

Vibration and Oscillation of Hydraulic Machinery

HYDRAULIC MACHINERY BOOK SERIES

International Editorial Committee

Chairman, Duan C G , Secretary, A P Boldy

Vibration and Oscillation of Hydraulic Machinery

H. OHASHI, Editor

Avebury Technical

Wokingfield USA · Hong Kong · Singapore · Sydney

HYDRAULIC MACHINERY BOOK SERIES

- **Hydraulic Machinery Systems**
Editors: Prof D K Liu, Prof V Karelin
- **Hydraulic Design of Hydraulic Machinery**
Editor: Prof H Radha Krishna
- **Mechanical Design and Manufacturing of Hydraulic Machinery**
Editor: Prof Mei Z Y
- **Transient Phenomena of Hydraulic Machinery**
Editors: Prof S Pejovic, Dr A P Boldy
- **Cavitation of Hydraulic Machinery**
Editors: Prof Li S C, Prof H Murai
- **Erosion and Corrosion of Hydraulic Machinery**
Editors: Prof Duan C G, Prof V Karelin
- **Vibration and Oscillation of Hydraulic Machinery**
Editor: Prof H Ohashi
- **Testing of Hydraulic Machinery**
Editor: Prof P Henry
- **Control of Hydraulic Machinery**
Editor: Prof H Brekke

The International Editorial Committee (IECBSHM):

Chairman: Prof Duan C G (China)

Secretary: Dr A P Boldy (UK)

Treasurer: Dr R K Turton (UK)

Committee Members:

Prof H Brekke (Norway)

Prof E Egusquiza (Spain)

Dr H R Graze (Australia)

Prof P Henry (Switzerland)

Prof V Karelin (USSR)

Ass Prof Li Sheng-cai (China)

Prof M Tadeu de Almeida (Brazil)

Prof M Matsumura (Japan)

Prof A Mobarak (Egypt)

Prof H Netsch (Canada)

Prof S Pejovic (Yugoslavia)

Prof H Petermann (Germany)

Prof C S Song (USA)

Prof Hans Ingo Weber (Brazil)

Honorary Members:

Prof B Chaiz (Switzerland)

Prof V P Chebaevski (USSR)

Prof M Fanelli (Italy)

Prof R Guarga (Uruguay)

Dr H B Horlacher (Germany)

Prof G Krivchenko (USSR)

Prof Liu D K (China)

Prof C S Martin (USA)

Prof Mei Zu-yan (China)

Prof H Murai (Japan)

Prof H Ohashi (Japan)

Prof D Perez-Franco (Cuba)

Prof H C Radha Krishna (India)

Prof C Thirriot (France)

Prof G Ziegler (Austria)

Prof J Raabe (Germany)

©International Editorial Committee (IECBSHM) 1991

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise without the prior permission of the publisher.

Published by
Avebury Technical
Gower House
Croft Road
Aldershot
Hants GU11 3HR
England

Gower Publishing Company
Old Post Road
Brookfield
Vermont 05036
USA

A CIP catalogue record for this book is available from
the British Library and the US Library of Congress.

ISBN 1 85628 185 X

Printed in Great Britain at the University Press, Cambridge

CONTENTS

Preface

Foreword from the Editor

Contributing Authors

1 Fundamentals

H I Weber, Brazil

1.1 Introduction

1.1.1 Hydraulic Machinery as a Mechanical System

1.1.2 Dynamics of a Hydraulic Unit

1.1.3 System Parameters and Excitations

1.2 Basic Dynamics of Mechanical Systems

1.2.1 Eigendynamics of Linear Systems

1.2.2 Excited Dynamics of Linear Systems

1.2.3 Non-Linearities, Self-Excitations

1.3 Eigenproperties and Excitations of Hydraulic Machinery

1.3.1 Typical Structure of the Dynamical Model

1.3.2 Parameter Uncertainties

1.3.3 Identification Problems

1.3.4 Measurement Difficulties

1.3.5 Excitations and System Parameters of Hydraulic

Origin

References

2 Modelling and Analysis

H Tomita, Japan

2.1 Fluid-Structure Interaction

2.1.1 Basic Equations

2.1.2 Basic Aspects of Fluid-Structure Interaction

2.1.3 Influence of Flexibility of Outer Confinement

2.2 Modal Analysis Based on Finite Element Method

2.2.1 Consolidated Equations for Fluid-Structure

Analysis

2.2.2 Modal Analysis

2.2.3 Analysis of Fluid-Structure System

2.3 Model Test of Hydroelastic Vibration

2.3.1 Similarity Law for Hydroelastic Vibration

2.3.2 Model Test under Actual Head Condition

2.3.3 Model Test under Reduced Head Condition

2.3.4 Self-Excited Vibration of Francis Turbine

References

3 Structural Vibration due to Mechanical Excitation	
Dung Yu-Xin, China	85
3.1 Excitation by Rotating Shaft	85
3.1.1 Introduction	85
3.1.2 Response to Unbalance	85
3.1.3 Dry Friction Excitation	87
3.1.4 Vibration Severity	88
3.2 Other Excitation Source	93
3.2.1 Piping Reaction	93
3.2.2 Internal Hysteresis of Rotating Shaft as a Cause of Instability	96
References	99
4 Structural Vibration due to Hydraulic Excitation	
H. Netsch, Canada	101
4.1 Introduction to Flow Phenomena in Hydraulic Machinery	101
4.1.1 Idealized Steady Flow	101
4.1.2 Idealized Flow Conditions	103
4.1.3 Rotating Stall and Cork Screw Vortex	106
4.1.4 Actual Flow Conditions	107
4.1.5 The Flow Acceleration in the Runner	109
4.2 Pressure Fluctuations due to Hydraulic Excitation	114
4.2.1 Interaction of Guide Vanes and Runner Channels	114
4.2.2 Interaction of Spiral Case Tongue and Runner Blades	116
4.2.3 Pressure Fluctuations due to Unstable Cork Screw Vortex	116
4.2.4 Periodic Pressure Fluctuations due to Vortex Street	117
4.3 Level of Hydraulic Excitation	120
4.3.1 Amplitudes of Pressure Fluctuations	120
4.3.2 Periodic Shock and Fourier Frequency Spectrum	120
4.4 Determination of Vibration Transmission Path	121
4.4.1 Resonance of Turbine Structural Elements	121
4.4.2 Experimental Determination of Vibration Transmission Path	123
4.4.3 Interpretation of Test Results	128
4.5 Reduction of Pressure Fluctuations	129
4.5.1 Prediction	129
4.5.2 Methods for Reducing Pressure Pulsations	129
References	132

5 Rotordynamics

R Nordmann and W Diewald, Germany	135
5.1 Introduction	135
5.2 Basic Equations for Lateral Vibrations	136
5.2.1 A Simple Rotor Model (Jeffcott-Rotor)	136
5.2.2 Jeffcott-Rotor in Flexible Supports	139
5.2.3 External Damping	142
5.2.4 Transient Vibrations	144
5.3 Influence of Fluid Forces in Journal Bearings and Seals	147
5.3.1 Journal Bearings	147
5.3.2 Seals	153
5.4 Vibrations of Large Rotating Machinery	159
5.4.1 Modelling for Large Rotor Systems	160
5.4.2 Dynamic Calculations	162
5.4.3 Realistic Example	167
References	173

6 System Instability Caused by Hydraulic Machinery **175**

6.1 Instability due to Performance Characteristics	
R Guarga, Uruguay	175
6.1.1 Concepts of Stability	175
6.1.2 Formulation of Linear Stability	176
6.1.3 Stability Analysis of Industrial Installations	179
6.1.4 Transfer Matrix Based on Static Characteristics	182
6.1.5 Transfer Matrix Based on Dynamic Behaviour	183
6.1.6 Hysteresis Phenomena	195
6.2 Power Swing	
M A Fanelli, Italy	197
6.2.1 Qualitative Description of the Phenomena	197
6.2.2 Qualitative Interpretation of the Phenomena	201
6.2.3 Quantitative Relationship	203
6.2.4 Conclusions and Further Developments	208
6.3 Pressure Surge due to Vortex Core in Draft Tube	
M Nishi, Japan	210
6.3.1 Cavitating Vortex Core	210
6.3.2 Swirl Flow Model and Similarity Law	211
6.3.3 Flow Regimes in a Draft Tube	216
6.3.4 Pressure Surge Physics	218
6.4 Cavitation Induced Oscillation and Two-Phase Flow Instability	
M Nishi, Japan	225
6.4.1 Cavitation Induced Oscillation	225

6.4.2 Two-Phase Flow Instability	240
References	244
7 Noise of Hydraulic Machinery	
E Egusquiza, Spain	251
7.1 Fundamentals of Noise	251
7.1.1 Introduction	251
7.1.2 Fluid-Borne Noise Generation	252
7.1.3 Structural Response	255
7.2 Propagation and Radiation	258
7.2.1 Introduction	258
7.2.2 Acoustic Waves	259
7.2.3 Fundamental Parameters of Acoustics	261
7.2.4 Radiation Fundamentals	263
7.3 Noise Generation	265
7.3.1 Introduction	265
7.3.2 Fluid-Borne Noise Generation	265
7.3.3 Prediction of Noise Levels	269
7.3.4 Noise of Mechanical Origin	271
7.4 Noise Control	272
7.4.1 Noise Isolation	272
7.4.2 Sound in Enclosed Spaces	273
7.4.3 Silencers	277
7.4.4 Control of Noise in Hydraulic Machinery	277
References	281
8 Diagnosis	
S K Bhawe, India	285
8.1 Introduction	285
8.1.1 Characteristics of Periodic Vibration	285
8.2 Sensing and Measurement	288
8.2.1 General Considerations	288
8.2.2 Accelerometers	290
8.2.3 Shaft Vibration Transducers	292
8.2.4 Phase Measurement	293
8.2.5 General Purpose Vibration Analyzer	295
8.2.6 Tape Recorders	297
8.2.7 Real Time Analyzers	297
8.2.8 Remote Sensing	300
8.3 Data Reduction and Processing	300
8.3.1 Vibration Amplitudes versus Frequency Analysis	303

8.3.2 Amplitude versus Frequency versus Time Analysis	306
8.3.3 Amplitude/Phase versus rpm Analysis	308
8.3.4 Time Wave form Analysis	311
8.3.5 Lissajous Pattern (Orbit) Analysis	311
8.3.6 Mode Shape Analysis	311
8.4 Diagnosis and Corrective Actions	313
8.4.1 Steady State Operating Regime	313
8.4.2 Detection of Perturbation Forces	314
8.4.3 Preventive Maintenance	320
8.4.4 Expert Systems	321
References	325
Appendix I Unified Nomenclature of Symbols	327
Appendix II Reference list of organisations	347
Appendix III Reference list of Educational Establishments	357

Preface

The publishing of this book series on Hydraulic Machinery, organised and edited by the International Editorial Committee for Book Series on Hydraulic Machinery (IECBSHM), marks the results of successful cooperation between the Committee, the authors and the editors of each volume.

The Editorial Committee consists of 35 scholars from 20 countries. More than 100 academics and engineers from 23 countries have participated in the compilation of the book series. The volumes reflect the latest developments, gained from many countries, in concepts, techniques, and experiences related to specific areas of hydraulic machinery. This is a great joint exercise by so many experts on a world wide basis that will inevitably bring impetus to technical achievement and progress within the hydraulic machinery industry and promote understanding and cooperation among scholars and professional societies throughout the world.

The authors have devoted considerable time and energy to complete the manuscripts and even more time was occupied by the editors in revising and correlating the individual volumes. Dr A P Boldy, Secretary IECB-SHM, contributed greatly to the overall editing and preparation of the final manuscripts. Mr J G R Hindley, of Avebury Technical, offered many suggestions and remained helpful in every phase of the editorial and publishing work.

Great assistance in the preparation of the manuscripts from numerous persons in different parts of the world have been received, without which the publication of the book series would not have been possible. I would like to express appreciation both from myself and on behalf of the Editorial Committee to these people, the list of names being too lengthy to include here.

Duan Chang Guo
Chairman IECB-SHM

Foreword of the Editor

The present book *Vibration and Oscillation of Hydraulic Machinery* is a volume in the Book Series on Hydraulic Machinery organized by the International Editorial Committee. It deals with the vibration and oscillation problems which are hazardous to the safety and reliable operation of hydraulic machinery. It restricts its scope, however, to the problems which are caused by a mechanical or hydraulic excitation induced by the rotating machine itself or by a self-exciting mechanisms inherent in a specific flow pattern in the machine. It excludes, therefore, so-called transient phenomena from the scope, where the interaction between the piping and the machine plays the predominant role. These phenomena are treated in the volume on hydraulic transients of this Book Series.

Hydraulic machinery, or pumps and hydraulic turbines to be concrete, is the machine which converts shaft power to hydraulic energy or vice versa. The conversion is done in the rotating impellers of pumps or in the runners of hydraulic turbines and the hydrodynamic force on the vanes of impellers or runners is the direct medium of the energy conversion. The effectiveness of this conversion process, i.e. efficiency, must be as high as possible and the hydrodynamic design of impellers or runners together with their surrounding stationary parts is the most important part of the whole design procedures.

Hydraulic machinery with an excellent hydrodynamic performance occasionally experiences a vibration or oscillation problem, which results in the fracture of a specific machine element or forces to shut down the operation. If such situation happens, the machine cannot continue the operation. To assure hydraulic machinery of vibration-free smooth operation is therefore as vital as to materialize a good hydrodynamic performance.

Many of vibration and oscillation troubles of hydraulic machinery are found or detected after the machine was constructed and started its operation at the site. This makes the situation quite unfavorable because the search for the true cause of the trouble is difficult due to limited possibility of measurement at the site and also because the choice of remedies applicable to the machine after the installation is quite restricted. If once such trouble happens, the damages are quite severe both for suppliers and users through the loss of operation and the cost of man power and additional reconstruction works at the site. Utmost precautions must be paid therefore to prevent vibration and oscillation troubles especially at off-design operating condition where most of unexpected vibration events take place.

The present volume consists of nine chapters: Chapter 1 and chapter 2 describe fundamental concepts and methods of modelling and mathematical analysis of vibration phenomena. Chapter 3 and chapter 4 are on the vibration of structure due to mechanical and hydraulic excitations of rotating machinery. Chapter 5 deals with the vibration of rotating shaft system, i.e. rotordynamics aspects. In chapter 5 the stability of the flow in the machine and examples of self-exciting mechanism of the fluid system are described. Chapter 7 deals with the noise problem, that is, generation, transmission and control of noise. The last chapter 8 summarizes the diagnosis and remedy of vibration problems.

The coordinator is responsible for the grand design and composition of the contents of this book. Each chapter was written by a single author or by a group of authors, totaling eleven authors from nine countries. The authors are all experts of global fame in the specific fields. The authors are in nature prone to select materials which they are most interested in and they have experienced often in the practice. Consequently some items, for example vibration caused by vortex core formation in the draft tube of Francis turbines, are referred to in plural chapters of this Volume. The coordinator has overlooked these duplications deliberately, since different authors describe the same phenomena in different ways and such duplication could help readers understand the phenomena better and from various view points.

The recent development of technology has been accelerated by the use of electronic computers to a great extent. The vibration analysis of large structures and the computation of fluid flow are the very fields which have been and are enjoying the powerful assistance of computers. This situation necessarily requires more mathematical modeling and expressions for the numerical analysis and simulation of the phenomena. The reader will find in the text rather heavy mathematical expressions, in many cases in matrix form, which are indispensable for computational purposes. In the era of computers the importance of mathematical modeling is steadily increasing even for an engineer in practice. The coordinator hope that the readers would appreciate these equations and formulations when they encounter the demands which require a quantitative prediction beyond a qualitative one.

None of the authors including the coordinator of this Volume is native English speaker. Though we are deeply obliged to Dr A P Boldy of the University of Warwick, UK, for his careful reading and polishing of the text, there remain still a lot of 'English as foreign language' in the book. We would like to ask the readers the forbearance in this respect.

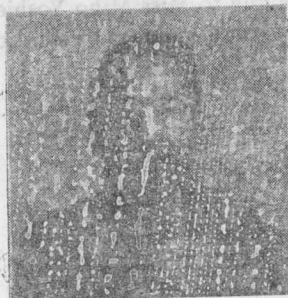
Each author submitted the manuscript in floppy disc to the coordinator, who converted the files by different word processors into the format of LaTeX system and prepared the camera-ready copy for the publication. Appreciation is due to Miss Miho Yoshie who helped the conversion including expression of complicated mathematical formulae.

Hideo Ohashi,
Coordinator

Contributing Authors

Hideo Ohashi, Professor,
Department of Mechanical Engineering,
University of Tokyo, Japan.

Born in 1931, male, Japanese. BS in 1954 at Univ. of Tokyo, Dr.-Ing. (T.H. Braunschweig) in 1958 and Dr. Eng. (Univ. of Tokyo) in 1963. 5 years experience in compressor design. Education and research at Univ. of Tokyo since 1959 on dynamic characteristics of turbopumps, fluid forces on vibrating centrifugal impellers, unsteady and two-phase flow in cascades and ventilation of vehicle tunnels.



Hans Ingo Weber, Professor,
Faculty of Mechanical Engineering,
UNICAMP-State University of Campinas,
Brazil.

Born in 1943, Brazilian. Graduated Univ. of São Paulo in 1966, Dr.-Ing. (T.U. München) in 1971. Fellow of the Alexander von Humboldt Foundation. Active at UNICAMP since 1974, initiated area of dynamics for mechanical systems in lecturing and research. Main topic is rotordynamics, emphasizing hydraulic machinery and centrifuges. Identification and reduced order modeling are priority research subjects.



Hisao Tomita, Director,
Nuclear Engineering Laboratory,
Toshiba Corp., Japan.

Born in 1936, male, Japanese. BS in 1959 and Dr. Eng. in 1984 at Univ. of Tokyo. Specialized in analysis of dynamics of mechanical systems. Engaged in mechanical vibration problem studies for 10 years at Toshiba R&D Center. Directed the Toshiba project for the development of the gas centrifuge for the Japanese Uranium Enrichment Program. Deputy director of Toshiba R&D center in 1984.



Dung Yu-xin, Professor,
Department of Civil Engineering,
Dalian University of Technology, China.

Born in 1926, male, Chinese. BE in 1951 at Northeast Institute of Technology, Post graduate (Harbin Univ. of Tech.) in 1954 and Dr. Eng. (Moscow Energetic Inst.) in 1958. Education and research at Dalian Univ. of Tech. since 1959 on vibration of hydro-generator units, dynamic and static characteristics of hydropower structures and concrete dams.

Herbert Netsch, Consulting Engineer.

Born in 1921, male, Canadian. Dipl.-Ing. in 1943 at T.H. Stuttgart, Dr.techn. in 1948 at Univ. Wien and assistant at chair for turbomachinery and regulation. Industrial design of pumps and turbines. Senior Engineer, Snowy Mountains Hydro Elec. Authority, Sydney, Australia. Executive Engineer, Morse & Co., Fairbanks, USA. Calculation, design, model test, large mass flow axial pumps (watersupply to Chicago and Florida) and radial pumps. Prof. at Univ. Laval (until 1989), Québec, Canada. Design of pump-turbines and turbines, measurements of large power turbines; efficiency, vibrations and governor parameters. Development of autonomous turbines of small power. Consulting activities in various countries.

Rainer Nordmann, Professor,
Department of Mechanical Engineering,
University of Kaiserslautern, Germany.

Born in 1943, male, German. Dipl.-Ing. in 1970 at T.H. Darmstadt. Education and research at Univ. of Kaiserslautern since 1980 on rotordynamics, finite elements, modal analysis and parameter identification with applications to vibrations in turbomachinery. Actual research is in the field of fluid structure interactions (bearings, seals, balance pistons, impellers) of turbopumps and in mechatronics.

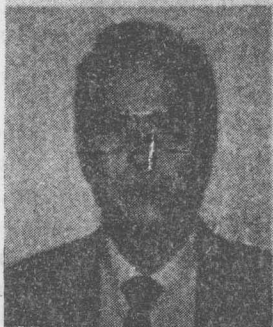
Werner Diewald, Design Department,
BASF AG, Ludwigshafen, Germany.

Born in 1958, male, German. Dipl.-Ing. in 1985 and Dr.-Ing. in 1989 at Univ. of Kaiserslautern. Education and research at Univ. of Kaiserslautern since 1985 on dynamic characteristics of turbopumps, machine dynamics and control theory. Since 1990 design department of BASF company for reactors and agitator vessels.



Michele Fanelli, Professor, Engineer,
Deputy Director of Centre for Hydraulic and
Structural Research, ENEL (Italian National
Power Board), Milano, Italy.

Born in 1931, male, Italian. Degree in hydraulic Engineering in 1954 at Univ. of Bologna (Italy); Diploma Ingénieur Hydraulicien de l'Université de Grenoble in 1956 at Grenoble (France); free-teaching Professorship in technique of constructions at Rome, 1970. Employed first by Edison Society and then by ENEL. Extended experience in dam analysis and design, hydraulic transients, physical hydraulic modeling, instationary behaviour of hydraulic machinery and systems.



Rafael Guarga, Professor, Director,
Institute of Fluid Mechanics and
Environmental Engineering (IFMEE),
University of Uruguay.

Born in 1940 in Uruguay. Mechanical engineer, graduate of Univ. of Uruguay. Dr.-Ing. in 1988 at National University of Mexico (UNAM). Assistant Prof. at Univ. of Uruguay until 1973. Researcher at Univ. of Mexico until 1985 and until today IFMEE Director. Research and education since 1980 on dynamic behaviour of hydraulic machinery, hydraulic transients in pressure conduits, stability of swirl flow in Francis and Kaplan units, combustion chambers and hydrocyclones.



Michihiro Nishi, Professor,
Department of Mechanical Engineering,
Kyushu Institute of Technology, Japan.

Born in 1943, male, Japanese. Graduated from School of Engineering Teachers, Kyushu Univ. in 1965. Dr. Eng. (Kyushu Univ.) in 1976. Studies on fluid dynamics at Res. Inst. of Industrial Sci., Kyushu Univ. from 1965 to 1971. Education and research at Kyushu Inst. Tech since 1971 on fluid mechanics of internal flow, boundary layer control, diffuser performance, draft tube surging and flow measurement.

Eduard Egusquiza, Professor.
Department. of Fluid Mechanics,
Polytechnical University of Catalonia
(UPC) at Barcelona, Spain.

Born in Barcelona. Industrial Eng. and Dr. Eng. by the UPC. Assistant and Associate Prof. in 1977-83 at the Faculty of Industrial Eng. (ETSEI) in Terrassa. Prof. in 1983 at the Univ. of Oviedo. Prof. in 1988 at the ETSEI in Barcelona. Research on unsteady flows, flow induced vibrations and condition monitoring in turbomachinery (axial flow fans and hydraulic turbines). Researches also on molten metals.

Shrikant Bhawe, Senior Deputy General Manager, Corporate R&D Division, Bharat Heavy Electricals Limited, Hyderabad, India.

Born in 1942, male, Indian. BE in 1964 at M.S. University, Baroda, M.E. in 1967 at M.S. University, Baroda and Ph.D. in 1975 at Univ. of Kanpur. 10 years teaching experience in Department of Mechanical Engineering, Univ. of Kanpur till 1976. Research in the area of vibration and stress analysis in rotating machinery, trouble shooting in power plant equipments, up-rating and life extension studies of power plants.

