SHIGEHIKO KANEKO | TOMOMICHI NAKAMURA | FUMIO INADA |
MINORU KATO | KUNIHIKO ISHIHARA | TAKASHI NISHIHARA |
TRANSLATORS: NJUKI W. MUREITHI AND MIKAEL A. LANGTHJEM

SECOND EDITION

FLOW-INDUCED VIBRATIONS

CLASSIFICATIONS AND LESSONS FROM PRACTICAL EXPERIENCES

AP

Flow-Induced Vibrations

Classifications and Lessons from Practical Experiences

Second Edition

Editors

Shigehiko Kaneko

Tomomichi Nakamura

Fumio Inada

Minoru Kato

Kunihiko Ishihara

Takashi Nishihara

Njuki W. Mureithi

Translating editor

Mikael A. Langthjem

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

Academic Press is an imprint of Elsevier
32 Jamestown Road, London NW1 7BY, UK
225 Wyman Street, Waltham, MA 02451, USA
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA

Second Edition 2014

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-098347-9

For information on all Academic Press publications
visit our website at elsevierdirect.com

Typeset by MPS Limited, Chennai, India
www.adi-mps.com

Printed and bound in Great Britain

14 15 16 17 18 10 9 8 7 6 5 4 3 2 1

Preface

The soundness of the energy plant system and its peripheral equipment is attracting strong interest not only from people in industry engaged in nuclear power generation, thermal power generation, hydroelectric power generation and chemical plant operation etc., but also from ordinary citizens. In addition, abnormal vibrations and noise that arise in aircraft and automobiles, for example, are also important problems related to reliability.

One of the key factors inhibiting the soundness of the energy plant system and reliability of equipment is flow-induced vibration (FIV), which arises via flow and structural system coupling or flow acoustics and structural system coupling. Research on FIV, ranging from basic research in laboratories to practical research at the prototypical industrial scale in various research institutes around the world, has been widely carried out.

However, the number of incidents due to flow-induced vibration or noise generation leading to structural failure does not show any signs of significant decline. Indeed, there is an increase in the number of incidents, which might lead to loss of confidence from society as well as economic loss. Problems in nuclear power stations are a case in point.

The reason why such phenomena arise is because a network for the purpose of transmission of knowledge and information on flow-induced vibration between researchers, designers, builders and operation managers has not been constituted.

Once a vibration problem arises, it must be solved in a short time. To achieve this, investigation of similar past cases is energetically carried out. However, the number of well-documented previous cases with useful information is very limited due to the veil of business secrecy.

It is against this background that the researchers who gathered at the Japan Society of Mechanical Engineers FIV workshops undertook the task of extracting the most useful information from the literature reviewed at the series of workshops over the past 27 years.

The information has been put together in the form of a database in which fundamental knowledge on flow-induced vibration is explained in detail and the information vital for the designer is conveniently compiled and consolidated.

The first edition issued in 2003, which comprises the core part of the database, was composed of six chapters, which are:

1. Introduction, 2. Vibration induced by cross-flow, 3. Vibration induced by external axial flow, 4. Vibrations induced by internal fluid flow, 5.Vibration induced by pressure waves in piping, 6. Acoustic vibration and noise caused by heat (now titled: Heating-related oscillations and noise). In the second edition, two more chapters, i.e., 7. Vibrations in rotary machines and, 8. Vibrations in

fluid–structure interaction systems, are added to complete the systematization of flow-induced vibration analysis, evaluation and research.

We hope this volume will be useful to engineers and students both for the systematic evaluation and understanding of flow-induced vibration and in contributing to the creation of new research topics based on knowledge acquired in the field.

Representatives of the technical section on FIV,
Japan Society of Mechanical Engineers

Shigehiko Kaneko
(The University of Tokyo)

Tomomichi Nakamura
(Osaka Sangyo University)

Fumio Inada
(Central Research Institute of Electric Power Industry)

Minoru Kato
(Kobelco Research Institute, Inc.)

Kunihiko Ishihara
(Tokushima Bunri University)

Takashi Nishihara
(Central Research Institute of Electric Power Industry)

Njuki W. Murethi
(Polytechnique Montreal)

Mikael A. Langthjem
(Yamagata University)

List of Contributors

Takeshi Fujikawa
Ashiya University

Tsuyoshi Hagiwara
Toshiba Corporation

Itsuro Hayashi
Chiyoda Advanced Solutions Corporation

Kazuo Hirota
Mitsubishi Heavy Industries, Ltd.

Tohru Iijima
Muroran Technology Institute

Fumio Inada
Central Research Institute of Electric Power Industry

Kunihiko Ishihara
Tokushima Bunri University

Shigehiko Kaneko
University of Tokyo

Minoru Kato
Kobelco Research Institute, Inc.

Tatsuhiko Kiuchi
Toyo Engineering Corporation

Mikael A. Langthjem
Yamagata University

Hiroyuki Matsuda
Chiyoda Advanced Solutions Corporation

Shigeki Morii
MHI Soltech Corporation

Ryo Morita
Central Research Institute of Electric Power Industry

Hisayuki Motoi
IHI Corporation

Njuki W. Mureithi
Ecole Polytechnique Montreal

Hiroshi Nagakura
Mitsubishi Heavy Industries, Ltd.

Tomomichi Nakamura
Osaka Sangyo University

Akira Nemoto
Toshiba Corporation

Eiichi Nishida
Syonan Technical Institute

Takashi Nishihara
Central Research Institute of Electric Power Industry

Toru Okada
Kobe Stell, Ltd.

Noboru Saito
Toshiba Corporation

Masashi Sano
Shizuoka Institute of Science and Technology

Yoshihiko Urata
Shizuoka Institute of Science and Technology

Masahiro Watanabe
Aoyama Gakuin University

Kazuaki Yabe
Toyo Engineering Corporation

Kazuyuki Yamaguchi
Hitachi Corporation

Akira Yasuo
Central Research Institute of Electric Power Industry

Kimitoshi Yoneda
Central Research Institute of Electric Power Industry

Koichi Yonezawa
Osaka University

Contents

Preface xi
List of Contributors xiii

CHAPTER 1 Introduction 1
1.1 General overview 1
1.1.1 History of FIV research 1
1.1.2 Origin of this book 4
1.2 Modeling approaches 5
1.2.1 The importance of modeling 5
1.2.2 Classification of FIV and modeling 7
1.2.3 Modeling procedure 10
1.2.4 Analytical approach 12
1.2.5 Experimental approach 13
1.3 Fundamental mechanisms of FIV 15
1.3.1 Self-induced oscillation mechanisms 17
1.3.2 Forced vibration and added mass and damping 23
References 27

CHAPTER 2 Vibration Induced by Cross-Flow 29
2.1 Single circular cylinder 29
2.1.1 Structures under evaluation 29
2.1.2 Vibration mechanisms and historical review 31
2.1.3 Evaluation methods 38
2.1.4 Examples of component failures due to vortex-induced vibration 44
2.2 Two circular cylinders in cross-flow 46
2.2.1 Outline of structures of interest 46
2.2.2 Historical background 47
2.2.3 Evaluation methodology 52
2.2.4 Examples of practical problems 56
2.3 Multiple circular cylinders 57
2.3.1 Outline of structures considered 57
2.3.2 Vibration evaluation history 58
2.3.3 Estimation method 61
2.3.4 Examples of component failures 70

2.4 Bodies of rectangular and other cross-section shapes 70
2.4.1 General description of cross-section shapes 71
2.4.2 FIV of rectangular-cross-section structures and historical review 73
2.4.3 Evaluation methods 76
2.4.4 Examples of structural failures and suggestions for countermeasures 85
2.5 Acoustic resonance in tube bundles 87
2.5.1 Relevant industrial products and brief description of the phenomenon 87
2.5.2 Historical background 89
2.5.3 Resonance prediction method at the design stage 97
2.5.4 Examples of acoustic resonance problems and hints for anti-resonance design 102
2.6 Prevention of FIV 109
References 109

CHAPTER 3 Vibration Induced by External Axial Flow 117
3.1 Single cylinder/multiple cylinders 117
3.1.1 Summary of objectives 117
3.1.2 Random vibration due to flow turbulence 118
3.1.3 Flutter and divergence 127
3.1.4 Examples of reported component-vibration problems and hints for countermeasures 131
3.2 Vibration of elastic plates and shells 131
3.2.1 Bending–torsion flutter 132
3.2.2 Panel flutter 134
3.2.3 Shell flutter due to annular flow 136
3.2.4 Turbulence-induced vibration 137
3.2.5 Hints for countermeasures 138
3.3 Vibration induced by leakage flow 139
3.3.1 General description of the problem 139
3.3.2 Evaluation method for single-degree-of-freedom translational system 140
3.3.3 Analysis method for single-degree-of-freedom translational system with leakage-flow passage of arbitrary shape 143
3.3.4 Mechanism of self-excited vibration 147

3.3.5 Self-excited vibrations in other cases 149
3.3.6 Hints for countermeasures 152
3.3.7 Examples of leakage-flow-induced vibration 153
References 154

CHAPTER 4 Vibrations Induced by Internal Fluid Flow 157
4.1 Vibration of straight and curved pipes conveying fluid 157
4.1.1 Vibration of pipes conveying fluid 157
4.1.2 Vibration of pipes excited by oscillating and two-phase fluid flow 166
4.1.3 Piping vibration caused by gas–liquid two-phase flow 170
4.2 Vibration related to bellows 176
4.2.1 Vibration of bellows 176
4.2.2 Hints for countermeasures and examples of flow-induced bellows vibrations 188
4.3 Collapsible tubes 189
4.3.1 Summary 189
4.3.2 Self-excited vibration of collapsible tubes 190
4.3.3 Key to prevention of collapsible-tube vibration 193
References 193

CHAPTER 5 Vibration Induced by Pressure Waves in Piping 197
5.1 Pressure pulsation in piping caused by compressors 197
5.1.1 Summary 197
5.1.2 Explanation of the phenomenon, and the history of research/evaluation 197
5.1.3 Calculation and evaluation methods 199
5.1.4 Hints for countermeasures 207
5.1.5 Case studies 212
5.2 Pressure pulsations in piping caused by pumps and hydraulic turbines 215
5.2.1 Outline 215
5.2.2 Explanation of phenomena 215
5.2.3 Vibration problems and suggested solutions 232

5.3 Pressure surge or water hammer in piping system 235
5.3.1 Water hammer 235
5.3.2 Synopsis of investigation 235
5.3.3 Solution methods 236
5.3.4 Countermeasures 240
5.3.5 Examples of component failures 240
5.4 Valve-related vibration 245
5.4.1 Valve vibration 245
5.4.2 Coupled vibrations involving valves, fluid and piping 247
5.4.3 Problem cases 255
5.4.4 Hints for countermeasures against valve vibration 259
5.5 Self-excited acoustic noise due to flow separation 260
5.5.1 Summary 260
5.5.2 Outline of excitation mechanisms 261
5.5.3 Case studies and hints for countermeasures 267
References 269

CHAPTER 6 Heating-Related Oscillations and Noise 277
6.1 Acoustic oscillations and combustion noise 277
6.1.1 Introduction 277
6.1.2 Combustion-driven oscillations 279
6.1.3 Combustion roar 291
6.2 Oscillations due to steam condensation 294
6.2.1 Introduction 294
6.2.2 Characteristics and prevention 294
6.2.3 Examples of practical problems 296
6.3 Flow-induced vibrations related to boiling 299
6.3.1 Introduction 299
6.3.2 Vibration mechanisms 299
6.3.3 Analytical approach 299
6.3.4 Vibration/oscillation problems and solutions 303
References 307

CHAPTER 7 Vibrations in Rotary Machines 311
7.1 Vibration of blades and cascades 311
7.1.1 Overview and categorization of phenomena 311
7.1.2 Vibration of blades under gust loading (forced vibration) 314

7.1.3 Flutter of blades and cascades (self-excited vibration) ... 326
7.1.4 Blade damping ... 328
7.1.5 Numerical approach to evaluation of blade vibration ... 330
7.2 Vibrations of rotating bodies partially filled with liquid ... 334
7.2.1 Summary of phenomena ... 334
7.2.2 Research history ... 335
7.2.3 Self-excited vibration of a cylindrical rotating body partially filled with liquid ... 335
7.2.4 Hints for countermeasures ... 345
7.3 Vibration induced by annular flow in seals ... 346
7.3.1 Seal-related self-exciting vibration of rotors ... 346
7.3.2 Historical background ... 346
7.3.3 Stability analysis methods ... 347
7.3.4 Examples of practical problems ... 351
References ... 356

CHAPTER 8 Vibrations in Fluid–Structure Interaction Systems ... 359
8.1 Summary ... 359
8.2 Added mass and damping ... 361
8.2.1 Structures under evaluation ... 361
8.2.2 Evaluation methods ... 361
8.3 Sloshing and bulging ... 376
8.3.1 Overview ... 376
8.3.2 Description and historical review of vibration phenomena ... 376
8.3.3 Evaluation methods ... 377
8.3.4 Examples of sloshing problems and countermeasures ... 393
References ... 400

Index ... 403

CHAPTER

Introduction

1

1.1 General overview

Vibration and noise problems due to fluid flow occur in many industrial plants. This obstructs smooth plant operation and in serious cases can lead to significant maintenance and repair costs and costly losses in productivity. These flow-related vibration phenomena are generally known as 'flow-induced vibrations' (FIV). The term 'flow-induced vibration and noise' (FIVN) is used when flow-induced noise is present.

It is fairly evident that the fluid force acting on an obstacle in flow will vary due to the flow unsteadiness and that the varying force, in turn, may cause vibration of the obstacle. In the case of piping connected to reciprocating fluid machines, for example, it is well-known that the oscillating (fluctuating) flow in the piping generates excitation forces causing piping vibration.

However, even for steady flow conditions, vibration problems may be caused by vortex shedding behind obstacles or by other phenomena. The drag direction vibration of the thermocouple well in the fast-breeder reactor at Monju in Japan is an example of a vibration problem caused by the symmetric vortex shedding behind the well. This kind of self-excited FIV occurs even in steady flow, making it much more difficult to determine the underlying mechanism and thus, one of the most difficult problems to deal with at the design stage or during troubleshooting. Flow-induced acoustic noise is also an important problem in industry.

1.1.1 History of FIV research

Two conferences (Naudascher [1]; Naudascher and Rockwell [2]) on fluid-related vibration were held in 1972 and 1979, on the initiative of Prof. Naudascher of the University of Karlsruhe, Germany. At the 1979 conference, many practical problems related to flow-induced vibration and noise in a wide variety of industrial fields, such as mechanical systems, civil engineering, aircrafts, ships, and nuclear power plants, were presented. The conference included many interesting results that are still pertinent today.

In 1977, Dr. Robert Blevins wrote the first book [3] in the field. The term flow-induced vibration became popular after he used it for the book's title. In the book and probably for the first time, FIV phenomena were classified based on the two basic flow types: steady flow induced and unsteady flow related. Blevins went on to publish a handbook [4] focused on the frequencies and the eigenmodes of structural systems and fluid systems related to FIV. A second handbook (Blevins [5]), aimed at designers, gave systematic information for pipe flows, open water channels, separated flow, flow resistance, shear flow, etc. These handbooks contain valuable information on FIV-related problems and the underlying phenomena. The second edition of the book *Flow-Induced Vibration* (Blevins [6]) was published in 1990.

On the other side of the Atlantic, Prof. Naudascher in Germany wrote a book [7] on the hydraulic forces acting on dams and gates mainly from the civil engineering and hydraulics point of view. He and Prof. Rockwell co-authored a textbook [8] for designers where the vibration classifications are based on excitation mechanisms. The text is useful for the design of mechanical systems.

Several books focusing on specific phenomena have been written. These include a book [9] on cylindrical structures by Dr. S.S. Chen; a book [10] on the fluid–structure interaction (FSI) of pressure vessels by Dr. Morand and Dr. Ohayon; and two volumes [11] by Prof. Païdoussis dealing extensively with the subject of axial FIV. Païdoussis and Li [12] have written an important paper discussing pipes conveying fluids and the fundamental mechanisms behind the coupled fluid–structure oscillations. In the paper, the pipe conveying fluid problem was introduced as a model problem or paradigm useful for the understanding of the excitation mechanisms underlying FIV. Most recently, Païdoussis, Price and De Langre have published a book [13] dedicated to cross-flow-induced instabilities.

In Japan, a chapter [14] containing a detailed introduction to FIV was published in 1976. However, this formed only a small part of a large handbook on the vibration of fluid machines (including topics such as piping vibration and surging in reciprocating compressors). In 1980, the Japan Society of Mechanical Engineers (JSME) committee on FIV, under the leadership of Prof. Tajima, reviewed the state of the art in FIV, producing a report [15] which included many examples of experiences with flow-induced phenomena in Japanese industry. In 1989, another report [16] focusing on piping system pressure pulsations caused by reciprocating compressors was published under the leadership of Prof. Hayama. Other important papers have also been published on the excitation mechanisms underlying FIV (Iwatsubo [17]) or introducing examples from industrial experience (Fujita [18]).

On the specific topic of FIV in nuclear power plants, the Yayoi Research Seminar has been held since 1990 at the nuclear test facility of the University of Tokyo to introduce research studies and disseminate new information (Madarame [19]). The leader, Prof. Madarame, indicated at the first meeting that a FIV design support system such as depicted in Fig. 1.1 was required. The system incorporates analytical tools and a database on FIV. Such systems are already used in other fields. His idea later appeared in the form of published guidelines of the JSME. Examples include the guidelines [20] motivated by the steam generator tube failure in the Mihama nuclear power plant of the Kansai Electric Power Corporation

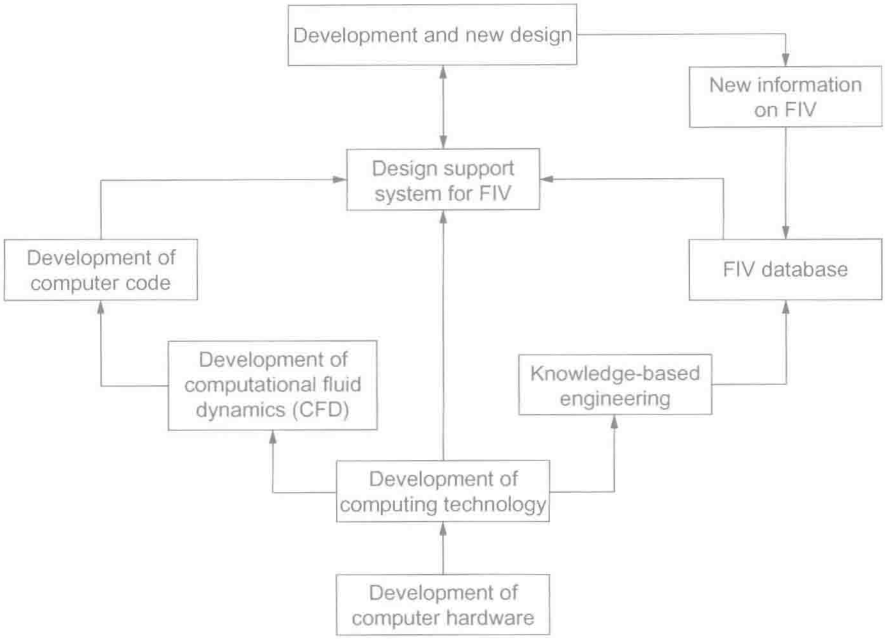

FIGURE 1.1

Design support system for FIV.

or the guidelines [21] developed following the thermocouple well failure in the Monju fast-breeder reactor.

With regard to flow-induced noise, an international conference was held in 1979 (Müller [22]), and a book on the subject was written by Blake [23] in 1986. In Japan, a book on *Examples of Noise & Vibration Resistance Systems* was published in 1990 by the Japanese Noise Control Academy [24]. The book includes many examples of flow-induced noise, making it very useful for designers. A paper (Maruta [25]) introducing the subject of FIV and including a review of recent research papers on noise was also published.

A number of important FIV meetings are held around the world. Within the American Society of Mechanical Engineers (ASME), the International Symposium on Fluid–Structure Interactions, Flow-Sound Interaction and Flow-Induced Vibration & Noise (FSI^2 & FIV+N) is held every 4 years. A FIV symposium is also held every second year at the ASME Pressure Vessel and Piping Conference. The latter is mainly geared toward the investigation of FIV problems in industrial pressure vessels & piping. In Europe, the International Conference on Flow-Induced Vibrations is also held every 4 years. This conference is related to the 1973 Keswick conference in England. The conference has since expanded to many fields. In Japan, a FIV session is held yearly during every JSME conference.

1.1.2 Origin of this book

The FIV seminar, which is held by the JSME, began in 1984 under the leadership of Profs. Hara (Science University of Tokyo) and Iwatsubo[1] (Kobe University at the time). The aim of the seminar is to collect and analyze worldwide information on FIV in the field of mechanical engineering, and to communicate this information to participants and Japanese researchers. More than 100 young researchers have attended this seminar. Its first-phase activities ended in February 1999. From April 1999, Prof. Kaneko took up the leadership of the second phase, to study and come up with the best method to use the information accumulated over more than 10 years of activities. The most important objective was to develop collaborations for future research and development using the technical information.

The main activity of the first phase was to gather information from around the world and present it to Japanese engineers and researchers. Reports on FIV problems and research papers from outside Japan were organized and translated into Japanese language summaries, which currently number more than 400. These organized files are considered to be of high quality because almost all Japanese specialists and researchers in FIV were involved. However, the information has, to date, not been compiled into a comprehensive document. This book is therefore intended to be an adequate reference documenting the present worldwide activities on FIV, but useful not only as an information source, but also as a resource for the creation of new knowledge.

FIV can be roughly divided into five fields. Similarly, the FIV seminar consists of five working groups who contributed to this book:

1. Vibration induced by cross-flow (Leader: Tomomichi Nakamura).
2. Vibration induced by parallel flow (Leader: Fumio Inada).
3. Vibration of piping conveying fluid, pressure fluctuation, and thermal excitation (Leader: Minoru Kato).
4. Vibrations in rotating structures in flow (Leader: Kunihiko Ishihara).
5. Vibrations in fluid–structure interaction systems (Leader: Takashi Nishihara).

The first edition of this book presented, as the first step, the results of work on the first three fields (above). In this second edition, material on these fields has been updated or revised and two new chapters have been added covering the final two subjects. Throughout the book, an effort has been made to include examples from actual practical experience to the extent possible. The description of a practical problem is followed by presentation of the evaluation method, the vibration mechanisms, and finally, practical hints for vibration prevention.

As outlined above, depending on the FIV problem, different evaluation methods are required. The different types of FIV problems are presented and explained in detail beginning in Chapter 2. It is recommended, however, to start by reading

[1]Currently at Nagahama corporation.

Sections 1.2 and 1.3 later in this chapter, where information on modeling and general basic mathematical methods that can be used, are first presented.

1.2 Modeling approaches

1.2.1 The importance of modeling

Figure 1.2 shows a semi circular pillar. The pillar is only lightly supported in the vertical and horizontal directions. How will the pillar respond when subjected to (wind) flow from left to right, as depicted in the figure?

A designer or technician with sufficient engineering knowledge would likely answer that the pillar will vibrate. We guess that the majority of engineers would answer that the pillar would vibrate in the direction transverse to the wind direction. Most, when asked to explain the cause of the vibration, are likely to suggest that vortex shedding behind the pillar is the source of the additional energy responsible for the vibrations.

For vortex-induced vibration (VIV), the typical analysis and resolution procedure is as depicted on the left in Fig. 1.3. This means proceeding as follows:

1. Determine the frequency of the vortex shedding responsible for the vibration excitation.
2. Measure the resonant frequency of the pillar.
3. Separate the structural frequency from the vortex shedding frequency as a countermeasure.

Changing the structural resonance frequency by changing the support conditions is more easily achievable than changing the vortex shedding frequency.

For the present problem though, the vortex excitation countermeasure presented in Fig. 1.3 would not work at all. It turns out that the pillar vibrates at a frequency far above the vortex shedding frequency. Thus, countermeasures based

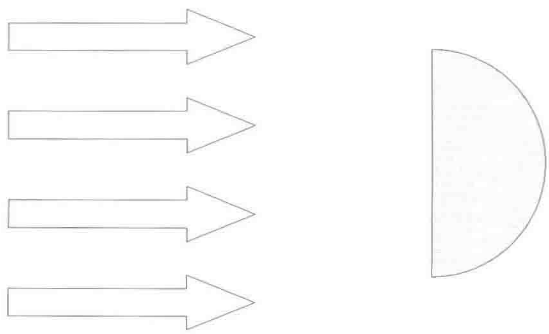

FIGURE 1.2

How will this half cylinder respond to wind flow?