Flow-Induced Vibration Handbook for Nuclear and Process Equipment

Michel J. Pettigrew, Colette E. Taylor
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Registered Office
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Library of Congress Cataloging-in-Publication Data applied for:

ISBN: 9781119810964

Cover Design: Wiley
Cover Images: © iStock\olegback

Set in 9.5/12.5pt STIX Two Text by Straive, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface *xv*
Acknowledgments *xvii*
Contributors *xix*

1 Introduction and Typical Vibration Problems *1*
Michel J. Pettigrew
1.1 Introduction *1*
1.2 Some Typical Component Failures *2*
1.3 Dynamics of Process System Components *9*
1.3.1 Multi-Span Heat Exchanger Tubes *9*
1.3.2 Other Nuclear and Process Components *10*
Notes *10*
References *10*

2 Flow-Induced Vibration of Nuclear and Process Equipment: An Overview *13*
Michel J. Pettigrew and Colette E. Taylor
2.1 Introduction *13*
2.1.1 Flow-Induced Vibration Overview *13*
2.1.2 Scope of a Vibration Analysis *14*
2.2 Flow Calculations *14*
2.2.1 Flow Parameter Definition *14*
2.2.2 Simple Flow Path Approach *15*
2.2.3 Comprehensive 3-D Approach *16*
2.2.4 Two-Phase Flow Regime *18*
2.3 Dynamic Parameters *18*
2.3.1 Hydrodynamic Mass *18*
2.3.2 Damping *19*
2.4 Vibration Excitation Mechanisms *25*
2.4.1 Fluidelastic Instability *25*
2.4.2 Random Turbulence Excitation *27*
2.4.3 Periodic Wake Shedding *31*
2.4.4 Acoustic Resonance *34*
2.4.5 Susceptibility to Resonance *35*

2.5 Vibration Response Prediction *36*
2.5.1 Fluidelastic Instability *37*
2.5.2 Random Turbulence Excitation *38*
2.5.3 Periodic Wake Shedding *38*
2.5.4 Acoustic Resonance *38*
2.5.5 Example of Vibration Analysis *38*
2.6 Fretting-Wear Damage Considerations *40*
2.6.1 Fretting-Wear Assessment *40*
2.6.2 Fretting-Wear Coefficients *41*
2.6.3 Wear Depth Calculations *42*
2.7 Acceptance Criteria *42*
2.7.1 Fluidelastic Instability *42*
2.7.2 Random Turbulence Excitation *43*
2.7.3 Periodic Wake Shedding *43*
2.7.4 Tube-to-Support Clearance *43*
2.7.5 Acoustic Resonance *43*
2.7.6 Two-Phase Flow Regimes *43*
Note *43*
References *44*

3 Flow Considerations *47*
John M. Pietralik, Liberat N. Carlucci, Colette E. Taylor, and Michel J. Pettigrew
3.1 Definition of the Problem *47*
3.2 Nature of the Flow *48*
3.2.1 Introduction *48*
3.2.2 Flow Parameter Definitions *50*
3.2.3 Vertical Bubbly Flow *54*
3.2.4 Flow Around Bluff Bodies *55*
3.2.5 Shell-Side Flow in Tube Bundles *56*
3.2.6 Air-Water versus Steam-Water Flows *63*
3.2.7 Effect of Nucleate Boiling Noise *63*
3.2.8 Summary *67*
3.3 Simplified Flow Calculation *67*
3.4 Multi-Dimensional Thermalhydraulic Analysis *74*
3.4.1 Steam Generator *74*
3.4.2 Other Heat Exchangers *78*
Acronyms *81*
Nomenclature *81*
Subscripts *82*
Notes *83*
References *83*

4 Hydrodynamic Mass, Natural Frequencies and Mode Shapes *87*
Daniel J. Gorman, Colette E. Taylor, and Michel J. Pettigrew
4.1 Introduction *87*
4.2 Total Tube Mass *88*

4.2.1 Single-Phase Flow *89*
4.2.2 Two-Phase Flow *90*
4.3 Free Vibration Analysis of Straight Tubes *93*
4.3.1 Free Vibration Analysis of a Single-Span Tube *94*
4.3.2 Free Vibration Analysis of a Two-Span Tube *97*
4.3.3 Free Vibration Analysis of a Multi-Span Tube *99*
4.4 Basic Theory for Curved Tubes *100*
4.4.1 Theory of Curved Tube In-Plane Free Vibration *102*
4.4.2 Theory of Curved Tube Out-of-Plane Free Vibration *104*
4.5 Free Vibration Analysis of U-Tubes *105*
4.5.1 Setting Boundary Conditions for the In-Plane Free Vibration Analysis of U-Tubes Possessing Geometric Symmetry *106*
4.5.2 Development of the In-Plane Eigenvalue Matrix for a Symmetric U-Tube *109*
4.5.3 Generation of Eigenvalue Matrices for Out-of-Plane Free Vibration Analysis of U-Tubes Possessing Geometric Symmetry *109*
4.5.4 Free Vibration Analysis of U-Tubes Which Do Not Possess Geometric Similarity *112*
4.6 Concluding Remarks *114*
Nomenclature *115*
References *116*

5 Damping of Cylindrical Structures in Single-Phase Fluids *119*
Michel J. Pettigrew
5.1 Introduction *119*
5.2 Energy Dissipation Mechanisms *119*
5.3 Approach *123*
5.4 Damping in Gases *124*
5.4.1 Effect of Number of Supports *127*
5.4.2 Effect of Frequency *128*
5.4.3 Vibration Amplitude *128*
5.4.4 Effect of Diameter or Mass *128*
5.4.5 Effect of Side Loads *128*
5.4.6 Effect of Higher Modes *129*
5.4.7 Effect of Support Thickness *129*
5.4.8 Effect of Clearance *132*
5.5 Design Recommendations for Damping in Gases *132*
5.6 Damping in Liquids *133*
5.6.1 Tube-to-Fluid Viscous Damping *133*
5.6.2 Damping at the Supports *136*
5.6.3 Squeeze-Film Damping *138*
5.6.4 Damping due to Sliding *141*
5.6.5 Semi-Empirical Formulation of Tube-Support Damping *143*
5.7 Discussion *147*
5.8 Design Recommendations for Damping in Liquids *148*
5.8.1 Simple Criterion Based on Available Data *148*
5.8.2 Criterion Based on the Formulation of Energy Dissipation Mechanisms *148*

Nomenclature *149*
Subscripts *150*
References *151*

6 Damping of Cylindrical Structures in Two-Phase Flow *155*
Michel J. Pettigrew and Colette E. Taylor
6.1 Introduction *155*
6.2 Sources of Information *155*
6.3 Approach *157*
6.4 Two-Phase Flow Conditions *158*
6.4.1 Definition of Two-Phase Flow Parameters *158*
6.4.2 Flow Regime *161*
6.5 Parametric Dependence Study *162*
6.5.1 Effect of Flow Velocity *163*
6.5.2 Effect of Void Fraction *163*
6.5.3 Effect of Confinement *168*
6.5.4 Effect of Tube Mass *168*
6.5.5 Effect of Tube Vibration Frequency *168*
6.5.6 Effect of Tube Bundle Configuration *169*
6.5.7 Effect of Motion of Surrounding Tubes *169*
6.5.8 Effect of Flow Regime *170*
6.5.9 Effect of Fluid Properties *171*
6.6 Development of Design Guidelines *172*
6.7 Discussion *177*
6.7.1 Damping Formulation *177*
6.7.2 Two-Phase Damping Mechanisms *177*
6.8 Summary Remarks *178*
Nomenclature *178*
Subscripts *179*
Note *179*
References *180*

7 Fluidelastic Instability of Tube Bundles in Single-Phase Flow *183*
Michel J. Pettigrew and Colette E. Taylor
7.1 Introduction *183*
7.2 Nature of Fluidelastic Instability *183*
7.3 Fluidelastic Instability: Analytical Modelling *185*
7.4 Fluidelastic Instability: Semi-Empirical Models *186*
7.5 Approach *191*
7.6 Important Definitions *191*
7.6.1 Tube Bundle Configurations *191*
7.6.2 Flow Velocity Definition *191*
7.6.3 Critical Velocity for Fluidelastic Instability *196*
7.6.4 Damping *197*
7.6.5 Tube Frequency *198*

7.7 Parametric Dependence Study *198*
7.7.1 Flexible versus Rigid Tube Bundles *198*
7.7.2 Damping *201*
7.7.3 Pitch-to-Diameter Ratio, *P/D* *201*
7.7.4 Fluidelastic Instability Formulation *204*
7.8 Development of Design Guidelines *206*
7.9 In-Plane Fluidelastic Instability *209*
7.10 Axial Flow Fluidelastic Instability *212*
7.11 Concluding Remarks *213*
Nomenclature *214*
Subscript *214*
References *215*

8 Fluidelastic Instability of Tube Bundles in Two-Phase Flow *219*
Michel J. Pettigrew and Colette E. Taylor
8.1 Introduction *219*
8.2 Previous Research *219*
8.2.1 Flow-Induced Vibration in Two-Phase Axial Flow *220*
8.2.2 Flow-Induced Vibration in Two-Phase Cross Flow *221*
8.2.3 Damping Studies *221*
8.3 Fluidelastic Instability Mechanisms in Two-Phase Cross Flow *221*
8.4 Fluidelastic Instability Experiments in Air-Water Cross Flow *224*
8.4.1 Initial Experiments in Air-Water Cross Flow *224*
8.4.2 Behavior in Intermittent Flow *227*
8.4.3 Effect of Bundle Geometry *229*
8.4.4 Flexible versus Rigid Tube Bundle Behavior *230*
8.4.5 Hydrodynamic Coupling *232*
8.5 Analysis of the Fluidelastic Instability Results *234*
8.5.1 Defining Critical Mass Flux and Instability Constant *234*
8.5.2 Comparison with Results of Other Researchers *235*
8.5.3 Summary of Air-Water Tests *238*
8.6 Tube Bundle Vibration in Two-Phase Freon Cross Flow *239*
8.6.1 Introductory Remarks *239*
8.6.2 Background Information *240*
8.6.3 Experiments in Freon Cross Flow *240*
8.7 Freon Test Results and Discussion *244*
8.7.1 Results and Analysis *244*
8.7.2 Proposed Explanations *247*
8.7.3 Concluding Remarks *247*
8.7.4 Summary Findings *249*
8.8 Fluidelastic Instability of U-Tubes in Air-Water Cross Flow *250*
8.8.1 Experimental Considerations *250*
8.8.2 U-Tube Dynamics *251*
8.8.3 Vibration Response *251*
8.8.4 Out-of-Plane Vibration *251*
8.8.5 In-Plane Vibration *254*

8.9 In-Plane (In-Flow) Fluidelastic Instability *255*
8.9.1 In-Flow Experiments in a Wind Tunnel *255*
8.9.2 In-Flow Experiments in Two-Phase Cross Flow *255*
8.9.3 Single-Tube Fluidelastic Instability Results *256*
8.9.4 Single Flexible Column and Central Cluster Fluidelastic Instability Results *258*
8.9.5 Two Partially Flexible Columns *258*
8.9.6 In-Flow Fluidelastic Instability Results and Discussion *261*
8.10 Design Recommendations *261*
8.10.1 Design Guidelines *261*
8.10.2 Fluidelastic Instability with Intermittent Flow *263*
8.11 Fluidelastic Instability in Two-Phase Axial Flow *264*
8.12 Concluding Remarks *265*
Nomenclature *265*
Subscripts *266*
Note *266*
References *266*

9 Random Turbulence Excitation in Single-Phase Flow *271*
Colette E. Taylor and Michel J. Pettigrew
9.1 Introduction *271*
9.2 Theoretical Background *271*
9.2.1 Equation of Motion *272*
9.2.2 Derivation of the Mean-Square Response *273*
9.2.3 Simplification of Tube Vibration Response *274*
9.2.4 Integration of the Transfer Function *275*
9.2.5 Use of the Simplified Expression in Developing Design Guidelines *275*
9.3 Literature Search *277*
9.4 Approach Taken *277*
9.5 Discussion of Parameters *279*
9.5.1 Directional Dependence (Lift versus Drag) *279*
9.5.2 Bundle Orientation *279*
9.5.3 Pitch-to-Diameter Ratio (P/D) *279*
9.5.4 Upstream Turbulence *280*
9.5.5 Fluid Density (Gas versus Liquid) *283*
9.5.6 Summary *283*
9.6 Design Guidelines *284*
9.7 Random Turbulence Excitation in Axial Flow *287*
Nomenclature *287*
References *288*

10 Random Turbulence Excitation Forces Due to Two-Phase Flow *291*
Colette E. Taylor and Michel J. Pettigrew
10.1 Introduction *291*
10.2 Background *291*
10.3 Approach Taken to Data Reduction *295*

10.4 Scaling Factor for Frequency *296*
10.4.1 Definition of a Velocity Scale *297*
10.4.2 Definition of a Length Scale *298*
10.4.3 Dimensionless Reduced Frequency *301*
10.4.4 Effect of Frequency *301*
10.5 Scaling Factor for Power Spectral Density *302*
10.5.1 Effect of Flow Regime *302*
10.5.2 Effect of Void Fraction *304*
10.5.3 Effect of Mass Flux *306*
10.5.4 Effect of Tube Diameter *306*
10.5.5 Effect of Correlation Length *306*
10.5.6 Effect of Bundle and Tube-Support Geometry *307*
10.5.7 Effect of Two-Phase Mixture *308*
10.5.8 Effect of Nucleate Boiling *310*
10.6 Dimensionless Power Spectral Density *311*
10.7 Upper Bounds for Two-Phase Cross Flow Dimensionless Spectra *314*
10.7.1 Bubbly Flow *314*
10.7.2 Churn Flow *315*
10.7.3 Intermittent Flow *316*
10.8 Axial Flow Random Turbulence Excitation *318*
10.9 Conclusions *323*
Nomenclature *324*
References *325*

11 Periodic Wake Shedding and Acoustic Resonance *329*
David S. Weaver, Colette E. Taylor, and Michel J. Pettigrew
11.1 Introduction *329*
11.2 Periodic Wake Shedding *332*
11.2.1 Frequency: Strouhal Number *332*
11.2.2 Calculating Tube Resonance Amplitudes *335*
11.2.3 Fluctuating Force Coefficients in Single-Phase Flow *336*
11.2.4 Fluctuating Force Coefficients in Two-Phase Flow *338*
11.2.5 The Effect of Bundle Orientation and *P/D* on Fluctuating Force Coefficients *346*
11.2.6 The Effect of Void Fraction and Flow Regime on Fluctuating Force Coefficients *347*
11.3 Acoustic Resonance *354*
11.3.1 Acoustic Natural Frequencies *354*
11.3.2 Equivalent Speed of Sound *355*
11.3.3 Acoustic Natural Frequencies $(f_a)_n$ *356*
11.3.4 Frequency Coincidence — Critical Velocities *356*
11.3.5 Damping Criteria *358*
11.3.6 Sound Pressure Level *361*
11.3.7 Elimination of Acoustic Resonance *364*

11.4 Conclusions and Recommendations *366*
Nomenclature *367*
References *369*

12 Assessment of Fretting-Wear Damage in Nuclear and Process Equipment *373*
Michel J. Pettigrew, Metin Yetisir, Nigel J. Fisher, Bruce A.W. Smith, and Victor P. Janzen
12.1 Introduction *373*
12.2 Dynamic Characteristics of Nuclear Structures and Process Equipment *374*
12.2.1 Heat Exchangers *374*
12.2.2 Nuclear Structures *375*
12.3 Fretting-Wear Damage Prediction *376*
12.3.1 Time-Domain Approach *376*
12.3.2 Energy Approach *380*
12.4 Work-Rate Relationships *380*
12.4.1 Shear Work Rate and Mechanical Power *380*
12.4.2 Vibration Energy Relationship *381*
12.4.3 Single Degree-of-Freedom System *381*
12.4.4 Multi-Span Beams Under Harmonic Excitation *382*
12.4.5 Response to Random Excitation *382*
12.4.6 Work-Rate Estimate: Summary *384*
12.5 Experimental Verification *384*
12.6 Comparison to Time Domain Approach *385*
12.7 Practical Applications: Examples *386*
12.8 Concluding Remarks *392*
Nomenclature *392*
Note *393*
References *394*

13 Fretting-Wear Damage Coefficients *397*
Nigel J. Fisher and Fabrice M. Guérout
13.1 Introduction *397*
13.2 Fretting-Wear Damage Mechanisms *397*
13.2.1 Impact Fretting Wear *397*
13.2.2 Trends *398*
13.2.3 Work-Rate Model *402*
13.3 Experimental Considerations *404*
13.3.1 Experimental Studies *404*
13.3.2 Room-Temperature Test Data *404*
13.3.3 High-Temperature Experimental Facility *407*
13.3.4 Wear Volume Measurements *409*
13.4 Fretting Wear of Zirconium Alloys *409*
13.4.1 Introduction *409*
13.4.2 Experimental Set-Up *410*
13.4.3 Effect of Vibration Amplitude and Motion Type *412*
13.4.4 Effect of Pressure-Tube Pre-Oxidation and Surface Preparation *412*

13.4.5 Effect of Temperature *412*
13.4.6 Effect of pH Control Additive and Dissolved Oxygen Content *413*
13.4.7 Discussions *414*
13.5 Fretting Wear of Heat Exchanger Materials *417*
13.5.1 Work-Rate Model and Wear Coefficient *417*
13.5.2 Effect of Test Duration *419*
13.5.3 Effect of Temperature *422*
13.5.4 Effect of Water Chemistry *424*
13.5.5 Effect of Tube-Support Geometry and Tube Materials *426*
13.5.6 Discussion *427*
13.6 Summary and Recommendations *429*
Nomenclature *429*
Notes *429*
References *430*

Component Analysis *433*
Introduction *433*
Analysis of a Process Heat Exchanger *435*
Analysis of a Nuclear Steam Generator U-Bend *445*

Subject Index *463*

Preface

Excessive flow-induced vibration causing failures by fatigue or fretting wear must be avoided in process and nuclear components. That is the purpose of this handbook. In this book, the term process components is used generally to describe nuclear reactor internals, nuclear fuels, piping systems, and all shell-and-tube heat exchangers, including nuclear steam generators, power plant condensers, boilers and coolers.

There are already a number of good books on flow-induced vibration. So, why another one? This handbook is to help engineers to design, operate, and diagnose heat transfer equipment. The emphasis in this handbook is on two-phase flow-induced vibration. Despite the fact that roughly half of all heat exchanger equipment operates in two-phase flow, previous flow-induced vibration texts have provided limited guidance regarding vibration induced by two-phase flow. The prediction of fretting-wear damage is another important priority. The state of the art is presented in the design guidelines, figures and tables. The use of these design guidelines is illustrated with example calculations. To assist students and new design engineers, the calculations are supplemented and presented with more explanation in an appendix.

Largely, this handbook is the outcome of some 40 years of research and development at the Canadian Nuclear Laboratories. The emphasis of this book is the presentation of design guidelines based on extensive analysis of the literature and, in particular, on experimental data obtained in the field and at the Canadian Nuclear Laboratories in Chalk River.

We believe that this book will be useful to engineering design firms in the nuclear, petrochemical and aerospace industries, graduate schools in mechanical engineering and technical support groups in operating nuclear and petrochemical plants. This handbook is not a textbook, although it could be used as a resource in a graduate course. We also hope that this book will help to stimulate further research in the area of two-phase flow-induced vibration.

Michel J. Pettigrew
Colette E. Taylor
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Acknowledgments

The authors would like to recognize the institutions and colleagues who have provided permissions, support and inspiration to this project. We begin by recognizing the publishers who have kindly given permission to use copyrighted tables and figures. Rather than add the requested recognition statements to each figure, the following general statements are provided to avoid repetition.

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This document is based on some 40 years of research and development conducted at Chalk River Laboratories in the area of flow-induced vibration. This technology development effort was largely supported by Atomic Energy of Canada Limited (AECL) and by the CANDU Owners Group (COG). It also received support from the Heat Transfer and Fluid Flow Service (HTFS), the Centre d'Etudes Nucleaires de Saclay (CEN-Saclay), the Pressure Vessel Research Council (PVRC) and the Washington Public Power Supply System (WPPSS). The support of all these organizations is very gratefully acknowledged. Many people have contributed to this effort including colleagues from industry and universities. Recognizing that we will fail to acknowledge all of our partners, we have decided to name some of the key individuals and institutions.

The authors have benefited from discussions with researchers in other institutions such as F. Axisa and B. Villard, Centre d'Etudes Nucleaires de Saclay; H.G.D. Goyder, UKAEA Harwell; R.T. Hartlen, Ontario Hydro; N.W. Mureithi and many graduate students at École Polytechnique, Montreal; I.G. Currie, University of Toronto; R.J. Rogers, University of New Brunswick and M.P. Païdoussis, McGill University.

Visiting scientists, B.S. Kim, Korea Power Engineering Company Inc., Taejon, Korea; A. Yasuo, Central Research Institute of Electric Power Industry, Japan; and Z.L. Qiao, Xian Jiaotong University, China, contributed to the development of the flow-induced vibration database.

The contributors would also like to recognize the input of colleagues from the Canadian Nuclear Laboratories throughout the past 50 years: J. Albrecht, K.M. Boucher, W.A. Cook, T. Dickinson, P. Feenstra, E.G. Hagberg, Y. Han, G. Knowles, J. Mastorakos, J. McGregor, K. Moore, J.N. Patrick, P.J. Smith, Y. Sylvestre, J. H. Tromp, M.K. Weckwerth, and T. Whan. These individuals ably assisted with construction, instrumentation and installation of various flow loops and test sections, as well as copious data analysis.

Finally, the authors wish to express our gratitude to our understanding partners in life, for allowing us to take the time to write this handbook and for their moral support.

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1

Introduction and Typical Vibration Problems

Michel J. Pettigrew

1.1 Introduction

Excessive flow-induced vibration must be avoided in process and nuclear system components. That is the purpose of this handbook. The term “process components” is used generally here to describe nuclear reactor internals, nuclear fuels, piping systems, and all shell-and-tube heat exchangers, including nuclear steam generators, power plant condensers, boilers, coolers, etc. Higher heat-transfer performance often requires higher flow velocities and more structural supports. On the other hand, additional supports may increase pressure drop and costs. The combination of high flow velocities and inadequate structural support may lead to excessive tube vibration. This vibration can cause failures by fatigue or fretting wear. Failures are very undesirable in terms of repair costs and lost production, particularly for high-capital-cost plants such as nuclear power stations, petroleum refineries and oil exploitation platforms. To prevent these problems at the design stage, a thorough flow-induced vibration analysis is recommended. Such analysis requires good understanding of the dynamic parameters and vibration excitation mechanisms that govern flow-induced vibration.

This handbook covers all relevant aspects of component vibration technology, namely: examples of vibration failures, flow analysis, and vibration excitation and damping mechanisms. The latter includes fluidelastic instability, periodic wake shedding, acoustic resonance, random turbulence, flow-induced vibration analysis and fretting-wear predictions.

Chapter 2 is an overview of flow-induced vibration technology. The reader should start with this chapter. In many cases, Chapter 2 will be sufficient to provide the required information. Each aspect of the technology is covered in detail in the succeeding chapters. Typically, each chapter includes a review of the state of the art, available laboratory data, brief review of theoretical considerations and modeling, parametric analysis, recommendations for design, and sample calculations.

The performance of process components is often limited by excessive vibration in a localized area, e.g., near inlets, outlets, etc. The combination of detailed flow calculations and vibration technology allows the designer to avoid such problems. Flow velocities and support design can be optimized to allow maximum heat transfer in all regions of process components, resulting in higher heat-transfer performance, less corrosion and fouling problems and reduced component size. The latter means capital cost reduction and a more competitive manufacturing industry.

This handbook is for the practicing engineer who is designing or troubleshooting nuclear and process system components. Design guidelines are proposed based on extensive analysis of the

Flow-Induced Vibration Handbook for Nuclear and Process Equipment, First Edition.
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literature and, in particular, on experimental data obtained in the field and at the Canadian Nuclear Laboratories of Atomic Energy of Canada Limited at Chalk River, Ontario, Canada. Although it is not intended as an undergraduate text book, it could be useful as a source of design data and practical examples. To assist students and new design engineers, the example calculations provided throughout this handbook are supplemented and presented with more explanation in Appendix A.

There are already several useful books on flow-induced vibration, e.g. Au-Yang (2001), Blevins (1990), Chen (1987), Kaneko et al (2014), Naudascher and Rockwell (1994), and Païdoussis (1998). So, why another one in the form of a handbook? This book is complementary to the above books for the following reasons. This book has greater emphasis on design guidelines. Much experimental data is presented in the form of comprehensive data bases that include a significant number of two-phase flow results. Particular attention is given to damping in single- and two-phase flow, two-phase flow-induced vibration mechanisms such as fluidelastic instability and random turbulence excitation, and the prediction of fretting-wear damage. Simple examples of calculations are given throughout the handbook.

1.2 Some Typical Component Failures

In heat exchangers, tube failures due to fretting wear may occur at the tube supports or at midspan if the tubes vibrate with sufficient amplitude to contact each other. Figure 1-1 shows an example of tube-to-tube fretting wear. It occurred in the U-bend of an early nuclear steam generator with tubes that were inadequately supported near the outlet in a region of high-velocity two-phase cross flow. Extensive fretting-wear damage was also observed between tube and tube support, as shown in Fig. 1-2. Here, the damage was sufficient to cause a hole in the tube resulting in leakage between tube-side and shell-side. Obviously, this kind of problem must be avoided. An additional support near the outlet region was an easy solution to this problem.

Figure 1-3 shows extensive tube-to-tube fretting-wear damage in the inlet region of a triple segmental liquid-liquid process heat exchanger. The problem was due to the combination of long tube spans (1.45 m) and high flow velocities impinging directly on the tubes in the inlet region. Lacing

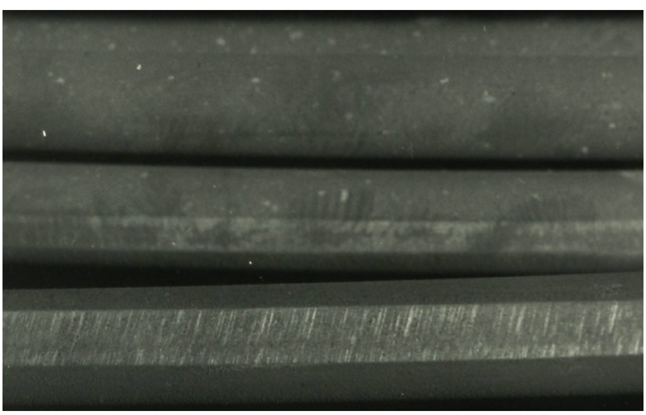

Fig. 1-1 Tube-to-Tube Fretting Wear in the U-Bend Region of an Early Nuclear Steam Generator (Pettigrew, 1976).

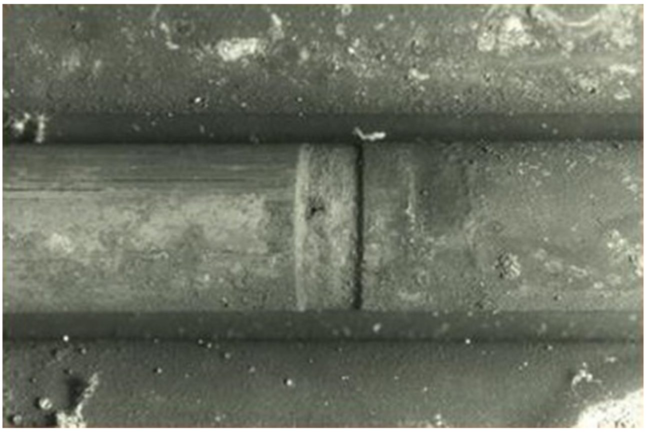

Fig. 1-2 Tube-to-Support Fretting Wear: Note Hole Through Tube Wall (Pettigrew, 1976).

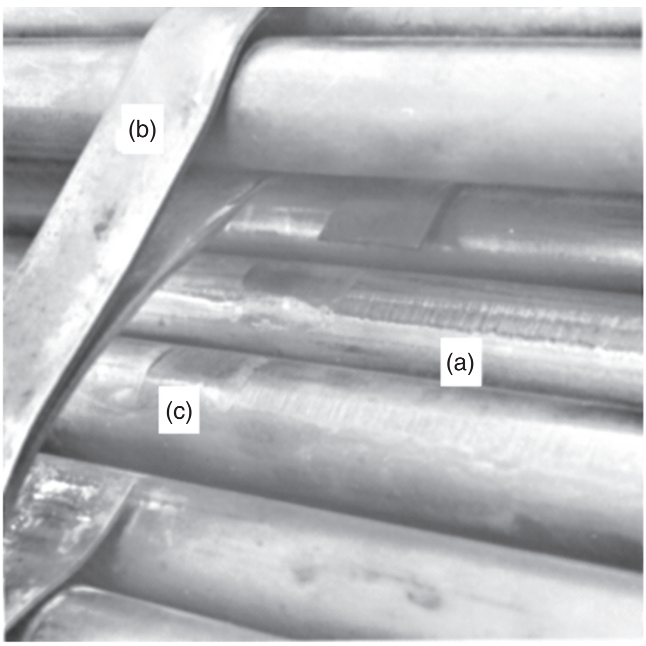

Fig. 1-3 Fretting Wear in the Inlet Region of a Liquid Process Heat Exchanger: a) Tube-to-Tube Initial Damage, b) Lacing Strip, and c) Damage at Lacing Strip Location (Pettigrew, 1976).

strips were installed to support the tubes near the inlet. Unfortunately, they were excessively loose. Fretting wear occurred between the tube and the lacing strips. Tubes wore through, as shown in Fig. 1-4. Eventually, proper baffle-supports were installed, as shown in Fig. 1-5. No further problems occurred.

In power condensers, very-high-velocity steam may impinge on the tubes, causing excessive vibration. Figure 1-6 shows a fatigue failure of a titanium condenser tube. The vibration amplitude was

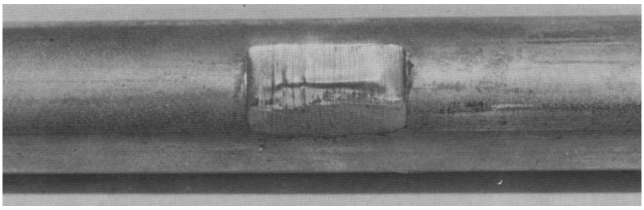

Fig. 1-4 Fretting Wear Through Tube Wall at a Lacing Strip Location in a Process Heat Exchanger (Pettigrew et al, 1977).

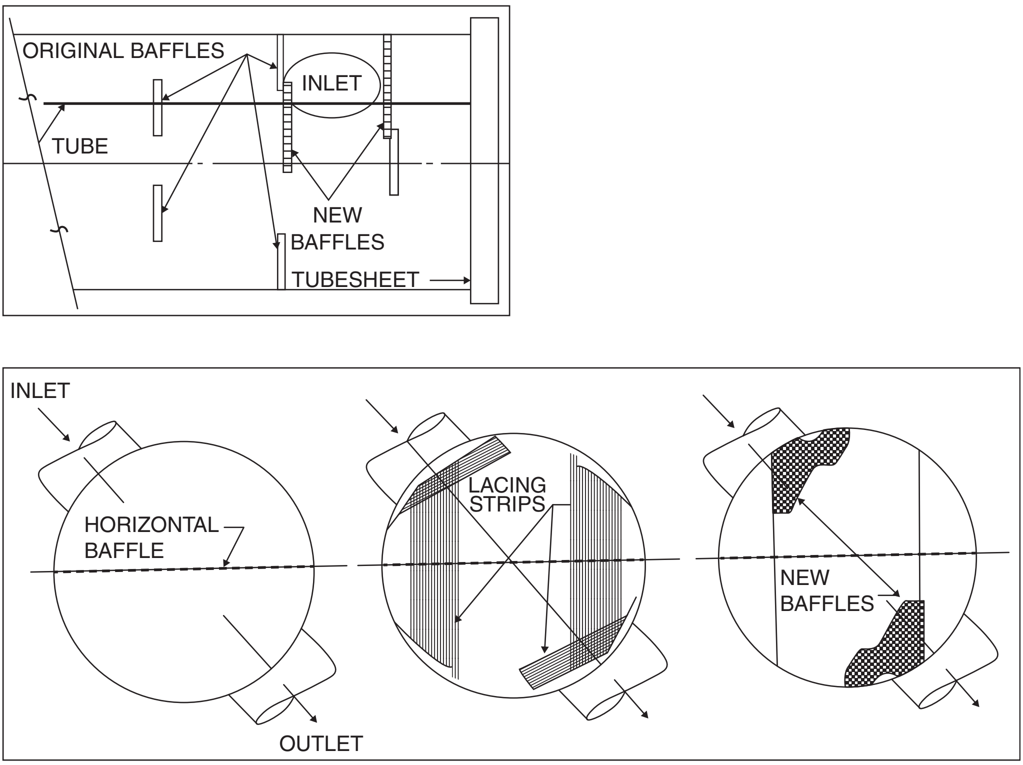

Fig. 1-5 Fretting Wear of Process Heat Exchanger: Repair (Pettigrew and Campagna, 1979 / with permission of Atomic Energy of Canada Limited).

sufficient for the tubes to contact each other at midspan. In this case, the condenser was operated with only four of the six tube bundles, resulting in 150% of design flow velocity. Operation at 100% design flow did not cause any vibration damage.

Figure 1-7 shows tube-to-tube fretting-wear damage in another power condenser. In this case, the damage was sufficient to wear through the tube wall, causing leakage of sea water into the secondary side of a power plant.

An example of fretting-wear damage of a tube located just beyond the baffle cut (window tube) vibrating against a baffle edge is shown in Fig. 1-8. This tube came from a gas-to-gas heat exchanger,

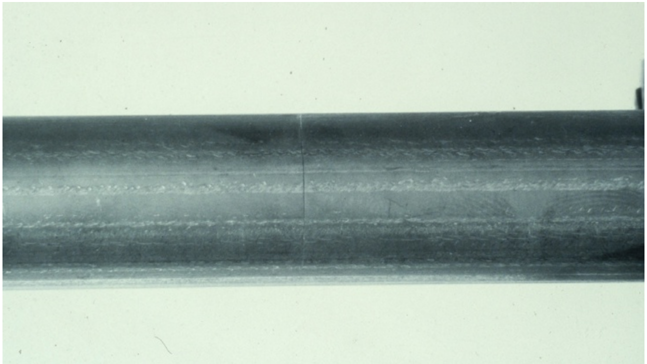

Fig. 1-6 Fatigue Failure of a Titanium Tube in a Nuclear Power Plant Condenser (Pettigrew et al, 1991).

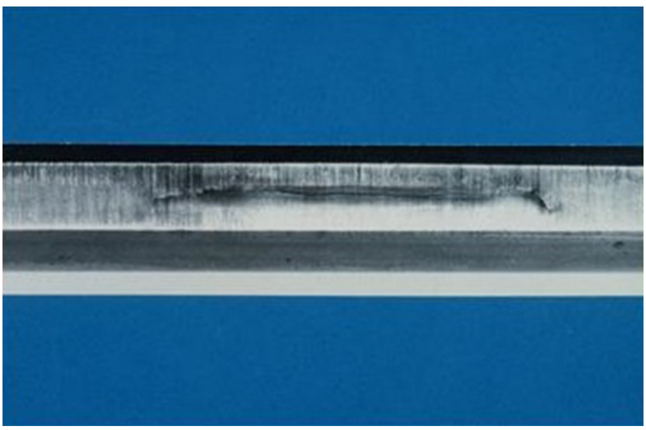

Fig. 1-7 Tube-to-Tube Fretting Wear in a Power Plant Condenser.

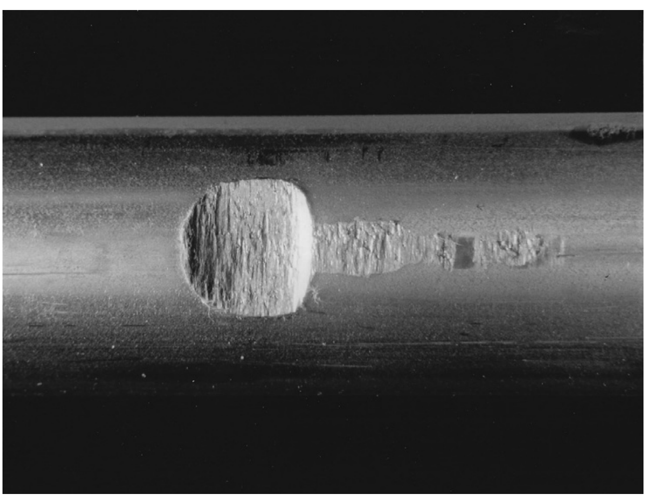

Fig. 1-8 Fretting Wear of a Gas Heat Exchanger Tube at a Baffle Edge Location.

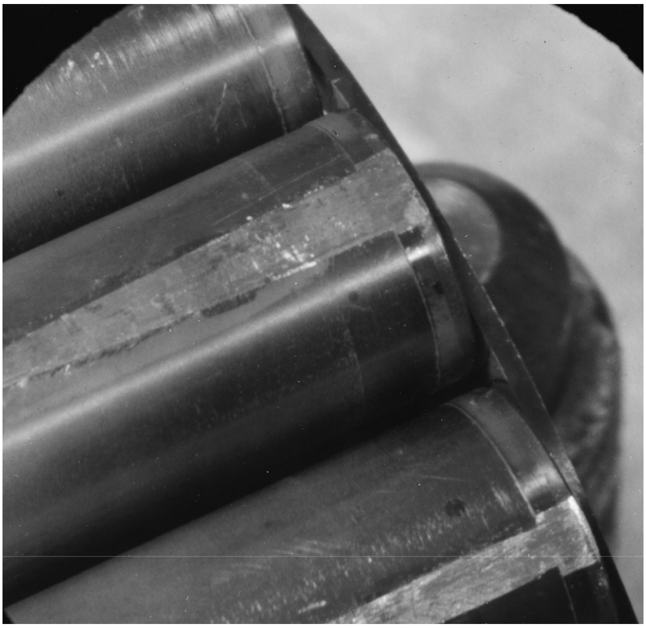

Fig. 1-9 Fretting-Wear Damage on Nuclear Fuel (Hot Cell Examination) (Pettigrew, 1976).

which was inadvertently operated at several times above design flow during a commissioning operation.

Figure 1-9 is an example of fretting wear of nuclear fuel as seen through an optical magnifier during "hot cell" examination. The damage occurred at the top of fuel string assemblies in 40% of the high flow fuel channels of a prototype CANDU-BLW®[1] nuclear station. The fuel strings were inserted in upward-flow vertical fuel channels where they were attached at the bottom and free at the top. The flow in each channel became two-phase as boiling occurred along the fuel and reached approximately 16% steam quality near the top. The mass flux was typically 4400 kg/m^2 s. The fretting problem was attributed to transverse flow-induced vibration of the fuel strings. Inadvertently, some of the fuel strings were assembled eccentrically. This caused the strings to be bent and promoted fretting wear. The corrective measures taken were to ensure concentric assembly of the fuel and increase fuel string flexural rigidity to reduce vibration.

One of the most costly vibration related problems took place in the early 1990s at the Darlington Nuclear Power Station, where nuclear fuel bundles were seriously damaged by fatigue and fretting wear (Fig. 1-10). The cost of investigation, repairs and particularly lost production totalled approximately 1 billion dollars Canadian. The problem was caused by acoustic resonance in the inlet headers due to coincidence of the pump pressure pulsation frequency, (30 Hz x 5 vanes = 150 Hz) and the natural acoustic frequency of the headers. The pressure pulsations were transmitted and amplified in the fuel channels, subjecting the fuel bundles to significant pressure fluctuations causing extensive damage. The problem was solved by simply replacing the five-vane pump impellers by seven-vane impellers, thus eliminating the acoustic resonance.

Sometimes vibration problems develop because of changes in operating conditions. For example, pressurized water reactor (PWR) fuel failures occurred in the 1990s due to fretting wear between fuel rods and support grids. The problem was related to longer fuel residence time, which caused increased clearances between the rods and grids due to creep, and deregulation of fuel

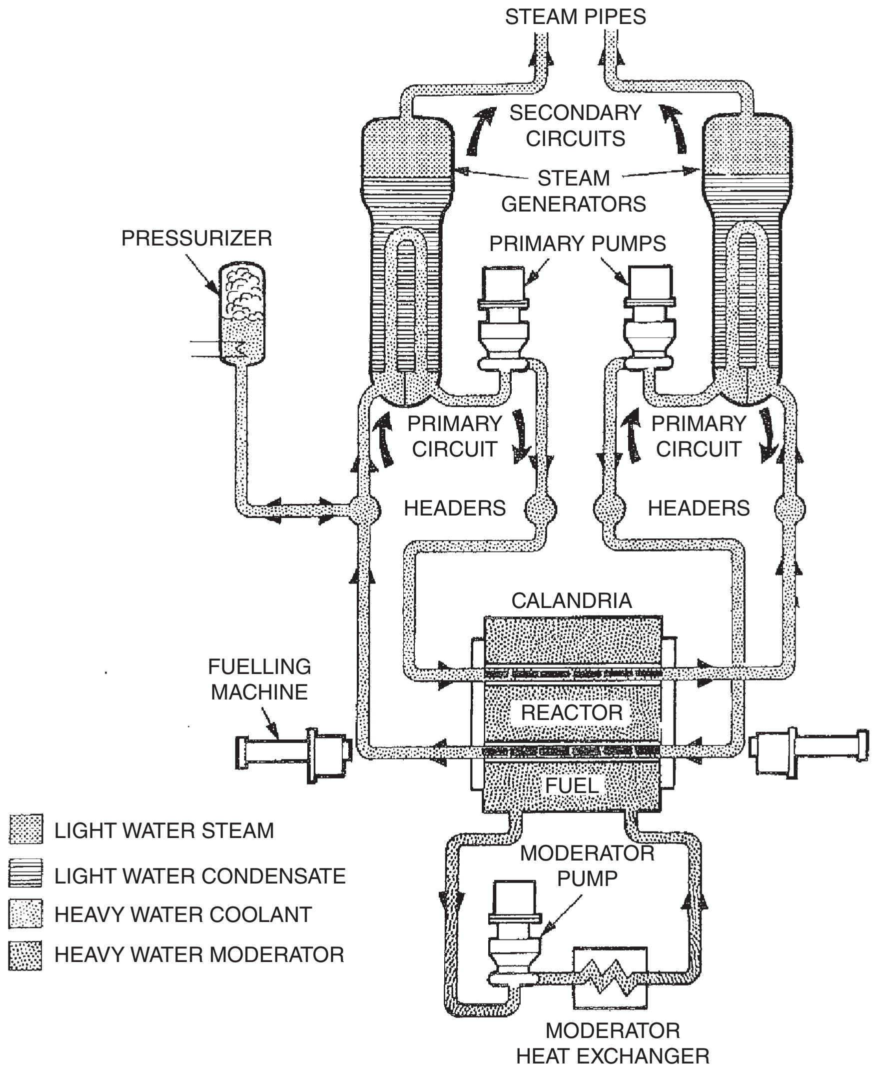

Fig. 1-10 Schematic Drawing of CANDU-PHW®2 Reactor (Pettigrew, 1978 / with permission of Atomic Energy of Canada Limited)

procurement. The latter allowed fuels from different suppliers at the same time in the reactor core. Differences in design caused slight differences in impedance resulting in increased cross flows and, thus, more flow-induced vibration excitation. Changes in support grid design solved this problem.

Vibration problems are not limited to material damage such as fatigue and fretting wear. For example, excessive vibration of control absorber guide tubes due to jet impingement could have caused a serious reactor control problem (see Fig. 1-11a). The problem was avoided by shielding the guide tube with a protective shroud, as shown in Fig. 1-11b.

Many other vibration problems have been encountered, such as fatigue failures of PWR core barrel tie rods and in-core instrumentation nozzles, excessive acoustic noise due to control valve

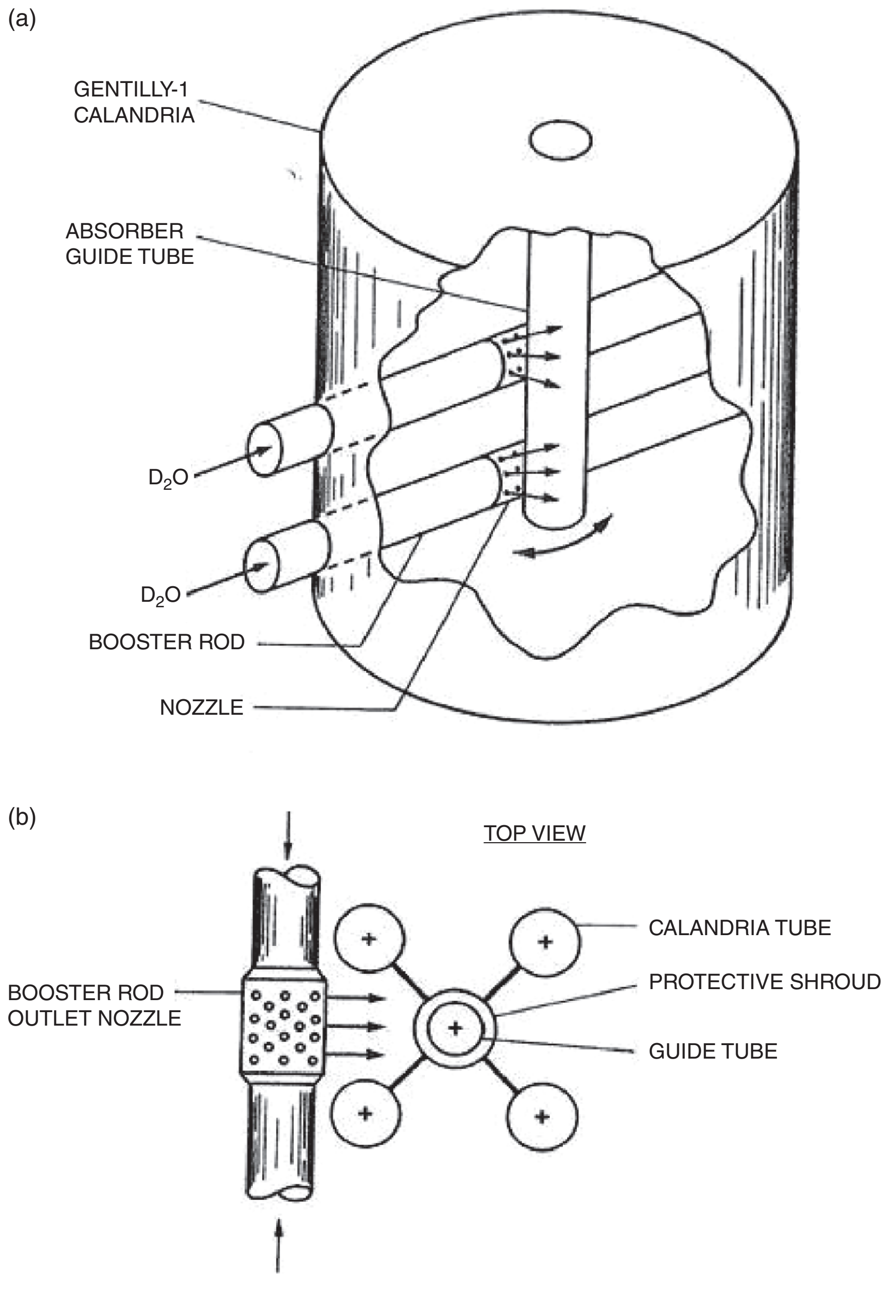

Fig. 1-11 a) Control Absorber Guide Tube Vibration due to Jetting, b) Modification with Protective Shroud (Pettigrew, 1976 / with permission of Atomic Energy of Canada Limited).

dynamics and mechanical damage resulting from acoustic resonance in gas heat exchangers. Although most vibration problems have very costly consequences, they are usually solved by simple design modifications or changes in operating conditions. After the fact, it is easy to see that most problems could have been avoided by proper understanding of flow-induced vibration phenomena.