Flow-Induced Pulsation and Vibration in Hydroelectric Machinery

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Engineer's Guidebook for Planning, Design and Troubleshooting

Springer

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ISBN 978-1-4471-4251-5 ISBN 978-1-4471-4252-2 (eBook)
DOI 10.1007/978-1-4471-4252-2
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2012942709

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Printed on acid-free paper

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Preface

Hydraulic turbomachines have played a prominent role in the procurement of renewable energy for more than a century. Embedded in the context of general technological progress, their design for efficiency and reliability has reached an outstanding level of quality, and no other turbomachines have reached the efficiency levels of Francis turbines, now close to 96 %. To maintain such a level in every project is a permanent engineering challenge because, unlike other types of equipment, the turbines and storage pumps for a hydroelectric power plant are usually ‘tailor-made’, that is their design is adapted to the flow and head available for a given location. Furthermore, with the fundamental changes in the electricity markets due to the integration of non-dispatchable renewables, such as wind and solar power, the role of hydropower in the electrical grid has dramatically changed from being a contributor of constant energy supply to a highly flexible supplier of ancillary services. Hydraulic turbomachines are nowadays operated in a far more dynamic way thereby requiring substantial progress in technology development.

The main hydraulic performance issues of hydroelectric machinery—output, efficiency, and cavitation—have been in the focus of interest right from the beginning because they are obviously linked with the owner’s financial success. Well-established practice and standards for testing these properties of the machines have existed for a long time. It is more difficult to assess in advance the durability of the equipment. Mechanical failure of one or more components after some period of operation is in most cases due to fatigue caused by fluctuating stress added to the steady-state load. These fluctuating stresses are, like the steady-state ones, a consequence of the working principle of the hydraulic machines. To predict them becomes more and more important if the machines should be designed for good hydraulic performance, but at the same time be developed for the lowest possible cost and the most flexible operation.

Apart from issues of mechanical safety, there are other reasons for limiting the unsteady phenomena. For example, spontaneous power swings due to some mechanism of instability are not acceptable for the electrical network. There are also some issues at the border between safety and convenience, phenomena like pressure shocks, vibrations, and noise where both operators and suppliers may disagree about what is acceptable or not.

To make things even more challenging, the flexibility of modern power plants leads to a remarkable trend toward operating the equipment in off-design conditions for a larger percentage of time. As a consequence, the importance of fluctuating loads increases and the unsteady operational behavior must receive more attention.

The idea for this book was born a few years ago, when a number of researchers in the field, including one of the authors, reached the age of retirement. Engineers who have acquired specific knowledge in the field, both empirical and theoretical, owe a good deal of that knowledge to unforeseen technical mistakes and their correction. The problems that had to be dealt with typically occurred once in every few years, or even over many years. Within a well-governed company, however, such incidents drive a process of rule-making to provide guidelines to avoid similar events. Over the years, the body of rules and guidelines increases and the errors are finally avoided. It is not quite the same in the open literature of the technical community. Paradoxically, the very large number of conference papers seems to assist in the merciless erosion of know-how. In view of this we recognized that we should make this specific knowledge available in a more compact form, some of it being owed to publicly funded research projects, or collected in exchange of experience with colleagues from other companies in working groups organized by IAHR.

In addition, this book is intended as a contribution to help improving the efficiency of collaboration between the buyers and suppliers of hydroelectric machinery. We are faced in many projects with unrealistic or unpractical technical requirements with regard to unsteady performance. This is mainly due to lack of available information about the actual behavior of hydraulic machines. With our book, we want to close this gap of knowledge and contribute to a more rational handling of the subject in future projects.

Zurich, Switzerland, April 2012 Peter Dörfler

Acknowledgments

The authors are indebted to their company ANDRITZ HYDRO, and the many smaller companies that have merged to form this unit, for permission to publish this book. The head of ANDRITZ HYDRO Research & Development, Dr. Helmut Keck, is thanked for his agreement and encouragement that this valuable collection of company know-how can be published. The work of many colleagues in the company is incorporated in the form of measurement data, graphs, or theoretical results, and in addition they assisted by means of discussions and explanations, in order to ensure proper presentation of all the various subjects. We are grateful for all their many contributions that made this publication possible.

Special thanks are due to Prof. Michael Casey who, as a turbomachinery engineer not specialized in hydraulics and as an English native speaker, endeavored to read our text in a critical way to ensure it will be understood correctly, and at the same time to rectify the linguistic shortcomings of the three non-native English speaking authors.

Part of the work included in this book has been carried out within the scope of a contract with CEATI International (The Centre for Energy Advancement through Technological Innovation, Montréal, CDN). Under project T082700-0364, ANDRITZ Hydro provided a Technology Report "Hydraulic Phenomena that Occur in Operating Hydraulic Turbines" to the Hydraulic Plant Life Interest Group (HPLIG) of CEATI which was partly funded by the customers of CEATI. The financial support of CEATI and the excellent collaboration with the responsible persons, Messrs. Alastair Wilson and Chris Hayes, is gratefully acknowledged.

The authors thank the International Electrotechnical Commission (IEC) for permission to reproduce Information its International Standard IEC 60193 ed. 2.9 (1999), in particular Fig. 1.1 of this book. The authors thank Prof. M. Nishi, Tsinghua University, Beijing (CN) for permission to reproduce Fig. 2.2a from his IAHR 1980 paper. Permission given by Voith Hydro Holding GmbH, Heidenheim (D), for reproducing Fig. 5.1 is gratefully acknowledged.

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Contents

Nomenclature

Latin Letters

a	Velocity of wave propagation
a_{ij}	Elements of transfer matrix
A	Cross-section area
A	Transfer matrix
A	Amplitude
B_0	Height of wicket gates
c	Flow velocity
c_m	Meridional flow velocity
c_t	Peripheral flow velocity
C_C	Cavitation compliance
C	Damage ratio
C_p	Pressure coefficient
d	Thickness, width
D	Diameter
D(s)	Denominator
E	Energy
E	Modulus of elasticity
f	Frequency
F	Force
g	Gravity acceleration
G	Transfer function
h	Variation of head
h_{dyn}	Velocity head
H	Head
I	Inertance
I, J	Moment of inertia
j	Imaginary unit

k	Friction factor (unsteady)
k	Harmonic of runner blade frequency
k	Polytropic exponent
K	Speed coefficient, relative to $\sqrt{(2E)}$
L	Length
n	Runner speed, frequency of runner rotation
m	Harmonic of stationary blade frequency
m	Swirl ratio
M	Mach number
M	Torque, bending moment
N	Number of samples
N(s)	Numerator
p	Pressure
P	Power
q	Variation of flow
Q	Mean value of flow
R	Radius
R	Resistance
s	Laplace transform parameter
S	Surface tension
St	Strouhal number
t or T	Time
T	Torque
u	Peripheral velocity of runner
u	Radial source velocity
v	Velocity
V_C	Volume of cavity
w	Relative velocity
x	Longitudinal coordinate
X	(general) Variable
X2	Dimensionless relative discharge variable
Y	Hydraulic admittance
Y	Guide vane opening
Z	Hydraulic impedance
Z	Number of blades

Greek letters

α	Void fraction
α	Real part of eigenvalue
α	(Guide vane opening) Angle
β	Inclination angle
β	(Runner blade opening) Angle
χ	Mass flow gain factor
Δ	Fluctuation of .. , difference of ..
γ	Propagation constant
η	Hydraulic efficiency
φ, ϕ	Discharge coefficient
κ	Upstream portion of mass flow gain
λ	Friction factor (steady-state)
Λ or λ	Wave length
μ	Bulk viscosity
ν	Specific speed
ν	Signed number of node diameters
π	3.141592…
ρ	Density
σ	Cavitation number
σ	Mechanical stress
Σ	Sum
ω	Angular velocity
Ω	Angular velocity of runner rotation
ψ	Pressure coefficient
ζ	Damping ratio

Abbreviations

asyn	Asynchronous part of DTPP
CFD	Computational fluid dynamics
DES	Detached eddy simulation (turbulence model)
DNS	Direct numerical simulation (turbulence model)
DOF	Degrees-of-freedom
DTPP	Draft tube pressure pulsation
EPFL	Swiss Federal Institute of Technology (Lausanne, CH)
FEA	Finite element analysis
FFT	Fast Fourier transform
FRR	Frequency reduction ratio
GV	Guide vanes
IEC	International electrotechnical commission
ISO	International organization for standardization
lcm	Lowest common multiple
LES	Large eddy simulation (turbulence model)
LMH	Laboratory of Hydraulic Machines (at EPFL)
MFGF	Mass flow gain factor
MIV	Main inlet valve
ND	(number of) Node diameters
ND	Non-drive
NPSE	Net positive suction energy
NR	Noise rating
p-p	Peak-to-peak
PSS	Power system stabilizer
p.u.	Per unit
rms	Root mean square
RSI	Rotor–stator interaction
SAS	Scale-adaptive simulation
SPL	Sound pressure level
SR	Suction coefficient
SST	Shear stress transport (turbulence model)

sync	Synchronous part of DTPP
TVA	Tennessee Valley Authority
USBR	US Bureau of Reclamation
VoF	Volume of fluid
WG	Wicket gate

Subscripts

B	Barometric
BP	Runner blade passage
c	Related to cm (at runner exit)
C	Cavity
DT	Draft tube
EX	Exciting (forcing)
G	Generator
G	Guide vane
h	Horizontal, hydraulic
HW	Headwater
L	Liquid
max	Minimum
min	Maximum
n	Natural (frequency)
NB	Narrow-band
nom	Nominal = rated
opt	At best efficiency point
r	Rated
r	Rotating cascade
R	Radial at runner
R	Runaway
RF	Risk factor
s	Stationary cascade
sp, SC	Spiral casing
v	Vertical
T	Turbine
TW	Tail water

u	Related to u (at runner exit)
W	Wall
W-B	Wide-band
11	Per unit of reference variables
1, 2	Upstream, downstream
2	Related to runner exit (diameter)