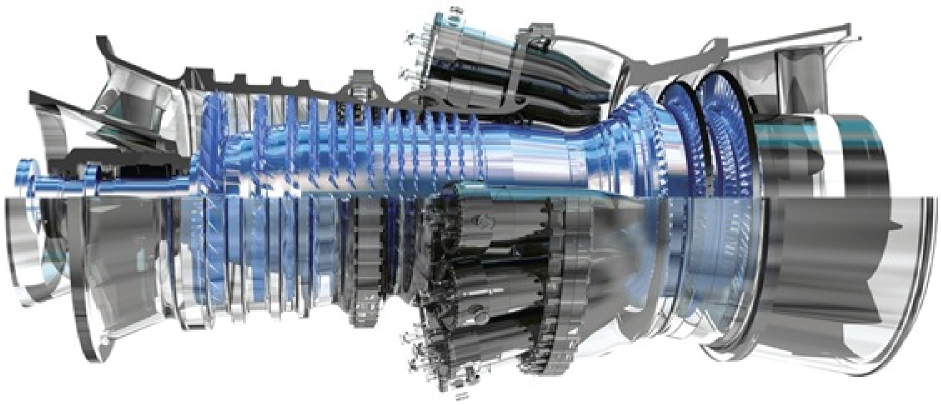
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Energy Conversion

Report

Experimental Methods For Engineers

Intrusive Probe Measurement Technique In Turbomachinery



Maximilian Boosfeld

Michel Heusser

Kaspar Schlegel

(October 2012)

Advisor:
Prof. Dr. R.S. Abhari

Supervisor:
Sebastiano Lazzi

Contents

List of Figures

List of Tables

Abstract

In this experiment the flow of a one-stage turbomachine is examined. As a measuring tool a five-pinhole-probe is introduced to analyze the pressure and velocity of the flow in different positions behind the stator. All data is stored in LabView, the program that controls the entire measurement process. Finally the information obtained is post processed and visualized in Matlab.

The flow after the stator is highly unsteady. Even though the measured steady data is expressive. By averaging over the mass flow some unsteady influences were removed. The effect of the boundary layer around the blade was visible on most of the plots and also the radial pressure difference due to the rotating fluid.

The performed experiment shows clearly that with this setup it is possible to improve the efficiency of blades by analyzing the pressure and velocity distribution.

Chapter 1

Introduction

Turbomachines are devices that transfer energy either to or from a continuously fluid by dynamic action of moving blades. While a turbine transfers energy from a fluid to a rotor, a compressor transfers energy from a rotor to a fluid. Due to a change of pressure and velocity provoked by rotating blades the enthalpy of the fluid changes, which implies a positive or negative amount of work. In a fan ($W < 0$) the fluid pressure is increased and therefore work is needed. In contrary turbines are expanding the fluid ($\Delta p < 0$) and result in a power-producing machine. Turbomachines are widely used and of extraordinary importance for most energy conversion processes.

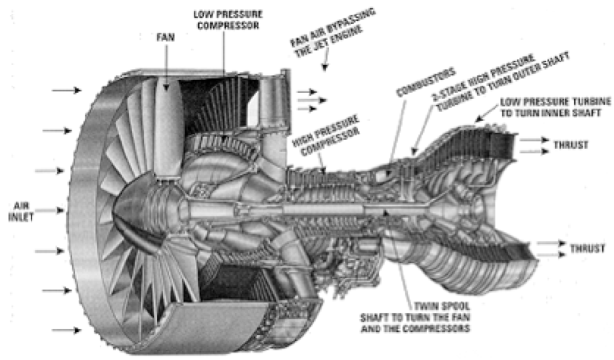


Figure 1.1: Typical Axial Flow Compressor Engine

Chapter 2

Experimental Setup

In the experiment performed at ETH Oct. 11th, 2012 an axial fan LTG is used, powered by a 7kW electrical engine providing up to 5000 rpm. The experimental setup consists of a 3m long inlet tunnel and a diffuser behind the probe device (Figure 2.1).

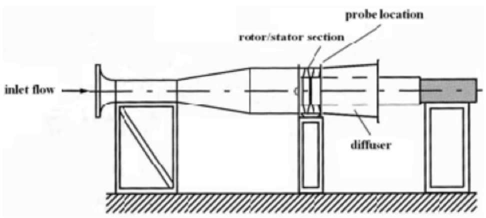


Figure 2.1: Overview Test Rig LTG

The actual fan comprises a rotor (upstream) and a stator behind. The probe is located downstream of the stator and can be moved in radial, circumferential (Θ) and yaw (γ) direction. The cobra shaped five-hole probe (Figure 2.2 measures the individual pressures of the holes (ø $2mm$).

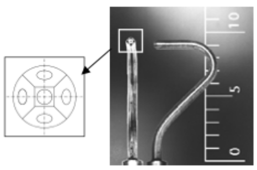


Figure 2.2: Cobra-Shaped 5-Hole Probe

With this data yaw angle, pitch angle, total pressure, static pressure and Mach number are computed. Now absolute velocity and its components can be derived.

Chapter 3

Method Of Attack

After turning on the engine the fan is set to approximately 5000 rpm, which results in a mean velocity of 20.66 m/s in the test section. A LabView program controls the pressure measurements. The actuator moves automatically in radial direction. The distance between two measuring points is 5.5 mm. After measuring the individual pressure of each hole at one circumferential angle (Θ) (Figure 3.1)the probe needs to be moved manually to the next angle where the measurement starts all over again.

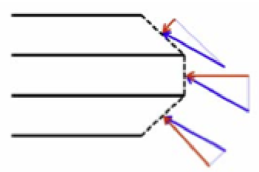


Figure 3.1: Two-dimensional model of the probe tip

The evaluated range is 22.5 $^\circ$ with a step size of approximately 1.125 $^\circ$. The data has been saved in a text file and is analyzed in MATLAB. Finally velocity components can be derived from the definition of mach number and geometrical concepts.

Chapter 4

Results

4.0.1 Velocities

First of all we see that the velocity in axial direction (Figure 4.1) is significantly bigger as the ones in radial and tangential direction (Figures 4.3 and 4.2 respectively). This is due to the fact that the fluid is only slightly deviated by the blades in radial and tangential directions.

In Figure 4.1 we see how the velocity (in axial direction) is highest on the sides of the measurement area. In the middle, we see a decrease of velocity due to the stator blade. We see in both plots, how towards the inner tube and outer shell the velocity drops due to the wall-friction.

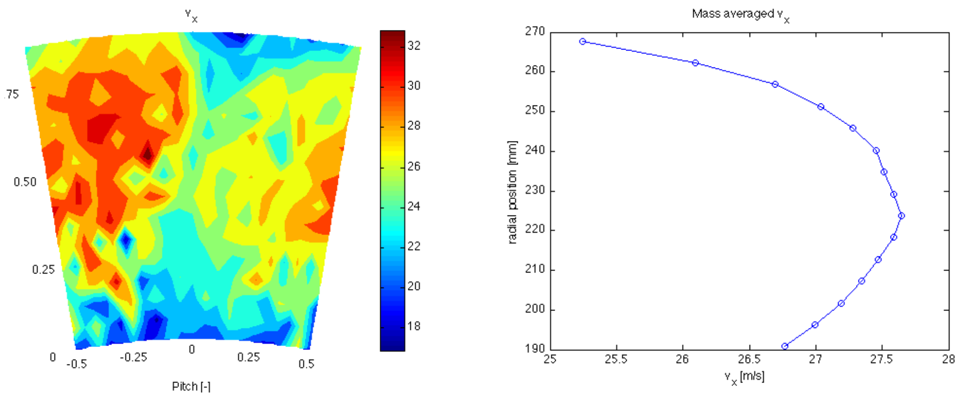


Figure 4.1: Measured Axial Velocity Over The Measuring Range And Mass Averaged Axial Velocity Over The Measured Pitch

For a clearer analysis we plotted only the absolute value of v_θ in Figure 4.2, the direction of the velocity can be analysed in the angle section. In both plots we see the influence of the rotating inner tube on the fluid. As it is expected, there is a higher tangential velocity towards the axis due to the friction of the inner tube. The influence towards the outer wall is much lower. In the measurement area we see that the values are not constant throughout the pitch at the different radii. This comes from the influence of the stator blade.

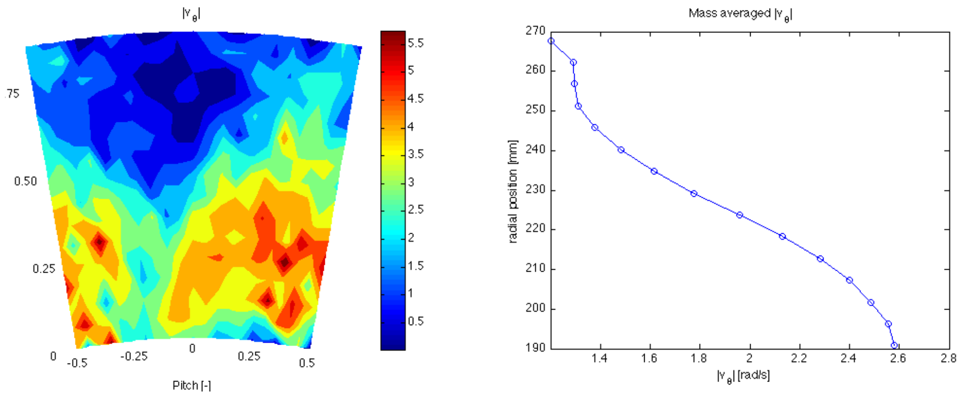


Figure 4.2: Measured Tangential Velocity Over The Measuring Range And Mass Averaged Tangential Velocity Over The Measured Pitch

In Figure 4.3 we see clearly an influence of the stator blade since the measurement area has a drop in velocity on the rght side. On the left side we a slow increase of velocity when moving from the inner tube to the outer wall, the mass averaged plot confirms this tendency. The cause for this phenomenon is the centrifugal force that drags the fluid to the outside. As the velocity of the blades is faster when the distance is greater from the rotation axis. Of course, the radial velocity should be zero when reaching the outer wall, but this deceleration of the fluid should happen between the gap of the measurement area and the wall itself.

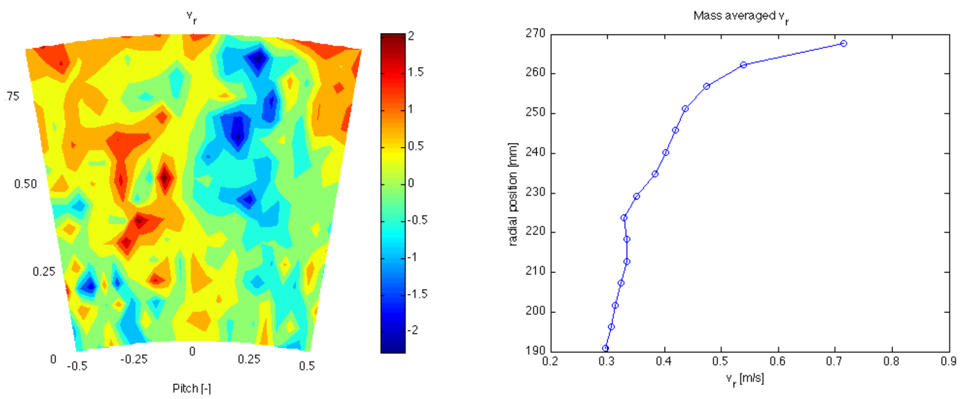


Figure 4.3: Measured Radial Over The Measuring Range And Mass Averaged Radial Velocity Over The Measured Pitch

4.0.2 Pressures

In Figure 4.4 the total pressure over the evaluated area and mass averaged is showed. The measured values at zero pitch angle show a decrease of pressure. This is due to the fact that the stator blade is in this position which causes friction and thus a loss of momentum. Near the walls the same effect takes place but in a higher degree, we conclude therefore that the friction is the highest in the area of the rotating axis).

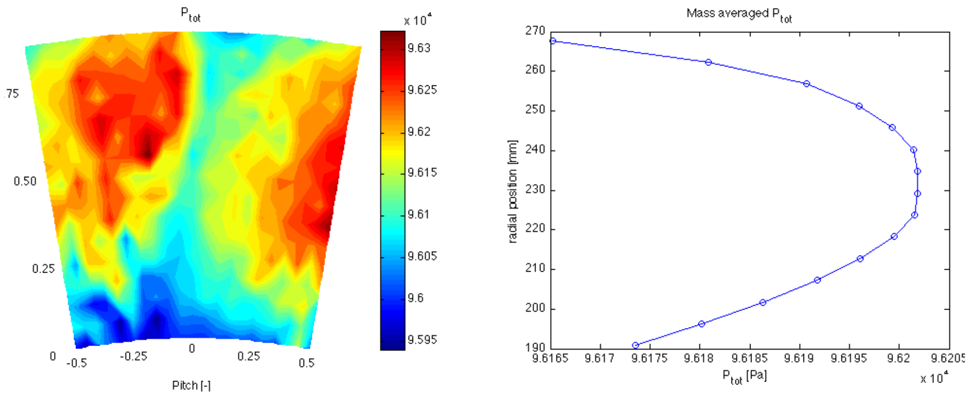


Figure 4.4: Measured Total Pressure Over The Measuring Range And Mass Averaged Total Pressure Over The Measured Pitch

In the mass averaged plot we see the maximum p_{tot} towards the middle of the measured radii. In this area the friction is minimized due to the maximal distance to the turbine shell and rotation axis.

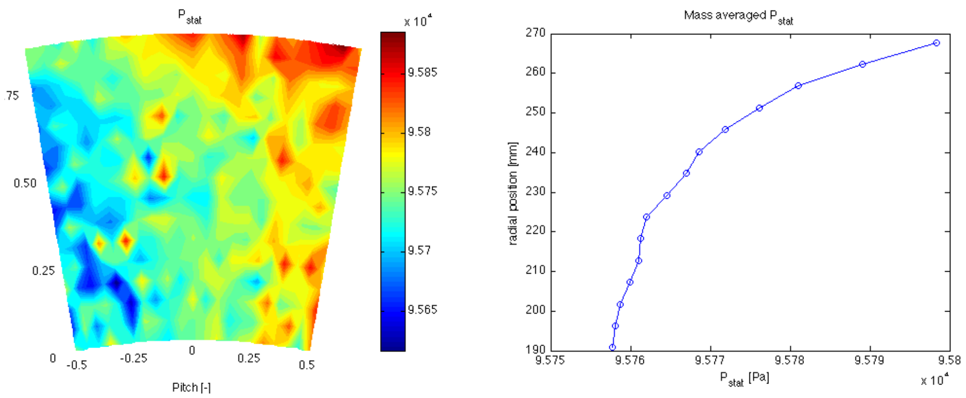


Figure 4.5: Measured Static Pressure Over The Measuring Range And Mass Averaged Static Pressure Over The Measured Pitch

To understand the results of the static pressure we have to work with the velocity of the fluid (4.6) as it is bounded to the static pressure p_{stat} over the Bernoulli equation (Equation 4.1).

$$p_{\text{tot}} = p_{\text{stat}} + \rho \frac{v_{\text{tot}}^2}{2} \tag{4.1}$$

The results for p_{stat} are showed in Figure 4.5. In the measured area we cannot see an effect of the stator blade as clearly as in the previous figure. However we see a clear gradient of pressure over the pitch angle. We see a rise in static pressure on the upper right and a slight pressure drop on the left side due to the circulation of the fluid around the blade: The total velocity on the upper right side should therefore be lower and higher on the left side which matches with the measurements of Figure 4.6

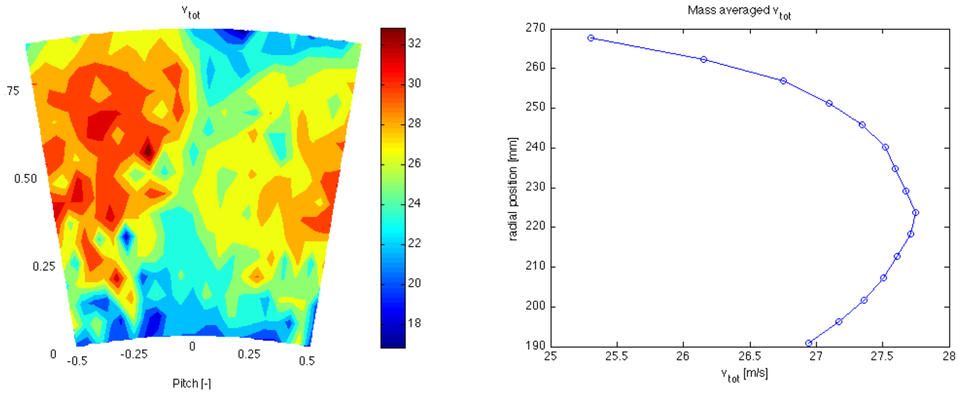


Figure 4.6: Measured Total Velocity Over The Measuring Range And Mass Averaged Total Velocity Over The Measured Pitch

By analysing the mass averaged plots we observe how the total velocity decreases towards the outer shell making an increase of static pressure in the same zone. Towards the inner tube, the velocity decreases again, this time not as much as towards the outer wall. The static pressure stays almost constant in that zone, which means that the loss of total pressure that we observe in Figure 4.4 comes almost entirely from the decrease of total velocity.

4.0.3 Mach number

From Equation 4.2 we can trace the correlation between p_{stat} and v_{tot}.

$$Ma = \frac{v_{\text{tot}}}{c} = \frac{v_{\text{tot}}}{\sqrt{\gamma \frac{p_{\text{stat}}}{\rho}}} \tag{4.2}$$

From our measurements we would expect a high Ma-number on the left side and a relatively low Ma-number on the upper right. This matches the measurements for Ma-number (Figure 4.7 quite well. On the lower part we have the lowest Ma-number because of the low velocity and high static pressure.

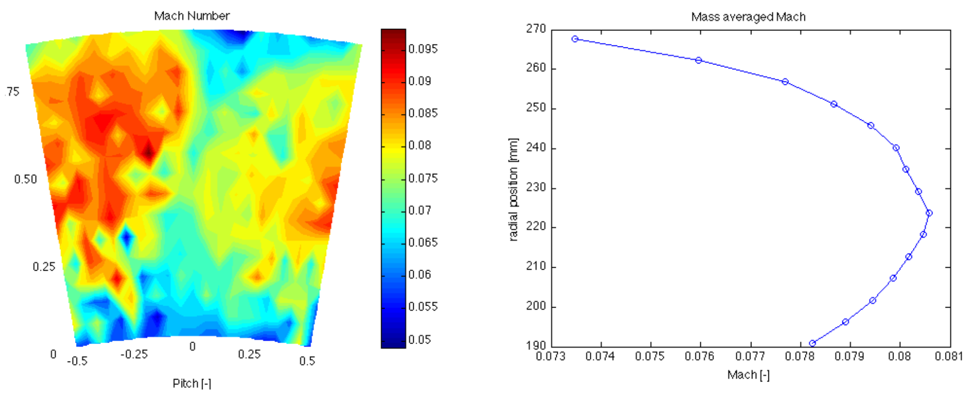


Figure 4.7: Measured Mach-number Over The Measuring Range And Mass Averaged Mach-number Over The Measured Pitch

Working analogously with Equation 4.2, we see the correlations between the mass averaged plots of p_{stat}, v_{tot} and Ma. In the lower part of the plots p_{stat} behaves like a constant making the curve of Ma similar to the one of v_{tot}. In the middle and upper part of the plots v_{tot} decreases and p_{tot} increases making the curve of Ma-number fall when approaching the wall.

4.0.4 Angles

In the Figure 4.8, the Pitch angle is plotted. A clear tendency is not visible. The pitch angle is only slightly higher on the left hand side. In the mass averaged plot, we can see that the pitch angle increases to the outer wall. This correlates with the radial velocity, that is increased when moving away from the rotational axis.

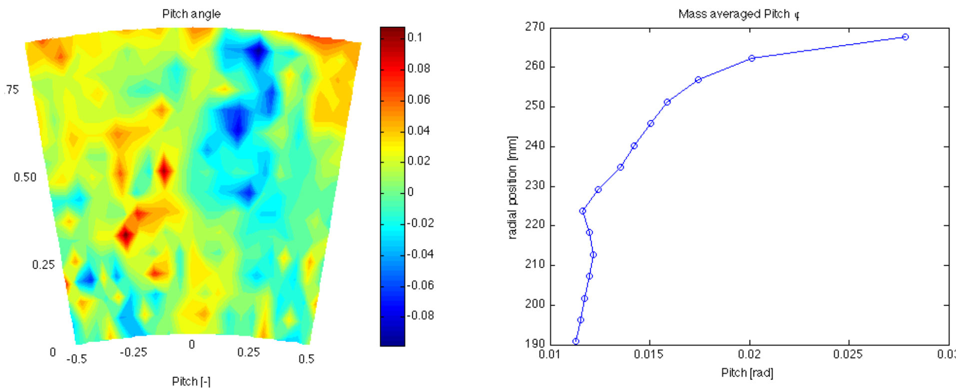


Figure 4.8: Measured Pitch Angle Over The Measuring Range And Mass Averaged Pitch Angle Over The Measured Pitch

Figure 4.9 shows the yaw angle. Near the rotational axis, the yaw angle is higher than near the outer walls. In this area the fluid is more deflected, due to the shape of the blade, just as expected. In the mass averaged plot, this becomes even more visible. In addition, we can observe a correlation with the tangential velocity, which has its maximum near the rotational axis.

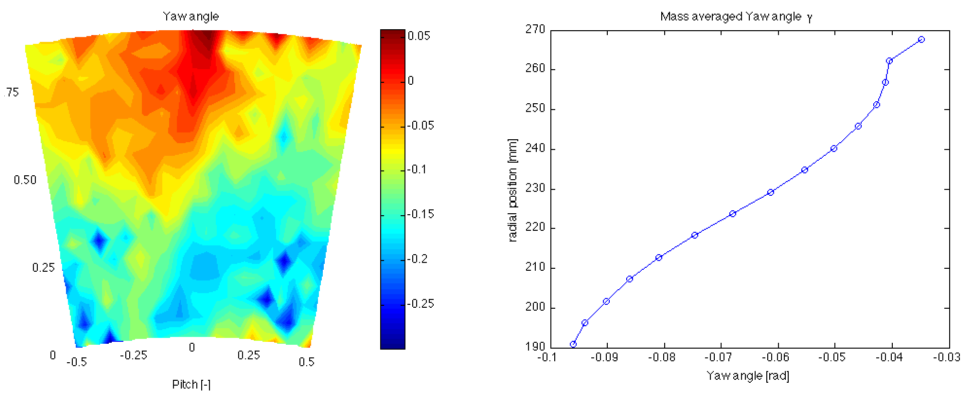


Figure 4.9: Measured Yaw Angle Over The Measuring Range And Mass Averaged Yaw Angle Over The Measured Pitch

4.0.5 Velocity Triangles

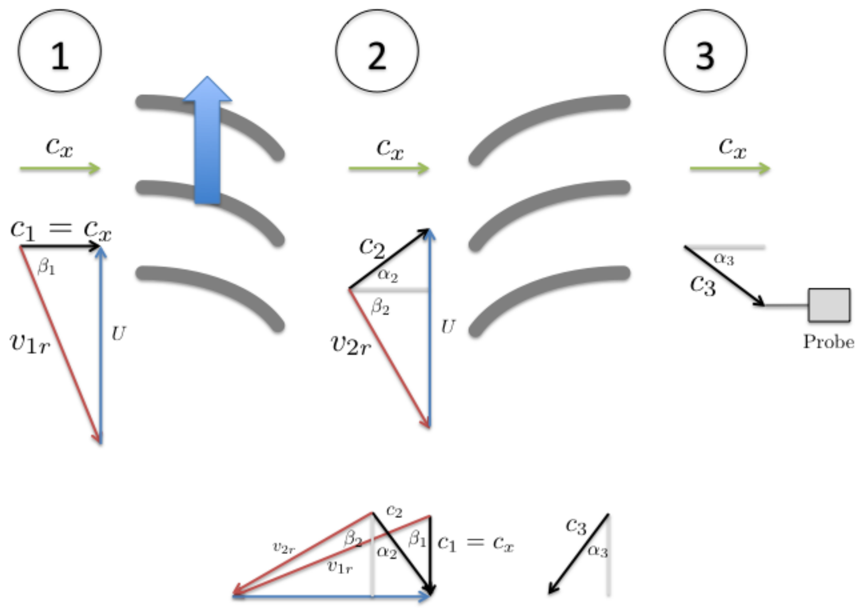


Figure 4.10: Velocity Scheme Of A Compressor And Velocity Triangles

In the Table 4.1 we see can compare the different yaw angles to the actual blade angles at each height of the blade. We see that the fluid deviation decreases towards the inner tube.

Span	Yaw angle (measured) [°]	Yaw angle (blade) [°]
90%	-2.009	9
70%	-2.527	8
50%	-3.466	6
30%	-4.723	4
10%	-5.466	-0.5

Table 4.1: Measured Yaw Angle And Stator Outlet Blade Angle Over The Measured Heights)

To calculate the velocity triangles we worked consistently with the scheme shown in Figure 4.10. We assumed an optimal flow and no incidence angle (α_1) in the rotor inlet. The outlet angle of the stator (α_3) is assumed to be the measured yaw angle.

Span	U $[\frac{m}{s}]$	c_3 $[\frac{m}{s}]$	c_2 $[\frac{m}{s}]$	c_1 $[\frac{m}{s}]$	v_{2r} $[\frac{m}{s}]$	v_{1r} $[\frac{m}{s}]$	v_x $[\frac{m}{s}]$	v_r $[\frac{m}{s}]$	v_θ $[\frac{m}{s}]$
90%	140.115	25.281	31.635	25.265	123.684	142.375	25.265	0.710	-0.910
70%	130.271	27.146	35.180	27.146	111.257	133.070	27.146	0.429	-1.199
50%	120.428	27.576	36.820	27.576	99.911	123.545	27.576	0.355	-1.673
30%	110.584	27.433	38.797	27.433	87.559	113.936	27.576	0.331	-2.255
10%	100.740	26.8371	42.645	26.837	72.732	104.254	26.837	0.300	-2.524

Table 4.2: Calculated Velocities Of The Velocity Triangles

With help of basic trigonometric relations we were able to calculate the rest of the angles and velocities including the inlet and outlet angles of the rotor (β_1 and β_2). The results are listed in Tables 4.2 and 4.3.

Span	α_3 [°]	α_2 [°]	β_2 [°]	α_1 [°]	β_1 [°]
90%	-2.009	37.000	78.213	0	79.778
70%	-2.527	39.500	75.878	0	78.229
50%	-3.466	41.500	73.978	0	77.102
30%	-4.723	45.000	71.741	0	76.068
10%	-5.466	51.000	68.347	0	75.083

Table 4.3: Calculated Angles Of The Velocity Triangles

Chapter 5

Conclusion

This experiment illustrates the general structure of a flow inside of a turbomachine. Furthermore it elaborates how to compute various angles, pressures and velocity components from a single five-hole measurement. The importance of the flows shape to improve the blades is obvious. Even though the flow is highly unsteady this measurement method provides expressive results without having as much data as in an unsteady technique.

Appendix A

MATLAB Code

```
%Turbomachinery

clc
clear all
close all

%Reading input file; if it doesnt work, change path
filename='5HP_data_points.txt'

fid = fopen(filename,'r');
[line1,count] = fscanf(fid,'%s',[1,32]);
col = 18; % number of columns
[A,count] = fscanf(fid,'%g',[col,inf]); % reading parameters into Matrix A
fclose(fid);

A=A';

% Post Processing
% polar coordinates -> cartesian coordiantes
Theta=10-reshape(A(:,3),16,[]);
Theta=pi*Theta./180; % Grad -> Radiant
radius=300.5-reshape(A(:,4),16,[]);
[x,y]=pol2cart(Theta,radius);

% Constants
kappa=1.4;
R=287; %specific cas constant of air
T_S=22+273.15;



% Figures
% 2D plot Ptot
f1 = figure(1);
set(f1, 'Position', [0 0 1500 400])
subplot(1,2,1)
Ptot=reshape(A(:,8),16,[]);
contourf(y,x,Ptot, 30)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',
90,'HorizontalAlignment','center')
title('P_{tot}')

% 2D plot Pstat
f2 = figure(2);
set(f2, 'Position', [0 0 1500 400])
subplot(1,2,1)
Pstat=reshape(A(:,9),16,[]);
contourf(y,x,Pstat, 30)
shading flat
colorbar
axis off
text(-60,277,'1')
```

```
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',
90,'HorizontalAlignment','center')
title('P_{stat}')


% 2D plot Mach Number
f3 = figure(3);
set(f3, 'Position', [0 0 1500 400])
subplot(1,2,1)
Mach=reshape(A(:,10),16,[]);
contourf(y,x,Mach, 30)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',
90,'HorizontalAlignment','center')
title('Mach Number')

% 2D plot Yawangle
f4 = figure(4);
set(f4, 'Position', [0 0 1500 400])
subplot(1,2,1)
Yawangle=reshape(A(:,6),16,[]);
Yawangle=2*pi/360.*Yawangle;
contourf(y,x,Yawangle, 30)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',
90,'HorizontalAlignment','center')
title('Yaw angle')

% 2D plot Pitchangle
f5 = figure(5);
```

```
set(f5, 'Position', [0 0 1500 400])
subplot(1,2,1)
Pitchangle=reshape(A(:,7),16,[]);
Pitchangle=2*pi/360.*Pitchangle;
contourf(y,x,Pitchangle, 30)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',↙
90,'HorizontalAlignment','center')
title('Pitch angle')

% 2D plot v_x
v_x=Mach.*sqrt(kappa*R*T_S)./sqrt(1.+tan(Pitchangle).^2.+tan(Yawangle).↙
^2);
f6 = figure(6);
set(f6, 'Position', [0 0 1500 400])
subplot(1,2,1)
contourf(y,x,v_x, 10)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',↙
90,'HorizontalAlignment','center')
title('v_x')

% 2D plot Vr
v_r=v_x.*tan(Pitchangle);
f7 =figure(7);
set(f7, 'Position', [0 0 1500 400])
subplot(1,2,1)
contourf(y,x,v_r, 10)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
```

```
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',↵
90,'HorizontalAlignment','center')
title('v_r')

% 2D plot Vtetha
v_tetha=abs(v_x.*tan(Yawangle));
f8 = figure(8);
set(f8, 'Position', [0 0 1500 400])
subplot(1,2,1)
contourf(y,x,v_tetha, 10)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',↵
90,'HorizontalAlignment','center')
title('|v_{\theta}|')

%2D Plot Vtot
v_tot=sqrt(v_x.^2+v_tetha.^2+v_r.^2);
f9 = figure(9);
set(f9, 'Position', [0 0 1500 400])
subplot(1,2,1)
contourf(y,x,v_tot, 10)
shading flat
colorbar
axis off
text(-60,277,'1')
text(-55,183+23.5*3,'0.75')
text(-50,183+23.5*2,'0.50')
text(-45,183+23.5,'0.25') % (277-183)*25%/100=23.5
text(-40,183,'0')
text(-32,181,'-0.5','HorizontalAlignment','center')
text(-32/2,183,'-0.25','HorizontalAlignment','center')
text(0,185,'0','HorizontalAlignment','center')
text(32/2,183,'0.25','HorizontalAlignment','center')
text(32,181,'0.5','HorizontalAlignment','center')
text(0,175,'Pitch [-]','HorizontalAlignment','center')
text(-65,183+23.5*2,'Span [-]','Rotation',↵
90,'HorizontalAlignment','center')
title('v_{tot}')


%Mass averaging
%v_n=v_x (bcs v_n velocity normal to the measuring plane)
for i=1:20
    for j=1:15
        v_x_mean(j,i)=(v_x(j,i)+v_x(j,i+1)+v_x(j+1,i)+v_x(j+1,i+1))/4;
    end
end

% density
density_mean=Ptot./(R*T_S);
```

```
dRi=5.5; %radial grid spacing
radial_pos=radius(:,1)+dRi/2;

% mass averaged Ptot
for i=1:20
    for j=1:15
        Ptot_mean(j,i)=(Ptot(j,i)+Ptot(j,i+1)+Ptot(j+1,i)+Ptot(j+1,i+1))
/4;
    end
end

Ptot_sum=0;
m_dot_cell_tot=0;

for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        Ptot_sum=Ptot_sum+Ptot_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
end
Ptot_mmean(j)=Ptot_sum;
Ptot_mmean(j)=Ptot_mmean(j)/m_dot_cell_tot;
end

figure(1)
subplot(1,2,2)
plot(Ptot_mmean,radial_pos(2:16),'-o')
title('Mass averaged P_{tot}')
xlabel('P_{tot} [Pa]')
ylabel('radial position [mm]')

% mass averaged Pstat
for i=1:20
    for j=1:15
        Pstat_mean(j,i)=(Pstat(j,i)+Pstat(j,i+1)+Pstat(j+1,i)+Pstat(j+1,
i+1))/4;
    end
end
Pstat_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        Pstat_sum=Pstat_sum+Pstat_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    Pstat_mmean(j)=Pstat_sum;
    Pstat_mmean(j)=Pstat_mmean(j)/m_dot_cell_tot;
end

figure(2)
subplot(1,2,2)
plot(Pstat_mmean,radial_pos(2:16),'-o')
title('Mass averaged P_{stat}')
xlabel('P_{stat} [Pa]')
ylabel('radial position [mm]')

% mass averaged Mach
for i=1:20
    for j=1:15
        Mach_mean(j,i)=(Mach(j,i)+Mach(j,i+1)+Mach(j+1,i)+Mach(j+1,i+1))
/4;
    end
end
```

```
Mach_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        Mach_sum=Mach_sum+Mach_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    Mach_mmean(j)=Mach_sum;
    Mach_mmean(j)=Mach_mmean(j)/m_dot_cell_tot;
end

figure(3)
subplot(1,2,2)
plot(Mach_mmean,radial_pos(2:16),'-o')
title('Mass averaged Mach')
xlabel('Mach [-]')
ylabel('radial position [mm]')

% mass averaged Yawangle
for i=1:20
    for j=1:15
        Yawangle_mean(j,i)=(Yawangle(j,i)+Yawangle(j,i+1)+Yawangle(j+1,i)
+Yawangle(j+1,i+1))/4;
    end
end
Yawangle_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        Yawangle_sum=Yawangle_sum+Yawangle_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    Yawangle_mmean(j)=Yawangle_sum;
    Yawangle_mmean(j)=Yawangle_mmean(j)/m_dot_cell_tot;
end

figure(4)
subplot(1,2,2)
plot(Yawangle_mmean,radial_pos(2:16),'-o')
title('Mass averaged Yaw angle \gamma')
xlabel('Yaw angle [rad]')
ylabel('radial position [mm]')

% mass averaged Pitch angle
for i=1:20
    for j=1:15
        Pitchangle_mean(j,i)=(Pitchangle(j,i)+Pitchangle(j,i+1)+Pitchangle
(j+1,i)+Pitchangle(j+1,i+1))/4;
    end
end
Pitchangle_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        Pitchangle_sum=Pitchangle_sum+Pitchangle_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    Pitchangle_mmean(j)=Pitchangle_sum;
    Pitchangle_mmean(j)=Pitchangle_mmean(j)/m_dot_cell_tot;
end
```

```
figure(5)
subplot(1,2,2)
plot(Pitchangle_mmean,radial_pos(2:16),'-o')
title('Mass averaged Pitch \phi')
xlabel('Pitch [rad]')
ylabel('radial position [mm]')


% mass averaged v_x
for i=1:20
    for j=1:15
        v_x_mean(j,i)=(v_x(j,i)+v_x(j,i+1)+v_x(j+1,i)+v_x(j+1,i+1))/4;
    end
end
v_x_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        v_x_sum=v_x_sum+v_x_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    v_x_mmean(j)=v_x_sum;
    v_x_mmean(j)=v_x_mmean(j)/m_dot_cell_tot;
end

figure(6)
subplot(1,2,2)
plot(v_x_mmean,radial_pos(2:16),'-o')
title('Mass averaged v_x')
xlabel('v_x [m/s]')
ylabel('radial position [mm]')

% mass averaged v_r
for i=1:20
    for j=1:15
        v_r_mean(j,i)=(v_r(j,i)+v_r(j,i+1)+v_r(j+1,i)+v_r(j+1,i+1))/4;
    end
end
v_r_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        v_r_sum=v_r_sum+v_r_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    v_r_mmean(j)=v_r_sum;
    v_r_mmean(j)=v_r_mmean(j)/m_dot_cell_tot;
end

figure(7)
subplot(1,2,2)
plot(v_r_mmean,radial_pos(2:16),'-o')
title('Mass averaged v_r')
xlabel('v_r [m/s]')
ylabel('radial position [mm]')

% V_tetha
for i=1:20
    for j=1:15
        v_tetha_mean(j,i)=(v_tetha(j,i)+v_tetha(j,i+1)+v_tetha(j+1,i)↙
+v_tetha(j+1,i+1))/4;
```

```
    end
end
v_tetha_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        v_tetha_sum=v_tetha_sum+v_tetha_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    v_tetha_mmean(j)=v_tetha_sum;
    v_tetha_mmean(j)=v_tetha_mmean(j)/m_dot_cell_tot;
end

figure(8)
subplot(1,2,2)
plot(v_tetha_mmean,radial_pos(2:16),'-o')
title('Mass averaged |v_{\theta}|')
xlabel('|v_{\theta}| [rad/s]')
ylabel('radial position [mm]')

% v_tot
for i=1:20
    for j=1:15
        v_tot_mean(j,i)=(v_tot(j,i)+v_tot(j,i+1)+v_tot(j+1,i)+v_tot(j+1,↙
i+1))/4;
    end
end
v_tot_sum=0;
m_dot_cell_tot=0;
for j=1:15
    for i=1:20
        dA=dRi*pi*1*(2*radius(j,i)+dRi)/360;
        m_dot_cell=dA*density_mean(j,i)*v_x_mean(j,i);
        v_tot_sum=v_tot_sum+v_tot_mean(j,i)*m_dot_cell;
        m_dot_cell_tot=m_dot_cell_tot+m_dot_cell;
    end
    v_tot_mmean(j)=v_tot_sum;
    v_tot_mmean(j)=v_tot_mmean(j)/m_dot_cell_tot;
end

figure(9)
subplot(1,2,2)
plot(v_tot_mmean,radial_pos(2:16),'-o')
title('Mass averaged v_{tot}')
xlabel('v_{tot} [m/s]')
ylabel('radial position [mm]')



format long
%Matrix with all data


span = 100*(radial_pos(2:16) - 183)/94; %span in porcentage
MEAN_DATA = [span radial_pos(2:16) Ptot_mmean' Pstat_mmean' Mach_mmean'↙
Yawangle_mmean' Pitchangle_mmean' v_x_mmean' v_r_mmean' v_tetha_mmean'];


   SPAN_DATA(1,1) = 90;
   SPAN_DATA(2,1) = 70;
   SPAN_DATA(3,1) = 50;
   SPAN_DATA(4,1) = 30;
   SPAN_DATA(5,1) = 10;
```

```
for i = 2:10



    SPAN_DATA(1,i) = MEAN_DATA(2,i) + (MEAN_DATA(1,i)-MEAN_DATA(2,i))*(90-
MEAN_DATA(2,1))/(MEAN_DATA(1,1)-MEAN_DATA(2,1));
    SPAN_DATA(2,i) = MEAN_DATA(5,i) + (MEAN_DATA(4,i)-MEAN_DATA(5,i))*(70-
MEAN_DATA(5,1))/(MEAN_DATA(4,1)-MEAN_DATA(5,1));
    SPAN_DATA(3,i) = MEAN_DATA(8,i) + (MEAN_DATA(7,i)-MEAN_DATA(8,i))*(50-
MEAN_DATA(8,1))/(MEAN_DATA(7,1)-MEAN_DATA(8,1));
    SPAN_DATA(4,i) = MEAN_DATA(12,i) + (MEAN_DATA(11,i)-MEAN_DATA(12,i))*
(30-MEAN_DATA(12,1))/(MEAN_DATA(11,1)-MEAN_DATA(12,1));
    SPAN_DATA(5,i) = MEAN_DATA(15,i) + (MEAN_DATA(14,i)-MEAN_DATA(15,i))*
(10-MEAN_DATA(15,1))/(MEAN_DATA(14,1)-MEAN_DATA(15,1));



end


SPAN_DATA;


%Blade angles
%Rotor velocity
N=5000; %Rounds per Minute
U=2*pi*N/60.*SPAN_DATA(:,2)*10^(-3);
%stator Blade entry angles
alpha2=[37.000; 39.500; 41.500; 45.000; 51.000];

%Behind stator
C3=sqrt(SPAN_DATA(:,8).^2+SPAN_DATA(:,10).^2);
alpha3=tan(SPAN_DATA(:,10)/SPAN_DATA(:,8));

%Behind rotor
C2=sqrt((SPAN_DATA(:,8).*tan(2*pi/360*alpha2)).^2+SPAN_DATA(:,8).^2);
beta2=360/(2*pi)*atan((U-SPAN_DATA(:,8).*tan(alpha2*2*pi/360))./SPAN_DATA
(:,8));
v2r=((U-SPAN_DATA(:,8).*tan(alpha2*2*pi/360)).^2+SPAN_DATA(:,8).^2).^
(0.5);

%in front of rotor
beta1=360/(2*pi)*atan(U./SPAN_DATA(:,8));
v1r=sqrt(SPAN_DATA(:,8).^2+U.^2);
```