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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 send such work to a consulting firm should understand what is being done even if they aren't proficient in particular areas, as the results will need to be understood and explained to others.

Although exact solutions may not be possible with the simplified equations shown, in most cases they will allow the specialist to better understand the causes of the vibrations and to address them. Sometimes it will just indicate that a vibration consultant should be contacted and provides the specialist with information to discuss the problem intelligently with the consultant.

Many torsional vibration case histories are used in this book. There are two reasons for this. The first is that when a torsional vibration problem occurs in machinery, it is usually an expensive failure and not easily fixed. Calculations need to be expedited and solutions need to be practical. The second reason is that I have an extensive background in analyzing and testing design-related systems for torsional vibration. Thus, there were a considerable number of actual case histories. Most of the failure case histories have interesting stories associated with them, which in some sections are included.

It is difficult to identify a true vibration failure. For example, a shaft failure may be written up as a vibration failure since extreme vibrations were felt. In reality, a rub may have developed that caused bending loads which resulted in a fatigue failure. In this case, rotating bending was the true cause and vibration was a result, not the cause.

The total number of major failures examined during my 45 years in industry and consulting was approximately 400, which would be a total of 100% of the major failures examined. Only 20% were similar to those shown in this book and were defined as vibration problems. This is more typical than atypical for engineers dealing with failures in industry. Not all of an engineer's time is spent investigating vibration-related failures, but when these types of failures do occur they are usually major investigations. Most vibration alignment or balance problems are just annoying and can be eliminated with a quick realignment or field balance and don't result in a failure.

Before we begin it will be useful to describe briefly the two types of vibrations that are discussed in this book. The first are linear vibration systems, which in this book have units of in., lb, and sec, and the second are torsional systems, which have units of rad, in.-lb, and sec. Many of the problems are described as single-degree-of-freedom problems, those with one mass and one spring (Figure 1.1). If either is pulled (linear) or twisted (torsional) and released, they will vibrate at their natural frequency, which is $f_n = 9.55(k/m)^{1/2}$ cycles per minute (cpm) for the linear system and $f_n = 9.55(C/J)^{1/2}$ cpm for the torsional case. The similarity between the two equations comes in very handy for understanding vibration. Single-degree-of-freedom models are extremely useful, since many complex vibration systems can be reduced to them. They are much easier to understand and analyze and their results are much easier to explain to others, as is shown by the case histories in this book.

Even single-degree-of-freedom (SDF) models can become complex, as in the case of self-excited vibration, transient, or forced damped vibration problems.

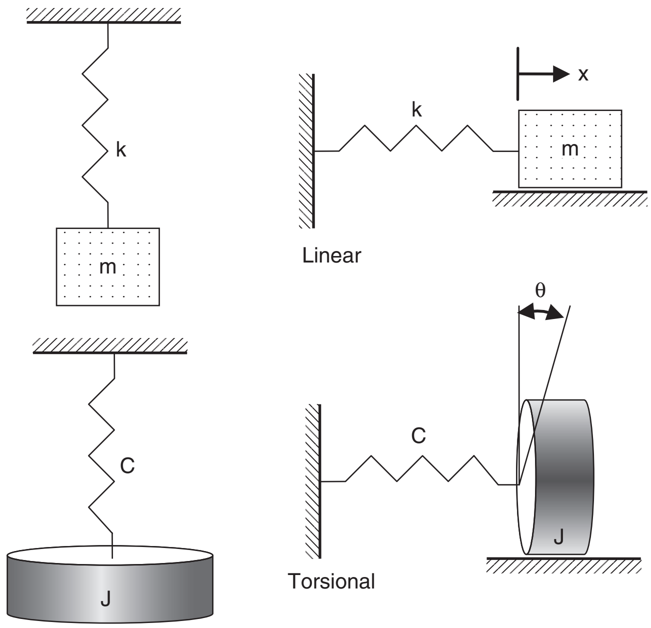

Figure 1.1 Linear and torsional vibration systems.

Most of the time they are useful because multi-degree-of-freedom problems or several masses with their attaching springs can be "lumped" to form a single mass–spring model. The first example in Chapter 2 shows this.

Also described are the variety of fatigue failures that can occur and that are typical for industry. The types discussed occur many times, and seeing actual photographs should help the specialist understand what may have caused the fatigue. Impacts that occur several times and cause a failure are not truly fatigue failures, which are usually thought of as representing a very high number of cycles. I once worked with an extremely talented and experienced mechanical engineer when I was just starting work in industry. This engineer said: "Everything fails in fatigue." When I questioned his statement and asked him about a one-cycle impact failure, his remark was: "That's low-cycle fatigue." His point was, of course, that most failures on machinery spinning at high speeds are usually fatigue related. With speeds and power increasing over time, these types of fatigue failures are becoming even more common.

REFERENCE

1. Sofronas, A., *Analytical Troubleshooting of Process Machinery and Pressure Vessels: Including Real-World Case Studies*, Wiley, Hoboken, NJ, 2006.