Fluid Mechanics and Its Applications

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Fundamentals of Turbomachines

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Erik Dick
Department of Flow, Heat and Combustion
Mechanics
Ghent University
Gent
Belgium

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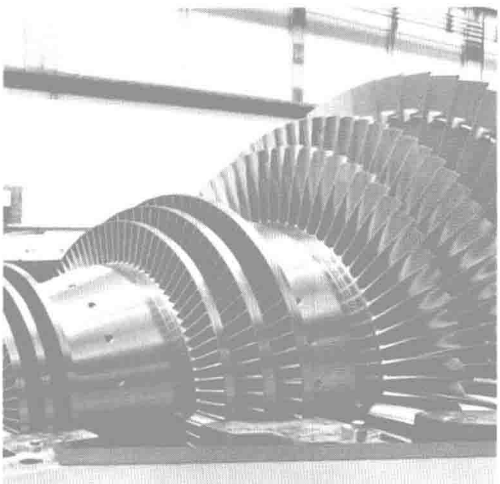
Preface



This book is the English language version of a course on turbomachines, taught in Dutch by the author at Ghent University from 1992 to 2013. It was composed at the occasion of the change to English as teaching language in master programmes in engineering, starting with the academic year 2013–2014. Meanwhile, the text was adapted to include some modern evolutions in the field of turbomachinery, however avoiding advanced topics, since the objective of the book is to teach fundamentals of turbomachines.

In the first chapter, the basic equations of fluid mechanics and thermodynamics are derived from first principles, formulated for application to turbomachines. With this chapter, the necessary prior knowledge for the study of turbomachines is refreshed. The prior knowledge needed is basic fluid mechanics and basic technical thermodynamics. For fluid mechanics, this comprises topics such as mechanical properties of fluids, fluid statics, equations of flow in integral and differential form, dimensional analysis and internal laminar and turbulent flow of constant density fluids. For technical thermodynamics, the supposed prior knowledge encompasses thermal properties of fluids, first law and second law of thermodynamics, basic heat engine cycles, gas mixtures, combustion and detailed analysis of steam cycles.

The course on turbomachines is taught at Ghent University in two parts. Chapters 1–10 form a first part, taught to all master students in electromechanical engineering. This part requires basic knowledge of flow past profiles, boundary layer flow and high speed flow of compressible fluids, which are topics often covered in an advanced fluid mechanics course. The necessary fundamentals of these topics are explained in the beginning of Chap. 2 and in Chap. 4. The second part is Chaps. 11–15, taught to students with specialisation in mechanical energy engineering. This part requires somewhat more advanced knowledge of fluid mechanics. Relevant topics are transition, turbulence and heat transfer in boundary layer flows and shock and expansion phenomena in high speed flows of compressible fluids. However, care has been taken not to rely too much on prior knowledge of these topics.

The objective of the book is, as already said, study of the fundamentals of turbomachines. The approach is analysis of all kinds of turbomachines with the same theoretical framework. Basic equations are formulated for a general equation of state of a fluid. Specification of constant density or ideal gas is only done when analysing particular machines. The building up of theory is mixed in the sense that first derivations are general, but that elaboration of the theoretical concepts is done on a particular machine, however taking into account the possibility for reuse on other machines or generalisation from constant density formulation to variable density formulation. The analysis starts with radial and axial fans, because these machines are the simplest ones. The next machines are steam turbines. The order of treating the different types of turbomachines is governed by the possibility of gradually building up the theoretical concepts. For each of the machine types, a balance is sought between fundamental understanding and acquiring knowledge of practical aspects. The main concern is always fundamental understanding and bringing the reader to independent reasoning. The point of view taken by the author is that readers should be able to understand what they see when a turbomachine is opened. They should also be able to make a reasoned choice of a turbomachine for a specific application and understand its operation. Design is not a primary objective. Design requires a more specialised study, although basic design of the simplest turbomachines such as a centrifugal fan, an axial steam turbine or a centrifugal pump is possible with the topics covered in the book.

Ghent, September 2014 Erik Dick

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The following companies kindly provided figures.

For fans: ebm-papst; Fläkt Woods; TLT-Turbo.

For pumps: ANDRITZ; Flygt (a Xylem company); Grundfos; Johnson Pump (SPX Flow Technology); Klaus Union; Sulzer; Sundyne; Wilo.

For steam turbines: Alstom; MAN Diesel &Turbo; Siemens Energy.

For hydraulic turbines: ANDRITZ HYDRO.

For wind turbines: ENERCON; Vestas.

For power gas turbines: Mitsubishi-Hitachi Power Systems; Siemens Energy.

For aero gas turbines: GE Aviation; Rolls-Royce.

For radial compressors, radial turbines and turbochargers: ABB Turbo Systems; Dresser-Rand; KBB Kompressorenbau Bannewitz; MAN Diesel &Turbo.

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Author Biography

Erik Dick was born on December 10, 1950 in Torhout, Belgium. He obtained a M.Sc. in electromechanical engineering from Ghent University in 1973 and a Ph.D. in computational fluid dynamics in 1980. From 1973 he worked as researcher and became full professor of mechanical engineering at Ghent University in 1995, where he teaches turbomachines and computational fluid dynamics. His area of research is computational methods and turbulence and transition models for flow problems in mechanical engineering. He is author or co-author of about 125 papers in international scientific journals and about 250 papers at international conferences. He is the recipient of the 1990 Iwan Akerman award for fluid machinery of the Belgian National Science Foundation.

List of Symbols

a		acceleration	m/s^2
	or	axial interference factor	–
A		through-flow section area	m^2
b		rotor width in axial direction	m
	or	tangential interference factor	–
	or	bypass ratio	–
c		chord	m
	or	velocity of sound	m/s
c_a		axial chord	m
C_D		drag coefficient	–
c_f		friction coefficient	–
Cf		centrifugal force by rotor rotation	N/kg
C_{Fu}		tangential force coefficient	–
C_L		lift coefficient	
C_M		Pfleiderer moment coefficient (3.30)	–
Co		Coriolis force by rotor rotation	N/kg
c_p		differential specific heat at constant pressure	J/kgK
C_p		pressure coefficient	–
	or	integral specific heat at constant pressure	J/kgK
C_P		power coefficient	–
C_T		thrust coefficient	–
Cu		centrifugal force by curvature	N/kg
d		diameter	m
D		drag per unit of span	N/m
DF		diffusion factor	–
D_{loc}		local diffusion factor	–
D_s		specific diameter (7.7)	–
e		internal energy per unit of mass	J/kg
E_k		kinetic energy per unit of mass	J/kg

E_m		mechanical energy per unit of mass	J/kg
E_p		pressure energy per unit of mass	J/kg
f		force per unit of mass	N/kg
	or	friction factor (2.30)	–
	or	fuel-air ratio	–
f_R		curvature factor (3.26)	–
g		gravitational force per unit of mass	N/kg
h		enthalpy	J/kg
	or	blade height or scroll height	m
H_m		manometric head	m
I		rothalpy	J/kg
k		equivalent sand-grain roughness	m
L		lift per unit of span	N/m
$\dot{m}$		mass flow rate	kg/s
M		rotor moment	Nm
M_d		disc or wheel friction moment	Nm
M_{shaft}		shaft moment	Nm
M_{st}		static moment of meridional section	m^3
$NPSH$		net positive suction head (8.5)	–
n		polytropic exponent	
$\vec{n}$		unit normal	–
p		pressure	Pa
P		power	W
Pf		Pfleiderer factor (3.23)	m^3
q		heat transferred per unit of mass	J/kg
	or	dynamic pressure	Pa
q_{irr}		heat by dissipation inside flow path	J/kg
q_{irr}^0		heat by dissipation outside flow path	J/kg
Q		volume flow rate	m^3/s
	or	heat transferred per unit of time	J/s=W
r		radius	m
	or	pressure ratio	–
R		kinematic degree of reaction	–
	or	radius of curvature	m
	or	gas constant	J/kgK
Re		Reynolds number	–
R_p		pressure degree of reaction (3.1)	–
R_s		isentropic degree of reaction (6.16)	–
s		entropy	J/kgK
	or	spacing of blades	m

S		surface area	m^2
t		time	s
	or	thickness of blades	m
T		temperature	K or °C
	or	thrust force	N
u		blade speed (radius x rotational speed)	m/s
U		gravitational potential energy	m/s
v_0		inflow velocity	m/s
v_e		energy reference velocity	m/s
w		flow velocity in relative frame	m/s
W		work per unit of time	J/s = W
x		coordinate along streamline	m
	or	coordinate in axial direction	m
y		coordinate perpendicular to streamline	m
	or	coordinate in circumferential direction	m
z		coordinate in vertical direction	m
	or	coordinate in radial direction	m
Z		number of blades	–
α		angle of absolute velocity w.r.t. meridional plane	°
β		angle of relative velocity w.r.t. meridional plane	°
Γ		circulation along a contour	m^2/s
δ		boundary layer thickness	m
ΔW		rotor work per unit of mass	J/kg
ε		Pfleiderer work reduction factor (3.23)	–
η_i		internal efficiency	–
η_m		mechanical efficiency	–
η_p		polytropic efficiency	–
	or	propulsive efficiency (12.7)	
η_s		isentropic efficiency	–
η_{sre}		isentropic re-expansion efficiency (11.7)	–
η_t		thermal efficiency (12.9)	–
η_{td}		thermodynamic efficiency (12.9)	–
η_{tt}		total-to-total isentropic efficiency	–
η_v		volumetric efficiency	
η_∞		infinitesimal efficiency	–
θ		angular coordinate	rad
	or	flow turning angle	rad
κ		heat transfer coefficient (11.18)	J/kJK
λ		speed ratio (u/v_0)	–

	or	coefficient in Pfleiderer factor Pf	–
μ		dynamic viscosity	Pas
$\mathbf{v}$		kinematic viscosity	Pas
ξ		pressure loss coefficient	–
ρ		density	kg/m^3
σ		solidity c/s	–
	or	Stodola slip factor (3.20)	–
	or	cavitation number(8.1)	–
σ_a		axial solidity c_a/s	–
σ_M		moment solidity (3.31)	–
τ		shear stress	N/m^3
	or	obstruction factor (Fig. 3.16)	–
ϕ		flow coefficient v_a/u or v_{2r}/u_2	–
Φ		flow factor (7.4)	–
ψ		work coefficient $\Delta W/u_2^2$	–
Ψ		head factor (7.5)	–
ψ_0		rotor total pressure coefficient	–
ψ_r		rotor static pressure coefficient	–
ω		rotor of relative velocity	m^2/s
	or	enthalpy loss coefficient	–
Ω		rotational speed	rad/s
Ω_s		specific speed (7.6)	–
Ω_{ss}		suction specific speed (8.14)	–

Subscripts

0		inlet of machine or installation	
	or	total state	
1		just upstream of rotor	
1b		just downstream of rotor inlet	
2		just downstream of rotor	
2b		just upstream of rotor outlet	
3		outlet of machine or installation	
∞		far away from object	
	or	with infinite number of blades	

	or	on infinitesimal flow path	
a		in axial direction	
c		compressor	
	or	critical or choking value	
d		discharge/delivery side	
def		deflection	
dyn		dynamic value	(12.6–12.7)
gas		gas value	(12.6–12.7)
id		ideal	
irr		due to irreversibility	
m		in meridional direction	
	or	mechanical or manometric or mean	
mean		mean value	
o		optimum	
p		pressure side	
prop		propulsive value	(12.6–12.7)
r		in radial direction or in relative frame	
	or	rotor or reversible	
s		suction side or stator	
	or	isentropic	
ss		isentropic for stator	
sr		isentropic for rotor	
sre		isentropic re-expansion value	
t		theoretical value	
	or	turbine	
T		tip value	
tt		total-to-total isentropic	
u		in circumferential direction	

Superscripts

*		design value
	or	choking value
–		average
→		vector quantity
b		blade value

Contents