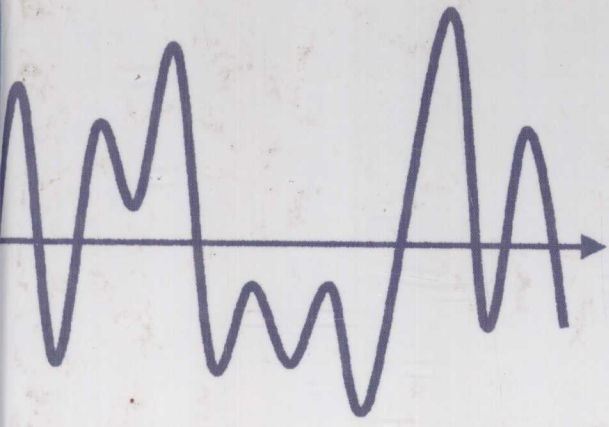
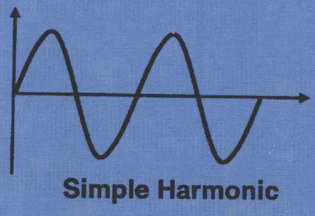
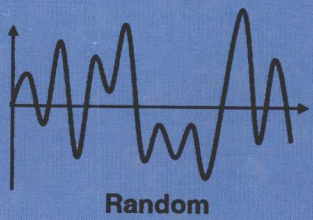


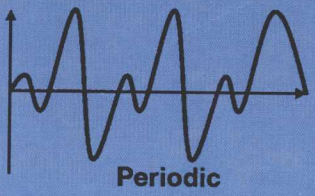
CASE HISTORIES IN VIBRATION ANALYSIS AND METAL FATIGUE

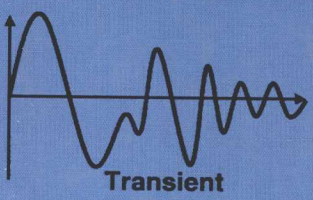
for the Practicing Engineer

ANTHONY SOFRONAS









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CASE HISTORIES IN VIBRATION ANALYSIS AND METAL FATIGUE FOR THE PRACTICING ENGINEER

To The One Who Has Made This All Possible
and
To My Family

PREFACE

Purpose of the Book

In over 45 years as a practicing engineer, troubleshooting and preventing failures were my primary responsibility, with design, especially of torsional systems, as an additional function. In the area of failure analysis, by far the majority of failures were metal fatigue failures. Since metal fatigue is caused by cycling forces and moments, vibration is introduced.

In a production environment an engineer is burdened with many day-to-day decisions and does not have the luxury of developing elegant mathematical solutions to solve the problem at hand. Trying to understand and utilize differential equations and other concepts and terminology presented in college vibration textbooks is time consuming and may not be cost-effective. Expedient, simple-to-explain solutions are required to get equipment functioning again.

Explaining what caused a failure, along with the proposed solution, to those not well versed in vibration and metal fatigue can be a challenge. This is something engineers must be able to do to generate the necessary funding to implement a solution. Too often we have heard stories about catastrophic failures related to nuclear reactors, space exploration vehicles, and drilling platforms, for example, and that a problem and solution were known by the engineers but ignored by those in control of the budget. A typical comment from those in control might be: "The system has had this problem in the past and worked fine, so there is little risk." In such cases, time and funding control the decision rather than analysis of the risk involved in not solving the problem. It is the engineer's responsibility to present risks clearly and concisely in language and, if necessary, in experiments that can be understood.

This book is about helping engineers obtain solutions to difficult vibration problems using techniques that can be easily explained. This is done using personal case histories. The subject of metal fatigue is in the book simply because excessive vibration often results in fatigue failures. Identifying fatigue-based failures can help identify the source of the vibration. It is my hope that the book will help readers understand vibration and metal fatigue and use the contents in a practical manner to solve industrial problems and enhance their careers.

Content and Arrangement

In Chapter 1 we introduce background history on vibration and what we set out to accomplish.

Chapter 2 is a basic introduction to the single-degree-of-freedom problem and an example is used to show how systems can be simplified. Multiple-spring systems are combined into equivalent systems, and some common properties needed in vibration analysis are shown. How to determine the natural frequencies of pipes, beams, and plates, how vibration absorbers function, and how clearance affects the natural frequency of a system are explained.

Chapter 3 addresses methods for measuring and presenting vibration information. The shock pulse method is illustrated, as it has practical use in monitoring vibrations and data trending. A systematic method for identifying the source of vibration is shown in a case history.

Chapter 4 is an important chapter that shows how amplitudes can be calculated using the dynamic magnifier method. The stresses and torques due to vibration can be determined quickly using this method and field data can be used to better define the data. The chapter contains many actual case histories showing use of the method to evaluate several unique and interesting problems.

In Chapter 5 we review problems that vibration can cause and the sources of the problems. Fatigue, wear, bearing failures, why bolts loosen, flow-induced vibrations, and surging of fans are just a few of the topics explained. In addition, the slip-stick phenomenon is introduced and illustrated with actual problems.

In Chapter 6 we discuss imbalance and misalignment. Vibration in pumps, motors, gearboxes, and other equipment, together with their unique vibration problems, are examined in detail. Various types of couplings are also described.

In Chapter 7 we analyze piping and pressure vessel vibration. Here screening charts which show vibration levels that have resulted in failures are presented. Heat-exchanger tube vibration prediction methods and ways to avoid such vibration are explained. Ways to evaluate acoustical vibration problems arising from the amplification of pressure pulses, and fluid water hammer analysis, are introduced using case histories. Also described is crack growth in plates and welds.

Chapter 8 is about torsional vibrations, beginning with what they are and progressing into many case histories on how they were applied. Frequency, amplitude, and excitation calculations are all discussed in detail. Internal combustion engines and electric motors driving geared systems are analyzed. Many are reduced to two-mass systems, but multimass systems are also evaluated. Torque applied suddenly and grid closures that are out of synchronization are evaluated. A Holzer analysis is shown for spreadsheet use and can be used to analyze the frequencies, mode shapes, and relative torques and forces for torsional and linear multimass systems.

In Chapter 9 we examine turbomachinery rotor dynamics, a complex subject, by utilizing simple rotor models to explain the principles and to solve several case histories. The system is modeled as a multidiameter shaft on springs and the fundamental frequency is determined. Various case histories show how the model

is used in troubleshooting problems. Determining the stiffness of hydrodynamic bearings is also reviewed.

In Chapter 10 we look at very low cycle vibrations. These are the types of cyclic loads that can cause metal fatigue failures, which may occur after only a few hundred cycles. Gear face pitting failures and rotary dryer failures are only a few of the types of case histories examined, along with crack growth due to cyclic loads. The chapter ends with examples of the imprinting method to determine the loads causing failures. The use of vibratory and rotational wear equations is also shown.

Chapter 11 contains case histories on some actual failures that I have witnessed, with descriptions of the causes of the failures. Springs, splines, crankshafts, bearings, pistons, and other components are analyzed, and the appearance of the fracture surfaces is discussed. With this information on fatigue failures due to cyclic loads, vibration can be better understood.

Chapter 12 covers the fundamentals of metal fatigue as it applies to investigating vibration problems. What can be expected from a metallurgical examination and how it can be applied to troubleshooting a vibration problem are illustrated. The chapter ends with a brief discussion of risk taking and presentations to management that can benefit an engineer.

In Chapter 13 we present a short history of practical vibration analysis and some of the people responsible for developing much of the theory.

Acknowledgments

First I wish to thank my dear wife, Mrs. Cruz Velasquez Sofronas, for putting up with my technical discussions over the years and even beginning to understand them. She has been extremely helpful in suggesting better wording for many of the sections.

I also wish to thank Heinz Bloch, a prolific writer, educator, and friend for suggesting that I write the book.

I thank Richard S. Gill, my colleague and friend, for bringing many of these case histories to my attention and for the enjoyable hours of technical discussions on many of them.

In addition, I thank Dr. Khalil Taraman, my doctoral advisor and friend, who introduced me to areas of research and course development as well as providing expert guidance on my thesis.

Many thanks go to John Wiley & Sons, Inc., especially Bob Esposito, for agreeing to publish this work.

I wrote the book in memory of Dr. J. P. Den Hartog, whose summer seminar and books have made vibration analysis much clearer to me and allowed me to explore new techniques.

ANTHONY SOFRONAS

CONTENTS

1

INTRODUCTION

Throughout my career I have been involved in many areas of mechanical engineering and machinery operation, as well as pressure vessel and piping problems. Any analysis was for the purpose of solving an actual problem that was occurring at the time. There usually wasn't time for a detailed study—an answer was required immediately so that equipment could be restarted safely and reliably with the most probable cause of failure having been determined. High-visibility failures, those drawing top management interest, usually required the attention of many experienced specialists. One discipline that I used to troubleshoot failures was vibration analysis, and over the years sufficient cases with known outcomes were developed that this book could be written. A notable focus is metal fatigue, because where there is excessive vibration, there is usually a fatigue-related problem. For the practicing engineer it is difficult to separate the two when a solution is needed to prevent a repeat failure.

Many books on vibration analysis are available. Some are heavy with theory and others are too simplified for practical everyday use. In this book I fill the void by using actual case histories to discuss the equations presented or the results shown, to heighten their usefulness for practical troubleshooting purposes. I do not consider specific vibration-measuring equipment or computer programs presently in use so that the book will be useful for a long time. The equations don't change much with time, only the methods used to solve them.

Nearly all machinery, pressure vessels, and piping systems will experience some vibration. In dealing with vibration concerns, the following questions are typically raised:

Case Histories in Vibration Analysis and Metal Fatigue for the Practicing Engineer, First Edition. Anthony Sofronas.

- What is causing the vibration?
- Is the vibration of sufficient magnitude that it needs to be controlled?
- How can the vibration be controlled?

Vibration-related problems occur less often than static stress-related failures such as bending, torsional, overload, or inadequate material properties. When severe vibration does occur, it can be very costly to remedy, sometimes requiring total system redesign. Vibration is the result of dynamic forces and moments acting on equipment. When severe enough, these can result in fatigue-related failures.

It is therefore important for those who design equipment or for users of the equipment to understand vibration and fatigue.

The book contains cases and information on problems in the petrochemical, component manufacturing, and transportation industries and encompasses over 45 years of personal experience. As such, it should be useful in many sectors of industry and also to those new to industry or new to vibration analysis. Many experienced engineers will also find problems and solutions that they haven't yet encountered.

The cases used are not based on developing new designs but on investigating the causes of failures or on troubleshooting newly installed, up-rated, or in-service equipment. New machinery, piping systems, and pressure vessel designs are usually based on the manufacturers' experience with the equipment, and reputable manufacturers use the latest analysis techniques available. It is only when a piece of equipment is the first one ever built, or the biggest ever built, that problems can occur. When large equipment is designed as simply a scale-up of a smaller design, things don't always scale up as hoped. Manufacturers may also use linear scale-up techniques on nonlinear problems, resulting in fatigue failures.

In a previous book of mine [1] many areas of mechanical engineering and their associated failures were examined using theory and case histories. In this book, only failures due to excessive vibration are considered. Since the book represents primarily my personal experiences, it does not cover all types of vibration. Excellent references are provided to supplement the information. The book does present vibration problems that engineers responsible for many types of equipment will encounter during their careers. Some of the work presented in this book has also been taught to personnel in various companies in seminar format and therefore contains input from many participants.

Most of the examples are simplified so that the reader doesn't have to have, or purchase, special software to solve many of the vibration problems that occur. The simplified solutions were enough to determine the cause of the vibration problem and implement a solution. I show the development of simplified equations when appropriate. In some cases simplification is not possible, and more complex software must be used. For example, torsional vibration of a multimass system driven by a gasoline or diesel engine can have many harmonics and can require specialized software for frequency and amplitude calculations. Engineers who