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Turbo-Machinery Dynamics

DESIGN and OPERATION

✔ Turbine characteristics and operating features

A. S. Rangwala

TURBO-MACHINERY DYNAMICS

Design and Operation

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Gas Turbine Consulting Engineer

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FOREWORD

Dynamic analysis of rotating machinery has come a long way since Professor Stephen Timoshenko considered the case of a uniform shaft with a disk at each end in his first technical paper "O Yavleniyakh Rezonansa v Valakh (On Resonance Phenomena in Shafts)" in the *Bulletin of the Polytechnical Institute* of St. Petersburg. Modern turbo-machines have a large number of compressor and turbine blades. The design of turbo-machinery airfoils is far more complicated due to the complex configuration. The shape of the airfoils is designed from aerodynamics consideration, but the blades must structurally withstand constant changes in the loads imposed by the flow of fluids over its surface.

When Abdulla S. Rangwala came to America in 1967 as a student he was influenced by the works of Professors S. Timoshenko and J. den Hartog, using Lord Rayleigh's method for resolving vibration problems in engineering. His first job was with the Large Steam Turbines Department of General Electric Company in Schenectady, New York. His initial practical experience was with calculating fundamental periods of torsional and flexural vibrations of turbine rotor and journal bearing systems and in balancing of disks and rotors. At GE's Aircraft Engines Group he gradually shifted his attention to the design and evaluation of compressor and turbine components. The experience with practical problems has culminated in his writing of *Turbo-machinery Dynamics—Design and Operation*. The book represents a unique compilation of a large number of topics in an organized manner that is closely associated with the design and evaluation of turbo-machinery. The author presents the latest technical developments in the areas of engineering, manufacturing, and operation for turbine engineers.

With the advent of computers, many important developments in the design and development of turbo-machinery have occurred. Though computers do not fundamentally change the principles of fluid flow and structural vibration mechanics, they greatly influence the choice of methods of calculation that are most attractive. To uphold the technical excellence and unique appeal while keeping pace with new developments in the field is no small responsibility, and the author is to be commended for his fine work.

MARK BELLONI
Brewster, Ohio

PREFACE

Considerable interest in the application of the theory of structural dynamics to the design of compressors, steam and gas turbines, and pumps has existed for several years. The need for a comprehensive textbook on the dynamics of the rotating and stationary blades and vanes and the associated disks and shafts incorporating the most recent developments of the subject has been strongly felt for a long time.

Since the advent of the earliest water-driven power saw mills, problems of deformed and broken turbine blades, shafts, and bearings have plagued the operators and manufacturers of the machines. Problems associated with the relative motion between the rotating and stationary parts and lubrication were so extensive that little effort was expended in understanding the impact of material fatigue, elevated temperature, and load cycling on the dynamic characteristics of the airfoils. Although very extensive research has been done and a great number of publications exist on the subject, little effort has been made to put together—in one concise publication—topics such as conceptual design, fluid flow, structural dynamic analysis, design optimization, vibration measurement, and dynamic balance. Numerous other topics closely related to operation, manufacturing, and materials selection of turbo-machinery components and system have been covered extensively. Special emphasis is placed on computer simulation using finite element methods, correlation of analysis with experimental test results, and procedures to improve performance efficiency and structural integrity.

The basic premise in the operation of all turbo-machines calls for an interaction between the fluid media flowing over the surfaces of the stationary and rotating airfoils. Hence, the aerodynamic and structural dynamic characteristics of the airfoils are closely intertwined. The overall profile of the blades must be contoured to maximize the aerodynamic efficiency, but at the same time the part must have adequate structural strength to withstand the many different dynamic excitations imposed on it. Dynamic loads arise from many sources, the predominant one being the source of the operating principles itself on which the machine is designed. When a rotor blade passes the stationary vanes of the nozzle, it experiences repeated fluctuating lift and moment loads at a frequency dependent on the number of vanes and the speed of the machine. The rotating airfoils are flexible members, and possess a number of natural frequencies of vibration about their torsional axis, bending in and out of the plane of rotation of the disk. In addition to the steady centrifugal forces arising from its mass, the airfoil must also withstand the dynamic loads due to the aerodynamic excitation. Although the blades are designed to avoid resonance at its design speed, resonant vibrations are still encountered. A good example is an aircraft engine as the aircraft accelerates from ground to flight idle, cruise, and takeoff speeds.

This book is written to meet the needs of students in engineering colleges and practicing engineers in a large variety of industries where turbo-machines are used. All the material has been specifically tailored for college undergraduate and graduate level design engineering and vibration of rotating machine courses. Electronic spread-sheet type of calculations are used in example problems to calculate natural frequencies of vibration, dynamic response, fatigue life, and design parameters related to fluid flow and component sizing. It is expected that the reader is familiar with basic- to medium-level calculus offered at the college undergraduate level.

The book is split into three parts. The first part focuses on the many different applications and forms of turbine engines and their special characteristics and operating features. The five chapters in this part look into the salient features of compressor, turbine, and combustor components for various applications of turbo-machines. The second part investigates the design aspects of the major components. The third part discusses associated topics such as material characteristics and manufacturing methods. Since the design features of a turbomachinery and its parts play such an overwhelming role in establishing the dynamic behavior of the components, module, or assembly during operation, a close correlation has been maintained throughout the book between the design and dynamics disciplines.

The first chapter of Part 1 provides some historical insights about turbo-machines, outstanding characteristics of aircraft engines and power-generation turbines, and the latest trends in compression, combustion, and turbine expansion processes. The second, third, fourth, and fifth chapters are devoted to applications of turbo-machines for propelling aircraft, power generation and related industrial usage, aviation technology derived marine and industrial turbines, and turbocharging for diesel and automotive engines. In Part 2, Component Design, structural integrity in the form of strength and component life management issues for fan and compressor blades are discussed at length in Chapter 6, impellers and bladed disks in Chapter 7, turbine blades and vanes in Chapter 8, combustion systems for gas turbines in Chapter 9, and bearings and seals in Chapter 10. Super alloys and manufacturing methods are discussed in Part 3, Chapters 11 and 12.

A list of symbols is provided mostly to facilitate identification with commonly used parameters in the equations and the associated text. However, because of the considerable number of topics the corresponding variables are adequately defined within each section. Oftentimes it is found necessary within the sections to redefine many of the symbols for convenience and better understanding of the subject matter. Thus, the list of symbols may be used only as a general guideline.

ACKNOWLEDGMENTS

I gratefully remember and appreciate past students of the course on this topic who have sent in comments and reported errors, and express my hope that those who work with this treatise will do likewise. I am indebted to Mr. Mark Belloni and Dr. Fred Ehrich of General Electric Company for performing a vast amount of computational work in finite element analysis and for valuable advice on the text and layout of the book. I greatly appreciate comments provided by Dr. Ahmad Kamel, Mr. George Robinson, and Dr. Raj Subbiah of Siemens-Westinghouse Power Corporation, who checked the problems and read the proof.

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LIST OF SYMBOLS

The symbols provided here are mostly to facilitate identification with commonly used parameters in the equations and the associated text. However, because of the considerable number of topics discussed in the text, the relevant variables are defined within each section, and may even be redefined for convenience and better understanding of the subject matter.

a, A	cross sectional area
a_o	amplitude of support
a_n	Fourier coefficient of Sin($n\omega t$)
b_n	Fourier coefficient of Cos($n\omega t$)
c	damping constant, clearance
C	condenser capacity
c_c	critical damping constant
C_1, C_2	constants
d, D	diameters
e	eccentricity
e	amplitude of pendulum support
E	modulus of elasticity
E_o	maximum voltage
f	frequency $= \omega/2\pi$
f_n	natural frequency
f and g	numerical factors
F	force in general or dry friction force in particular
g	acceleration of gravity
G	shear modulus
h	height
i	station number, $\sqrt{(-1)}$, imaginary unit of complex number
I	moment of inertia
J	polar mass moment of inertia
j	$\sqrt{(-1)}$, imaginary unit of complex number
k	spring constants
K	kinetic energy
Δk	variation in spring constant
l, L	length
l_n	distance from nth station
L	inductance
m, M	mass
M	moment or torque
	angular momentum vector
	magnitude of angular momentum vector

n	station number, number in general, gear ratio
p	real part of complex frequency s, pressure
p_1, p_2	parameters
P_o	maximum force
P	force, potential energy
q	natural frequency of damped vibration
R	electrical resistance
s	complex frequency $= p \pm jq$
r, R	radius of circle
q	load per unit length on beam
Q	condenser charge
t	time
T	period of vibration $= 1/f$
T_o	maximum torque T = Torque, tension
V	velocity
v, V	volume
W	weight, work or work per cycle
X	displacement
X_o	maximum amplitude
x_{st}	static deflection, usually, P_o/k
y	y_o Sin(ωt) = amplitude of relative motion
y	lateral deflection of string or bar
Y	response
Z	impedance
α	angle, bypass factor
α_n	nth crank angle in reciprocating engine
α_{mn}	influence number, deflection at m caused by unit force at n
β_n	angular amplitude of vibration of nth crank
δ	small length or other parameter in general
δ_{st}	static deflection
ε	eccentricity, parameter
λ	length, multiplier
μ	mass ratio m/M
μ_1	mass per unit length of strings, bars
ξ	damping coefficient
ρ	radius of gyration, density
θ	angle
ϕ, φ	phase angle or some other angle
φ_n	phase angle between vibration of nth crank and first crank
ψ	an angle
ω	circular frequency $= 2\pi f$
ω	angular velocity
Ω	large angular velocity
ω_n, Ω_n	natural circular frequencies

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P · A · R · T · 1

APPLICATIONS

CHAPTER 1
ADVANCED TURBINE TECHNOLOGY

1.1 INTRODUCTION

The successful development of modern aviation engines and industrial turbines is a classic example of engineering ingenuity, enduring leadership, and technical substance at their best. In the new order of globalization and an international market economy the role played by the turbine industry stands at the forefront. Turbine technology has given rise to the greatest inventions of the past century in the aviation and power generation industries. Brand new technologies have developed to satisfy the ever increasing demands and complexities of turbine parts. Superalloys have come into existence due to the need for turbine components to operate at very high temperatures. Airfoils for compressors and turbines are designed using aerodynamic theory to determine the concept of lift and losses arising from turbulent fluid flow. Safe combustion of fuels alleviates smoke, nitric oxides, and other harmful pollutants. New manufacturing processes have evolved to form the complex shape of the parts.

The value of aviation and nonaviation gas turbines produced worldwide during the calendar year 2001 reached an all-time high, just short of $50 billion, exemplifying the long way the industry has come since its inception 100 years ago. The turbines span a wide range of capacities, starting with microturbines weighing little more than 100 lb and producing 25 kW to provide electrical power and heat for small or remote locations. At the other extreme, base load electric power gas turbines with power ratings up to 250 MW and weighing 300 tons drive electric generators and at the same time supply heat for steam turbines in combined cycle operations.

Throughout the history of mechanical devices the power of rising hot air has been recognized in performing useful work, as it became apparent that efficiency is related to the use of high temperatures. This observation has led to the development of the thermodynamic Brayton cycle with its basic physical tenet that higher operating temperatures (in conjunction with lower heat rejection temperatures) lead to enhanced efficiency. Applying the concept to rotating engines, improvements were introduced in steam turbines for power generation appearing in the 1800s, and to gas turbines in the 1900s.

In the early stages of engine development and their use on airplanes, it was imperative to pressurize the air–fuel mixture for the internal combustion engines because of the lower ambient pressure at flight altitudes. One joint research effort between the U.S. Army, General Electric Company, and Cornell University succeeded in the development of a turbocharger for piston-driven engines. Advances in aerodynamics theory brought the realization that turbulence can cause a substantial loss of power at the tip of the propellers of a conventional piston-driven engine beyond set limits. This was coupled by the observation that the weight-to-power ratio of reciprocating engines increases exponentially as the size and speed capability of the airplane increase. The two limitations provided the incentive to develop turbine engines to power larger aircrafts carrying a bigger load and flying at faster speeds.

Progress in jet propulsion and power generation turbines has come at a steady pace, with the new technologies inexorably assuming immense importance. Steam and gas turbines now provide the most widespread and effective method for the transportation of passengers and goods by air and on the high seas, for the generation of electrical power to illuminate the furthest corners of the world and for mechanical power to drive other industrial machines.

A major cause of breakdowns in steam and gas turbines is the failure of turbine blades. Blade failures due to fatigue are caused by resonant vibrations. Dynamic loads arise from many sources, the predominant one being the source of the operating principles on which the machine is designed. When a rotor blade passes the stationary vanes of the nozzle, it experiences repeated fluctuating lift and moment loads at a frequency dependent on the number of vanes and the speed of the machine. The rotating airfoils are flexible members, and possess a number of natural frequencies of vibration about their torsional axis, bending in and out of the plane of rotation of the disk. In addition to the steady centrifugal forces arising from its mass, the airfoil must also withstand the dynamic loads due to the aerodynamic excitation. Although the blades are designed to avoid resonance at the design speed, resonant vibrations are still encountered as an aircraft engine accelerates from ground to flight idle, cruise, and takeoff speeds. Even in power generation turbines operating at a near constant speed it is not infrequent to find a major shutdown of the machine due to the failure of the blades. Fleeting and Coats (1970) report experiences of blade failure in the high-pressure (HP) turbine of Royal Mail Ship (RMS) *Queen Elizabeth II*. The ship left the manufacturer's shipyard on November 19, 1968 and failure occurred on December 24, 1968 during the ship's maiden voyage. The fractured turbine blade caused extensive damage to the ninth and tenth stages of the machine. The failure of the blade was attributed to the resonant vibration of the blade packets arising from nozzle excitation.

1.2 HISTORICAL FIRSTS

Hero of Alexandria is credited with developing the first steam turbine nearly 2000 years ago. Leonardo da Vinci portrayed a paddle wheel driven by a rising plume of hot air to rotate a barbecue spit. In the 1600s the Italian engineer Giovanni Branca employed a steam jet to run an impulse form of a turbine wheel. The Frenchman Burdin coined the word "turbine" in a technical publication to denote a water wheel designed by him in 1824, and in 1883 the Swedish engineer Patrick de Laval operated the first successful steam turbine using a nozzle characteristic shape capable of producing supersonic velocity at the exit. A Parsons steam turbine was tested in England to power a ship for the first time in 1897, followed by the launching of the turbine-driven cruiser *Lubeck* in Germany 7 years later.

Gas turbines, and more generally "turbomachinery," emerged in the wake of early electrification. In 1867 Werner von Siemens presented the first dynamo after the discovery of the principle of electrodynamics. In 1879 Thomas A. Edison invented the light bulb, which eventually led to the creation of the powerful General Electric Company in 1895 to manufacture power generation equipment. More than 100 years ago engineers at Switzerland's Brown-Boveri Company made significant contributions to the development of today's advanced gas turbine concept. And in 1891 Charles E. L. Brown succeeded in transmitting 220 kW of power from Lauffen/Neckar to Frankfurt/Main, a distance of 175 km. This offered considerable prospects of not requiring power generation and consumption at the