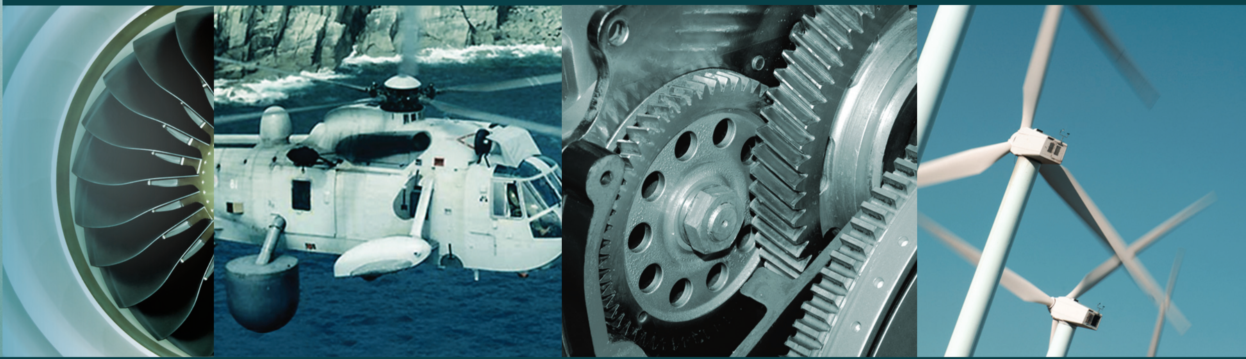
Robert Bond Randall

Vibration-based Condition Monitoring



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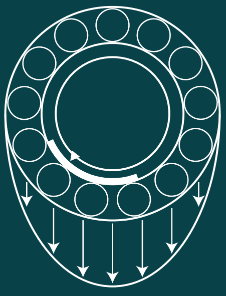

VIBRATION-BASED CONDITION MONITORING

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INDUSTRIAL, AEROSPACE AND AUTOMOTIVE APPLICATIONS

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To my daughters Katrina and Deborah.

Contents

Foreword

Robert Randall uses state-of-the-art vibration measurement and analysis in this book about condition-based monitoring of machinery; other forms of condition monitoring, including oil analysis and infrared thermography are briefly described. The text is the result of the author's years of involvement in the development, practice, and teaching of techniques used in the field, including contributions to digital signal analysis.

A highly sophisticated methodology for assessing machine condition has evolved in the last 70 years with respect to techniques, digital instruments, and computer chips. Despite many years of effort, the technique that every maintenance manager yearns for – prognostics (run time to failure) – does not yet exist in a usable form. However, condition monitoring of machinery using vibration measurements and analysis is a major component of all manufacturing processes (chemical, petroleum, automobile, paper, and power) as well as military and airline operations.

The relationship between vibration signals and machine condition was first recognized by Rathbone in his 1939 paper on *Vibration Tolerance*. The Rathbone chart that appeared in the paper was a plot of amplitude versus frequency based on the concept that machine condition is related to vibration amplitude. His zones of severity (six dB apart) were based on constant velocity and applied over the common frequency range of most machines. The chart was later refined by IRD Mechanalysis, the U.S. Navy, Blake, and others. Blake developed a chart containing plots of displacement, velocity, and acceleration versus frequency with severity levels spaced at 10 dB and service factors for various machines. During this period simple meters and oscilloscopes were used to extract vibration levels from transducers.

Overall vibration levels were used non-systematically until 1960 to identify machine condition. By this time it had been recognized that periodic monitoring could be useful in avoiding costly machine failures and improving return on investment. A meter and clipboard were used to measure and record vibration levels, another development – the proximity probe by Bently for non-contacting shaft vibration measurement – allowed permanent machine monitoring.

Although screening involved overall vibration levels until the 1970s, vibration analysis expanded to address difficult and complex cases as a result of FFT analyzers that had greater resolution than analog filtered instruments. Portable tape recorders were used to acquire vibration data on defined routes; sometimes heavy analyzers were hauled into the field on carts and trucks. Blake and Jackson published the first texts related to condition monitoring in 1972 and 1979 respectively.

Data collectors that use high-frequency accelerometers interfaced with digital computers were developed in the 1980s. They had a higher level of efficiency and effectiveness and spurred development of new monitoring and analysis techniques using innovative signal processing. Recent improvements in condition monitoring include more sophisticated miniaturized data acquisition systems, physics and experience-based expert systems, Internet data sharing, and wireless data transmission. Unfortunately, progress with prognostic techniques has not produced practical techniques.

Randall has written an authoritative monograph on state-of-the-art methods for evaluating the condition of machinery using vibration analysis. For the first time practitioners can refer to one source for the techniques commonly used. Because machines are complex and the range of application of signal processing techniques is wide, the user must be aware of their power and limitations. The text is interesting, well written, and well illustrated. This work on vibration signals, signal processing techniques, fault detection, diagnostic techniques, and fault trending and prognostics will provide guidance for individuals struggling to keep down maintenance costs on complex machines using the art and science of condition monitoring.

Ronald L. Eshleman
Vibration Institute
Willowbrook, Illinois, USA
October 2010

About the Author

Bob Randall is a visiting Emeritus Professor in the School of Mechanical and Manufacturing Engineering at the University of New South Wales (UNSW), Sydney, Australia, which he joined as a Senior Lecturer in 1988. Prior to that, he worked for the Danish company Brüel & Kjær for 17 years, after 10 years' experience in the chemical and rubber industries in Australia, Canada and Sweden. He was promoted to Associate Professor in 1996 and to Professor in 2001, retiring in 2008. He has degrees in Mechanical Engineering and Arts (Mathematics, Swedish) from the Universities of Adelaide and Melbourne, respectively. He is the invited author of chapters on vibration measurement and analysis in a number of handbooks and encyclopaedias and a member of the editorial boards of four journals, including *Mechanical Systems and Signal Processing* and *Transactions of the IMechE Part C*. He is the author of more than 190 papers in the fields of vibration analysis and machine diagnostics, and has supervised 14 PhD and 3 Masters projects to completion in those and related areas. Since 1996, he has been Director of the DSTO (Defence Science and Technology Organisation) Centre of Expertise in Helicopter Structures and Diagnostics at UNSW.

Preface

This book is based largely on a course on machine condition monitoring taught at the University of New South Wales (UNSW), Sydney, Australia, from 1997 to 2006. However, its origins date back to courses I developed while working for the Danish company Brüel & Kjær, from 1971 to 1987. In conjunction with a number of colleagues, in particular Hans Mærsk-Møller and Roger Upton, a four-day course was given about 40 times in 20 countries. Perhaps half the material comes from my contributions to those courses and from my book *Frequency Analysis*, published by Brüel & Kjær, the last edition in 1987.

My reasons for writing this book are not only because *Frequency Analysis* is now out of print, but also because of my frustration at not being able to find a suitable textbook for the machine condition monitoring course at UNSW. I acknowledge with thanks the permission given by Brüel & Kjær Sound and Vibration Measurement A/S to reuse much of the material from the earlier Brüel & Kjær publications.

The other and much more up-to-date half of the material comes from research work carried out since I have been at UNSW, and owes a great deal to the contributions of my PhD students at UNSW, in particular those who worked with machine diagnostic topics. Although all of my students have contributed greatly to my understanding of a range of topics, with respect to the material of the book I would like to acknowledge specially the contributions of Drs Peter Sweeney, Shu Du and Hiroaki Endo in gear diagnostics, Dominique Ho and Nader Sawalhi in bearing diagnostics, and Yaping Ren in engine diagnostics. As will be seen in the references, a number of undergraduate students have also made valuable contributions in their Bachelor of Engineering theses.

While at UNSW, I have enjoyed a considerable amount of interaction and collaboration with overseas universities and research establishments, with sabbatical periods at *inter alia* CETIM (Centre Technique des Industries Mécaniques), Senlis, France; l'Università di Roma La Sapienza, Italy; Katholieke Universiteit Leuven, Belgium; the University of Manchester, UK; and a number of universities in France. These include l'Université de Technologie de Compiègne (UTC); the laboratory LASPI of l'Université Jean Monnet de St Etienne, Roanne; and l'Université d'Orléans at IUT Chartres. There has also been a close collaboration with the French universities l'Institut National Polytechnique de Grenoble (INPG) and l'Institut National des Sciences Appliquées (INSA) Lyon, as well as Luleå Tekniska Universitet (LTU), Sweden. A number of my students have spent time at UTC and INSA Lyon, in the former case arranged on the French side by Professor Ménad Sidahmed, and I have received a number of exchange PhD students from UTC, LASPI, INPG and LTH.

The contacts with France have been particularly valuable, as I believe that France leads the world in many areas of signal processing, in particular as applied to mechanical problems. Most important has been my contact with Professor Jérôme Antoni, of UTC, who first visited UNSW during his PhD candidature at LASPI and INPG. Many of the more recent developments in the book have been introduced or inspired by Jérôme.

Over many years I have received research support from the Australian government's Defence Science and Technology Organisation (DSTO) which set up the Centre of Expertise in Vibration Analysis at UNSW in 1996, with a name change to the Centre of Expertise in Helicopter Structures and Diagnostics in the year 2000. I have also received support from the Australian Research Council, with a number of Discovery and Linkage grants. The research supported by such grants has given rise to much of the newer material in the book, in particular the sections on the diagnostics of helicopter gearboxes. DSTO has itself been responsible for much of the development of diagnostic techniques for helicopter gearboxes, including the pioneering work of researchers such as Peter McFadden and David Forrester.

My association with the Elsevier journal *Mechanical Systems and Signal Processing*, as a member of the editorial board, has been very valuable in allowing me to keep up with the latest developments in the application of signal processing to machine diagnostics. I have received much encouragement and support from the Editor-in-Chief, Professor Simon Braun, which is gratefully acknowledged.

The book has been written to appeal to condition monitoring practitioners as well as researchers and academics. Thus, mathematics is kept to a minimum and explained where possible by analogy with mechanical and graphical concepts. Certainly, this is the way I, as a mechanical engineer, best understand it myself. The book is written primarily for mechanical engineers, who are most likely to be responsible for the condition monitoring of machines, and so quite a bit of fundamental knowledge of machine function and operation is assumed. On the other hand, specialists in electrical engineering and signal processing might find some of the explanations somewhat simplistic.

The layout of the book is as follows:

Chapter 1 – Introduction to machine condition monitoring, by a range of methods, and its application in predictive maintenance. Explanation of the primary role of the analysis of vibration, and in particular accelerometer signals, for the detection, diagnosis and prognosis of incipient faults in machines.

Chapter 2 – Discussion of the vibration signals produced by rotating and reciprocating machines, and machine components, both with and without faults.

Chapter 3 – Basic signal processing in the time domain, frequency domain and time–frequency domain, giving generally applicable methods for separating different signal constituents, such as deterministic, stationary random and cyclostationary random components, and source and transmission path effects (either of which might be indicative of failure), as well as performing amplitude and phase/frequency demodulation.

Chapter 4 – Widely applicable methods for fault detection, on both rotating and reciprocating machines. Detection is the first stage in the three-stage process, detection–diagnosis–prognosis, and must be efficient so it can be applied to a large number of signals, and if possible automated.

Chapter 5 – Specific but widely applicable diagnostic techniques, illustrated by application to a number of specific cases such as gears, rolling element bearings and internal combustion engines.

Chapter 6 – Prognostics, starting with trend analysis of a range of simple and more complicated parameters, and extraction of such parameters. Introduction to more advanced prognostic techniques based on relating vibration symptoms to degree of degradation and theories of failure.

Appendix – Tutorial and examination questions and assignments.

The book can be used as a text for Masters courses at both a fundamental and more advanced level. For that reason the Appendix contains a selection of tutorial and examination questions, as well as assignments using real data. The data and further details are to be found on the web site www.wiley.com/go/randall, where new examples will be added from time to time.

Finally, I would like to acknowledge the support of my wife, Helen, who encouraged me to keep writing at all times, even when it threw a greater load on her.

1

Introduction and Background

1.1 Introduction

Machine condition monitoring is an important part of condition-based maintenance (CBM), which is becoming recognized as the most efficient strategy for carrying out maintenance in a wide variety of industries. Machines were originally ‘run to break’, which ensured maximum operating time between shutdowns, but meant that breakdowns were occasionally catastrophic, with serious consequences for safety, production loss and repair cost. The first response was ‘preventive maintenance’, where maintenance is carried out at intervals such that there is a very small likelihood of failure between repairs. However, this results in much greater use of spare parts, as well as more maintenance work than necessary.

There is now a considerable body of evidence that CBM gives economic advantages in most industries. An excellent survey of the development of maintenance strategies is given by Rao in a keynote paper at a recent Comadem (Condition Monitoring and Diagnostic Engineering Management) conference [1]. Maintenance is often regarded as a cost centre in many companies, but Al-Najjar *et al.* [2, 3] have long promoted the idea that CBM can convert maintenance to a profit centre. Jardine *et al.* [4,5] from the University of Toronto have documented a number of cases of savings given by the use of CBM. The case presented in [5], from the Canadian pulp and paper industry, is discussed further in Chapter 6, in connection with the authors’ approach to prognostics.

To base maintenance on the perceived condition of operating machines (many of which are required to run continuously for 12 months or more) requires that methods are available to determine their internal condition while they are in operation. The two main ways of getting information from the inside to the outside of operating machines are vibration analysis and lubricant analysis, although a few other techniques are also useful.

This chapter includes a description of the background for and methods used in condition monitoring, while most of the rest of the book is devoted solely to the methods based on vibration analysis, which are the most important. This chapter describes the various types of vibration measurement used in condition monitoring, and the transducers used to provide the corresponding vibration signals. It also describes the basic problem in interpretation of vibration signals, in that they are always a compound of forcing function effects (the source)

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and transfer function effects (the structural transmission path), and how the two effects may be separated.

1.2 Maintenance Strategies

As briefly mentioned above, the available maintenance strategies are broadly:

1. ***Run-to-Break***. This is the traditional method where machines were simply run until they broke down. This in principle gives the longest time between shutdowns, but failure when it does occur can be catastrophic and result in severe consequential damage, for example of components other than the ones that failed, and also of connected machines. As a result, the time to repair can be greatly increased, including the time required to obtain replacement parts, some of which might be major items and take some time to produce. In such a case, the major cost in many industries would be production loss, this often being much greater than the cost of individual machines. There is still a place for run-to-break maintenance, in industries where there are large numbers of small machines, for example sewing machines, where the loss of one machine for a short time is not critical to production, and where failure is unlikely to be catastrophic.
2. ***(Time-Based) Preventive Maintenance***. Maintenance is done at regular intervals which are shorter than the expected ‘time between failures’. It is common to choose the intervals to be such that no more than 1–2% of machines will experience failure in that time. This does mean that the vast majority could have run longer by a factor of two or three [6]. The advantage of this method is that most maintenance can be planned well in advance and that catastrophic failure is greatly reduced. The disadvantages, in addition to the fact that a small number of unforeseen failures can still occur, are that too much maintenance is carried out and an excessive number of replacement components consumed. This approach has been known to cause reduced morale in maintenance workers (who are aware that most of the time they are replacing perfectly good parts) so that their work suffers and this can give rise to increased ‘infant mortality’ of the machines, by introducing faults which otherwise never would have happened. Time-based preventive maintenance is appropriate where the time to failure can be reasonably accurately predicted, such as where it is based on well-defined ‘lifing’ procedures, which can predict the fatigue life of crucial components on the basis of a given operational regime. Some components do tend to wear or fatigue at a reasonably predictable rate, but with others, such as rolling element bearings, there is a large statistical spread around the mean, leading to estimates such as the one given above, where the mean time to failure is two to three times the minimum [6].
3. ***Condition-Based Maintenance (CBM)***. This is also called ‘predictive maintenance’ since the potential breakdown of a machine is predicted through regular condition monitoring and maintenance is carried out at the optimum time. It has obvious advantages compared with either run-to-break or preventive maintenance, but does require having access to reliable condition monitoring techniques, which not only are able to determine current condition, but also give reasonable predictions of remaining useful life. It has been used with some success for 30–40 years, and for example the above-mentioned report [6] by Neale and Woodley predicted back in 1978 that maintenance costs in British industry could be reduced by approximately 65% by appropriate implementation in a number of industries that they

identified. However, the range of monitoring techniques was initially quite limited, and not always correctly applied, so it is perhaps only in the last 15 years or so that it has become recognized as the best maintenance strategy in most cases. Initially the greatest successes were attained in industries where machines were required to run for long periods of time without shutting down, such as the power generation and (petro)chemical industries. The machines in such industries typically run at near constant speed, and with stable load, so the technical problems associated with the condition monitoring were considerably reduced. As more powerful diagnostic techniques have become available, it has been possible to extend condition monitoring to other industries in which the machines have widely varying speed and load, and are perhaps even mobile (such as ore trucks in the mining industry). The potential benefits given by CBM applied to hydroelectric power plants and wind turbines are discussed in [7, 8], respectively.

This book aims at explaining a wide range of techniques, based on vibration analysis, for all three phases of machine condition monitoring, namely fault detection, fault diagnosis and fault prognosis (prediction of remaining useful life).

1.3 Condition Monitoring Methods

Condition monitoring is based on being able to monitor the current condition and predict the future condition of machines while in operation. Thus it means that information must be obtained externally about internal effects while the machines are in operation.

The two main techniques for obtaining information about internal conditions are:

1. ***Vibration Analysis***. A machine in standard condition has a certain vibration signature. Fault development changes that signature in a way that can be related to the fault. This has given rise to the term 'mechanical signature analysis' [9].
2. ***Lubricant Analysis***. The lubricant also carries information from the inside to the outside of operating machines in the form of wear particles, chemical contaminants, and so on. Its use is mainly confined to circulating oil lubricating systems, although some analysis can be carried out on grease lubricants.

Each of these is discussed in a little more detail in the following, along with a couple of other methods, performance analysis and thermography, that have more specialized applications.

1.3.1 Vibration Analysis

Even in good condition, machines generate vibrations. Many such vibrations are directly linked to periodic events in the machine's operation, such as rotating shafts, meshing gearteeth, rotating electric fields, and so on. The frequency with which such events repeat often gives a direct indication of the source and thus many powerful diagnostic techniques are based on frequency analysis. Some vibrations are due to events that are not completely phase locked to shaft rotations, such as combustion in IC (internal combustion) engines, but where a fixed number of combustion events occur each engine cycle, even though not completely repeatable. As will be seen, this can even be an advantage, as it allows such phenomena to be separated from perfectly periodic ones. Other vibrations are linked to fluid flow, as in pumps and gas turbines, and these also have particular, quite often unique, characteristics. The term 'vibration' can be interpreted in different ways, however, and one of the purposes of this chapter is to clarify the differences between them and the various transducers used to convert the vibration into electrical signals that can be recorded and analysed.

One immediate difference is between the absolute vibration of a machine housing and the relative vibration between a shaft and the housing, in particular where the bearing separating the two is a fluid film or journal bearing. Both types of vibration measurement are used extensively in machine condition monitoring, so it is important to understand the different information they provide.

Another type of vibration which carries diagnostic information is torsional vibration, that is, angular velocity fluctuations of the shafts and components such as gears and rotor discs.

All three types of vibration are discussed in this chapter, and the rest of the book is devoted to analysing the resulting vibration signals, though overwhelmingly from accelerometers (acceleration transducers) mounted on the machine casing.

It should perhaps be mentioned that a related technique, based on measurement of acoustic emission (AE), has received some attention and is still being studied. The name derives from high-frequency solid-borne rather than airborne acoustic signals from developing cracks and other permanent deformation, bursts of stress waves being emitted as the crack grows, but not necessarily otherwise. The frequency range for metallic components is typically 100 kHz to 1 MHz, this being detected by piezoelectric transducers attached to the surface.

One of the first applications to machine diagnostics was to detection of cracks in rotor components (shafts and blades) in steam turbines, initiated by the Electric Power Research Institute (EPRI) in the USA [10]. Even though EPRI claimed some success in detecting such faults on the external housing of fluid film bearings, the application does not appear to have been developed further. AE monitoring of gear fault development was reported in [11], where it was compared with vibration monitoring. The conclusion was that indications of crack initiation were occasionally detected a day earlier (in a 14 day test) than symptoms in the vibration signals, but the latter persisted because they were due to the presence of actual spalls, while the AE was only present during crack growth. Because of the extremely high sampling rate required for AE, huge amounts of data would have to be collected to capture the rare burst events, unless recording were based on event triggering. In [12], AE signals are compared with vibration signals (and oil analysis) for gear fault diagnostics and prognostics, but the AE sensors had to be mounted on the rotating components and signals extracted via slip rings. Because of the difficulty of application of AE monitoring to machine condition monitoring, it is not discussed further in this book, although new developments may change the situation.

1.3.2 Oil Analysis

This can once again be divided into a number of different categories:

1. ***Chip Detectors***. Filters and magnetic plugs are designed to retain chips and other debris in circulating lubricant systems and these are analysed for quantity, type, shape, size, and so on. Alternatively, suspended particles can be detected in flow past a window.

2. ***Spectrographic Oil Analysis Procedures (SOAP)***. Here, the lubricant is sampled at regular intervals and subjected to spectrographic chemical analysis. Detection of trace elements can tell of wear of special materials such as alloying elements in special steels, white metal or bronze bearings, and so on. Another case applies to oil from engine crankcases, where the presence of water leaks can be indicated by a growth in NaCl or other chemicals coming from the cooling water. Oil analysis also includes analysis of wear debris, contaminants and additives, and measurement of viscosity and degradation. Simpler devices measure total iron content.
3. ***Ferrography***. This represents the microscopic investigation and analysis of debris retained magnetically (hence the name) but which can contain non-magnetic particles caught up with the magnetic ones. Quantity, shape and size of the wear particles are all important factors in pointing to the type and location of failure.

Successful use of oil analysis requires that oil sampling, changing and top-up procedures are all well defined and documented. It is much more difficult to apply lubricant analysis to grease lubricated machines, but grease sampling kits are now available to make the process more reliable.

1.3.3 Performance Analysis

With certain types of machines, performance analysis (e.g. stage efficiency) is an effective way of determining whether a machine is functioning correctly.

One example is given by reciprocating compressors, where changes in suction pressure can point to filter blockage, valve leakage could cause reductions in volumetric efficiency, and so on. Another is in gas turbine engines, where there are many permanently mounted transducers for process parameters such as temperatures, pressures and flowrates, and it is possible to calculate various efficiencies and compare them with the normal condition, so-called ‘flow path analysis’.

With modern IC engine control systems, for example for diesel locos, electronic injection control means that the fuel supply to a particular cylinder can be cut off and the resulting drop in power compared with the theoretical.

1.3.4 Thermography

Sensitive instruments are now available for remotely measuring even small temperature changes, in particular in comparison with a standard condition. At this time, thermography is used principally in quasi-static situations, such as with electrical switchboards, to detect local hot spots, and to detect faulty refractory linings in containers for hot fluids such as molten metal.

So-called ‘hot box detectors’ have been used to detect faulty bearings in rail vehicles, by measuring the temperature of bearings on trains passing the wayside monitoring point. These are not very efficient, as they must not be separated by more than 50 km or so, because a substantial rise in temperature of a bearing only occurs in the last stages of life, essentially when ‘rolling’ elements are sliding. Monitoring based on vibration and/or acoustic measurements appears to give much more advance warning of impending failure.

1.4 Types and Benefits of Vibration Analysis

1.4.1 Benefits Compared with Other Methods

Vibration analysis is by far the most prevalent method for machine condition monitoring because it has a number of advantages compared with the other methods. It reacts immediately to change and can therefore be used for permanent as well as intermittent monitoring. With oil analysis for example, several days often elapse between the collection of samples and their analysis, although some online systems do exist. Also in comparison with oil analysis, vibration analysis is more likely to point to the actual faulty component, as many bearings, for example, will contain metals with the same chemical composition, whereas only the faulty one will exhibit increased vibration.

Most importantly, many powerful signal processing techniques can be applied to vibration signals to extract even very weak fault indications from noise and other masking signals. Most of this book is concerned with these issues.

1.4.2 Permanent vs Intermittent Monitoring

Critical machines often have permanently mounted vibration transducers and are continuously monitored so that they can be shut down very rapidly in the case of sudden changes which might be a precursor to catastrophic failure. Even though automatic shutdown will almost certainly disrupt production, the consequential damage that could occur from catastrophic failure would usually result in much longer shutdowns and more costly damage to the machines themselves. Critical machines are often ‘spared’, so that the reserve machines can be started up immediately to continue production with a minimum of disruption. Most critical high-speed turbomachines, in for example power generation plants and petrochemical plants, have built-in proximity probes (Section 1.5.2) which continuously monitor relative shaft vibration, and the associated monitoring systems often have automatic shutdown capability. Where the machines have gears and rolling element bearings, or to detect blade faults, the permanently mounted transducers should also include accelerometers, as explained below in Section 1.5.4.

The **advantages** of permanent monitoring are:

- It reacts very quickly to sudden change and gives the best potential for protecting critical and expensive equipment.
- It is the best form of protection for sudden faults that cannot be predicted. An example is the sudden unbalance that can occur on fans handling dirty gas, where there is generally a build-up of deposits on the blades over time. This is normally uniformly distributed, but can result in sudden massive unbalance when sections of the deposits are dislodged.

The **disadvantages** of permanent monitoring are:

- The cost of having permanently mounted transducers is very high and so they can only be applied to the most critical machines in a plant.
- Where the transducers are proximity probes, they virtually have to be built into the machine at the design stage, as modification of existing machines would often be prohibitive.

- Since the reaction has to be very quick, permanent monitoring is normally based on relatively simple parameters, such as overall RMS or peak vibration level and the phase of low harmonics of shaft speed relative to a 'key phasor', a once-per-rev pulse at a known rotation angle of the shaft. In general such simple parameters do not give much advance warning of impending failure; it is likely to be hours or days, as opposed to the weeks or months lead time that can be given by the advanced diagnostic techniques detailed in later chapters of this book.

Of course, if transducers are mounted permanently, it is still possible to analyse the signals in more detail, just not continuously. This gives the advantage that intermittent monitoring can be carried out in parallel with the permanent monitoring and updated at much more frequent intervals, typically once per day instead of once per week or once per month, to give the best of both worlds. In order to take advantage of the powerful diagnostic techniques, the permanently mounted transducers would have to include accelerometers, for the reasons discussed below in Section 1.5.4.

For the vast majority of machines in a plant it is not economically justified to equip them with permanently attached transducers or permanent monitoring systems. On the other hand, since the major economic benefit from condition monitoring is the potential to predict incipient failure weeks or months in advance, so as to be able to plan maintenance to give the minimum disruption of production, acquire replacement parts, and so on, it is not so important to do the monitoring continuously. The intervals must just be sufficiently shorter than the minimum required lead times for maintenance and production planning purposes. A procedure for determining the optimum intervals is described in [13]. A very large number of machines can then be monitored intermittently with a single transducer and data logger and the data downloaded to a monitoring system capable of carrying out detailed analysis.

The **advantages** of intermittent monitoring are:

- Much lower cost of monitoring equipment.
- The potential (through detailed analysis) to get much more advance warning of impending failure and thus plan maintenance work and production to maximize availability of equipment.
- It is thus applied primarily where the cost of lost production from failure of the machine completely outweighs the cost of the machine itself.

The **disadvantages** of intermittent monitoring are:

- Sudden rapid breakdown may be missed and in fact where failure is completely unpredictable this technique should not be used. On the other hand, the reliability of detection and diagnostic techniques for predictable faults is increasing all the time and can now be said to be very good, in that considerable economic benefit is given statistically by correct application of the most up-to-date condition monitoring techniques [2–5].
- The lead time to failure may not be as long as possible if the monitoring intervals are too long for economic reasons. This is in fact an economic question, balancing the benefits of increased lead time against the extra cost of monitoring more frequently [13].

To summarize, **permanent monitoring** is used to shut machines down in response to sudden change and is thus primarily used on critical and expensive machines to avoid catastrophic failure. It is based on monitoring relatively simple parameters that react quickly to change and typically uses proximity probes and/or accelerometers. **Intermittent monitoring** is used to give long-term advance warning of developing faults and is used on much greater numbers of machines and where production loss is the prime economic factor rather than the cost of the machines themselves. It is usually based on analysis of acceleration signals from accelerometers, which can be moved from one measurement point to another.

1.5 Vibration Transducers

Transducers exist for measuring all three of the parameters in which lateral vibration can be expressed, namely displacement, velocity and acceleration. However, the only practical (condition monitoring) transducers for measuring displacement, proximity probes, measure relative displacement rather than absolute displacement, whereas the most common velocity and acceleration transducers measure absolute motion. This is illustrated in Figure 1.1, which shows a bearing pedestal equipped with one horizontal accelerometer and two proximity probes at 90° to each other. The latter, even though termed vertical and horizontal, would normally be located at ±45° to the vertical so as not to interfere with the usual bolted flange in the horizontal diametral plane of the bearing (Figure 1.2).

1.5.1 Absolute vs Relative Vibration Measurement

Proximity probes measure the relative motion between a shaft and casing or bearing housing (as illustrated in Figure 1.1). It is important to realize that this gives very different information from the absolute motion of the bearing housing, as measured by a so-called 'seismic transducer' as exemplified by an accelerometer. These two parameters are probably as different as the temperature and pressure of steam, even though sometimes related.

The relative motion, in particular for fluid film bearings, is most closely related to oil film thickness, and thus to oil film pressure distribution, as calculated using Reynolds' equation [14]. It is thus also very important in rotor dynamics calculations, as these are greatly influenced

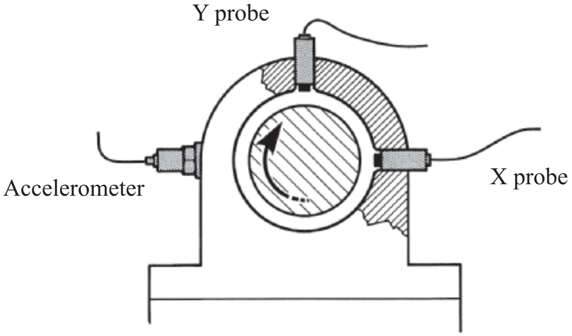

Figure 1.1 Illustration of absolute against relative vibration (Courtesy Brüel & Kjær).

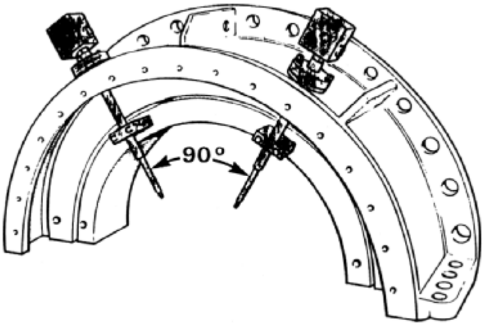

Figure 1.2 Proximity probes installed in a turbine bearing cap.

by the bearing properties. These questions are discussed in more detail in Chapter 2, which gives further references on fluid film bearings and rotor dynamics. However, a fluid film bearing is a very nonlinear spring, and therefore the amplitude of relative vibration does not give a direct measure of the forces between the shaft and its bearing. An increase in static load, for example, causes the oil film to become thinner, and the bearing stiffer, with reduced vibration amplitude, even though the higher load might be more likely to cause failure.

The absolute motion of the bearing housing, on the other hand, responds directly to the force applied by the shaft on the bearing (these being the same since the inertia of the oil film is negligible), and since the machine structure tends to have linear elastic properties, the vibration amplitude will be directly proportional to the force variation, independent of the static load.

In other words, the journal bearing stiffness and damping properties, and thus the dynamic bearing forces, are most directly related to the relative position and motion of the shaft in the bearing, but the response to these forces is most directly indicated by the absolute motion of the housing. An advantage of proximity probes is that they can measure both the absolute position of the shaft in the bearing and the vibrations around the mean position. Direct current (DC) accelerometers do exist, but are rarely used in machine monitoring, since it is still not possible to integrate the signals directly to total velocity and displacement because of the lack of constants of integration. Accelerometers are thus used to measure fluctuations in acceleration around a mean value of zero. This can be integrated to absolute velocity and displacement (fluctuations), but excluding zero frequency.

Other comparisons between the different types of transducers depend on the technical specifications for dynamic range, frequency range, and so on, so each type will be discussed in turn.

1.5.2 Proximity Probes

Proximity probes give a measure of the relative distance between the probe tip and another surface. They can be based on the capacitive or magnetic properties of the circuit including the gap to be measured, but by far the most ubiquitous proximity probes are those based on the changes in electrical inductance of a circuit brought about by changes in the gap. Such probes were pioneered by the company Bently Nevada, now owned by GE, and are very widely used for machine monitoring [15]. Figure 1.2 shows typical proximity probes installed in the bearing cap of a turbine.

The medium in the gap must have a high dielectric value, but can be air or another gas, or for example the oil in fluid film bearings. The surface whose distance from the probe tip is being measured must be electrically conducting, so as to allow the generation of eddy currents by induction. A signal is generated by a 'proximitor' (oscillator/demodulator) at a high frequency and its amplitude is directly dependent on the size of the gap between the probe and the measurement surface. Amplitude demodulation techniques are used to retrieve the signal. A typical probe can measure reasonably linearly in the gap range from 0.25 to 2.3 mm with a maximum deviation from linearity of 0.025 mm (1.1% of full scale) with a sensitivity of 200 mV/mil (7.87 V/mm). Thus, in the sense of the ratio of maximum to minimum value, the dynamic range is less than 20 dB, but in the sense of the ratio of the maximum to minimum component in a spectrum, this would be limited by the nonlinearity to at best 40 dB.

Linearity is not the only factor limiting the dynamic range of valid measurement. By far the biggest limitation is given by runout, called 'glitch' by Bently Nevada [16]. Runout is the signal measured in the absence of actual vibration and is composed of 'mechanical runout' and 'electrical runout'. Mechanical runout is due to mechanical deviations of the shaft surface from a true circle, concentric with the rotation axis, and these include low-frequency components such as eccentricity, shaft bow and out-of-roundness, and shorter components from scratches, burrs and other local damage. Electrical runout is due to variations in the local surface electrical and magnetic properties and can be affected by residual magnetism, and even residual stresses, as well as subsurface imperfections. Much can be done to minimize runout before a shaft goes into service [16], but in general it is unlikely that the dynamic range from the highest measured component to the highest runout component would be more than 30 dB. It is possible to use 'runout subtraction' to compensate to some extent for runout, but the benefits are very limited. In principle, the runout, both mechanical and electrical, can be measured under 'slow roll' conditions ($<10\%$ of normal operating speed), when it can be assumed that the vibration is negligible, and then subtracted from measurements at higher speed. This is most valid for the first harmonic (fundamental frequency) of rotation and can often be done by the monitoring system by vector subtraction. It is unlikely to be valid above critical speed for measurements made below critical speed, at least where the runout is due to shaft bow. Another reason why the runout subtraction might not be valid is that, on large machines, thermal expansion from low to high load/speed means that the section of shaft on which the slow roll measurements are made is different from that aligned with the probes under normal operating conditions. Some machines are required to run without shutdown for one or more years, and the monitoring position on the shaft is also subject to change through wear of thrust bearings. Proximity probes are in fact used in axial position monitoring of rotors.

Interestingly, the dominant standard for shaft vibration monitoring, the American Petroleum Institute's API 670 [15], states that no correction is to be made for runout in indicated vibration levels. It also states that the total runout should not exceed 25% of the maximum allowed peak-to-peak vibration amplitude. This corresponds to just -12 dB and is the best indicator of the valid dynamic range of a proximity probe measurement. Even where runout subtraction can be carried out successfully, it is unlikely the improvement in dynamic range would be more than 10 dB, say from 30 to 40 dB, and that primarily at low harmonics. The higher the harmonic, the shorter the wavelength, and thus the greater the likelihood that measured runout would be affected by small axial displacement due to thermal expansion or wear.