Scilab Textbook Companion for Fluid Mechanics and Thermodynamics of Turbomachinery by S. L. Dixon and C. A. Hall[1]

Created by
Varun S S
B.Tech.
Others
IIT Bombay
College Teacher
None
Cross-Checked by
Spandana

July 31, 2019

[1]Funded by a grant from the National Mission on Education through ICT, http://spoken-tutorial.org/NMEICT-Intro. This Textbook Companion and Scilab codes written in it can be downloaded from the "Textbook Companion Project" section at the website http://scilab.in

Book Description

Title: Fluid Mechanics and Thermodynamics of Turbomachinery

Author: S. L. Dixon and C. A. Hall

Publisher: Butterworth-Heinemann, London

Edition: 6

Year: 2010

ISBN: 978-1-85617-793-1

Scilab numbering policy used in this document and the relation to the above book.

Exa Example (Solved example)

Eqn Equation (Particular equation of the above book)

AP Appendix to Example(Scilab Code that is an Appednix to a particular Example of the above book)

For example, Exa 3.51 means solved example 3.51 of this book. Sec 2.3 means a scilab code whose theory is explained in Section 2.3 of the book.

Contents

List of Scilab Codes

Chapter 1

Introduction Basic Principles

Scilab code Exa 1.1 Ex 1

```
clear all;
clc;
funcprot(0);

//given data
gamma = 1.4;
pi = 8;//pressure ratio
T01 = 300;//inlet temperature in K
T02 = 586.4;//outlet temperature in K

//Calculations
//Calculation of Overall Total to Total efficiency
Tot_eff = ((pi^((gamma-1)/gamma))-1)/((T02/T01)-1);

//Calculation of polytropic efficiency
Poly_eff = ((gamma-1)/gamma)*((log(pi))/log(T02/T01)
    );

//Results
printf('The Overall total-to-total efficiency is %.2
    f.\n',Tot_eff);
```

```
printf('The polytropic efficiency is %.4f.',Poly_eff
);
```

Chapter 2

Dimensional Analysis Similitude

Scilab code Exa 2.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
T01_te = 298;//in K
mdot_te = 15;//in kg/s
p01_te = 101;//in kPa
T01_cr = 236;//in K
p01_cr = 10.2;//in kPa
N_te = 6200;//in rpm
pi = 20;//pressure ratio
gamma = 1.4;
Cp = 1005;//in J/(kg.K)
eff = 0.85;//efficiency

//Calculations
mdot_cr = (p01_cr/sqrt(T01_cr))*(mdot_te*sqrt(T01_te
   )/p01_te);
```

```
N_cr = sqrt(T01_cr/T01_te)*N_te;
delT0_T01 = (((pi^((gamma-1)/gamma)) - 1)/eff);
P_cr = mdot_cr*Cp*T01_cr*delT0_T01;

//Results
printf('The mass flow rate = %.2f kg/s',mdot_cr);
printf('\n Rotational speed = %d rpm',N_cr);
printf('\n The power input at the cruise condition = %d kW.',P_cr/1000);

//there is a small error in the answer given in textbook
```

Scilab code Exa 2.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data
D = 4.31;//in m
H = 543;//in m
Q = 71.4;//in m^3/s
P = 350;//in MW
N = 333;//in rev/min
D1 = 6;//in m
H1 = 500;//in m
g = 9.81;//in m/s^2
rho = 1000;//in kg/m^3

//Calculations
omega = N*%pi/30;
omega_s = omega*(Q^0.5)/(g*H)^0.75;
D_s = D*(g*H)^0.25 /Q^0.5;
P_n = rho*g*Q*H;
```

```
eff_t = P*10^6 /P_n;
Q1 = ((D1/D_s)^2)*(g*H1)^0.5;
P1 = eff_t*rho*g*Q1*H1;
N1 = (30/%pi)*omega_s*((g*H1)^0.75)/(Q1^0.5);

//Results
printf('(a)The specific speed = %.3f rad.',omega_s);
printf('\n The specific diameter = %.3f',D_s);
printf('\n The turbine efficiency is = %.3f',eff_t);
printf('\n(b) The required flow rate = %d m^3/s',ceil(Q1));
printf('\n The expected power output = %.1f MW',P1/(10^6));
printf('\n The rotational speed of the turbine = %.1f rpm.',N1);
```

Scilab code Exa 2.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
N = 300000;//in rpm
Q = 10;//in L/min
p01 = 3;//in bar
T01 = 300;//in K
p02 = 1;//in bar
rho = 1.16;//in kg/m^3
Cp = 1005;//in J/(kg.K)
gamma = 1.4;

//Calculations
N = N/60;//in rev/s
Qe = Q/(1000*60);
```

```
delh0s = Cp*T01*(1-(p02/p01)^((gamma-1)/gamma));
Ns = N*sqrt(Qe)*(delh0s^-0.75);
omega_s = Ns*2*%pi;
P = rho*Qe*delh0s;

//Results
printf('The specific speed of the turbine = %.3f rad.',omega_s);
printf('\n The type of machine required for this very low specific speed is a Pelton wheel.');
printf('\n The power consumption of the turbine = %.1f W.',P);
printf('\n The majority of this power will be dissipated as heat through friction in the bearings, \n losses in the Pelton wheel and friction with the tooth.')
```

Chapter 3

Two Dimensional Cascades

Scilab code Exa 3.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
alpha1 = 55;//flow inlet angle in deg
alpha2 = 30;//flow exit angle in deg
cmaxs_c2 = 1.95;//expected design value of the
    diffusion ratio
DF = 0.6;//diffusion factor

//Calculation
theta2_l = 0.004/(1-1.17*log(cmaxs_c2));
alpham = (180/%pi)*atan(0.5*(tan(alpha1*%pi/180)+tan
    (alpha2*%pi/180)));
CD = 2*(theta2_l)*((cos(alpham*%pi/180))^2)/((cos(
    alpha2*%pi/180))^2);
s_l_max = ((2*cos(alpha1*%pi/180)/cos(alpha2*%pi
    /180))-0.8)/(cos(alpha1*%pi/180) *(tan(alpha1*%pi
    /180)-tan(alpha2*%pi/180)));
CL = 2*s_l_max*cos(alpham*%pi/180)*(tan(alpha1*%pi
```

```
/180)-tan(alpha2*%pi/180)) - CD*tan(alpham*%pi/180);

//Results
printf('CD = %.5f\n CL = %.3f',CD,CL);
printf('\n The maximum allowable pitch chord ratio = %.3f',s_l_max);

//there is some error in the answer given in textbook
```

Scilab code Exa 3.2 Ex 2

```
clear all;
clc;
funcprot(0);

//function to calculate m and delta
function [m,delta] = func(a_l,alpha2,theta)
    m = 0.23*(2*a_l)^2 + alpha2/500;
    delta = m*theta;
endfunction

//given data
alpha1_ = 50;// in deg
alpha2_ = 20;// in deg
a_l = 0.5;//percentage
s_l = 1.0;
eps = 21;//in deg

//Calculations
theta = alpha1_ - alpha2_;
alpha21 = 20;//in deg
[m1,delta1] = func(a_l,alpha21,theta);
alpha22 = 28.1;//in deg
```

```
[m2,delta2] = func(a_l,alpha22,theta);
alpha23 = 28.6;//in deg
[m3,delta3] = func(a_l,alpha23,theta);
alpha1 = eps + alpha23;
i = alpha1 - alpha1_;
alpham = (180/%pi)*atan(0.5*(tan(alpha1*%pi/180) + tan(alpha23*%pi/180)));
CL = 2*(s_l)*cos(alpham*%pi/180)*(tan(alpha1*%pi/180) - tan(alpha23*%pi/180));

//Results
printf('The fluid deflection = %d deg.',eps);
printf('\n The fluid incidence = %.1f deg.',i);
printf('\n The ideal lift coefficient at the design point = %.2f',CL);
```

Scilab code Exa 3.4 Ex 4

```
clear;
clc;
funcprot(0);

//given data
alpha1 = 22;//inlet flow angle in deg
M1 = 0.3;//inlet Mach number
M2 = 0.93;//exit Mach number
alpha2 = 61.4;//exit flow angle in deg
Q1 = 0.6295;//Q(M1) from compressible flow tables
Q2 = 1.2756;//Q(M2) from compressible flow tables
gamma = 1.333;
Z = 0.6;

//Calculations
p02_p01 = (Q1/Q2)*(cos(alpha1*%pi/180)/cos(alpha2*%pi/180));
```

```
p01_p2 = (1+0.5*(gamma-1)*M2)^(gamma/(gamma-1)) *(1/p02_p01);
YP = (1-(p02_p01))/(1-(1/p01_p2));
K1 = M1/sqrt((1+0.5*(gamma-1)*(M1^2))/(gamma-1));
K2 = M2/sqrt((1+0.5*(gamma-1)*(M2^2))/(gamma-1));
s_b = ((1-(1/p01_p2))*Z)/(Q1*(K1*sin(alpha1*%pi/180)+K2*sin(alpha2*%pi/180))*cos(alpha1*%pi/180));

//Results
printf('The ratio of inlet stagnation pressure to exit static pressure = %.3f',p01_p2);
printf('\n The cascade stagnation pressure loss coefficient = %.4f',YP);
printf('\n The pitch to axial chord ratio for the blades = %.3f',s_b);

//there are errors in the answers given in textbook
```

Chapter 4

Axial Flow Turbines Mean Line Analysis and Design

Scilab code Exa 4.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
n = 5;//number of stages
T01 = 1200;//Turbine inlet stagnation temperature in K
p01 = 213;//inlet stagnation pressure in kPa
mdot = 15;//mass flow rate in kg/s
P = 6.64;//Mechanical power in MW
alpha1 = 15;//in deg
alpha2 = 70;//in deg
rm = 0.46;//turbine mean radius in m
N = 5600;//rotational speed in rpm
gamma = 1.333;
R = 287.2;//in J/(kg.K)
Cp = 1150;// in J/(kg.K)

```

```
//Calculations
U = rm*N*2*%pi/60;
psi = P*(10^6)/(mdot*n)/(U^2);
phi = psi/(tan(alpha1*%pi/180) + tan(alpha2*%pi/180));
R = 1-0.5*psi+phi*tan(alpha1*%pi/180);

k1 = phi*U/sqrt(Cp*T01);
k2 = 0.3663;

//iteration to find out Mach number
i = 1;
M = 0.0;//initial guess of Mach number
while (i>0), i = i+1
    res = M*(sqrt(gamma-1))*(1 + 0.5*(gamma-1)*(M^2))^(-0.5)- k1;
    if res > 0 then
        M = M - 0.0001;
    elseif res < 0
        M = M + 0.0001;
    end
    if abs(res)<0.000001 then
        break;
    end
end
Ax = mdot*sqrt(Cp*T01)/(k2*p01*1000);
H = Ax/(2*%pi*rm);
HTR = (rm-0.5*H)/(rm+0.5*H);

//Results
printf('(a) The turbine stage loading coefficient = %.3f',psi);
printf('\n  The flow coefficient = %.3f',phi);
printf('\n  The reaction = %.1f',R);
printf('\n (b) The annulus area at inlet to the turbine = %.3f m^2',Ax);
printf('\n  The blade height = %.4f',H);
printf('\n  The hub-to-tip ratio, HTR = %.3f',HTR);
```

Scilab code Exa 4.2 Ex 2

```
clear all;
clc;
funcprot(0);

//given data
phi = 0.4;
epsilon = 28.6;//in deg

//calculations
alpha2 = (180/%pi)*atan(1/phi);//in deg
zeta = 0.04*(1+ 1.5*(alpha2/100)^2);
eta = 1 + (phi^2)*(zeta*((1/cos(%pi*alpha2/180))^2)
    +0.5);

//results
printf('The efficiency = %.3f.\n',1/eta);
printf('This value appears to be the same as the
    peak value of efficiency curve.\n');
```

Scilab code Exa 4.3 Ex 3

```
clear all;
clc;
funcprot(0);

//given data
alpha2 = 70;//in deg
p01 = 311;//in kPa
T01 = 850;//in degC
```

```
p3 = 100;//in kPa
eff_tot_stat = 0.87;
U = 500;//in m/s
Cp = 1.148;//in kJ/(kgC)
gamma = 1.33;

//Calculations
delW = eff_tot_stat*Cp*(T01+273.15)*(1-(p3/p01)^((
    gamma-1)/gamma));//specific work
cy2 = delW*1000/U;//in m/s
c2 = cy2/sin(%pi*alpha2/180);//in m/s
T2 = (T01+273.15) - 0.5*(c2^2)/(Cp*1000);//Nozzle
    exit temperature in K
M2 = c2/sqrt(gamma*287*T2);//Nozzle exit mach number
cx = c2*cos(%pi*alpha2/180);//axial velocity in m/s
eff_tot_tot = 1/((1/eff_tot_stat)-((cx^2)/(2*1000*
    delW)));//Total to total efficiency
R = 1 - 0.5*(cx/U)*tan(%pi*alpha2/180);//stage
    reaction

//results
printf('(i) The specific work done = %d kJ/kg.\n',
    delW);
printf('(ii) The Mach number leaving the nozzle = %
    .2f.\n',M2);
printf('(iii) The axial velocity = %d m/s.\n',cx);
printf('(iv) The total-to-total efficiency = %.2f.\n
    ',eff_tot_tot);
printf('(v) The stage reaction = %.3f.\n',R);


//there are small errors in the answers given in the
     book
```

Scilab code Exa 4.4 Ex 4

```
clear all;
clc;
funcprot(0);

//given data
H_b = 5.0;//average bladeaspect ratio for the stage
t_c = 0.2;//max. blade thickness to chord ratio
Re = 1*10^5;//average Reynolds number
cx = 200;//in m/s
cy2 = 552;//in m/s
U = 500;//in m/s
c2 = 588;//in m/s
delW = 276;//in kJ
c3 = 200;//in m/s
Cp = 1.148;//in kJ/(kgC)
T2 = 973;//in K
T01 = 1123;//in K
alpha1 = 0;//in deg
alpha2 = 70;//in deg

//calculations
eps = alpha1 + alpha2;//in deg
zetaN = 0.04*(1 + 1.5*(eps/100)^2);
zetaN1 = (1+zetaN)*(0.993 + 0.021/H_b) - 1;
beta2 = (180/%pi)*atan((cy2-U)/cx);
beta3 = (180/%pi)*atan(U/cx);
epsR = beta2 + beta3;
zetaR = 0.04*(1 + 1.5*(epsR/100)^2);
zetaR1 = (1+zetaR)*(0.975 + 0.075/H_b) - 1;
w3_U = sqrt(1+(cx/U)^2);
eff_ts = 1/(1 + (zetaR1*w3_U + zetaN1*((c2/U)^2) + (
   cx/U)^2)/(2*cy2/U));
T3 = T01 - (delW*1000 + 0.5*c3^2)/(Cp*1000);
eff_ts1 = 1/(1 + (zetaR1*(w3_U)^2 + (T3/T2)*zetaN1
   *((c2/U)^2) + (cx/U)^2)/(2*cy2/U));

//Results
printf('The total-to static efficiency = %.3f.',
```

```
eff_ts);
printf('\n The result is very close to the value
   assumed in first example.')
printf('\n The total-to-static efficiency after
   including the temperature ratio in the equation =
    %.3f.',eff_ts1);

//there are small errors in the answers given in the
    book
```

Scilab code Exa 4.5 Ex 5

```
clear;
clc;
funcprot(0);

//given data
T02 = 1200;//in K
p01 = 4.0;//in bar
dt = 0.75;//tip diameter in m
hb = 0.12;//blade height in m
v = 10500;//shaft speed in rev/min
R = 0.5;//degree of reaction at mean radius
phi = 0.7;//flow coefficient
psi = 2.5;//stage loading coefficient
eff_noz = 0.96;//Nozzle efficiency
Cp = 1160;//in kJ/(kgC)
gamma = 1.33;
Rg = 287.8;//specific gas constant
A2 = 0.2375;//in m^2
K = 2/3;//stress taper factor
rho = 8000;//in kg/m^3

//calculations
beta3 = (180/%pi)*atan((0.5*psi + R)/phi);
```

```
beta2 = (180/%pi)*atan((0.5*psi - R)/phi);
alpha2 = beta3;
alpha3 = beta2;
rm = (dt-hb)/2;
Um = (v/30)*%pi*rm;
cx = phi*Um;
c2 = cx/(cos(alpha2*%pi/180));
T2 = T02 - 0.5*(c2^2)/Cp;
p2 = p01*((1-((1-(T2/T02))/eff_noz))^(gamma/(gamma-1)));
mdot = ((p2*10^5)/(Rg*T2))*A2*cx;
Ut = (v/30)*%pi*0.5*dt;
sig_rho = K*0.5*(Ut^2)*(1-((dt-2*hb)/dt)^2);
sig = rho*sig_rho;
Tb = T2 + 0.85*((cx/cos(beta2*%pi/180))^2)/(2*Cp);

//Results
printf('(i)The relative and absolute angles for the flow: \n beta3 = %.1f deg, and beta2 = %.2f deg.',beta3,beta2);
printf('\n alpha2 = %.1f deg, and alpha3 = %.2f deg.',alpha2,alpha3);
printf('\n (ii) The velocity at nozzle exit = %.2f m/s',c2);
printf('\n (iii)The static temperature and pressure at nozzle exit assuming a nozzle efficiency of %.2f: \n T2 = %.1f K\n p2 = %.3f bar',eff_noz,T2,p2);
printf('\n and mass flow = %.1f kg/s',mdot);
printf('\n (iv)The rotor blade root stress assuming the blade is tapered with a stress taper factor K of 2/3 and \n the blade material density is %d kg/m2 = %.1f MPa',rho,sig/(10^6));
printf('\n (v) The approximate average mean blade temperature is Tb = %.1f K',Tb);
printf('\n (vi)Inspection of the data for Inconel 713 cast alloy suggests that it might be a better choice \n of blade material as the
```

```
temperaturestress point of the above calculation is to the \n left of the line marked creep strain of 0.2 percentage in 1000 hr.')


//there are very small errors in the answers given in textbook
```

Chapter 5

Axial Flow Compressors and Ducted Fans

Scilab code Exa 5.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
T01= 288;//inlet absolute stagnation temperature in
    K
p01 = 101;//inlet absolute stagnation pressure in
    kPa
beta1 = 45;//relative flow angle at inlet to the
    rotor in deg
M1_rel = 0.9;//inlet relative Mach number
Yp = 0.068;//rotor loss coefficient
Yp1 = 0.04;//stator loss coefficient
M = 0.5;//rotor exit relative Mach number
gamma = 1.4;
R = 287.15;
Cp = 1005;//in J/(kg.K);
Q1 = 1.2698;//Q(0.9) from compressible flow tables
```

```
Q2 = 0.9561;//Q(0.5) from compressible flow tables
M2_rel = 0.5;//rotor exit relative Mach number is 0.5,

//Calculations
M1 = M1_rel*cos(beta1*%pi/180);
T1 = T01/(1+(gamma-1)*0.5*M1^2);
U = M1*sqrt(gamma*R*T1);
p01_rel = p01*((T1/T01)^(gamma/(gamma-1)))*((1+(gamma-1)*0.5*M1_rel^2)^(gamma/(gamma-1)));
p1 = p01*((T1/T01)^(gamma/(gamma-1)));

p02_rel_p01_rel = 1-Yp*(1-((1+(gamma-1)*0.5*M1_rel^2)^(gamma/(gamma-1)))^-1);
beta2 = (180/%pi)*acos((Q1/Q2)*cos(beta1*%pi/180)/p02_rel_p01_rel);
p2_p02_rel = 0.8430;//from tables
p2_p1 = p2_p02_rel*p02_rel_p01_rel*((1+(gamma-1)*0.5*M1_rel^2)^(gamma/(gamma-1)));
p2 = p1*p2_p1;
T2_T2_rel = 0.9524;//from tables
T2 = T1*(T2_T2_rel)*(1+(gamma-1)*0.5*M1_rel^2);
W2 = M2_rel*sqrt(gamma*R*T2);
M2 = sqrt((W2*cos(beta2*%pi/180))^2 +(U-W2*sin(beta2*%pi/180))^2)/sqrt(gamma*R*T2);
T02 = T2*(1+(gamma-1)*0.5*M2^2);
p02 = p2*(1+(gamma-1)*0.5*M2^2)^(gamma/(gamma-1));
delS_rot = R*Yp*(1-(p1/p01_rel));
delS_sta = R*Yp1*(1-(p2/p02));
eff_tt = 1 - (T02*(delS_rot+delS_sta)/(Cp*(T02-T01)));

//Results
printf('(i) The rotor blade speed = %.1f m/s',U);
printf('\n The blade relative stagnation pressure = %d kPa',p01_rel);
printf('\n (ii) The rotor exit relative flow angle = %d deg.',ceil(beta2));
```

```
printf('\n   The static pressure ratio across the rotor = %.3f',p2_p1);
printf('\n (iii) The absolute stagnation temperature at entry to the stator = %.1f K',T02);
printf('\n  The absolute stagnation pressure at entry to the stator = %d kPa',ceil(p02));
printf('\n  The total-to-total isentropic efficiency of the compressor stage = %.3f',eff_tt);
```

Scilab code Exa 5.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data
T01 = 293;//in K
pi = 5;//pressure ratio
R = 0.5;//stage reaction
Um = 275;//in m/s
phi = 0.5;//flow coefficient
psi = 0.3;//stage loading factor
eff_stage = 0.888;//stage efficiency
Cp = 1005;//J/(kgC)
gamma = 1.4;

//Calculations
beta1 = (180/%pi)*atan((R + 0.5*psi)/phi);
beta2 = (180/%pi)*atan((R - 0.5*psi)/phi);
alpha2 = beta1;
alpha1 = beta2;
delT0 = psi*(Um^2)/Cp;
N = (T01/delT0)*((pi^((gamma-1)/(eff_stage*gamma))) - 1);
N = ceil(N);
```

```
eff_ov = ((pi^((gamma-1)/gamma)) - 1)/((pi^((gamma-1)/(eff_stage*gamma))) - 1);
printf('The flow angles are: beta1 = alpha2 = %.2f deg and beta2 = alpha1 = %d deg.',beta1,ceil(beta2));
printf('\n The number of stages required = %d',N);
printf('\n The overall efficiency = %.1f percentage',eff_ov*100);

//there is a small error in the answer given in textbook
```

Scilab code Exa 5.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
R = 0.5;//stage reaction
s_c = 0.9;//space-chord ratio
beta1_ = 44.5;//in deg
beta2_ = -0.5;//in deg
h_c = 2.0;//height-chord ratio
lamda = 0.86;//work done factor
i = 0.4;//mean radius relative incidence
rho = 3.5;//density in kg/m^3
Um = 242;//in m/s
eps_ = 30;//in deg
eps_max = 37.5;//in deg
eps = 37.5;//in deg
delp0 = 0.032;//the profile total pressure loss coefficient

//Calculations
```

```
theta = beta1_ - beta2_;
deltaN = (0.229*theta*(s_c^0.5))/(1 - (theta*(s_c^0.5)/500));
beta2N = deltaN + beta2_;
i_ = beta2N + eps_ - beta1_;
i = 0.4*eps_ + i_;
beta1 = beta1_ + i;
beta2 = beta1 - eps;
alpha2 = beta1;
alpha1 = beta2;
phi = 1/(tan(alpha1*%pi/180) + tan(beta1*%pi/180));
psi = lamda*phi*(tan(alpha2*%pi/180) - tan(alpha1*%pi/180));

//Results
printf('(i)The nominal incidence = %.1f deg.',i_);
printf('\n (ii)The inlet flow angle, beta1 = alpha2 = %.1f deg\n    Outlet flow angle beta2 = alpha1 = %.1f deg.',beta1,beta2);
printf('\n (iii)The flow coefficient = %.3f\n    The stage loading factor = %.3f',phi,psi);
//there are small errors in the answers given in textbook
```

Chapter 6

Three Dimensional Flows in Axial Turbomachines

Scilab code Exa 6.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
dt = 1.0;//tip diameter in m
dh = 0.9;//hub diameter in m
alpha1 = 30;//in deg
beta1 = 60;//in deg
alpha2 = 60;//in deg
beta2 = 30;//in deg
N = 6000;//rotational speed in rev/min
rhog = 1.5;//gas density in kg/m^3
Rt = 0.5;//degree of reaction at the tip

//Calculations
omega = 2*%pi*N/60;
Ut = omega*0.5*dt;
Uh = omega*0.5*dh;
```

```
cx = Ut/(tan(alpha1*%pi/180) + tan(beta1*%pi/180));
mdot = %pi*((0.5*dt)^2 - (0.5*dh)^2)*rhog*cx;
Wcdot = mdot*Ut*cx*(tan(alpha2*%pi/180)- tan(alpha1*
    %pi/180));
ctheta1t = cx*tan(alpha1*%pi/180);
ctheta1h = ctheta1t*(dt/dh);
ctheta2t = cx*tan(alpha2*%pi/180);
ctheta2h = ctheta2t*(dt/dh);
alpha1_ = (180/%pi)*atan(ctheta1h/cx);
beta1_ = (180/%pi)*atan((Uh/cx) - tan(alpha1_*%pi
    /180));
alpha2_ = (180/%pi)*atan(ctheta2h/cx);
beta2_ = (180/%pi)*atan((Uh/cx) - tan(alpha2_*%pi
    /180));
k = Rt*(0.5*dt)^2;
Rh = 1 - (k/(0.5*dh)^2);

//Results
printf('(i)The axial velocity , cx = %d m/s',cx);
printf('\n (ii)The mass flow rate = %.1f kg/s',mdot)
    ;
printf('\n (iii)The power absorbed by the stage = %
    .1f MW',Wcdot/(10^6));
printf('\n (iv)The flow angles at the hub are:\n
    alpha1 = %.2f deg,\n beta1 = %.2f deg,\n alpha2 =
     %.1f deg, and\n beta2 = %.2f deg.',alpha1_,
    beta1_,alpha2_,beta2_);
printf('\n (v)The reaction ratio of the stage at the
     hub, R = %.3f.',Rh);


//there are small errors in the answers given in
    textbook
```

Scilab code Exa 6.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data

R = 0.5;//degree of reaction
Cp = 1005;//kJ/(kgC)
cx1_Ut_rt = 0.4;
delT0 = 16.1;//temperature rise
Ut = 300;//in m/s

//calculations
A1 = cx1_Ut_rt^2 +(0.5-0.18*log(1));
c1 = 2*(1-R);
c2 = Cp*delT0/(2*Ut^2 *(1-R));
A2 = 0.56;
k = 0.4:0.01:1.0;
n = (1.0-0.4)/0.01 + 1;
i = 1;
for i = 1:n
    cx1_Ut(i) = sqrt(A1 - (c1^2)*(0.5*k(i)^2 - c2*log(k(i))));
    cx2_Ut(i) = sqrt(A2 - (c1^2)*(0.5*k(i)^2 + c2*log(k(i))));
    R_(i) = 0.778+log(k(i));
    Rn(i) = 0.5;
end

//Results
plot(k,cx1_Ut,'bo-');
plot(k,cx2_Ut,'<>r-');
title("Solution of exit axial-velocity profile for a first power stage","fontsize",3) ;//title of the plot
xlabel("Radius ratio, r/rt","fontsize",3) ;//x label
ylabel("cx/Ut","fontsize",3) ;//y label
legend(["(cx2/Ut)";"(cx1/Ut)"] , opt=2); //legend
```

```
    box
a=gca();
b = newaxes();
b.y_location = "right";
b.filled = "off";
b.axes_visible = ["off","on","on"];
b.axes_bounds = a.axes_bounds;
b.font_size = a.font_size;
plot(k,R_,"g");
plot(k,Rn,);
ylabel("Reaction","fontsize",3) ;//y label
legend(["True Reaction";"Nominal Reaction"] , opt=1)
    ; //legend box
```

Chapter 7

Centrifugal Pumps Fans and Compressors

Scilab code Exa 7.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
c1 = 300;//velocity in m/s
p01 = 200;//stagnation pressure in kPa
T01 = 200;//stagnation temperature in degC
c2 = 50;//exit velocity in m/s
eff_d = 0.9;//diffuser efficiency

gamma = 1.4;
R = 287;//in J/(kg.K)
Cp = 1005;//in J/(kg.K)

//Calculations
T01 = T01+273;//stagnation temperature in K
T1 = T01*(1-(c1^2)/(2*Cp*T01));
M1 = c1/sqrt(gamma*R*T1);
```

```
T2 = T01*(1-(c2^2)/(2*Cp*T01))
T2s_T1 = eff_d*(T2/T1 -1)+1;
p2_p1 = (T2s_T1)^(gamma/(gamma-1));
p01_p1 = (T01/T1)^(gamma/(gamma-1));
p1 = p01/p01_p1;
p2 = p2_p1*p1;
ds = Cp*log(T2/T1) - R*log(p2/p1);

//Results
printf('(i)The static temperature at inlet of the
    diffuser = %.1f K',T1);
printf('\n The static temperature at outlet of the
    diffuser = %.1f K',T2);
printf('\n The inlet Mach number = %.4f',M1);
printf('\n (ii) The static pressure at diffuser
    inlet = %.1f kPa',p1);
printf('\n (iii) The increase in entropy caused by
    the diffusion process = %.1f J/kg.K',ds);

//there are small errors in the answers given in
    textbook
```

Scilab code Exa 7.2 Ex 2

```
clear;
clc;
funcprot(0);

//function to calculate blade cavitation coefficient
function [res] = fun(sigmab,k,omega_ss)
    res = (sigmab^2)*(1 + sigmab)- (((3.42*k)^2)/(
        omega_ss^4));
endfunction

//given data
```

```
Q = 25;//flow rate in dm^3/s
omega = 1450;//rotational speed in rev/min
omega_ss = 3;//max. suction specific speed in rad/sec
r = 0.3;//inlet eye radius ratio
g = 9.81;//in m/s^2

//Calculations
k = 1-(r^2);
sigmab = 0.3;//initial guess
res = fun(sigmab,k,omega_ss);//initial value
i = 0;
while (abs(res)>0.0001)
    if res>0.0 then
        sigmab = sigmab - 0.0001;
    elseif res<0.0
        sigmab = sigmab + 0.0001;
    end
    res = fun(sigmab,k,omega_ss);
end
phi = (sigmab/(2*(1+sigmab)))^0.5;
rs1 = ((Q*10^-3)/(%pi*k*(omega*%pi/30)*phi))^(1/3);
ds1 = 2*rs1;
cx1 = phi*(omega*%pi/30)*rs1;
Hs = (0.75*sigmab*cx1^2)/(g*phi^2);

//Results
printf('(i)The blade cavitation coefficient = %.3f',sigmab);
printf('\n (ii)The shroud radius at the eye = %.5f m\n The required diameter of the eye = %.1f mm',rs1,ds1*10^3);
printf('\n (iii)The eye axial velocity = %.3f m/s',cx1);
printf('\n (iv)The NPSH = %.3f m',Hs);
```

Scilab code Exa 7.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
alpha1 = 30;//prewhirl in deg
hs = 0.4;//inlet hub-shrub radius ratio
Mmax = 0.9;//max Mach number
Q = 1;//air mass flow in kg/s
p01 = 101.3;//stagnation pressure in kPa
T01 = 288;//stagnation temperature in K
gamma = 1.4;
Rg = 287;//in J/(kgK)

//Calculations
beta1 = 49.4;//in deg
f = 0.4307;
a01 = sqrt(gamma*Rg*T01);
rho01 = p01*1000/(Rg*T01);
k = 1-(hs^2);
omega = (%pi*f*k*rho01*a01^3)^0.5;
N = (omega*60/(2*%pi));
rho1 = rho01/(1 + 0.2*(Mmax*cos(beta1*%pi/180))^2)
    ^2.5;
cx = ((omega^2)/(%pi*k*rho1*(tan(beta1*%pi/180) +
    tan(alpha1*%pi/180))^2))^(1/3);
rs1 = (1/(%pi*rho1*cx*k))^0.5;

ds1 = 2*rs1;
U = omega*rs1;

//Results
```

```
printf('(i)The rotational speed of the impeller = %.1f rad/s and N = %d rev/min.',omega,N);
printf('\n (ii)The inlet static density downstream of the guide vanes at the shroud = %.5f kg/m^3.\n The axial velocity = %.2f m/s.',rho1,cx);
printf('\n (iii)The inducer tip diameter = %.3f cm\n U = %.1f m/s.',ds1*100,U);

//there are errors in the answers given in textbook
```

Scilab code Exa 7.4 Ex 4

```
clear;
clc;
funcprot(0);

//given data
Q = 0.1;//in m^3/s
N = 1200;//rotational speed in rev/min
beta2_ = 50;//in deg
D = 0.4;//impeller external diameter in m
d = 0.2;//impeller internal diameter in m
b2 = 31.7;//axial width in mm
eff = 0.515;//diffuser efficiency
H = 0.1;//head losses
De = 0.15;//diffuser exit diameter
A = 0.77;
B = 1;
g = 9.81;

//Calculations
U2 = %pi*N*D/60;
cr2 = Q/(%pi*D*b2/1000);
sigmaB = (A - H*tan(beta2_*%pi/180))/(B - H*tan(beta2_*%pi/180));
```

```
ctheta2 = sigmaB*U2*(1-H*tan(beta2_*%pi/180));
Hi = U2*ctheta2/g;
c2 = sqrt(cr2^2 + ctheta2^2);
c3 = 4*Q/(%pi*De^2);
HL = 0.1*Hi + 0.485*((c2^2)-(c3^2))/(2*g) + (c3^2)/(2*g);
H = Hi - HL;
eff_hyd = H/Hi;

//Results
printf('The slip factor = %.3f.',sigmaB);
printf('\n The manometric head = %.2f m.',H);
printf('\n The hydraulic efficiency = %.1f percentage.',eff_hyd*100);

//there is a very small error in the answer given in textbook
```

Scilab code Exa 7.5 Ex 5

```
clear;
clc;
funcprot(0);

//given data
T01 = 22;//stagnation temperature in degC
Z = 17;//number of vanes
N = 15000;//rotational speed in rev/min
r = 4.2;//stagnation pressure ratio between diffuser and impeller
eff_ov = 0.83;//overall efficiency
mdot = 2;//mass flow rate in kg/s
eff_m = 0.97;//mechanical efficiency
rho2 = 2;//air density at impeller outle in kg/m^3
gamma = 1.4;
```

```
R = 0.287;//in kJ/(kg.K)
b2 = 11;//axial width at the entrance to the diffuser in mm

//Calculations
Cp = gamma*R*1000/(gamma-1);
sigmaS = 1 - 2/Z;
U2 = sqrt(Cp*(T01+273)*((r)^((gamma-1)/gamma) -1)/(sigmaS*eff_ov));
omega = N*%pi/30;
rt = U2/omega;
Wdot_act = mdot*sigmaS*(U2^2)/(eff_m);
cr2 = mdot/(rho2*2*%pi*rt*b2/1000);
ctheta2 = sigmaS*U2;
c2 = sqrt(ctheta2^2 +cr2^2);
delW = sigmaS*U2^2;
T2 = T01+273+(delW - 0.5*c2^2)/Cp;
M2 =  c2/sqrt(gamma*R*1000*T2);

//Results
printf('The impeller tip radius = %.3f m',rt);
printf('\n The actual shaft power = %d kW',Wdot_act/1000);
printf('\n Absolute mach number, M2 = %.2f.',M2);
```

Scilab code Exa 7.6 Ex 6

```
clear;
clc;
funcprot(0);

//given data
N_R = 8.0;//non-dimensional length
Cp = 0.7;//from Figure 7.26
Ag = 2.8;//from Figure 7.26
```

```
//Calculations
Cp_id = 1-(1/Ag^2);
eff_d = Cp/Cp_id;
theta = (180/%pi)*atan((1/N_R)*(sqrt(Ag) -1));

//Results
printf('The efficiency of a conical low speed
   diffuser = %.3f',eff_d);
printf('\n The included angle of the cone = %.1f deg
   .',2*theta);
```

Chapter 8

Radial Flow Gas Turbines

Scilab code Exa 8.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
D2 = 23.76;//diameter of rotor in cm
N = 38140;//rotational speed in rev/min
alpha2 = 72;//absolute flow angle in deg
d = 0.5*D2;//rotor mean exit diameter

//Calcultaions
U2 = %pi*N*D2/(100*60);
w2 = U2/tan(alpha2*%pi/180);
c2 = U2*sin(alpha2*%pi/180);
w3 = 2*w2;
U3 = 0.5*U2;
c3 = sqrt(w3^2 - U3^2);
delW = 0.5*((U2^2 - U3^2)+(w3^2 - w2^2)+(c2^2 - c3
    ^2));
inp_U2 =  0.5*(U2^2 - U3^2)/delW;
inp_w2 = 0.5*(w3^2 - w2^2)/delW;
```

```
inp_c2 = 0.5*(c2^2 - c3^2)/delW;

//Results
printf('The fractional inputs from the three terms are, for the U^2 terms, %.3f; \n for the w^2 terms, %.3f; for the c^2 terms, %.3f.',inp_U2,inp_w2,inp_c2);

//there are errors in the answers given in textbook
```

Scilab code Exa 8.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data
r = 1.5;//operating pressure ratio
K1 = 1.44*10^-5;
K2 = 2410;
K3 = 4.59*10^-6;
T01 = 400;//in K
D2 = 72.5;//rotor inlet diamete in mm
D3_av = 34.4;//rotor meaan outlet diameter in mm
b = 20.1;//rotor outlet annulus width in mm
zetaN = 0.065;//enthalpy loss coefficient
alpha2 = 71;//in deg
beta3_av = 53;//in deg
Cp = 1005;//inJ/(kg.K)
gamma = 1.4;

//Calculations
N = K2*sqrt(T01);
U2 = %pi*N*D2/(60*1000)
delW = U2^2;
```

```
delh = Cp*T01*(1-(1/r)^((gamma-1)/gamma));
eff_ts = delW/(delh);
delW_act = K3*K2*%pi*T01/(30*K1);
eff_ov = delW_act/delh;
zetaR = (2*((1/eff_ts)-1) - (zetaN/sin(alpha2*%pi/180)))*((D2/D3_av)^2)*(sin(beta3_av*%pi/180))^2 - (cos(beta3_av*%pi/180))^2;
r3 = 0.5*(D3_av-b)*10^-3;
w3_w2av_min = (D3_av/D2)*tan(alpha2*%pi/180)*((2*r3/D3_av)^2 + (1/tan(beta3_av*%pi/180))^2)^0.5;
w3_w2av = (D3_av/D2)*tan(alpha2*%pi/180)*(1+((1/tan(beta3_av*%pi/180))^2))^0.5;

//Results
printf('The total-to-static efficiency = %.2f percentage.',eff_ts*100);
printf('\n The overall efficiency = %.2f percentage.',eff_ov*100);
printf('\n The rotor enthalpy loss coefficient = %.3f',zetaR);
printf('\n The rotor relative velocity ratio = %.2f',w3_w2av);


//there are small errors in the answers given in textbook
```

Scilab code Exa 8.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
Z = 12;//number of vanes
```

```
delW = 230;//in kW
T01 = 1050;//stagnation temperature in K
mdot = 1;//flow rate in kg/s
eff_ts = 0.81;//total-to-static efficiency
Cp = 1.1502;//in kJ/(kg.K)
gamma = 1.333;
R = 287;//gas constant

//Calculations
S = delW/(Cp*T01);
alpha2 = (180/%pi)*acos(sqrt(1/Z));
beta2 = 2*(90-alpha2);
p3_p01 = (1-(S/eff_ts))^(gamma/(1-gamma));
M02 = sqrt((S/(gamma-1))*((2*cos(beta2*%pi/180))/(1+cos(beta2*%pi/180))));
M2 = sqrt((M02^2)/(1-0.5*(gamma-1)*(M02^2)));
U2 = sqrt((gamma*R*T01)*(1/cos(beta2*%pi/180))*(S/(gamma-1)));

//Results
printf('(i) The absolut and relative flow angles:\n alpha2 = %.2f deg\n beta2 = %.2f deg',alpha2,beta2);
printf('\n (ii) The overall pressure ratio = %.3f',p3_p01);
printf('\n (iii) The rotor rip speed = %.1f m/s\n The inlet absolute Mach number = %.3f',U2,M2);


//there are small errors in the answers given in textbook
```

Scilab code Exa 8.4 Ex 4

```
clear;
```

```
clc;
funcprot(0);

//given data
cm3_U2 = 0.25;
nu = 0.4;
r3s_r2 = 0.7;
w3av_w2 = 2.0;

//Calculations
r3av_r3s = 0.5*(1+nu);
r3av_r2 = r3av_r3s*r3s_r2;
beta3_av = (180/%pi)*atan(r3av_r2/cm3_U2);
beta3s = (180/%pi)*atan(r3s_r2/cm3_U2);
w3s_w2 = 2*cos(beta3_av*%pi/180)/cos(beta3s*%pi/180)
    ;

//Results
printf('The relative velocity ratio = %.3f.',w3s_w2)
    ;
```

Scilab code Exa 8.5 Ex 5

```
clear;
clc;
funcprot(0);

//given data
Z = 12;//number of vanes
delW = 230;//in kW
T01 = 1050;//stagnation temperature in K
mdot = 1;//flow rate in kg/s
eff_ts = 0.81;//total-to-static efficiency
Cp = 1.1502;//in kJ/(kg.K)
gamma = 1.333;
```

```
R = 287;//gas constant
cm3_U2 = 0.25;
nu = 0.4;
r3s_r2 = 0.7;
w3av_w2 = 2.0;
p3 = 100;//static pressure at rotor exit in kPa
zetaN = 0.06;//nozzle enthalpy loss coefficient
U2 = 538.1;//in m/s
p01 = 3.109*10^5;//in Pa

//Calculations
S = delW/(Cp*T01);
T03 = T01*(1-S);
T3 = T03 - (cm3_U2^2)*(U2^2)/(2*Cp*1000);
r2 = sqrt(mdot/((p3*1000/(R*T3))*(cm3_U2)*U2*%pi*(
    r3s_r2^2)*(1-nu^2)));
D2 = 2*r2;
omega = U2/r2;
N = omega*30/%pi;
ctheta2 = S*Cp*1000*T01/U2;
alpha2 = (180/%pi)*acos(sqrt(1/Z));
cm2 = ctheta2/tan(alpha2*%pi/180);
c2 = ctheta2/sin(alpha2*%pi/180);
T2 = T01 - (c2^2)/(2*Cp*1000);
p2 = p01*(1-(((c2^2)*(1+zetaN))/(2*Cp*1000*T01)))^(
    gamma/(gamma-1));
b2_D2 = (0.25/%pi)*(R*T2/p2)*(mdot/(cm2*r2^2));

//Results
printf('(i) The diamaeter of the rotor = %.4f m\n
    its speed of rotation = %.1f rad/s (N = %d rev/
    min)',D2,omega,N);
printf('\n(ii) The vane width to diameter ratio at
    rotor inlet = %.4f',b2_D2);

//there are some errors in the answers given in
    textbook
```

Scilab code Exa 8.6 Ex 6

```
clear;
clc;
funcprot(0);

//given data
Z = 12;//number of vanes
delW = 230;//in kW
T01 = 1050;//stagnation temperature in K
mdot = 1;//flow rate in kg/s
eff_ts = 0.81;//total-to-static efficiency
Cp = 1.1502;//in kJ/(kg.K)
gamma = 1.333;
R = 287;//gas constant
cm3_U2 = 0.25;
nu = 0.4;
r3s_r2 = 0.7;
w3av_w2 = 2.0;
p3 = 100;//static pressure at rotor exit in kPa
zetaN = 0.06;//nozzle enthalpy loss coefficient
U2 = 538.1;//in m/s
p01 = 3.109*10^5;//in Pa

//results of Example 8.4 and Example 8.5
r3av_r3s = 0.5*(1+nu);
r3av_r2 = r3av_r3s*r3s_r2;
alpha2 = (180/%pi)*acos(sqrt(1/Z));
beta2 = 2*(90-alpha2);
beta3_av = (180/%pi)*atan(r3av_r2/cm3_U2);
beta3s = (180/%pi)*atan(r3s_r2/cm3_U2);
w3s_w2 = 2*cos(beta3_av*%pi/180)/cos(beta3s*%pi/180)
    ;
S = delW/(Cp*T01);
```

```
T03 = T01*(1-S);
T3 = T03 - (cm3_U2^2)*(U2^2)/(2*Cp*1000);
r2 = sqrt(mdot/((p3*1000/(R*T3))*(cm3_U2)*U2*%pi*(
    r3s_r2^2)*(1-nu^2)));
D2 = 2*r2;
omega = U2/r2;
N = omega*30/%pi;
ctheta2 = S*Cp*1000*T01/U2;
alpha2 = (180/%pi)*acos(sqrt(1/Z));
cm2 = ctheta2/tan(alpha2*%pi/180);
c2 = ctheta2/sin(alpha2*%pi/180);
T2 = T01 - (c2^2)/(2*Cp*1000);
p2 = p01*(1-(((c2^2)*(1+zetaN))/(2*Cp*1000*T01)))^(
    gamma/(gamma-1));
b2_D2 = (0.25/%pi)*(R*T2/p2)*(mdot/(cm2*r2^2));

//Calculations
c3 = cm3_U2*U2;
cm3 = c3;
w3_av = 2*cm3/(cos(beta2*%pi/180));
w2 = w3_av/2;
c0 = sqrt(2*delW*1000/eff_ts);
zetaR = (c0^2 *(1-eff_ts)- (c3^2)- zetaN*(c2^2))/(
    w3_av^2);

//Results
printf('The rotor enthalpy loss coefficient = %.4f',
    zetaR);

//there are some errors in the answers given in
    textbook
```

Chapter 9

Hydraulic Turbines

Scilab code Exa 9.1 Ex 1

```
clear;
clc;
funcprot(0);

//given data
Q = 2.272;//water volume flow rate in m^3/s
l = 300;//length in m
Hf = 20;//head loss in m
f = 0.01;//friction factor
g = 9.81;//acceleration due to gravity in m/s^2

//Calculations
d = (32*f*l*((Q/%pi)^2)/(g*Hf))^(1/5);

//Results
printf('The diameter of the pipe = %.4f m',d);
```

Scilab code Exa 9.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data
P = 4.0;//in MW
N = 375;//in rev/min
H_eps = 200;//in m
KN = 0.98;//nozzle velocity coefficient
d = 1.5;//in m
k = 0.15;//decrease in relative flow velocity across
    the buckets
alpha = 165;//in deg
g = 9.81;//in m/s^2
rho = 1000;//in kg/m^3

//Calculations
U = N*%pi*d*0.5/30;
c1 = KN*sqrt(2*g*H_eps);
nu = U/c1;
eff = 2*nu*(1-nu)*(1-(1-k)*cos(alpha*%pi/180));
Q = (P*10^6 /eff)/(rho*g*H_eps);
Aj = Q/(2*c1);
dj = sqrt(4*Aj/%pi);
omega_sp = (N*%pi/30)*sqrt((P*10^6)/rho)/((g*H_eps)
   ^(5/4));

//Results
printf('(i)The runner efficiency = %.4f',eff);
printf('\n (ii)The diameter of each jet = %.4f m',dj
   );
printf('\n (iii)The power specific speed = %.3f rad'
   ,omega_sp);
```

Scilab code Exa 9.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
H_eps = 150;//in m
z = 2;//in m
U2 = 35;//runner tip speed in m/s
c3 = 10.5;//meridonal velocity of water in m/s
c4 = 3.5;//velocity at exit in m/s
delHN = 6.0;//in m
delHR = 10.0;//in m
delHDT = 1.0;//in m
g = 9.81;//in m/s^2
Q = 20;//in m^3/s
omega_sp = 0.8;//specific speed of turbine in rad
c2 = 38.73;//in m/s

//Calculations
H3 = ((c4^2 - c3^2)/(2*g)) + delHDT - z;
H2 = H_eps-delHN-(c2^2)/(2*g);
delW = g*(H_eps-delHN-delHR-z)-0.5*c3^2 -g*H3;
ctheta2 = delW/U2;
alpha2 = (180/%pi)*atan(ctheta2/c3);
beta2 = (180/%pi)*atan((ctheta2-U2)/c3);
eff_H = delW/(g*H_eps);
omega = (omega_sp*(g*H_eps)^(5/4))/sqrt(Q*delW);
N = omega*30/%pi;
D2 = 2*U2/omega;

//Results
printf('\n(i)The specific work = %.1f m^2/s^2\n The hydraulic efficiency of the turbine = %.4f',delW,eff_H);
printf('\n(ii) The absolute velocity at runner entry, c2 = %.2f m/s',c2);
printf('\n(iii)The pressure head H3 relative to the trailrace = %.1f m\n The pressure head H2 at exit
```

```
from the runner = %.2f m',H3,H2);
printf('\n(iv)The absolute and relative flow angles at runner inlet :\n alpha2 = %.1f deg\n beta2 = %.2f deg',alpha2,beta2);
printf('\n(v)The speed of rotation , N = %d rev/min',N);
printf('\n The runner diameter is , D2 = %.3f m',D2);


//there are small errors in the answers given in textbook
```

Scilab code Exa 9.4 Ex 4

```
clear;
clc;
funcprot(0);

//function to calculate flow angles
function [alpha2,beta2,beta3] =fun(r,N,cx2,ctheta2)
    alpha2 = (180/%pi)*atan(ctheta2/cx2);
    beta2 = (180/%pi)*atan((U2)*(r)/cx2 - tan(alpha2*%pi/180));
    beta3 = (180/%pi)*atan((U2)*r/cx2) ;
endfunction

//given data
P = 8;//output power in MW
HE = 13.4;//available head at entry in m
N = 200;//in rev/min
L = 1.6;//length of inlet guide vanes
d1 = 3.1;//diameter of trailing edge in m
D2t = 2.9;//runner diameter in m
nu = 0.4;//hub-tip ratio
eff = 0.92;//hydraulic efficiency
```

```
rho = 1000;//density in kg/m^3
g = 9.81;//acceleration due to gravity in m/s^2

//Calculations
Q = P*10^6 /(eff*rho*g*HE);
cr1 = Q/(2*%pi*0.5*d1*L);
cx2 = 4*Q/(%pi*D2t^2 *(1-nu^2));
U2 = N*(%pi/30)*D2t/2;
ctheta2 = eff*g*HE/U2;
ctheta1 = ctheta2*(D2t/d1);
alpha1 = (180/%pi)*atan(ctheta1/cr1);

//calculating flow angle for diffrent radii
[alpha21,beta21,beta31] = fun(1.0,U2,cx2,ctheta2);
[alpha22,beta22,beta32] = fun(0.7,U2,cx2,ctheta2
   /0.7);
[alpha23,beta23,beta33] = fun(0.4,U2,cx2,ctheta2
   /0.4);

//Results
printf('Calculated values of flow angles:\n
   Parameter                                   Ratio of r
   /ri                 ');
printf('\n
   -----------------------------------------------------------------
   ');
printf('\n                                   0.4               0.7
                      1.0');
printf('\n
   ------------------------------------------');
printf('\n ctheta2(in m/s)        %.3f            %.3f
                  %.3f',ctheta2/0.4,ctheta2/0.7,ctheta2
   /1.0);
printf('\n tan(alpha2)            %.3f            %.4f
                 %.3f',tan(alpha23*%pi/180),tan(alpha22
   *%pi/180),tan(alpha21*%pi/180));
printf('\n alpha2(deg)            %.2f            %.2f
                  %.2f',alpha23,alpha22,alpha21);
```

```
printf('\n U/cx2                        %.3f              %.4f
                 %.3f',(U2/cx2)*0.4,(U2/cx2)*0.7,(U2/
   cx2)*1.0);
printf('\n beta2(deg)                   %.2f              %.2f
                  %.2f',beta23,beta22,beta21);
printf('\n beta3(deg)                   %.2f              %.2f
                  %.2f',beta33,beta32,beta31);
printf('\n
   ___________________________________________________________
   ');
```

Scilab code Exa 9.5 Ex 5

```
clear;
clc;
funcprot(0);

//given data
k = 1/5;//scale ratio
Pm = 3;//in kW
Hm = 1.8;//in m
Nm = 360;//in rev/min
Qm = 0.215;//in m^3/s
Hp = 60;//in m
n = 0.25;
rho = 1000;//in kg/m^3
g = 9.81;//in m/s^2

//Calculations
Np = Nm*k*(Hp/Hm)^0.5;
Qp = Qm*(Nm/Np)*(1/k)^3;
Pp = Pm*((Np/Nm)^3)*(1/k)^5;
eff_m = Pm*1000/(rho*Qm*g*Hm);
eff_p = 1 - (1-eff_m)*0.2^n;
Pp_corrected = Pp*eff_p/eff_m;
```

```

//Results
printf('The speed = %.1f rev/min.',Np);
printf('\n The flow rate = %.2f m^3/s.',Qp);
printf('\n Power of the full-scale = %.2f MW.',Pp/1000);
printf('\n The efficiency of the model turbine = %.2f.',eff_m);
printf('\n The efficiency of the prototype = %.4f.',eff_p);
printf('\n The power of the full-size turbine = %.1f MW.',Pp_corrected/1000);

//there are errors in the answer given in textbook
```

Scilab code Exa 9.6 Ex 6

```
clear;
clc;
funcprot(0);

//given data
//data from EXAMPLE 9.3
H_eps = 150;//in m
z = 2;//in m
U2 = 35;//runner tip speed in m/s
c3 = 10.5;//meridonal velocity of water in m/s
c4 = 3.5;//velocity at exit in m/s
delHN = 6.0;//in m
delHR = 10.0;//in m
delHDT = 1.0;//in m
g = 9.81;//in m/s^2
Q = 20;//in m^3/s
omega_sp = 0.8;//specific speed of turbine in rad
c2 = 38.73;//in m/s
```

```

//data from this example
Pa = 1.013;//atmospheric pressure in bar
Tw = 25;//temperature of water in degC
Pv = 0.03166;//vapor pressure of water at Tw
rho = 1000;//density of wate in kg/m^3
g = 9.81;//acceleration due to gravity in m/s^2

H3 = ((c4^2 - c3^2)/(2*g)) + delHDT - z;
H2 = H_eps-delHN-(c2^2)/(2*g);
delW = g*(H_eps-delHN-delHR-z)-0.5*c3^2 -g*H3;
ctheta2 = delW/U2;
alpha2 = (180/%pi)*atan(ctheta2/c3);
beta2 = (180/%pi)*atan((ctheta2-U2)/c3);
eff_H = delW/(g*H_eps);
omega = (omega_sp*(g*H_eps)^(5/4))/sqrt(Q*delW);

Hs = (Pa-Pv)*(10^5)/(rho*g) - z;
sigma = Hs/H_eps;
omega_ss = omega*(Q^0.5)/(g*Hs)^(3/4);

//Results
printf('The NSPH for the turbine = %.3f m.',Hs);
if omega_ss>4.0 then
    printf('\n Since the suction specific speed (= %.4f.) is greater than 4.0(rad), the cavitation is likely to occur.',omega_ss);
end

//there is small error in the answer given in textbook
```

Scilab code Exa 9.7 Ex 7

```
clear;
```

```
clc;
funcprot(0);

//given data
P = 600;//power in kW
Cp = 0.3;//power coefficient
D = 16;//diameter in m
rho = 1025;//density in kg/m^3

//Calculations
cx1 = ((P*1000)/(0.5*rho*0.25*%pi*(D^2)*Cp))^(1/3);
Ut = (14/30)*%pi*0.5*D;
J = Ut/cx1;

//Results
printf('The minimum flow speed of the water = %.2f m/s.',cx1);
printf('\n The blade tip-speed ratio (when full power is reached) = %.2f',J);
```

Chapter 10

Wind Turbines

Scilab code Exa 10.2 Ex 2

```
clear;
clc;
funcprot(0);

//given data
a_ = 1/3;

//Calculations
R2_R1 = 1/(1-a_)^0.5;
R3_R1 = 1/(1-2*a_)^0.5;
R3_R2 = ((1-a_)/(1-2*a_))^0.5;

//Results
printf('R2/R1 = %.3f\n R3/R1 = %.3f\n R3/R2 = %.3f',
   R2_R1,R3_R1,R3_R2);
```

Scilab code Exa 10.3 Ex 3

```
clear;
clc;
funcprot(0);

//given data
d = 30;//tip diameter in m
cx1 = 7.5;//in m/s
cx2 = 10;//in m/s
rho = 1.2;//in kg/m^3
a_ = 1/3;

//Calculations
P1 = 2*a_*rho*(%pi*0.25*d^2)*(cx1^3)*(1-a_)^2;
P2 = 2*a_*rho*(%pi*0.25*d^2)*(cx2^3)*(1-a_)^2;


//Results
printf('(i)With cx1 = %.1f m/s, P = %d kW.',cx1,P1
    /1000);
printf('\n(ii)With cx1 = %d m/s, P = %.1f kW.',cx2,
    P2/1000);
```

Scilab code Exa 10.4 Ex 4

```
clear;
clc;
funcprot(0);

//given data
P = 20;//power required in kW
cx1 = 7.5;//steady wind speed in m/s
rho = 1.2;//density in kg/m^3
Cp = 0.35;
eta_g = 0.75;//output electrical power
eff_d = 0.85;//electrical generation efficiency
```

```
//Calculations
A2 = 2*P*1000/(rho*Cp*eta_g*eff_d*cx1^3);
D2 = sqrt(4*A2/%pi);

//Results
printf('The diameter = %.1f m.',D2);
```

Scilab code Exa 10.5 Ex 5

```
clear;
clc;
funcprot(0);

//given data
Z = 3;//number of blades
D = 30;//rotor diameter in m
J = 5.0;//tip-speed ratio
l = 1.0;//blade chord in m
r_R = 0.9;//ratio
beta = 2;//pitch angle in deg

//Calculations
//iterating to get values of induction factors
a = 0.0001;//inital guess
a_ = 0.0001;//inital guess
a_new = 0.0002;//inital guess
i = 0;
while (a_~=a_new)
   phi = (180/%pi)*atan((1/(r_R*J))*((1-a)/(1-a_)));
   alpha = phi-beta;
   CL = 0.1*alpha;
   lamda = (Z*l*CL)/(8*%pi*0.5*r_R*D);
   a = 1/(1+(1/lamda)*sin(phi*%pi/180)*tan(phi*%pi
      /180));
```

```
    a_new = 1/((1/lamda)*cos(phi*%pi/180) -1);
    if a_ < a_new
        a_ = a_ + 0.0001;
    elseif a_ > a_new
        a_ = a_ - 0.0001;
    end
    if (abs((a_-a_new)/a_new) < 0.1) then
        break;
    end
    i = i+1;
end

//Results
printf('Axial induction factor, a = %.4f',a);
printf('\n Tangential induction factor = %.5f',a_new);
printf('\n phi = %.3f deg.',phi);
printf('\n Lift coefficient = %.3f.',CL);

//The answers given in textbook are wrong
```

Scilab code Exa 10.6 Ex 6

```
clear;
clc;
funcprot(0);

//given data
D = 30;//tip diameter in m
CL = 0.8;//lift coefficient
J = 5.0;
l = 1.0;//chord length in m
Z = 3;//number of blades
r_R = [0.2 0.3 0.4 0.6 0.8 0.9 0.95 1.0];
n = 8;
```

```
//Calculations
//iterating to get values of induction factors
a = 0.1;//inital guess
anew = 0;
a_ = 0.006;//inital guess
a_new = 0.0;//inital guess
for i = 1:n
    while (a_~=a_new)
        lamda = (Z*l*CL)/(8*%pi*0.5*r_R(i)*D);
        phi = (180/%pi)*atan((1/(r_R(i)*J))*((1-a)/(1-a_)));
        a = 1/(1+(1/lamda)*sin(phi*%pi/180)*tan(phi*%pi/180));
        a_new = 1/((1/lamda)*cos(phi*%pi/180) -1);
        alpha = CL/0.1;
        beta = phi-alpha;
        if a_ < a_new
            a_ = a_ + 0.0001;
        elseif a_ > a_new
            a_ = a_ - 0.0001;
        end
        if (abs((a_-a_new)/a_new) < 0.01) then
            break;
        end
    end
    p(i) = phi;b(i) = beta;a1(i) = a;a2(i) = a_new;
end

//Results
printf('Summary of results of iterations (N.B. CL = 0.8 along the span)');
printf('\n --------------------------------------------------------------------------------------------------------');
printf('\n r/R      %.1f      %.1f       %.1f      %.1f      %.1f      %.1f      %.2f       %.1f  ',r_R(1),r_R(2),r_R(3),r_R(4),r_R(5),r_R(6),r_R(7),r_R(8));
```

```
printf('\n --------------------------------------------------------------------------------');
printf('\n phi     %.2f     %.2f     %.2f     %.2f     %.2f    %.2f    %.2f      %.3f',p(1),p(2),p(3),p(4),p(5),p(6),p(7),p(8));
printf('\n beta    %.2f     %.2f     %.2f     %.2f      %.2f     %.2f     %.2f      %.2f',b(1),b(2),b(3),b(4),b(5),b(6),b(7),b(8));
printf('\n a       %.4f   %.5f   %.5f   %.4f   %.4f    %.4f     %.4f     %.4f',a1(1),a1(2),a1(3),a1(4),a1(5),a1(6),a1(7),a1(8));
printf('\n a`      %.5f   %.5f   %.5f   %.5f   %.5f    %.5f   %.5f   %.5f',a2(1),a2(2),a2(3),a2(4),a2(5),a2(6),a2(7),a2(8));
printf('\n --------------------------------------------------------------------------------');

//there are some errors in the answers given in textbook
```

Scilab code Exa 10.7 Ex 7

```
clear;
clc;
funcprot(0);

//given data
//data from Exampla 10.5
Z = 3;//number of blades
D = 30;//rotor diameter in m
J = 5.0;//tip-speed ratio
l = 1.0;//blade chord in m
beta = 2;//pitch angle in deg
```

```
omega = 2.5;//in rad/s

rho = 1.2;//density in kg/m^3
cx1 = 7.5;//in m/s
sum_var1 = 6.9682;//from Table 10.3
sum_var2 = 47.509*10^-3;//from Table 10.4

//Calculations
X = sum_var1*0.5*rho*Z*l*0.5*D*cx1^2;
tau = sum_var2*0.5*rho*Z*l*(omega^2)*(0.5*D)^4;
P = tau*omega;
A2 = 0.25*%pi*D^2;
P0 = 0.5*rho*A2*cx1^3;
Cp = P/P0;
zeta = (27/16)*Cp;

//Results
printf('The total axial force = %d N.',X);
printf('\n The torque = %.3f *10^3 Nm.',tau/1000);
printf('\n The power developed = %.3f kW.',P/1000);
printf('\n The power coefficient = %.3f',Cp);
printf('\n The relative power coefficient = %.3f',
   zeta);
```

Scilab code Exa 10.8 Ex 8

```
clear;
clc;
funcprot(0);

//given data
X = 10583;//in N
D = 30;//rotor diameter in m
Cx = X/23856;
rho = 1.2;//density in kg/m^3
```

```
cx1 = 7.5;//in m/s

//sloving quadratic eqaution
a = 0;//inital guess
res = 1;
i = 0;
while (res~=0)
    res = a*(1-a) - Cx/4;
    if (res>0) then
        a = a-0.001;
    elseif (res<0)
        a = a+0.001;
    end
    if abs(res)<0.0001
        break;
    end
end
A2 = 0.25*%pi*D^2
P = 2*rho*A2*(cx1^3)*a*(1-a)^2;

//Results
printf('P = %.3f kW.',P/1000);

//there is small error in the answer given in
   textbook
```

Scilab code Exa 10.9 Ex 9

```
clear;
clc;
funcprot(0);

//given data
//data from Exampla 10.5
Z = 3;//number of blades
```

```
D = 30;//rotor diameter in m
J = 5.0;//tip-speed ratio
l = 1.0;//blade chord in m
beta = 1.59;//pitch angle in deg
omega = 2.5;//in rad/s
rho = 1.2;//density in kg/m^3
cx1 = 7.5;//in m/s
c1 = 1518.8;//from Ex 10.6
c2 = 0.5695*10^6;
P0 = 178.96;//Power developed in kW from Ex 10.7
X1 = 10582;//Total axial force in N from Ex 10.7
Cp1 = 0.378;//Power coefficient from Ex 10.7
zeta1 = 0.638;//rekative power coefficient from Ex 10.7

//Calculations
r_R = 0.25:0.1:0.95;
b = [28.4;19.49;13.80;9.90;7.017;4.900;3.00;1.59];
//b = [27.2985;17.8137;11.8231;7.8176;4.9972;3.0511;1.6476;1.59];

for j = 1:8
    i = 1;
    atemp = 0; a_temp = 0;
    while i>0,        i = i+1;
        f = (2/%pi)*acos(exp(-0.5*Z*(1-r_R(j))*(1+J^2)^0.5));
        phi = (180/%pi)*atan((1/(J*r_R(j)))*((1-atemp)/(1+a_temp)));
        CL = (phi-b(j))/10;
        lamda = f/(63.32/CL);
        anew = (lamda*cos(phi*%pi/180)/(lamda*cos(phi*%pi/180)+f*(sin(phi*%pi/180))^2));
        if atemp<anew then
            atemp = atemp+0.0001;
        elseif atemp>anew
            atemp = atemp-0.0001;
        end
```

```
        if (abs((atemp-anew)/anew) < 0.001) then
            break;
        end
    end
    F(j) = f;
    ph(j) = phi;
    cl(j) = CL;
    a(j) = anew;
    Var1(j) = ((1-anew)/sin(phi*%pi/180))^2 *cos(phi*%pi/180)*CL*0.1;
//    a_(j) = lamda/(F*cos(phi*%pi/180)-lamda);
//printf('r_R = %.2f, F = %.4f, a = %.4f, phi = %.4f\n',r_R(j),F(j),a(j),ph(j));
end

for k = 1:8
    lam(k) = F(k)*cl(k)/63.32;
    a_new(k) = lam(k)/(F(k)*cos(ph(k)*%pi/180)-lam(k));
    Var2(k) = ((1+a_new(k))/cos(phi*%pi/180))^2 *(r_R(k))^3 *cl(k)*sin(ph(k)*%pi/180)*0.1;
end
X = c1*sum(Var1(1:8));
sum_Var2 = 40.707*10^-3;
tau = c2*sum(Var2(1:8));
P = tau*omega;
Cp = P/(P0*1000);
zeta = (26/17)*Cp;

//Results
printf('                    Summary of Results:');
printf('\n--------------------------------------------------------------------------------');
printf('\n                                   Axial force, kN          Power, kW                  Cp              zeta');
printf('\n
```

```
    ----------------------------------------------------------------------------------
    ');
printf('\n Without tip correction           %.3f
                  %.2f                  %.3f                  %
    .3f',X1/1000,P0*Cp1,Cp1,zeta1);
printf('\n With tip correction              %.3f
                  %.2f                  %.3f
    %.3f',X/1000,P/1000,Cp,zeta);
printf('\n
    ----------------------------------------------------------------------------------
    ');

//There are errors in the answers given in textbook
```

Scilab code Exa 10.10 Ex 10

```
clear;
clc;
funcprot(0);

//function to calculate values of blade chord and
    radius (optimum conditions)
function [j,lamda,r,l] = fun(phi)
    lamda = 1-cos(phi*%pi/180);
    j = sin(phi*%pi/180)*(2*cos(phi*%pi/180)-1)
        /(1+2*cos(phi*%pi/180))/(lamda);
    r = 3*j;
    l = 8*%pi*j*lamda;
endfunction

//given data
D = 30;//tip diameter in m
J = 5.0;//tip-speed ratio
Z = 3;//in m
CL = 1.0;
```

```
//Calculations
phi1 = 30;//in deg
phi2 = 20;//in deg
phi3 = 15;//in deg
phi4 = 10;//in deg
phi5 = 7.556;//in deg
//Values of blade chord and radius (optimum conditions)
[j1,lamda1,r1,l1] = fun(phi1);
[j2,lamda2,r2,l2] = fun(phi2);
[j3,lamda3,r3,l3] = fun(phi3);
[j4,lamda4,r4,l4] = fun(phi4);
[j5,lamda5,r5,l5] = fun(phi5);

printf('Values of blade chord and radius(optimum conditions):');
printf('\n---------------------------------------------------------------------------');
printf('\n phi(deg)        j              4flamda              r(m)              l(m)');
printf('\n---------------------------------------------------------------------------');
printf('\n %d          %.2f                  %.3f             %.1f                  %.3f',phi1,j1,4*j1*lamda1,r1,l1);
printf('\n %d          %.2f                  %.3f             %.2f                 %.3f',phi2,j2,4*j2*lamda2,r2,l2);
printf('\n %d          %.2f                  %.3f             %.2f                 %.3f',phi3,j3,4*j3*lamda3,r3,l3);
printf('\n %d          %.3f                  %.4f           %.1f                %.3f',phi4,j4,4*j4*lamda4,r4,l4);
printf('\n %.3f          %d                  %.4f           %d                 %.3f',phi5,ceil(j5),4*j5*lamda5,ceil(r5),l5);
printf('\n
```

```
--------------------------------------------------------------------------------
');

l_R = [l1,l2,l3,l4,l5]/(0.5*D);
r_R = [r1,r2,r3,r4,r5]/(0.5*D);
plot(r_R,l_R);
xlabel("r/R",'fontsize',3);
ylabel("l/R",'fontsize',3);
title("Optimal variation of chord length with radius
    ",'fontsize',3);

//there are very small errors in the ansers given in
    textbook
```