmental conditions in design point are:

- $\sigma_d = 2.1615\,(10^2)\ \dfrac{lb}{ft^2}$
- $\rho = 3.229\,(10^{-4})\ \dfrac{slugs}{ft^3}$

Under these environmental conditions and assuming DSF of 2, rotational speed can be calculated as:

$$\omega r_r = \sqrt{\frac{4\sigma_d}{\rho}} = \sqrt{\frac{4\left(2.1615\,(10^2)\ \dfrac{lb}{ft^2}\right)}{3.229\,(10^{-4})\ \dfrac{slugs}{ft^3}}} = 1636.34 ft/s \tag{1}$$

which allows the initial estimate of the wheel speed

$$\omega r_m = 1665.95775 ft/s \tag{2}$$

## 3.1 Aerodynamic Design

It is important, particularly in the complex, expensive, and heavy high-pressure turbine, to reduce as much as reasonably possible the number of stages. For every stage these calculations must be performed:

$$\tau_{ts} = \frac{T_{t4,4}}{T_{t4,1}} = \frac{2154.2^{\circ} R}{3162.29^{\circ} R} = 0.6812152 \tag{1}$$

$$\Omega = \frac{\omega r_m}{\sqrt{g_c c_{pt} T_{t4,1}}} = \frac{1665.95775 ft/s}{\sqrt{\left(7378 \dfrac{ft^2}{s^2 -^{\circ} R}\right)(3162.29^{\circ} R)}} = 0.3449 \tag{2}$$

Stage temperature ratios can be determined as:

$$\Omega_{stage_i} = \frac{\omega r_m}{\sqrt{g_c c_{pt}\left(\tau_{ts}\right)_{stahei} T_{t4,1}}} = \frac{\Omega_{stagei}}{\sqrt{\left(\tau_{ts}\right)_{stagei}}} \tag{3}$$

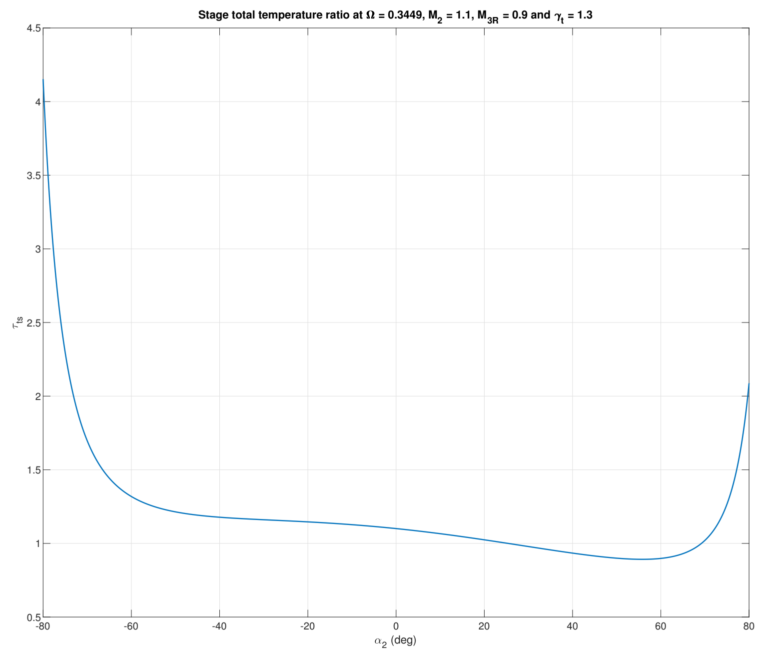


Figure 6: Stage total temperature ratio at $\Omega = 0.3449$, $M_2 = 1.1$, $M_{3R} = 0.9$ and $\gamma_t = 1.3$

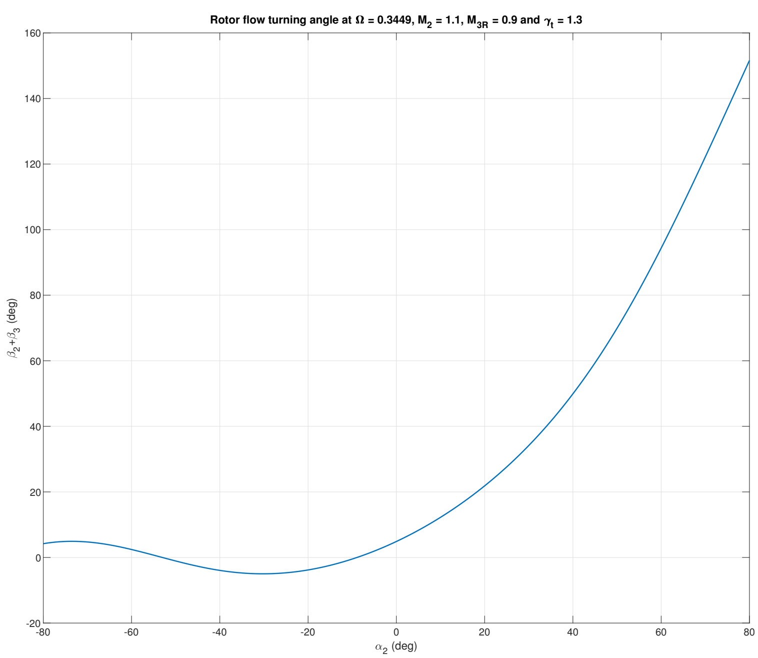


Figure 7: Rotor flow turning angle at $\Omega = 0.3449$, $M_2 = 1.1$, $M_{3R} = 0.9$ and $\gamma_t = 1.3$

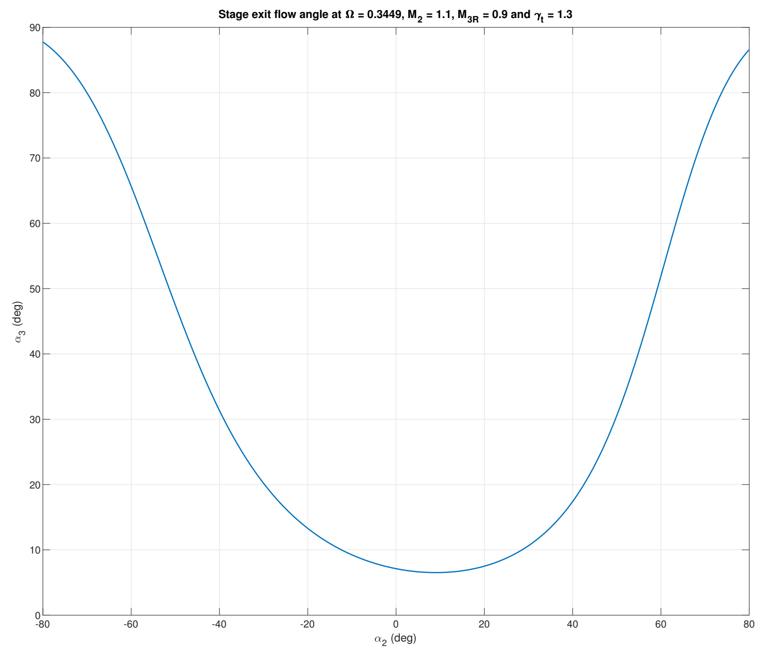


Figure 8: Stage exit flow angle at $\Omega = 0.3449$, $M_2 = 1.1$, $M_{3R} = 0.9$ and $\gamma_t = 1.3$

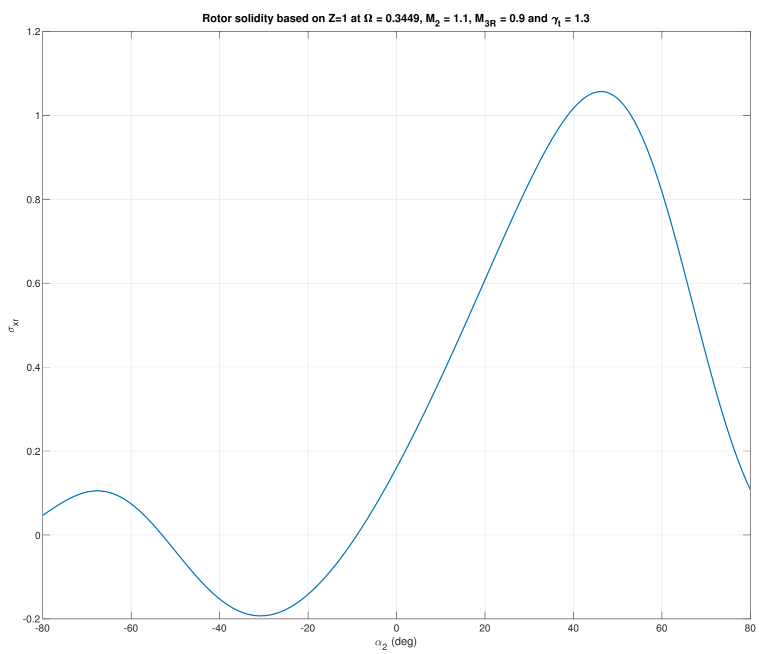


Figure 9: Rotor solidity based on Z=1 at $\Omega = 0.3449$, $M_2 = 1.1$, $M_{3R} = 0.9$ and $\gamma_t = 1.3$

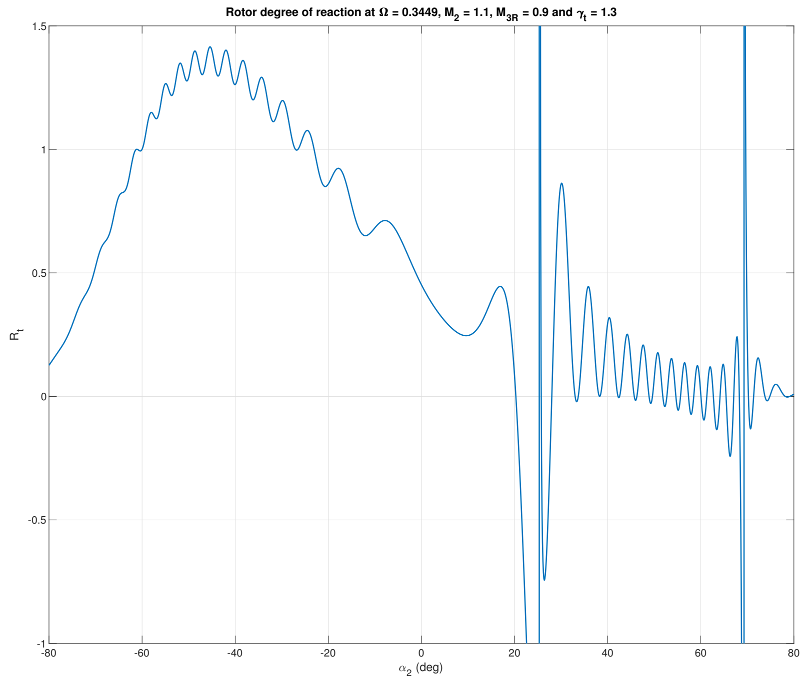


Figure 10: Rotor degree of reaction at $\Omega = 0.3449$, $M_2 = 1.1$, $M_{3R} = 0.9$ and $\gamma_t = 1.3$

In figure [10], it can be seen there are jumpings in the certain $\alpha_2$ angles. To avoid failure at those $\alpha_2$ angle values, FADEC controller system should drive the aircraft engine in order to remain at those $\alpha_2$ values in very few moments.

# 4 Low Pressure Turbine(LPT) Design

The story is quite similar to that of the high-pressure turbine. Because this process parallels that of the high-pressure turbine, other than the fact that the mechanical rotational speed is known in advance, only the outline will be repeated here. The process begins with the selection of the turbine design point. The number of stages is already determined by RFP as 4. And stage temperature ratios already determined. Design choices are then made for the stage parameters $M_2$ and $M_{3R}$ and the aerodynamic definition of each stage fixed.

$$\tau_{ts} = \frac{T_{t5}}{T_{t4,5}} = \frac{1733.66°R}{2165.23°R} = 0.8 \tag{1}$$

$$\Omega = \frac{\omega r_m}{\sqrt{g_c c_{pt} T_{t4,5}}} = \frac{1665.95775 ft/s}{\sqrt{\left(7378 \frac{ft^2}{s^2 -° R}\right)(2165.23°R)}} = 0.42 \tag{2}$$

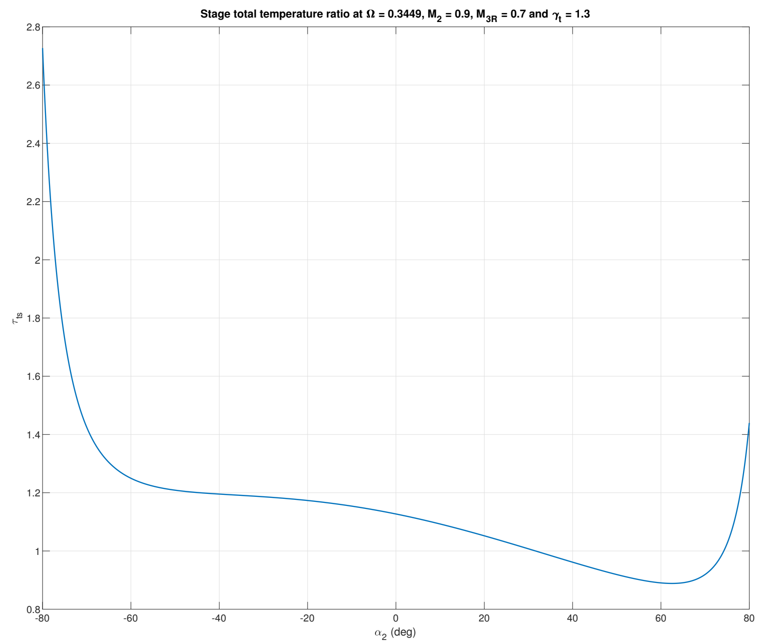


Figure 11: Stage total temperature ratio at $\Omega = 0.3449$, $M_2 = 0.9$, $M_{3R} = 0.7$ and $\gamma_t = 1.3$

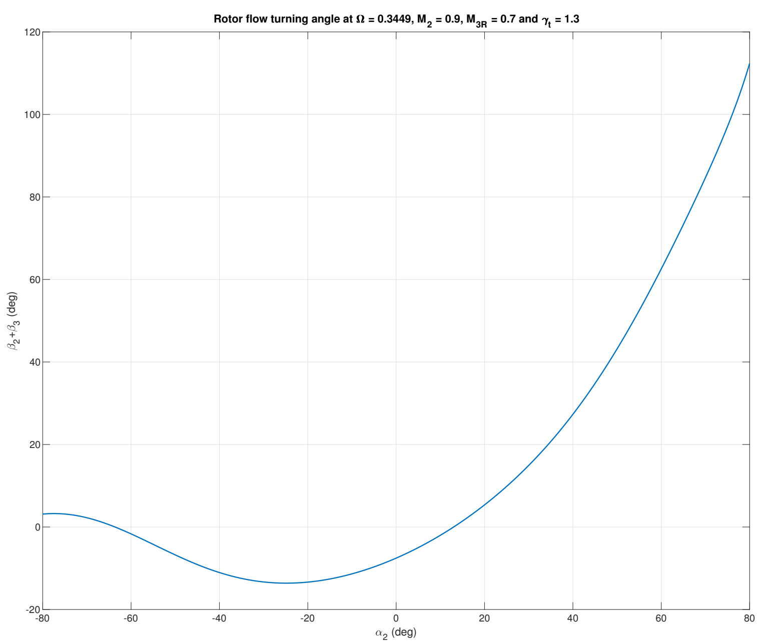


Figure 12: Rotor flow turning angle at $\Omega = 0.3449$, $M_2 = 0.9$, $M_{3R} = 0.7$ and $\gamma_t = 1.3$

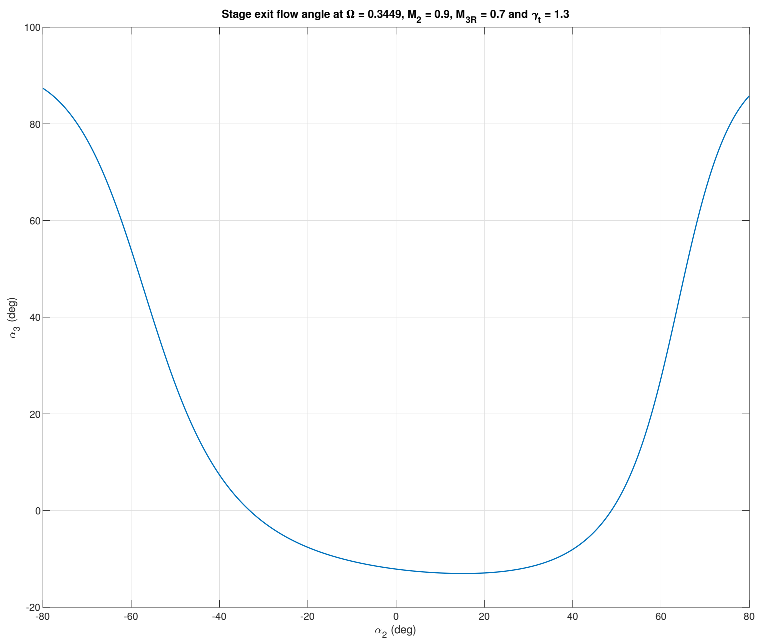


Figure 13: Stage exit flow angle at $\Omega = 0.3449$, $M_2 = 0.9$, $M_{3R} = 0.7$ and $\gamma_t = 1.3$

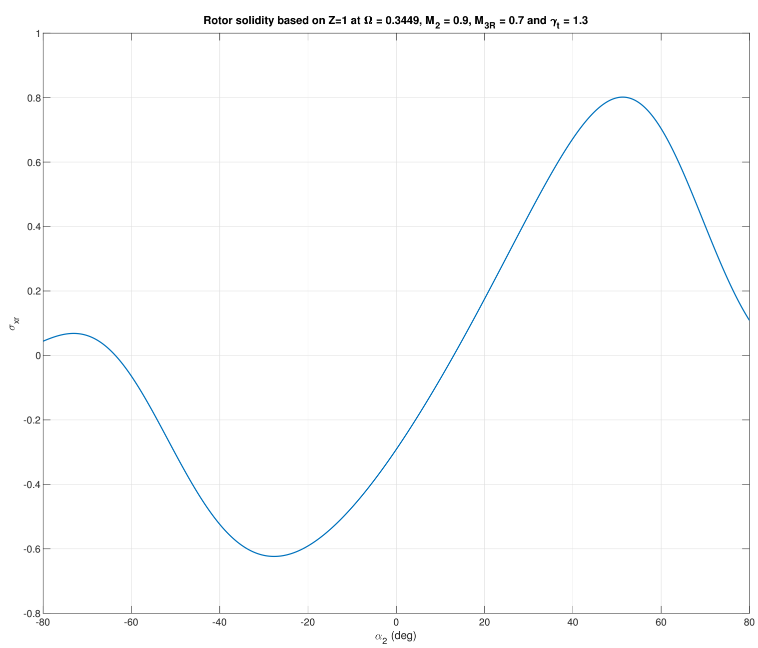


Figure 14: Rotor solidity based on Z=1 at $\Omega = 0.3449$, $M_2 = 0.9$, $M_{3R} = 0.7$ and $\gamma_t = 1.3$

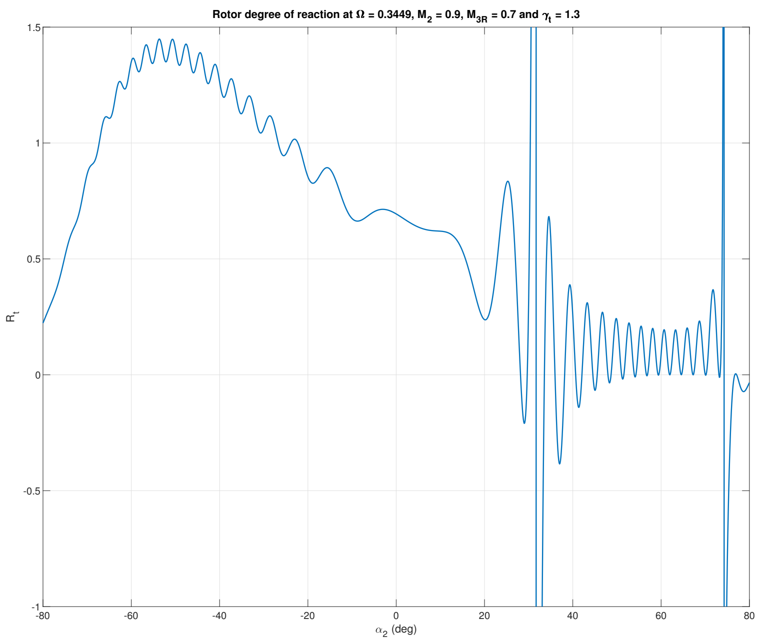


Figure 15: Rotor degree of reaction at $\Omega = 0.3449$, $M_2 = 0.9$, $M_{3R} = 0.7$ and $\gamma_t = 1.3$

In figure [15], it can be seen there are jumpings in the certain $\alpha_2$ angles. To avoid failure at those $\alpha_2$ angle values, FADEC controller system should drive the aircraft engine in order to remain at those $\alpha_2$ values in very few moments.

# 5 Appendix A: MATLAB Codes

## 5.1 Appendix A-1: High Pressure Turbine Aerodynamic Calculations Code

**HPT.m file :**

```
clc;clear;close all;
%% HPT Aerodynamic Calculations

alpha2 = -80:0.1:80; % Turning angle
M3R = 0.9; % Relative Mach number
M2 = 1.1; % Stage exit Mach number
gamma_t = 1.3; % ratio of specific heats
omega = 0.3449; % dimensionless turbine rotor speed
```

```

% Velocity Ratios
V2overV = sqrt(((gamma_t-1)*M2.^2)/(1+((gamma_t-1)*M2.^2)/2));
uOverV = V2overV*cosd(alpha2);
v2OverV = V2overV*sind(alpha2);
v2ROverV = v2OverV - omega;

Beta2 = atand(v2ROverV./uOverV);
rotorRelative = 1 + ((omega^2)*(0.5-(v2OverV./omega)));
Beta3 = ...
    atand((rotorRelative./uOverV.^2)*(((gamma_t-1)*M3R^2)/(1+((gamma_t-1)*M3R^2)/2)));
Beta = Beta2 + Beta3;
v3OverV = (uOverV.*tand(Beta3))-omega;
alpha3 = atand(v3OverV./uOverV);
T3OverTt1 = (rotorRelative)/(1+(((gamma_t-1)*M3R^2)/2)); % Temperature ...
    ratio
tauts = T3OverTt1 + ((uOverV.^2).*((1+(tand(alpha3)).^2)/2)); % Stage ...
    total temperature ratio
solidity = 2*((cosd(Beta3)).^2).*((tand(Beta2))+((tand(Beta3)))); % ...
    Rotor solidity

% Degree of Reaction
Tt1 = 3162.29;
gcOverCpt = 7378;
V = sqrt(gcOverCpt*Tt1);
V3R = 1004.8;
v3r = V3R*sin(Beta3);
v2r = (v2OverV-omega)*V;
Rt = ((v3r.^2)-(v2r.^2))./(2*(1-tauts)*V^2); % Rotor degree of reaction


figure(1)
plot(alpha2,tauts,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\tau_{ts}');
grid on;
title('Stage total temperature ratio at \Omega = 0.3449, M_{2} = 1.1, ...
    M_{3R} = 0.9 and \gamma_{t} = 1.3');

figure(2)
plot(alpha2,Beta,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\beta_{2}+\beta_{3} (deg)');
grid on;
title('Rotor flow turning angle at \Omega = 0.3449, M_{2} = 1.1, M_{3R} ...
```

```
    = 0.9 and \gamma_{t} = 1.3');

figure(3)
plot(alpha2,alpha3,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\alpha_{3} (deg)');
grid on;
title('Stage exit flow angle at \Omega = 0.3449, M_{2} = 1.1, M_{3R} = ...
    0.9 and \gamma_{t} = 1.3');

figure(4)
plot(alpha2,solidity,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\sigma_{xr}');
grid on;
title('Rotor solidity based on Z=1 at \Omega = 0.3449, M_{2} = 1.1, ...
    M_{3R} = 0.9 and \gamma_{t} = 1.3');

figure(5)
plot(alpha2,Rt,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('R_{t}');
grid on;
title('Rotor degree of reaction at \Omega = 0.3449, M_{2} = 1.1, M_{3R} ...
    = 0.9 and \gamma_{t} = 1.3');
axis([-80 80 -1 1.5]);
```

## 5.2 Appendix A-2: Low Pressure Turbine Aerodynamic Calculations Code

**LPT.m file :**

```
clc;clear; close all;
%% LPT Aerodynamic Calculations

alpha2 = -80:0.1:80; % Stage turning angle
M3R = 0.7; % Relative Mach number
M2 = 0.9; % Stage exit Mach number
gamma_t = 1.3; % Ratio of specific heats
omega = 0.42; % Dimensionless turbine rotor speed

% Velocity Ratios
V2overV = sqrt(((gamma_t-1)*M2.^2)/(1+((gamma_t-1)*M2.^2)/2));
uOverV = V2overV*cosd(alpha2);
```

```
v2OverV = V2overV*sind(alpha2);
v2ROverV = v2OverV - omega;

Beta2 = atand(v2ROverV./uOverV);
rotorRelative = 1 + ((omega^2)*(0.5-(v2OverV./omega)));
Beta3 = ...
    atand((rotorRelative./uOverV.^2)*(((gamma_t-1)*M3R^2)/(1+((gamma_t-1)*M3R^2)/2)));
Beta = Beta2 + Beta3;
v3OverV = (uOverV.*tand(Beta3))-omega;
alpha3 = atand(v3OverV./uOverV);
T3OverTt1 = (rotorRelative)/(1+(((gamma_t-1)*M3R^2)/2));% Temperature ratio
tauts = T3OverTt1 + ((uOverV.^2).*((1+(tand(alpha3)).^2)/2)); % Stage ...
    total temperature ratio
solidity = 2*((cosd(Beta3)).^2).*((tand(Beta2))+((tand(Beta3)))); % ...
    Rotor solidity

% Degree of Reaction
Tt1 = 3162.29;
gcOverCpt = 7378;
V = sqrt(gcOverCpt*Tt1);
V3R = 1004.8;
v3r = V3R*sin(Beta3);
v2r = (v2OverV-omega)*V;
Rt = ((v3r.^2)-(v2r.^2))./(2*(1-tauts)*V^2); % Rotor degree of reaction


figure(1)
plot(alpha2,tauts,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\tau_{ts}');
grid on;
title('Stage total temperature ratio at \Omega = 0.3449, M_{2} = 0.9, ...
    M_{3R} = 0.7 and \gamma_{t} = 1.3');

figure(2)
plot(alpha2,Beta,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\beta_{2}+\beta_{3} (deg)');
grid on;
title('Rotor flow turning angle at \Omega = 0.3449, M_{2} = 0.9, M_{3R} ...
    = 0.7 and \gamma_{t} = 1.3');

figure(3)
plot(alpha2,alpha3,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\alpha_{3} (deg)');
```

```
grid on;
title('Stage exit flow angle at \Omega = 0.3449, M_{2} = 0.9, M_{3R} = ...
    0.7 and \gamma_{t} = 1.3');

figure(4)
plot(alpha2,solidity,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('\sigma_{xr}');
grid on;
title('Rotor solidity based on Z=1 at \Omega = 0.3449, M_{2} = 0.9, ...
    M_{3R} = 0.7 and \gamma_{t} = 1.3');

figure(5)
plot(alpha2,Rt,'LineWidth',1.2);
xlabel('\alpha_{2} (deg)'); ylabel('R_{t}');
grid on;
title('Rotor degree of reaction at \Omega = 0.3449, M_{2} = 0.9, M_{3R} ...
    = 0.7 and \gamma_{t} = 1.3');
axis([-80 80 -1 1.5]);

%choosing parameters due to chosen angle1
%for i = 1:1:18001
%if alpha1(i) == 28
%end
%end
```

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