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Introduction

This chapter provides a short introduction to the field of noise and vibration analysis. Its main objective is to show new students in this field the wide range of applications and engineering fields where noise and vibration issues are of interest. If you are a researcher or an engineer who wants to use this book as a reference source, you may want to skim this chapter. If you decide to do so, I would recommend you to read Section 1.6, in which I present some personal ideas on how to use this book, as well as on how to go about becoming a good experimentalist – the ultimate goal after reading this book.

I want to show you not only the width of disciplines where noise and vibrations are found. I also want to show you that noise and vibration *analysis*, the particular topic of this book, is truly a fascinating and challenging discipline. One of the reasons I personally find noise and vibration analysis so fascinating is the interdisciplinary character of this field. Because of this interdisciplinary character, becoming an expert in this area is indeed a real challenge, regardless of which engineering field you come from. If you are a student just entering this field, I can only congratulate you for selecting (which I hope you do!) this field as yours for a lifetime. You will find that you will never cease learning, and that every day offers new challenges.

1.1 Noise and Vibration

Noise and vibration are constantly present in our high-tech society. Noise causes serious problems both at home and in the workplace, and the task of reducing community noise is a subject currently focused on by authorities in many countries. Similarly, manufacturers of mechanical products with vibrations causing acoustic noise, more and more find themselves forced to compete on the noise levels of their products. Such competition has so far occurred predominantly in the automotive industry, where the issues with sound and noise have long attracted attention, but, at least in Europe, e.g., domestic appliances are increasingly marketed stressing low noise levels.

Let us list some examples of reasons why vibration is of interest.

- Vibration can cause *injuries and disease* in humans, with ‘white fingers’ due to long-term exposure to vibration, and back injuries due to severe shocks, as examples.
- Vibration can cause *discomfort*, such as sickness feelings in high-rise buildings during storms, or in trains or other vehicles, if vibration control is not successful.
- Vibration can cause *fatigue*, i.e., products break after being submitted to vibrations for a long (or sometimes not so long) time.

Noise and Vibration Analysis: Signal Analysis and Experimental Procedures, First Edition. Anders Brandt.

- Vibration can cause *dysfunction* in both humans and things we manufacture, such as bad vision if the eye is subjected to vibration, or a radar on a ship performing poorly due to vibration of the radar antenna.
- Vibration can be used for cleaning, etc.
- Vibration can cause noise, i.e., unpleasant sound, which causes annoyance as well as disease and discomfort.

To follow up on the last point in the list above, once noise is created by vibrations, noise is of interest, e.g., for the following reasons.

- Excessive noise can cause hearing impairment.
- Noise can cause discomfort.
- Noise can (probably) cause disease, such as increased risk of cardiac disease, and stress.
- Noise can be used for burglar alarms and in weapons (by disabling human ability to concentrate or to cope with the situation).

The lists above are examples, meant to show that vibrations and noise are indeed interesting for a wide variety of reasons, not only to protect ourselves and our products, but also because vibration can cause good things.

Besides simply reducing sound levels, much work is currently being carried out within many application areas concerning the concept of *sound quality*. This concept involves making a psychoacoustic judgment of how a particular sound is experienced by a human being. Harley Davidson is an often-cited example of a company that considers the sound from its product so important that it tried to protect that sound by trademark, although the application was eventually withdrawn.

Besides generating noise, vibrations can cause mechanical fatigue. Now and then we read in the newspaper that a car manufacturer is forced to recall thousands of cars in order to exchange a component. In those cases it is sometimes mechanical fatigue that has occurred, resulting in cracks initiating after the car has being driven a long distance. When these cracks grow they can cause component breakdown and, as a consequence, accidents.

1.2 Noise and Vibration Analysis

This book is about the *analysis methods* for analyzing noise and vibrations, rather than the mechanisms causing them. In order to identify the sources of vibrations and noise, extensive analysis of measured signals from different tests is often necessary. The measurement techniques used to carry out such analyses are well developed, and in universities as well as in industry, advanced equipment is often used to investigate noise and vibration signals in laboratory and in field environments.

The area of experimental noise and vibration analysis is an intriguing field, as I hope this book will reveal. It is so partly because this field is multidisciplinary, and partly because dynamics (including vibrations) is a complicated field where the most surprising things can happen. Using measurement and analysis equipment often requires a good understanding of mechanics, sensor technology, electronic measurement techniques, and signal analysis.

Vibrations and noise are found in many disciplines in the academic arena. Perhaps we first think of mechanics, with engines, vehicles, and pumps, etc. However, vibrations are also found also in civil engineering, in bridges, buildings, etc. Many of the measurement instruments and sensors we use in the field of analyzing vibrations and noise are, of course, electrical, and so the field of electrical engineering is heavily involved. This makes the initial study of noise and vibration analysis difficult, perhaps, because you are forced to get into some of the other fields of academia. Hopefully, this book can help bridge some of the gaps between disciplines.

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If many academic disciplines are involved with noise and vibrations, the variety in industry is perhaps even more overwhelming. Noise and vibration are important in, for example, military, automotive, and aerospace industries, in power plants, home appliances, industrial production, hand-held tools, robotics, the medical field, electronics production, bridges and roads, etc.

1.3 Application Areas

As evident from the first sections of this chapter, noise and vibration are important for many reasons, and in many different disciplines. Within the field of noise and vibration, there are also many different, more specialized, disciplines. We need to describe some of these a little more.

Structural dynamics is a field which describes phenomena such as resonance in structures, how connecting structures together affect the resonances, etc. Often, vibration problems occur because, as you probably already know, resonances amplify vibrations – sometimes to very high levels.

Environmental engineering is a field in which environmental effects (not to be confused with the 'green environment') from such diverse phenomena as heat, corrosion, and vibration, etc., are studied. As far as vibrations are concerned, *vibration testing* is a large industrial discipline within environmental engineering. This field is concerned with a particular product's ability to sustain the vibration environment it will encounter during its lifetime. Sensitive products such as mobile phones and other electronic products are usually tested in a laboratory to ensure they can sustain the vibrations they will be exposed to during their lifetime. Producing standardized tests which are equivalent to the product's real-life vibration environment, is often a great challenge. Transportation testing of packaging is a closely related field, in which the interest is that, for example, the new video camera you buy arrives in one piece when you unpack the box, even if the ship that delivered it encountered a storm at sea.

Fatigue analysis is a field closely related to environmental engineering. However, the discipline of fatigue analysis is usually more involved with measuring the stresses on a product and, through mathematical models such as Wöhler curves etc., trying to predict the lifetime of the product, e.g., before fatigue cracks will appear. From the perspective of experiments, this practically means it is more common to measure with strain gauges rather than accelerometers.

Vibration monitoring is another field, where the aim is to try to predict when machines and pumps, for example, will fail, by studying (among many things) the vibration levels during their lifetime. In civil engineering, a somewhat related field, *structural health monitoring* attempts to assess the health of buildings and bridges after earthquakes as well as after aging and other deteriorating effects on the structure, based on measurements of (among many things) vibrations in the structures.

Acoustics is a discipline close to noise and vibration analysis, of course, as the cause of acoustic noise is often vibrations (but sometimes not, such as, for example, when turbulent air is causing the noise).

1.4 Analysis of Noise and Vibrations

There are several ways of analyzing noise and vibrations. We shall start with a brief discussion of some of the methods which this book is *not* aimed at, but which are crucial for the total picture of noise and vibration analysis, and which is often the reason for making experimental measurements.

Analytical analysis of vibrations is most commonly done using the *finite element method*, FEM, through normal mode analysis, etc. In order to successfully model vibrations, usually models with much greater detail (finer grid meshes, correctly selected element types, etc.) need to be used, compared with the models sufficient for static analysis. Also, dynamic analysis using FEM requires good knowledge of boundary conditions etc. For many of these inputs to the FEM software, experiments can help refine the model. This is a main cause of much experimental analysis of vibrations today.

For *acoustic analysis*, acoustic FEM can be used as long as the noise (or sound) is contained in a cavity. For radiation problems, the *boundary element method*, BEM, is increasingly used. With this method, known vibration patterns, for example from a FEM analysis, can be used to model how the sound radiates and builds up an acoustic field.

FEM and BEM are usually restricted to low frequencies, where the mode density is low. For higher frequencies, *statistical energy analysis*, SEA, can be used. As the name implies, this method deals with the mode density in a statistical manner, and is used to compute average effects.

1.4.1 Experimental Analysis

In many cases it is necessary to measure vibrations or sound pressure, etc., to solve vibration problems, because the complexity of such problems often make them impossible to foresee through analytical models such as FEM. This is often referred to as trouble-shooting. Another important reason to measure and analyze vibrations is to provide input data to refine analytical models. Particularly, damping is an entity which is usually impossible to estimate through models – it needs to be assessed by experiment.

Experimental analysis of noise and vibrations is usually done by measuring accelerations or sound pressures, although other entities can be measured, as we will see in Chapter 7. In order to analyze vibrations, the most common method is by *frequency analysis*, which is due to the nature of linear systems, as we will discuss in Chapter 2. Frequency analysis is a part of the discipline of *signal analysis*, which also incorporates filtering signals, etc. The main tool for frequency analysis is the FFT (fast Fourier transform) which is today readily available through software such as MATLAB and Octave (see Section 1.6), or by the many dedicated commercial systems for noise and vibration analysis. Methods using the FFT will take up the main part of this book.

Some of the analysis necessary to solve many noise and vibration problems needs to be done in the time domain. Examples of such analysis is fatigue analysis, which incorporates, e.g., cycle counting, and data quality analysis, to assess the quality of measured signals. For a long time, the tools for noise and vibration analysis were focused on frequency analysis, partly due to the limited computer performance and cost of memory. Today, however, sophisticated time domain analysis can be performed at a low cost, and we will present many such techniques in Chapters 3 and 4.

1.5 Standards

Due to the complexity of many noise and vibration measurements, international standards form an important part of vibration measurements as well as of acoustics and noise measurements. Acoustics and vibration standards are published by the main standardization organizations, ISO (International Standardization Organization), IEC (International Electrical Committee), and, in the U.S., by ANSI (American National Standards Institute). The general recommendation from many acoustics and vibration experts is that, if there is a standard for your particular application – use it. It is outside the scope of this book, and practically impossible, to summarize all the standards available. Some of the many standards for signal analysis methods used in vibration analysis are, however, cited in this book.

1.6 Becoming a Noise and Vibration Analysis Expert

The main emphasis in this book is on the signal analysis methods and procedures used to solve noise and vibration problems. To be successful in this, it is necessary to become a good experimentalist. Unfortunately, this is not something which can be (at least solely) learned from a book, but I want to make some recommendations on how to enter a road which leads in the right direction.

1.6.1 The Virtue of Simulation

As many of the theories of dynamics, as well as those of signal analysis, are very complex, a vital tool for understanding dynamic systems and analysis procedures, is to simulate simplified, isolated, cases, where the outcome can be understood without the complicating presence of disturbance noise, complexity of structures, non-ideal sensors, etc. I have therefore incorporated numerous examples in this book which use simulated measurement data with known properties. A practical method to create such signals is presented in Section 6.5. The importance of this cannot be overrated. Before making a measurement of noise or vibrations, it is crucial to know what a correct measurement signal should look like, for example. The hidden pitfalls in, particularly, vibration measurements are overwhelming for the beginner (and sometimes even for more experienced engineers). The road to successful vibration measurements therefore goes through careful, thought-through simulations.

Another important aspect of good experiments, is to make constant checks of the equipment. In Section 7.12 I present some ideas of things to check for in vibration measurements. In Section 7.8 I also present a by no means new technique, but nevertheless a simple and efficient one (mass calibration, if you already know it) to verify that accelerometers are working correctly. These devices are, like many sensors, sensitive and can easily break, and unfortunately, they often break in such a way that it can be hard to discover without a proper procedure to verify the sensors on a known signal. Single-frequency calibration, which is common for absolute calibration of accelerometers, usually completely fails to discover the faults present after an accelerometer has been dropped on a hard floor.

Having written this, I want to stress that good vibration measurements are performed every day in industry and universities. So, the intention is, of course, not to discourage you from this discipline, but simply to stress the importance of taking it slowly, and making sure every part of the experiment is under your control, and not under the control of the errors.

1.6.2 Learning Tools and the Format of this Book

If you anticipated finding a book with numerous data examples from the field by which you would learn how to make the best vibration measurements, you will be disappointed by this book. The main reasons for this are twofold; (i) for the reasons just given in the preceding section, real vibration measurements are usually full of artifacts from disturbance noise, complicated structures, etc.; and (ii) each structure or machine or whatever is measured, has its own vibration profile, which makes 'typical examples' very narrow. If you work with cars, or airplanes, or sewing machines, or hydraulic pumps, or whatever, your vibration signals will look rather different from signals from those other products.

I have instead based most examples in this book on simplified simulations, where the key idea of discussion is easily seen. These examples will, hopefully, provide much deeper insights into the fundamental signal analysis ideas we discuss in each part of the book. They are also easily repeated on your own computer, which leads us to the next important point.

I believe that signal analysis (like, perhaps, all subjects) is far too mathematically complicated to understand through reading about it. Instead, I believe strongly in simulation, and application of the theories by your own hands. I have therefore throughout the book given numerous examples using the best tool I know of – MATLAB. This software is, in my opinion, the best available tool for signal analysis and therefore also for the vibration analysis methods we are concerned with in this book. If you do not already know MATLAB, you will soon learn by working through the examples.

The drawback of MATLAB may be that it is commercial software, and therefore costs money. If you find this to be an obstacle you cannot overcome, you can instead use GNU Octave, which is free software published under the GNU General Public License (GPL) and can be freely downloaded from http:///www.gnu.org/software/octave/. Octave is to a large extent compatible with MATLAB in the sense that MATLAB code, with some minor tweaks, can run under Octave. I have made sure that all examples in this book run under both MATLAB and Octave, so you are free to choose whichever of the two software tools.

In addition to the examples in this book, there will be a free accompanying toolbox for MATLAB/Octave made available by me to aid your learning. There will also be more examples than could fit this book. More information about this toolbox and examples for instructors, etc., can be found at the book website at www.wiley.com/go/brandt.