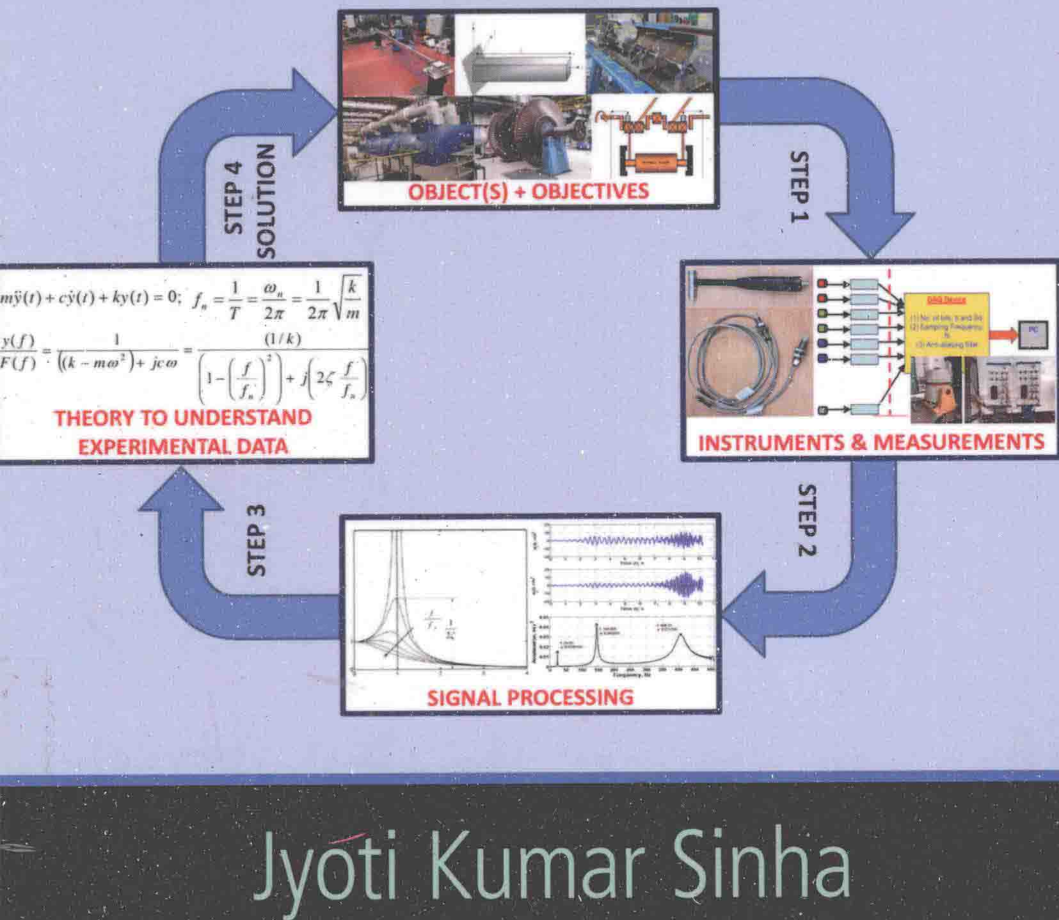
Vibration Analysis, Instruments, and Signal Processing



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Preface

Over the past four decades, the technology in vibration instrumentation and measurements, signal processing, and analytical simulation using finite element (FE) methods has advanced significantly. There are several dedicated books that have recorded these advancements. However, it has been consistently observed that several persons (students, researchers, designers, and maintenance personnel in industry) involved in, say, vibration-related works or research, do not fully comprehend the interrelation between theory and experiments. These individuals can be grouped as (1) good in vibration data collection but may not be aware of the applicable basic theory, and vice versa, (2) good in signal processing but may not know the basics of either the theory or vibration data collection and measurement procedures, and (3) involved in dynamic qualifications (FE analysis and modal testing) using standard commercially available software without knowing much about the basic principles and methods. It is imperative that persons involved in vibration-based analysis have at least a basic understanding of the different processes so that they can more effectively solve vibration-related problems.

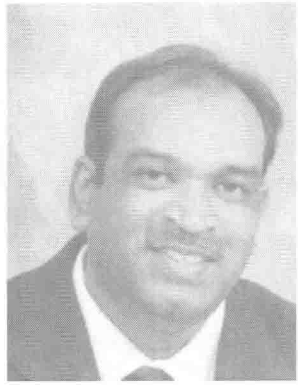
This book aims to communicate the fundamental principles of all three facets of vibration-based analysis (i.e., instruments and measurement, signal processing, and theoretical analysis) in a simplified tutorial manner, which is not readily available in literature. The unique content of this book will therefore be very useful for a diverse audience who are interested in vibration analysis. The target audience includes students (all levels), researchers, and engineers (involved in vibration-based condition monitoring). There are several chapters related to day-to-day requirements in vibration measurements and analysis so that the reader may become aware of the basics. He or she can then consult the many dedicated books in an area of interest if needed. A chapter is also added for real-life case studies relating the basic theory, types of measurements needed, and requisite signal processing that ultimately lead to effective fault diagnosis.

The author acknowledges his teachers and colleagues, particularly Prof. M.I. Friswell, Prof. Arthur Lees, Mr. K.K. Meher, Prof. R.I.K. Moorthy, Prof. P.M. Mujumdar, Mr. A. Rama Rao, Mr. R.K. Sinha, and Mr. B.C.B.N. Suryam. I am really thankful to Prof. R.I.K. Moorthy for his guidance at the beginning of my professional career and in research in the area of structural dynamics and vibration. I also acknowledge a number of the postgraduate students with industrial experience in the "Maintenance (Reliability) Engineering and Asset Management (MEAM/REAM)" MSc course and my diligent PhD students for their useful suggestions during the book's preparation.

Finally, I dedicate this book to my parents, Mr. Jagdish Prasad Sinha and Mrs. Chinta Sinha, my wife, Sarita Sinha, and my son, Aarambh Sinha. My parents stay miles away from me but give unconditional love to me every moment of my life. My wife and son are my real strength, with whom I share all the moments of my life.

Jyoti K. Sinha

About the Author



Dr. Jyoti K. Sinha joined the School of MACE, University of Manchester, in January 2007. He previously worked as a senior research scientist in the Bhabha Atomic Research Centre, India, for nearly 16 years. He also worked as a research fellow in Cranfield University, UK, for 18 months. He earned his bachelor's degree (Mech. Eng.) from BIT, Sindri (India), and master's degree (Aerospace Eng.) from IIT Bombay, Mumbai (India). He completed his PhD from the University of Wales Swansea (now Swansea University), UK.

His research area is in vibration and structural dynamics, using both experiments and analytical methods, including finite element (FE) model updating, vibration control, and health monitoring techniques. He is the recipient of the prestigious "Young Scientist (Boyscast) Fellowship" from the Department of Science and Technology, India, for his outstanding work in vibration diagnosis and structural dynamics related to the number of rotating machines and structural components of nuclear power plants (NPPs). Dr. Sinha has been extensively involved in a number of projects (nearly £2.5M) related to vibration and dynamics. He has also been instrumental in the development of a number of innovative techniques in his research area. He is the author of more than 60 technical reports and 135 technical papers in both international journals and conferences combined. He has delivered a number of invited lectures. Dr. Sinha is also the associate editor of two international journals, *Structural Health Monitoring: An International Journal* and *Advances in Vibration Engineering* (now *Journal of Vibration Engineering and Technology*), editorial board member of the journal *Structural Monitoring and Maintenance*, coauthor of two books, and a member of the Technical Committee on Rotor Dynamics, IFTOMM (2011 onward).

In academia, nine PhD and EngD students have completed their programs since January 2007 under Dr. Sinha's supervision in the different areas of vibration, rotordynamics, and signal processing. He has completed supervision of nearly 75 MSc dissertations, and he currently supervises a number of PhD students and MSc dissertations. Presently, Dr. Sinha is the principal investigator of different industrial projects related to steam and wind turbines in the areas of vibration-based condition monitoring, fault diagnosis, and life prediction.

Contents

1

Introduction

1.1 Introduction

Vibration measurements, tests, and analyses are becoming popular tools for several applications, a few of which are listed below:

- Design qualification and optimization
- Machine installation
- Health monitoring
  - Mechanical and civil structures
  - Machines
  - Human body, electrical panels, etc.

Over the decades, a significant advancement has been made in the experimental facilities and capabilities in terms of vibration instruments, sensors, and the computation power to analyze the experimental data. However, to achieve the requirements listed above, one needs a better understanding of dynamics and vibration behavior by both the experiments and theory. The correlation of the experimental observations with the theory is essential to suggesting a simple but effective and reliable solution. It has been observed that the following four aspects are very important to tackle any problem:

1. Understand the object(s) (e.g., structures, machines) and the objectives.
2. What kind of vibration instruments and experiments are required for measurements? This depends on the history of previous failures, malfunctioning in case of machinery, etc.
3. What kind of data processing is required for the measured vibration signals?

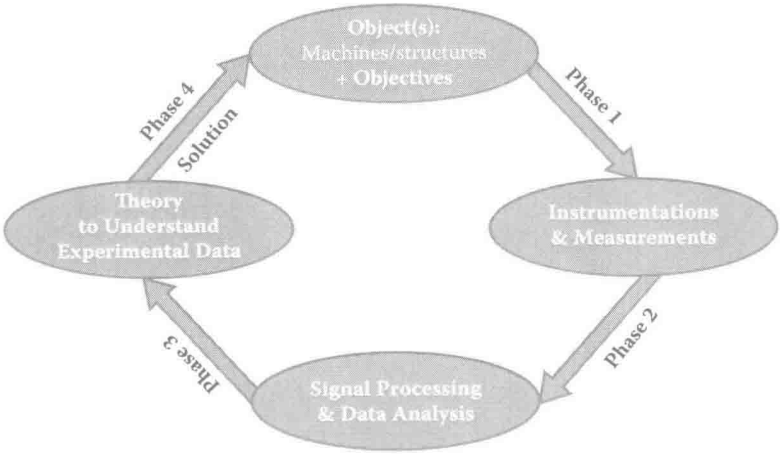


FIGURE 1.1
Typical abstract representations of different steps for analyzing any dynamic system.

4. Meet the expectation of an easy remedial suggestion (solution). In fact, it is always observed and experienced that a kind of "magic solution" is expected. It is only possible if the measurements, data processing, and their correlation to the theory are fully understood.

This book aims to communicate the above facets in a simplified tutorial manner, which is not readily available in a book. An abstract form of representation of the above facets is also illustrated in Figure 1.1 for better understanding.

1.2 Layout of the Chapters

The complete book is presented in 10 chapters (including Chapter 1) and aims to address a number of topics often useful for many day-to-day analyses and experiments in an illustrative and tutorial style, so the basic concept can be understood in a much better way. Although the book is divided into 10 chapters, it can be grossly classified into the following four categories.

1. Basic theories and analysis methods
2. Instrumentations and signal processing methods
3. Combined analysis and experimental approaches
4. Case studies relating 1 to 3

1.2.1 Basic Theories and Analysis Methods

Chapters 2 to 4 provide the basic understanding and concept of the vibration theory, mathematical modeling of structures and machines using the finite element (FE) method, and the vibration response computation using the FE model for the load applied.

Chapter 2 discusses a simplified vibration theory through a single degree of freedom (SDOF) system of a mass and a spring. A better understanding of vibration theory on a simplified system like a spring-mass system is often useful to understand several complex problems related to structures and machines.

Chapter 3 is on finite element (FE) modeling. This chapter introduces the concept of FE modeling at a very basic level through a few simple examples. This may provide a better concept and understanding even when developing an FE model using the commercial FE codes. The concept of the theoretical modal analysis using the FE model and eigenvalues and eigenvectors analysis is also discussed to introduce the concept of the mode shape at a natural frequency.

Chapter 4 is related to the use of the FE model discussed in Chapter 3. It discusses how the equation of motion in matrix form for any system can be integrated to solve for the responses (displacement, velocity, and acceleration) at all DOFs due to the time-varying external loadings. Broadly, two different approaches, the direct integration (DI) method and the mode superposition (MS) method, are used in practice and discussed in this chapter. The step-by-step concepts through a few examples are used to explain both methods. The Newmark-β method is used as the integration method for solving the dynamic equation of motion in matrix form for both the DI and MS methods to compute the responses.

1.2.2 Instrumentations, Signal Processing, and Experimental Methods

This book contains three exclusive chapters related to instrumentation, signal processing, and modal experiments, respectively. These are important elements for any vibration experiment.

Chapter 5 introduces the basic concept and working principles of different vibration sensors that include the proximity probes for displacement measurement, seismometers, accelerometers, and force sensors with their specifications. The concept of the experimental setup for the vibration measurements, experiments, and data collection is explained systematically for any experimental work. The basic understanding of the analogue-to-digital conversion (ADC) and the sampling frequency are discussed through the aid of a number of examples. The data acquisition (DAQ) device used to collect the experimental data in digital form from the analogue signals from the different sensors is also discussed so that appropriate DAQ and setting selection is possible for the experimental data collection.

Chapter 6 focuses on signal processing. It is a very important step to get the meaningful outputs from the measured vibration signals. Signal processing generally used in vibration, in both time and frequency domains, is explained through a number of vibration signals. A simplified concept for the fast Fourier transformation (FFT) and its use in the spectrum, cross-spectrum, frequency response function (FRF), and coherence are discussed. The use of the window function and averaging process while estimating the spectrum, FRF, etc., is explained through the aid of a number of signals. The usefulness of filters and the aliasing effect during data collection is also explained in this chapter.

Chapter 7 deals with experimental modal testing and analysis. Conducting modal experiments on any structure, machine, or equipment may be a straightforward procedure, but the data analysis needed to extract the natural frequencies, mode shapes, and modal damping accurately is a complex process. A number of modal analysis software codes are already available commercially to do such data analysis. In this chapter, a very simplified test procedure and the data analysis based on the theory of a SDOF system are outlined to extract the modal properties. It is generally observed to be an effective practical approach for many applications, including industrial structures and machines.

1.2.3 Combined Analysis and Experimental Methods

FE model updating and vibration-based condition monitoring and diagnosis require the knowledge of both analysis (Section 1.2.1) and experiments (Section 1.2.2). These are presented in the following chapters. The basic theories are explained through examples.

Chapter 8 describes the FE model updating method. The development of an FE model (Chapter 3) for any structure or machine is generally based on the material properties, physical dimensions, and ideally assumed boundary conditions. Such an a priori FE model may not be a true reflection of in situ dynamic behavior, and hence the FE model needs to be updated to get the model close to in situ behavior. The FE model updating approach uses the experimental modal parameters to update the model using updating parameters. The step-by-step procedure of this updating method is explained through a few simple laboratory examples and a case study.

Chapter 9 is dedicated to vibration-based condition monitoring, which is one of the most popular topics for monitoring the health of any structure or machine. A simplified concept about the requisite instrumentation, data collection, data analysis, diagnosis features, and the related International Organization for Standardization (ISO) codes is discussed in the chapter, mainly related to rotating machines.

1.2.4 Case Studies

Chapter 10 is exclusively on a few case studies, from laboratory examples to industrial examples, in order to provide a clear concept for analyzing different problems and the usefulness and relation of Sections 1.2.1 to 1.2.3 in each case study, and then how to achieve the magic solution to any problem.