

Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

---

## FLUID-STRUCTURE INTERACTIONS

Structures in contact with fluid flow, whether natural or man-made, are inevitably subject to flow-induced forces and flow-induced vibration: from plant leaves to traffic signs and to more substantial structures, such as bridge decks and heat exchanger tubes. Under certain conditions the vibration may be self-excited, and it is usually referred to as an instability. These instabilities and, more specifically, the conditions under which they arise are of great importance to designers and operators of the systems concerned because of the significant potential to cause damage in the short term. Such flow-induced instabilities are the subject of this book. In particular, the flow-induced instabilities treated in this book are associated with cross-flow, that is, flow normal to the long axis of the structure, although the book does not aim to cover every possible type. Instead it treats a specific set of problems that are fundamentally and technologically important: galloping, vortex-shedding oscillations under lock-in conditions, and rain-and-wind-induced vibrations, among others. The emphasis throughout is on providing a physical description of the phenomena that is as clear and up-to-date as possible.

Michael P. Paidoussis is a Mechanical Engineering professor at McGill University. He is a Fellow of the Royal Society of Canada, the Canadian Academy of Engineering, the Canadian Society for Mechanical Engineering (CSME), the Institution of Mechanical Engineers (IMEchE), the American Society of Mechanical Engineers (ASME), and the American Academy of Mechanics (AAM). Professor Paidoussis is the founding editor of the *Journal of Fluids and Structures*. His principal research interests are in fluid-structure interactions, flow-induced vibrations, aero- and hydroelasticity, dynamics, nonlinear dynamics, and chaos.

Stuart J. Price is a Mechanical Engineering professor at McGill University. His research is focused on the dynamics and stability of structures exposed to a fluid flow. The topics studied are inspired by, and often directly related to, real engineering problems – for example, heat exchangers, offshore structures, overhead transmission lines, and aircraft structures.

Emmanuel de Langre is a professor of Mechanics in École Polytechnique. He is an associate editor of the *Journal of Fluids and Structures*. He has worked as an engineer in the French nuclear industry. His principal research interests are in fluid-structure interactions and vibrations of engineering systems, such as heat exchangers and underwater offshore risers, but also of natural systems such as crops and trees moving under wind load.

Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

# Fluid-Structure Interactions

## CROSS-FLOW-INDUCED INSTABILITIES

**Michael P. Paidoussis**

McGill University

**Stuart J. Price**

McGill University

**Emmanuel de Langre**

École Polytechnique



**CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,  
São Paulo, Delhi, Dubai, Tokyo, Mexico City

Cambridge University Press

32 Avenue of the Americas, New York, NY 10013-2473, USA

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9780521119429](http://www.cambridge.org/9780521119429)

© Michael P. Paidoussis, Stuart J. Price, and Emmanuel de Langre 2011

This publication is in copyright. Subject to statutory exception  
and to the provisions of relevant collective licensing agreements,  
no reproduction of any part may take place without the written  
permission of Cambridge University Press.

First published 2011

Printed in the United States of America

*A catalog record for this publication is available from the British Library.*

*Library of Congress Cataloging in Publication data*

Paidoussis, M. P.

Fluid-structure interactions : cross-flow-induced instabilities / Michael Paidoussis, Stuart Price, Emmanuel de Langre.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-521-11942-9

1. Fluid-structure interaction. 2. Unsteady flow (Fluid dynamics) I. Price, Stuart, 1951– II. Langre, Emmanuel de, 1958–. III. Title.

TA356.5.F58P346 2010

624.1'7–dc22

2010031766

ISBN 978-0-521-11942-9 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

## Contents

|  |                |
|--|----------------|
| <i>Preface</i>   | <i>page ix</i> |
| <b>1 Introduction</b> . . . . .                                    | <b>1</b>       |
| 1.1 General Overview   | 1              |
| 1.2 Concepts and Mechanisms  | 3              |
| 1.2.1 Self-excited oscillations and instabilities                  | 4              |
| 1.2.2 Argand diagrams and bifurcations                             | 8              |
| 1.2.3 Energy considerations  | 12             |
| 1.3 Notation   | 13             |
| 1.4 Contents of the Book   | 14             |
| <b>2 Prisms in Cross-Flow – Galloping</b> . . . . .                | <b>15</b>      |
| 2.1 Introductory Comments  | 15             |
| 2.2 The Mechanism of Galloping                                     | 19             |
| 2.2.1 The linear threshold of galloping                            | 20             |
| 2.2.2 Nonlinear aspects  | 24             |
| 2.3 Further Work on Translational Galloping                        | 30             |
| 2.3.1 The effect of sectional shape                                | 30             |
| 2.3.2 Novak’s “universal response curve” and continuous structures | 38             |
| 2.3.3 Unsteady effects and analytical models                       | 43             |
| 2.3.4 Some comments on the flow field                              | 45             |
| 2.3.5 Shear-layer reattachment                                     | 49             |
| 2.4 Low-Speed Galloping  | 50             |
| 2.5 Prisms and Cylinders with a Splitter Plate                     | 55             |
| 2.6 Wake Breathing and Streamwise Oscillation                      | 62             |
| 2.6.1 Wake breathing of the first type                             | 62             |
| 2.6.2 Wake breathing of the second type                            | 64             |
| 2.7 Torsional Galloping  | 66             |
| 2.7.1 General comments   | 66             |
| 2.7.2 Linear quasi-steady analysis                                 | 67             |
| 2.7.3 Nonlinear quasi-steady analysis                              | 70             |

|          |   |            |
|----------|---|------------|
| 2.7.4    | Disqualification of quasi-steady theory   | 72         |
| 2.7.5    | Unsteady theory   | 75         |
| 2.8      | Multi-Degree-of-Freedom Galloping   | 77         |
| 2.8.1    | Quasi-steady models   | 77         |
| 2.8.2    | Unsteady models   | 81         |
| 2.9      | Turbulence and Shear Effects  | 81         |
| 2.10     | Conjoint Galloping and Vortex Shedding  | 86         |
| 2.11     | Elongated and Bridge-Deck Sections  | 90         |
| 2.12     | Concluding Remarks  | 102        |
| <b>3</b> | <b>Vortex-Induced Vibrations</b> . . . . .  | <b>105</b> |
| 3.1      | Elementary Case   | 105        |
| 3.2      | Two-Dimensional VIV Phenomenology   | 108        |
| 3.2.1    | Bluff-body wake instability   | 110        |
| 3.2.2    | Wake instability of a fixed cylinder  | 112        |
| 3.2.3    | Wake of a cylinder forced to move   | 115        |
| 3.2.4    | Cylinder free to move   | 120        |
| 3.3      | Modelling Vortex-Induced Vibrations   | 124        |
| 3.3.1    | A classification of models  | 124        |
| 3.3.2    | Type A: Forced system models  | 127        |
| 3.3.3    | Type B: Fluidelastic system models  | 129        |
| 3.3.4    | Type C: Coupled system models   | 132        |
| 3.4      | Advanced Aspects  | 139        |
| 3.4.1    | The issue of added mass   | 139        |
| 3.4.2    | From sectional to three-dimensional VIV   | 146        |
| 3.4.3    | VIV of noncircular cross-sections   | 149        |
| 3.4.4    | Summary and concluding remarks  | 153        |
| <b>4</b> | <b>Wake-Induced Instabilities of Pairs and Small Groups of Cylinders</b> . . .          | <b>155</b> |
| 4.1      | The Mechanisms  | 155        |
| 4.1.1    | Modified quasi-steady theory  | 156        |
| 4.1.2    | The damping-controlled mechanism  | 157        |
| 4.1.3    | The wake-flutter mechanism  | 158        |
| 4.2      | Wake-Induced Flutter of Transmission Lines  | 160        |
| 4.2.1    | Analysis for a fixed windward conductor   | 162        |
| 4.2.2    | Analysis for a moving windward conductor  | 183        |
| 4.2.3    | Three-dimensional effects and application to real<br>transmission lines                 | 192        |
| 4.3      | Fluidelastic Instability of Offshore Risers   | 195        |
| 4.3.1    | Experimental evidence for the existence of fluidelastic<br>instability in riser bundles | 196        |
| 4.3.2    | Analytical models   | 200        |
| <b>5</b> | <b>Fluidelastic Instabilities in Cylinder Arrays</b> . . . . .                          | <b>215</b> |
| 5.1      | Description, Background, Repercussions  | 215        |
| 5.2      | The Mechanisms  | 220        |
| 5.2.1    | The damping-controlled one-degree-of-freedom<br>mechanism                               | 220        |

Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

## Contents

vii

|          |  |            |
|----------|--|------------|
| 5.2.2    | Static divergence instability                                  | 223        |
| 5.2.3    | The stiffness-controlled wake-flutter mechanism                | 224        |
| 5.2.4    | Dependence of the wake-flutter mechanism on mechanical damping | 227        |
| 5.2.5    | Wake-flutter stability boundaries for cylinder rows            | 229        |
| 5.2.6    | Concluding remarks   | 230        |
| 5.3      | Fluidelastic Instability Models                                | 232        |
| 5.3.1    | Jet-switch model   | 232        |
| 5.3.2    | Quasi-static models  | 235        |
| 5.3.3    | Unsteady models  | 239        |
| 5.3.4    | Semi-analytical models   | 249        |
| 5.3.5    | Quasi-steady models  | 254        |
| 5.3.6    | Computational fluid-dynamic models                             | 261        |
| 5.3.7    | Nonlinear models   | 265        |
| 5.3.8    | Nonuniform flow  | 270        |
| 5.4      | Comparison of the Models                                       | 274        |
| 5.4.1    | Experimental support for and against Connors' equation         | 275        |
| 5.4.2    | Comparison of theoretical models with experimental data        | 277        |
| 5.4.3    | State of the art   | 287        |
| <b>6</b> | <b>Ovalling Instabilities of Shells in Cross-Flow</b>          | <b>291</b> |
| 6.1      | A Historical Perspective                                       | 291        |
| 6.2      | The Vortex-Shedding Hypothesis                                 | 293        |
| 6.3      | Ovalling with No Periodic Vortex Shedding                      | 296        |
| 6.3.1    | Païdoussis and Helleur's 1979 experiments                      | 296        |
| 6.3.2    | In search of a new cause                                       | 302        |
| 6.4      | Further Evidence Contradicting Vortex-Shedding Hypothesis      | 304        |
| 6.4.1    | Further experiments with cantilevered shells                   | 304        |
| 6.4.2    | Experiments with clamped-clamped shells                        | 307        |
| 6.5      | Counterattack by the Vortex-Shedding Proponents and Rebuttal   | 311        |
| 6.5.1    | The "peak of resonance" argument                               | 311        |
| 6.5.2    | Have splitter plates been ineffectual?                         | 312        |
| 6.5.3    | Dénouement   | 313        |
| 6.6      | Simple Aeroelastic-Flutter Model                               | 314        |
| 6.6.1    | Equations of motion and boundary conditions                    | 315        |
| 6.6.2    | Solution of the equations                                      | 317        |
| 6.6.3    | Theoretical results and comparison with experiment             | 319        |
| 6.7      | A Three-Dimensional Flutter Model                              | 322        |
| 6.7.1    | The model and methods of solution                              | 323        |
| 6.7.2    | Theoretical results  | 327        |
| 6.7.3    | Comparison with experiment                                     | 329        |
| 6.7.4    | Improvements to the theory                                     | 331        |
| 6.8      | An Energy-Transfer Analysis                                    | 334        |
| 6.9      | Another Variant of the Aeroelastic-Flutter Model               | 338        |
| 6.9.1    | The flutter model  | 338        |
| 6.9.2    | Typical results  | 340        |
| 6.9.3    | An empirical relationship for $U_{thr}$                        | 342        |
| 6.10     | Concluding Remarks   | 344        |

Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

viii

Contents

|  |     |
|--|-----|
| <b>7 Rain-and-Wind-Induced Vibrations</b> . . . . .  | 345 |
| 7.1 Experimental Evidence  | 345 |
| 7.1.1 Field cases  | 345 |
| 7.1.2 Wind-tunnel experiments  | 346 |
| 7.2 Modelling Rainwater Rivulets   | 348 |
| 7.2.1 Development of rivulets  | 348 |
| 7.2.2 Tearing of rivulets  | 349 |
| 7.3 VIV, Galloping and Drag Crisis   | 351 |
| 7.4 Yamaguchi's Model: A Cylinder-Rivulet-Coupled Instability                                  | 354 |
| 7.5 Concluding Remarks   | 355 |
| <i>Epilogue</i>  | 357 |
| <i>Appendix A The Multiple Scales Method</i>   | 359 |
| <i>Appendix B Measurement of Modal Damping for the Shells Used<br/>in Ovalling Experiments</i> | 361 |
| <i>References</i>  | 365 |
| <i>Index</i>   | 397 |

## Preface

Structures in contact with fluid flow, whether natural (e.g. wind and ocean currents) or man-made, are inevitably subject to flow-induced forces and flow-induced vibration: from plant leaves to traffic signs, to more substantial structures, such as bridge decks and heat-exchanger tubes. These vibrations may be of small or large amplitude, and they may be inconsequential, or of mild or even grave concern.

Consider overhead transmission lines, bridges, tall buildings, and chimneys subjected to wind, offshore risers and umbilicals in ocean currents, cylinders and cylindrical tube arrays in power-generating and chemical plants, for example. Such structures vibrate to some extent at any flow velocity, e.g. due to turbulence or vortex shedding. If the vibrations are of small amplitude, they may lead to fatigue or fretting wear *in the long term*. However, under certain circumstances, the vibration amplitude is large, and damage may occur *in the short term*, in hours or weeks. Moreover, the vibration may be *self-excited*. Typically, but not universally, such vibration is associated with a threshold of flow velocity: on one side of the threshold, oscillations due to some perturbation imparted to the system die out; on the other side, oscillations grow. More generally, we may define self-excited vibration simply as one that grows exponentially with time until it settles down to a limit-cycle motion. Clearly, such phenomena, more specifically the conditions under which they arise, are of great importance to designers and operators of the systems concerned, because of the great potential to cause damage in the short term. Such *flow-induced instabilities* are the subject of this book.

In particular, the flow-induced instabilities treated in this book are associated with cross-flow, i.e. flow normal to the long axis of the structure(s), presuming the geometry is such; i.e. we are mostly concerned with more or less slender structures in cross-flow. These *cross-flow-induced instabilities* are known to be very severe and to occur in the range of natural or engineering flow velocities. Axial-flow-induced instabilities are treated in other books.

Cross-flow about slender structures generally involves flow separation, making its modelling quite difficult compared with axial-flow-related analyses. For that reason, cross-flow-induced instability models inevitably involve some degree of empiricism, and progress in their understanding has only been possible via the intimate interweaving of theory and experiment.



Cambridge University Press

978-0-521-11942-9 - Fluid-Structure Interactions: Cross-Flow-Induced Instabilities

Michael P. Paidoussis, Stuart J. Price and Emmanuel de Langre

Frontmatter

[More information](#)

It is not the aim of this monograph to cover every possible type of cross-flow-induced instability. Instead, a specific set of problems is treated which are fundamentally and technologically important: galloping, vortex-shedding oscillations (VIV) under lock-in conditions, rain-and-wind-induced vibrations (RWIV), wake-induced vibrations of small groups of cylinders and flow-induced instabilities of arrays of cylinders, galloping and flutter of bridge decks, and ovaling oscillations of cylindrical shells (e.g. chimney stacks). Flutter in aeronautical structures is not treated in this book.

The emphasis throughout is to provide as clear a physical description of the phenomena as possible, as well as the state of the art in each topic, both in terms of physical understanding and means of prediction. Each topic is first treated in a simplified way, affording an easy grasp of the fundamentals; this is followed by more sophisticated treatment, ending with the most up-to-date state of the art. Care is taken to provide a coherent and fair account of the historical aspects of each topic. An extensive list of references is provided to direct the interested reader to the primary sources, if desired.

This is a monograph for engineers and applied scientists interested in these topics – researchers and practicing professionals alike, working in wind and ocean engineering and in the power-generating industry. It can also serve as a textbook in a graduate-level course.

We are grateful to the Natural Sciences and Engineering Research Council (NSERC) of Canada and Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) of Québec, as well as l'Institut Français du Pétrole, le Centre National de la Recherche Scientifique (CNRS), École Polytechnique, and McGill University.

Writing a book involves hard work and necessitates relentless concentration of effort from time to time, which has meant “disappearances” into our respective offices. We are very grateful to our respective spouses Vrisseis (*Βρισηϊς*), Carol, and Sabine for their forbearance and relentless support.

Finally, we express our unbounded gratitude to Mary Fiorilli for helping in the overall organization and for typing large tracts of the text with such loving care and exemplary commitment.

Michael P. Paidoussis  
Stuart J. Price  
Emmanuel de Langre