Mathematics for Industry 17

Osami Matsushita
Masato Tanaka
Masao Kobayashi
Patrick Keogh
Hiroshi Kanki

Vibrations of Rotating Machinery

Volume 2. Advanced Rotordynamics: Applications of Analysis, Troubleshooting and Diagnosis

Springer

Mathematics for Industry

Volume 17

Aims & Scope

The meaning of "Mathematics for Industry" (sometimes abbreviated as MI or MfI) is different from that of "Mathematics in Industry" (or of "Industrial Mathematics"). The latter is restrictive: it tends to be identified with the actual mathematics that specifically arises in the daily management and operation of manufacturing. The former, however, denotes a new research field in mathematics that may serve as a foundation for creating future technologies. This concept was born from the integration and reorganization of pure and applied mathematics in the present day into a fluid and versatile form capable of stimulating awareness of the importance of mathematics in industry, as well as responding to the needs of industrial technologies. The history of this integration and reorganization indicates that this basic idea will someday find increasing utility. Mathematics can be a key technology in modern society.

The series aims to promote this trend by 1) providing comprehensive content on applications of mathematics, especially to industry technologies via various types of scientific research, 2) introducing basic, useful, necessary and crucial knowledge for several applications through concrete subjects, and 3) introducing new research results and developments for applications of mathematics in the real world. These points may provide the basis for opening a new mathematics-oriented technological world and even new research fields of mathematics.

To submit a proposal or request further information, please use the PDF Proposal Form or contact directly: Swati Meherishi, Executive Editor.

Editor-in-Chief

Masato Wakayama (Kyushu University, Fukuoka, Japan)

Scientific Board Members

Robert S. Anderssen (Commonwealth Scientific and Industrial Research Organisation, Canberra, ACT, Australia)
Yuliy Baryshnikov (Department of Mathematics, University of Illinois at Urbana-Champaign, Urbana, IL, USA)
Heinz H. Bauschke (University of British Columbia, Vancouver, BC, Canada)
Philip Broadbridge (School of Engineering and Mathematical Sciences, La Trobe University, Melbourne, VIC, Australia)
Jin Cheng (Department of Mathematics, Fudan University, Shanghai, China)
Monique Chyba (Department of Mathematics, University of Hawaii at Mānoa, Honolulu, HI, USA)
Georges-Henri Cottet (Joseph Fourier University, Grenoble, Isère, France)
José Alberto Cuminato (University of São Paulo, São Paulo, Brazil)
Shin-ichiro Ei (Department of Mathematics, Hokkaido University, Sapporo, Japan)
Yasuhide Fukumoto (Kyushu University, Nishi-ku, Fukuoka, Japan)
Jonathan R. M. Hosking (IBM T.J. Watson Research Center, Scarsdale, NY, USA)
Alejandro Jofré (University of Chile, Santiago, Chile)
Masato Kimura (Faculty of Mathematics & Physics, Kanazawa University, Kanazawa, Japan)
Kerry Landman (The University of Melbourne, Victoria, Australia)
Robert McKibbin (Institute of Natural and Mathematical Sciences, Massey University, Palmerston North, Auckland, New Zealand)
Andrea Parmeggiani (Dir Partenariat IRIS, University of Montpellier 2, Montpellier, Hérault, France)
Jill Pipher (Department of Mathematics, Brown University, Providence, RI, USA)
Konrad Polthier (Free University of Berlin, Berlin, Germany)
Osamu Saeki (Institute of Mathematics for Industry, Kyushu University, Fukuoka, Japan)
Wil Schilders (Department of Mathematics and Computer Science, Eindhoven University of Technology, Eindhoven, The Netherlands)
Zuowei Shen (Department of Mathematics, National University of Singapore, Singapore, Singapore)
Kim Chuan Toh (Department of Analytics and Operations, National University of Singapore, Singapore, Singapur, Singapore)
Evgeny Verbitskiy (Mathematical Institute, Leiden University, Leiden, The Netherlands)
Nakahiro Yoshida (The University of Tokyo, Meguro-ku, Tokyo, Japan)

More information about this series at http://www.springer.com/series/13254

Osami Matsushita · Masato Tanaka ·
Masao Kobayashi · Patrick Keogh ·
Hiroshi Kanki

Vibrations of Rotating Machinery

Volume 2. Advanced Rotordynamics: Applications of Analysis, Troubleshooting and Diagnosis

Springer

Osami Matsushita
The National Defense Academy
Yokosuka, Japan

Masato Tanaka
The University of Tokyo
Tokyo, Japan

Masao Kobayashi
IHI Corporation
Yokohama, Japan

Patrick Keogh
University of Bath
Bath, UK

Hiroshi Kanki
Kobe University
Kobe, Japan

ISSN 2198-350X ISSN 2198-3518 (electronic)
Mathematics for Industry
ISBN 978-4-431-55452-3 ISBN 978-4-431-55453-0 (eBook)
https://doi.org/10.1007/978-4-431-55453-0

Library of Congress Control Number: 2018965430

© Springer Japan KK, part of Springer Nature 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Japan KK, part of Springer Nature.
The registered company address is: Shiroyama Trust Tower, 4-3-1 Toranomon, Minato-ku, Tokyo 105-6005, Japan

Preface

This book is a sequel to the previous book "Vibrations of Rotating Machinery Volume 1. Basic Rotordynamics: Introduction to Practical Vibration Analysis." Volume 1 used simplified models and mathematical expressions to give succinct explanations of various vibration phenomena occurring in rotating machinery. "Volume 2. Advanced Rotordynamics: Applications of Analysis, Troubleshooting and Diagnosis" provides actual vibration problems and fundamental key techniques for troubleshooting the problems by measurement, analysis, and diagnosis of the vibrations.

The *v_BASE* databook provides a database of vibration problems of actual machinery experienced by industry. The latest edition, published in 2011 March, includes 790 cases in total, and more than a half of them are involved with rotating machinery. A wide variety of vibration problems experienced are described, together with elaborate troubleshooting of the problems. For example, when a vibration problem is found in commissioning a rotating machine, full-power operation and/orfull-speed operation cannot be completed until the problem is solved. The same or similar vibration problems occur repeatedly in the field. This book aims to assist engineers in troubleshooting the problems effectively.

Rotating shafts are supported by various types of bearings. Chapters 2–4 describe the dynamical properties of oil film bearings, unbalance vibration of rotors supported by the bearings, and self-excited vibrations of rotors caused by the destabilizing action of bearing oil films or seal films, respectively. Chapter 5 describes the vibration diagnosis methods for rotors supported by rolling element bearings. Chapter 6 describes the mechanical and dynamical properties of active magnetic bearings (AMBs) and the rotor vibration control action available from AMBs. The related ISO information and case studies are introduced to accelerate the familiarization of AMB technologies. Chapters 7 and 8 give actual examples of forced vibration of rotors and self-excited vibration of rotors selected from the *v_BASE* databook, respectively.

The chapters mentioned above deal with the rotor lateral vibrations of whirling modes in a shaft axial rotational plane. In addition, Chapter 9 treats torsional vibration analysis of a turbo-rotor train system, together with shaft–blade coupled torsional resonances in turbine generator sets. Chapter 10 explains the rotor vibration signal processing based on the Fast Fourier transformation (FFT). The same signal processing is so specialized for the combination with rotor whirling motion that it could be convenient for other vibration diagnoses. Chapter 11 deals with our latest topics on modeling techniques and is recommended mainly for system reduction. It also enables prediction of the onset speed of oil film-induced instability without the need for eigenvalue evaluation and explains how to model the complete form of coupled vibration analysis between shafting and blading. Chapter 12, the final chapter, offers 100 selected questions and answers, referring to the ISO curriculum. We hope that they will be effective to re-affirm the knowledge stated in our books for vibration diagnosis.

This book is intended to help design engineers of rotating machinery to prevent the recurrence of the problems reported and also to help candidates pass the ISO machine condition monitoring and diagnosis examination. The target readers of this book also include graduate students, practicing engineers, and research scientists who can utilize methods of analysis, the mathematical approach, and the references cited.

While the authors have endeavored to eliminate errors and avoid bias, critical comments from readers are welcome. The authors are grateful to the authors of the literature cited in this book, especially Dr Ronald L. Eshleman (VI, USA). Special thanks are also due to Prof Hiroyuki Fujiwara (National Defense Academy of Japan), Mr Hisayuki Motoi (Deputy General Manager, IHI, Japan), and Dr Hidetomo Komura (3DIM, Japan) for providing valuable comments for the 100 Q&A list of Chapter 12. The authors deeply thank Mr Fumito Shinkawa, President of Shinkawa Electric Co., Ltd., for his support for our authoring.

The authors wish to thank Springer for its support in publishing this work.

Yokosuka, Japan Osami Matsushita
August 2018

Contents

Chapter 1
An Overview of Vibration Problems in Rotating Machinery

Abstract This book aims to explain various phenomena and mechanisms of vibrations in rotating machinery based on theory and field experiences. It also aims to help engineers in carrying out diagnosis and in implementing countermeasures for various vibration problems in the field. It is normally easy to know the condition of machinery by means of measurement of vibrations and/or noise. However, it is rather difficult to interpret the observed phenomena correctly, derive real causes of the problems, and ascertain effective countermeasures, because a sufficient knowledge of case studies is needed. This chapter provides an overview of vibration problems in rotating machinery and general approaches for the countermeasures, and is intended to be helpful in solving vibration problems at the front line. Condition monitoring of a machine and vibration diagnostics including relevant ISO standards are illustrated. Case studies of vibration problems and the countermeasures in excess of 1000 cases, which have been collected until now by the Vibration Database (***v_BASE***) Committee under the Japan Society of Mechanical Engineers (JSME), are also referred to in this chapter.

Keywords Rotor · Bearing · Stator · Vibration model · Vibration problems · Case study · Forced vibration · Self-excited vibration · ISO Standard · Condition monitoring · Vibration diagnostics · Causal relationship matrix · ***v_BASE*** database

1.1 Structure and Feature of Rotating Machinery

Figure 1.1 shows a schematic of a turbocharger for application in automotive engines. In this machine, exhaust gas from an internal-combustion engine drives the turbine wheel that in turn drives the compressor wheel via a shaft fixed coaxially. Thus, much more air can be supplied to the combustion chambers and power output can be increased compared with a naturally aspirated engine.

This machine consists of three parts, that are, (1) a rotating shaft with two wheels (rotors), (2) a stationary casing or housing (stator), and (3) bearings and seals (in-between connection parts).

© Springer Japan KK, part of Springer Nature 2019

O. Matsushita et al., *Vibrations of Rotating Machinery*, Mathematics for Industry 17,
https://doi.org/10.1007/978-4-431-55453-0_1

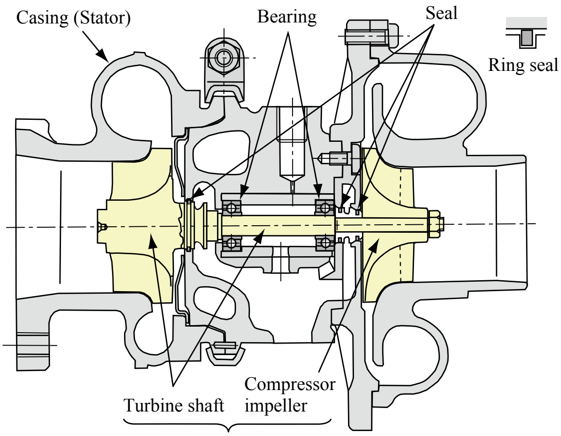


Fig. 1.1 Configuration of vehicular turbocharger

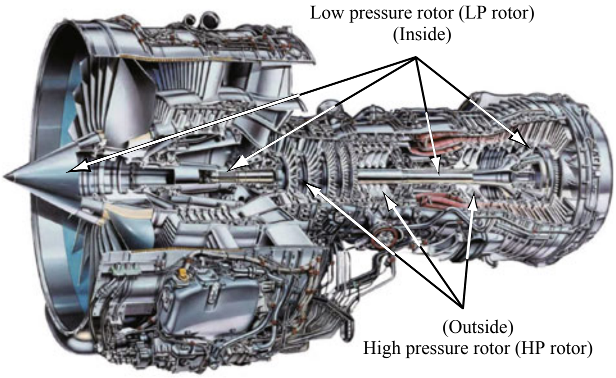


Fig. 1.2 Rotor configuration of aircraft engine (provided by Japanese Aero Engines Corporation)

Figure 1.2 shows a cutaway of aircraft gas turbine engine with a double spool arrangement, that is, the long LP rotor is placed inside the hollow HP rotor. This structure is complicated, but is the same as a turbocharger from a basic viewpoint.

Theoretical modeling of actual rotating machinery is not always easy. In the case of torsional vibration of a rotor in its rotational degree of freedom, the modeling of the rotor only is sufficient because bearing forces and seal forces do not adversely affect the vibration. On the other hand, in the case of rotor bending vibration, the dynamic characteristics of bearings and seals must be incorporated in the model because they exert significant influence on the analytical results. Furthermore, modeling with the dynamic characteristics of a soft casing needs to be incorporated when the critical speeds of the system are influenced by them and come near to or within the operating speed range.

From the perspective of a vibrating system, a rotating machine is special and differs widely from a general structure. First, the largest differences in a rotating machine are associated with the dynamic characteristics of the bearings and seals, which are specific to rotating machines. These dynamic characteristics may have sufficiently large influences to characterize the whole system. Consequently, this book intends to explain the features of bearings in detail, focusing on oil film bearings, rolling element bearings, and active magnetic bearings.

The dynamic characteristics of bearings and seals change significantly with operating conditions such as rotating speeds, loads, or pressures, and are represented in two-dimensional whirling degrees of freedom (x, y). Stiffness and damping coefficients are expressed with associated (2×2) matrices. Sometimes, the magnitudes of cross-coupled stiffnesses (xy and yx components) become much larger than those of diagonal stiffnesses (xx and yy components). In such cases, the rotor-bearing system can become unstable, resulting in self-excited vibration known as oil whip, for example.

Other significant differences in a rotating machine are gyroscopic moments acting on a rotor (e.g., giving rise to the standing up effect of a spinning top) that change in magnitude in proportion to rotating speed. As a result, vibrations in the x and y directions become coupled. The gyroscopic moments can be expressed using a skew-symmetric matrix.

From these differences, standard general-purpose finite element method (FEM) software, which is based on symmetric matrix calculation, is not applicable for a rotating machine. This is a reason why vibration analysis software specialized for rotordynamics, such as MyROT as described in R1_Chap. 12, plays an important role in this field.

Bearing characteristics sometimes cause self-excited vibration, but the damping coefficient of an oil film bearing or a squeeze film damper is much larger relatively than material or structural damping considered in a general structure. Therefore, it can be said for rotating machines that there are many stabilizing elements, yet also many destabilizing elements. It is important for rotating machinery to attain rotational stability throughout the operational range. For this reason, a complex eigenvalue analysis, which calculates not only natural frequencies but also damping ratios, is performed commonly for rotordynamic assessment.

1.2 Vibration Problems in Rotating Machinery and Countermeasures

Unexpected vibration problems often become evident at a stage of developing machinery for higher speed, higher load, and higher efficiency. If the causes of the phenomena are known, countermeasures are straightforward. In cases of phenomena not previously encountered, there may be great difficulties to elucidate the causes. However, the efforts to solve these problems will certainly contribute to the progress of machine technology.

Historically, in the field of structural vibration engineering, bridge design for wind-resistant stability progressed greatly after the famous problem of the Tacoma Narrows Bridge. Also, airfoil flutter technologies began with the development of high-speed aircraft. In rotordynamics, a typical example is oil whip, a self-excited vibration first reported in 1925, which was encountered in the development of a high-speed rotor supported by oil film bearings. The technology advanced by elucidating the instability mechanism. In this manner, vibration engineering has been making progress in tandem with machine performance.

For these reasons, in order to design high-performance machines without repetition of previously experienced problems, it is essential to know what types of vibration phenomena have occurred and also to know what countermeasures have been taken.

Figure 1.3 shows a survey of results relating to problematic modes in some rotating machines. In this case "abnormal vibration" 29%, "abnormal sound" 11%, and "fatigue" 8%, these vibration-related cases account for 48% in total. Also, "wear" or "crack" issues often arise due to vibration; therefore, more than half of problems can be attributed to vibrations in rotating machinery.

As this survey shows, a rotating machine is commonly associated with vibration phenomena. There are some causes of resulting vibration. A prompt investigation of these causes and remedies would be required for the benefit of the organization. Usually, troubleshooting is carried out with the following process steps shown below.

(1) Understanding of machine structure and mechanisms, and collection of information

At first, it is essential to know the structure and understand how the machine functions. Viewing drawings and reports from engineers commonly form this process step. Design difficulties concerning vibration technologies should be assessed using proper engineering judgment. It is also important to derive first-hand information from operators and maintenance engineers on-site.

(2) Vibration measurement and investigation

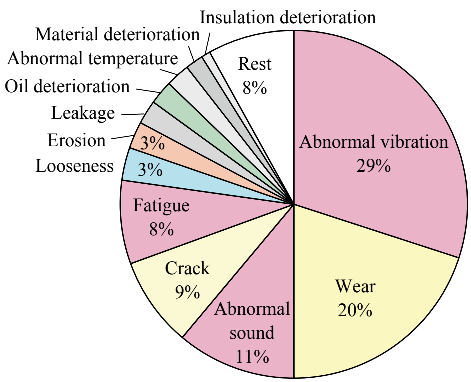


Fig. 1.3 Problematic case classifications in rotating machinery

Next, measurements are usually taken in order to comprehend the phenomena. In the case of a machine, measurements are necessary to evaluate the existing problematic conditions. For some reason, if a vibration level is high as a result, measurements should not necessarily be restricted to the vibration alone. Other possible causes, such as operational condition (pressure or temperature and so on) should be measured. It is also important to monitor the changes with variation of rotational speed.

It may seem better to gather more data, but final decisive data usually form only a relatively small subset from which to comprehend the phenomena and to identify the causes. Gathering data is not a final target, but it is important to identify the decisive data as early as possible.

(3) Estimation of the causes

When an approximate understanding of the phenomena becomes apparent, the next step is to estimate the cause. Study of relevant precedents and the simulation of simple models will take place in order to clarify the mechanism. It may also include large-scale analysis. Table 1.1 shows the approximately classified vibration phenomena and the causes in rotating machinery. We can see that vibration phenomena are separated into forced vibration and self-excited vibration.

(4) Implementing countermeasures

The next stage involves the implementation of countermeasures. At this stage, the real cause of the vibration may not be ascertained, but the solution process will be urgent. After building up a hypothesis about the mechanism, countermeasures are implemented. If the results coincide with the expectations, the hypothesis may be considered to be proven. At the end of this stage, it is important to file the result of the troubleshooting as a causal relationship for future use.

Table 1.1 Vibration phenomena and cause

Forced vibration	
Unbalance vibration	Excessive unbalance Thermal unbalance Rotor deformation Misalignment Cracked rotor Bowed rotor Foundation defect
Resonance	Unbalance resonance Harmonic, Sub-harmonic resonance Torsional resonance Selective resonance
Fluid force	Rotating stall Cavitation Organ pipe vibration Combustion vibration
Force by mechanism	Electromagnetic force Ball bearing force Gear force Cross (Hooke's) joint Mechanism (cam /link)

Self-excited vibration
Surge
Friction whip
Internal damping / hysteresis whip
Oil whirl /whip
Steam whirl
Labyrinth whirl
Impeller shroud force

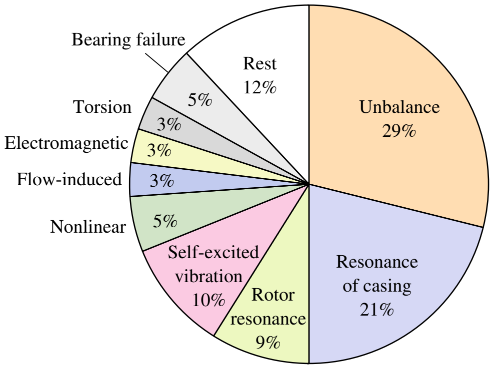


Fig. 1.4 Ratio of the categorized cause of vibration

Figure 1.4 shows the causes of vibration problems for a specific machine. Another chart would be presented for a different machine. In this case, the effects concerning forced vibration such as unbalanced resonance are experienced in a significant number of cases, and the effects concerning self-excited vibration are unexpectedly a few (10%).

Note: 1 Preventive maintenance of rotating machinery Machinery maintenance can be divided broadly into two categories. One is breakdown maintenance (BM), which implements maintenance work after a breakdown event. Another is preventive maintenance (PM), which implements maintenance work before breakdowns occur.

One of the PM categories is time-based maintenance (TBM) that repeats inspections, repairs, and component replacement at regular time intervals. With TBM applied, machinery needs to be shut down after operating for a preset time duration, even if it is running smoothly, and some machine components are replaced even when not necessary. Consequently, TBM tends to result in costly maintenance. Furthermore, it may lead to a higher risk of initial failure at the restart of operation.

The other PM category is condition-based maintenance (CBM) or predictive maintenance, which improves the possible shortcomings of TBM. Figure 1.5 illustrates the differences between TBM and CBM. With CBM applied, maintenance work is implemented before any predicted breakdown time, based on condition monitoring data obtained and analyzed. Machines are shut down when some representative measurements exceed preset limit values. The vibration amplitudes of bearing housings or rotating shafts are typically used in the monitoring. When vibration data alone are not sufficient to make a decision, data from wear particle sensors, acoustic emission (AE) sensor signals, and infrared thermography may be combined.

Note: 2 Online and offline condition monitoring Figure 1.6 shows a typical online condition monitoring system by means of permanently installed and continuously working sensing equipment. It is costly, but can monitor the system condition continuously. Consequently, this system is applied to machinery that is categorized as of high value and is risk critical. It is implemented in risk-based maintenance (RBM),

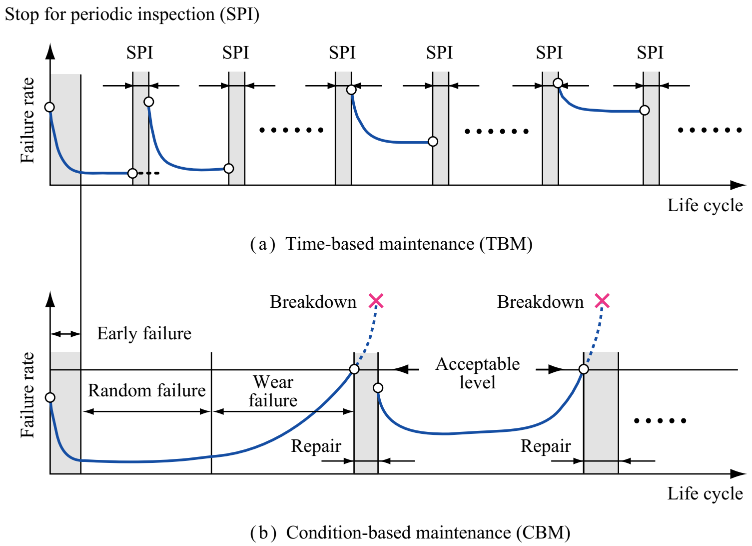
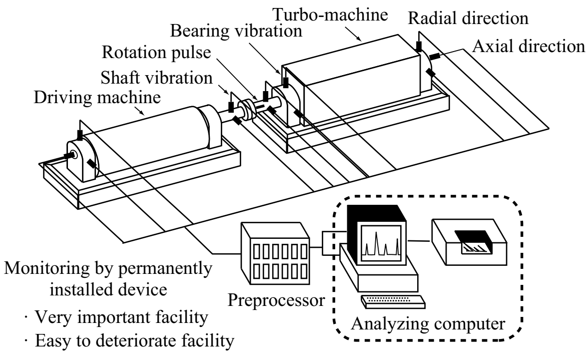


Fig. 1.5 Comparison of maintenance cycle between TBM and CBM

Fig. 1.6 Online monitoring (ISO 13373-1)



which uses the product of probability of failure and resulting damage as an evaluation index.

On the other hand, Fig. 1.7 shows an offline monitoring system to collect data by means of handheld vibration measurement device at specified time intervals, for example, once per day. It is applied to lower risk machinery. Terminal boxes are used for a machine with difficult human access.

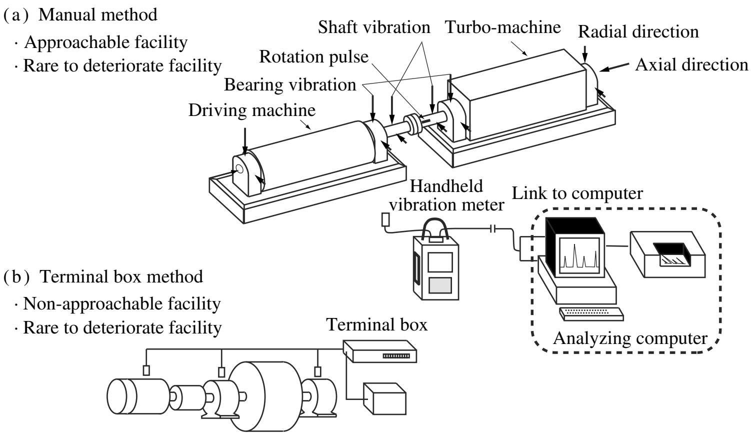


Fig. 1.7 Offline monitoring (ISO 13373-1)

1.3 Guidelines for Health Evaluation

The health condition of rotating machinery is often evaluated based on bearing or shaft vibration signals. Bearing vibration is measured as an absolute vibration (RMS value of vibration velocity) by means of electrodynamic vibration velocimeters or piezoelectric vibration accelerometers, both fixed on stationary bearing pedestals. Shaft vibration is measured as a relative vibration (vibration amplitude of shaft displacement) from stationary casings using displacement transducers.

Machinery manufacturers and users often have different criteria in categorizing measured vibration as normal or abnormal. Therefore, mutual agreements are needed in advance to evaluate health condition, inclusive of allowable vibration criteria. For this agreement, the ISO (International Organization for Standardization [1]) establishes and disseminates internationally unified standards for such agreements. Major international standards concerning vibrations of rotating machinery are presented in the following sections.

1.3.1 International Standards on Vibrations of Rotating Machinery

ISO consists of more than 200 Technical Committees (TCs), each TC consists of Sub-Committees (SCs), and each SC consists of Working Groups (WGs). Mechanical vibrations are treated in TC108 (mechanical vibrations, shock and condition monitoring). The following are the main SCs and WGs operated by TC108 concerning rotating machinery.

SC1 Balancing (currently WG31 under SC2)
SC2 Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles, and structures

/WG1 Rotordynamics and vibration of machines
/WG7 Vibration of machines with active magnetic bearings
/WG9 Vibration of pumps
/WG10 Basic techniques for vibration diagnostics

SC5 Condition monitoring and diagnostics of machine systems

/WG7 Training and accreditation in the field of condition monitoring and diagnostics

Many standards related to rotating machinery vibrations have been authorized and released by ISO, based on the discussions between international experts. Furthermore, the IEC [2] (International Electrotechnical Commission, ISO Cooperation Organization) and the API [3] (American Petroleum Institute) publish similar standards. The following standards are related to the content of this book:

- Basics
  ISO 2041 Mechanical vibration, shock and condition monitoring—Vocabulary
- Unbalance and balancing

  ISO 21940-11 (originated from 1940-1) Mechanical vibration – Rotor balancing – Part 11: Procedures and tolerances for rotors with rigid behaviour
  ISO 21940-12 (originated from 11342) Mechanical vibration – Rotor balancing – Part 12: Procedures and tolerances for rotors with flexible behaviour
  ISO 21940-31 (originated from 10814) Mechanical vibration – Rotor balancing – Part 31: Susceptibility and sensitivity of machines to unbalance

- Measurement and evaluation of mechanical vibrations and shock

  ISO 10816 Mechanical vibration—Evaluation of machine vibration by measurements on non-rotating parts, Parts 1–7
  ISO 7919 Mechanical vibration of non-reciprocating machines—Measurements on rotating shafts and evaluation criteria, Parts 1–5

  Note: Recently, some of ISO 10816 and ISO 7919 are now being unified to a new ISO 20816 series. In this book, we mention them by their original series numbers.

  ISO 8528 Reciprocating internal combustion engine driven alternating current generating sets, Part 9: Measurement and evaluation of mechanical vibrations.
  ISO 14839 Mechanical vibration—Vibration of rotating machinery equipped with active magnetic bearings,
  Part 1: Vocabulary,
  Part 2: Evaluation of vibration,
  Part 3: Evaluation of stability margin,
  Part 4: Technical guidelines.

ISO 22266 Mechanical vibration—Torsional vibration of rotating machinery

- Condition monitoring and diagnostics

ISO 13372 Condition monitoring and diagnostics of machines—Vocabulary
ISO 13373 Condition monitoring and diagnostics of machines—Vibration condition monitoring,
  Part 1: General procedures,
  Part 2: Processing, analysis and presentation of vibration data.

ISO 13374 Condition monitoring and diagnostics of machines—Data processing, communication and presentation,
  Part 1: General guidelines,
  Part 2: Data processing,
  Part 3: Communication.

ISO 13379 Condition monitoring and diagnostics of machines—General guidelines on data interpretation and diagnostics techniques
ISO 17359 Condition monitoring and diagnostics of machines—General guidelines
ISO 18436 Condition monitoring and diagnostics of machines—Requirements for qualification and assessment of personnel,
  Part 1: Requirements for certifying bodies and the certification process,
  Part 2: Vibration condition monitoring and diagnostics,
  Part 3: Requirements for training bodies and the training process,
  Part 4: Field lubricant analysis.

- IEC Standards [2]
  The following standards, defined according to ISO standards, are often used.

IEC 60034-14 Rotating electrical machines,
  Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher—Measurement, evaluation and limits of vibration severity.
IEC 60994 Guide for field measurement of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines).

- API Standards [3]
  The machine-dependent standards establish incoming inspection criteria from the viewpoint of users of rotating machinery.

API 610 Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries,
API 616 Gas Turbines for Petroleum, Chemical, and Gas Industry Services,
API 617 Axial and Centrifugal Compressors and Expander-compressors,
API 677 General Purpose Gear Units for Petroleum, Chemical and Gas Industry Services.

1.3.2 Allowable Vibration Criteria

Among the ISO Standards described above, the following are the guidelines to determine allowable vibration criteria.

(1) Bearing vibrations
ISO 10816 (Mechanical vibration—Evaluation of machine vibration by measurements on non-rotating parts) determines vibration evaluation criteria in terms of vibration severity, based on RMS value of broadband vibration velocity (normally 10 Hz–1 kHz) measured at non-rotating parts near bearing casings.

Note: As mentioned above, ISO 10816 and ISO 7919 series are now being integrated to new ISO 20816 series.

Part 1 General guidelines,
Part 2 Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500, 1800, 3000, and 3600 r/min,
Part 3 Industrial machines with nominal power above 15 kW and nominal speeds between 120 and 15 000 r/min when measured in situ,
Part 4 Gas turbine sets with fluid-film bearings,
Part 5 Machine sets in hydraulic power generating and pumping plants,
Part 6 Reciprocating machines with power ratings above 100 kW,
Part 7 Rotodynamic pumps for industrial application, including measurements on rotating shafts.

Part 7, published in 2009, includes the evaluation criteria of shaft vibration, corresponding to ISO 7919.

(2) Shaft vibration
ISO 7919 (Mechanical vibration of non-reciprocating machines—Measurements on rotating shafts and evaluation criteria) determines evaluation criteria of shaft vibration displacement measured by means of non-contacting sensors (contact-type sensors may also be applicable),
Part 1 General guidelines,
Part 2 Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500, 1800, 3000 and 3600 r/min,
Part 3 Coupled industrial machines,
Part 4 Gas turbine sets with fluid-film bearings,
Part 5 Machines set in hydraulic power generating and pumping plants.

These internationally agreed standards present allowable vibration values determined from past field experiences. Design engineers and operation managers need to know the content of the standards fully since they are important to judge machine vibrations as normal or abnormal.

1.3.3 Condition Monitoring of Machines and Certification System of Vibration Diagnostics Engineers

TC108/SC2/WG10 (Prof. Aly El-Shafei as convenor, Professor at Cairo University, Egypt) focuses its activities mainly on ISO 13373 that prescribes condition monitoring and diagnostic techniques of mechanical vibrations. TC108/SC5/WG7 (Dr. Eshlemann as convenor, President of Vibration Institute, USA) established ISO 18436 in 2003, defining an international training system for vibration diagnostics engineers, and also a certification system.

In accordance with the ISO requirements above, the Japan Society of Mechanical Engineers (JSME) started the certification business for professional engineers qualified for condition monitoring and diagnostics of mechanical vibrations in 2004. The qualification examination is staged twice per year, with more than 100 applicants at each time. The examination is explained in detail on the pages of Qualification and Certification in the JSME website [4]. Figure 1.8 shows a wide variety of the industrial fields (manufacturers and users) of the applicants up to the year of 2008.

The qualifications are needed to be able to carry out acceptance testing and vibration troubleshooting. The certified qualifications are classified into four categories, I to IV (highest). According to ISO 18436-2, each category is structured broadly as outlined by the following:

Category I

Being qualified to perform a range of a simple single-channel machinery vibration condition monitoring and diagnostics of machinery activities, in accordance with ISO 17359 and ISO 13373-1. However, it does not qualify the person to be responsible, for example, for the choice of sensor/transducer or for any analysis to be conducted, nor for the assessment of test results, and other judgment.

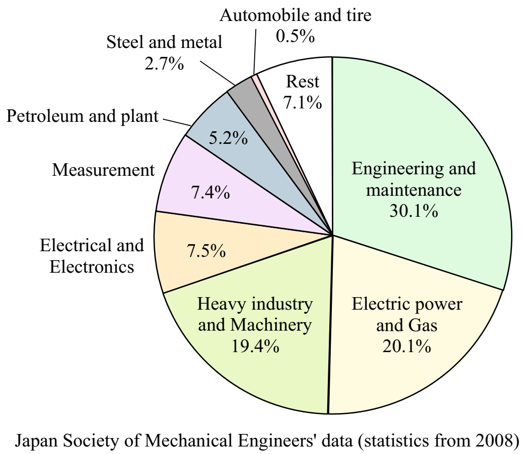


Fig. 1.8 Industrial fields of applicants for ISO vibration analyst for condition monitoring and diagnostics of machines

Category II

Being qualified to perform industrial machinery vibration measurements and basic vibration analysis using single-channel measurements according to established and recognized procedures, and also being qualified to recommend minor corrective actions, and others.

Category III

Being qualified to perform and/or direct and/or establish programmes for vibration condition monitoring and diagnostics of machines in accordance with ISO 17359 and ISO 13373-1. Also qualified to measure and perform diagnosis of single-channel frequency spectra, as well as waveforms and orbits, to establish vibration monitoring programmes, to recommend field corrective actions, and to report to management personnel regarding programme objectives, budgets, cost justification and personnel development, and other associated procedures.

Category IV

Being qualified to perform and/or direct vibration condition monitoring and diagnostics of machines in accordance with ISO 17359 and ISO 13373-1, and all types of machinery vibration measurements and analyses. Also being qualified to apply vibration theory and techniques, to recommend corrective actions and/or design modifications, to provide technical guidance to vibration trainees and to interpret and evaluate published ISO codes of practice, International Standards and specifications.

Individuals trying to get certification of Category III or IV are required to possess the certificates of the lower categories.

1.4 Vibrations in Rotating Machinery and Diagnosis

Figure 1.9 shows the classification of mechanical vibrations, based on ISO/TC108. The vibrations are classified primarily as deterministic or random. The former is classified further as periodic or aperiodic. For example, vibrations synchronous with shaft rotating frequency are classified as periodic, and cavitation vibration, as random. This classification is based on recording and analyzing time-series waveform of vibration.

From the practical viewpoint of rotating machinery, typical vibrations of rotors are classified as follows:

(1) Shaft bending vibration (lateral vibration)
    This vibration corresponds to shaft center whirling in the shaft rotational plane, showing the mode of shaft deflection as it varies in the axial direction. Rigid mode whirling is inclusive. This bending vibration is the most typical in rotating machinery.

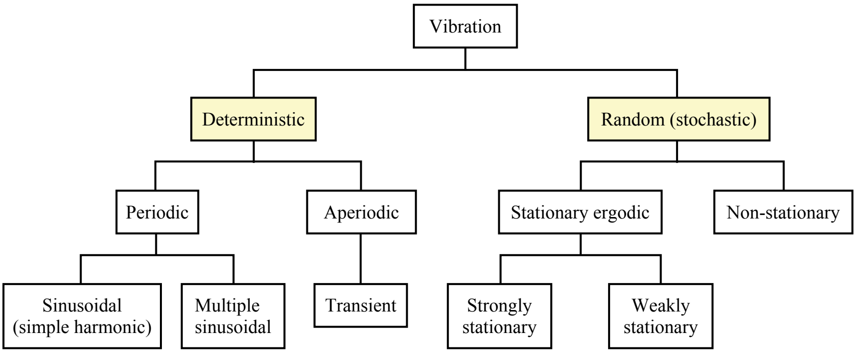


Fig. 1.9 Classification of vibrations (ISO 2041:1990 vocabulary)

(2) Shaft torsional vibration
This vibration corresponds to torsional relative deflection oscillating with time between each neighboring shaft element in the axial direction. Although rotating machinery has few inherent factors causing torsional shaft vibration compared to reciprocating machinery, oscillation of the electromagnetic torques of electric motors may lead to torsional vibration.

(3) Shaft longitudinal (axial) vibration
This vibration usually does not have importance because longitudinal stiffness of shaft is relatively high. However, rigid mode vibration or local resonance may cause contacts with stationary parts or excessive dynamic loading on thrust bearings.

(4) Rotating structure vibration
Turbine blades or impellers of pumps or compressors may cause vibration problems. Eigen frequencies and resonance amplitudes are calculated precisely by means of 3D FEM applied to real configurations of the structures, and in consideration of the stiffness increase due to the centrifugal field effect.

The vibration types mentioned above are classified in terms of vibration direction or of vibrating parts. Each specific vibration can take place alone, but coupled vibrations may also occur.

Vibration arises in response to causes. To reduce vibration, it is important to find out the cause. To investigate vibration problems and to probe the causes is referred to as vibration diagnosis.

1.4.1 Causal Relationship Matrix

ISO 13372 classifies equipment diagnosis procedure into two missions, that is, condition monitoring and diagnostics. Condition monitoring is defined as judging whether the vibration is normal or abnormal, based on the trend against allowable vibration levels. Diagnostics involve determining or estimating the probable causes from various vibration data of the equipment in abnormal situations. These diagnostics are the essentially same as undertaken by medical doctors to identify diseases of patients when examined from various bodily conditions obtained.

Many causal relationships between vibration phenomena and causes have been made clear up to now, and one can estimate causes from the vibration signatures on the basis of a causal relationship matrix. Table 1.2 shows an example of such a matrix based on related research achievements and field experiences. Double circles represent strong relationships between vibration phenomena and causes. Double circles and single circles are found in both cells of stabilization and destabilization depending on some phenomena. For instance, in the case of hysteresis whip, internal

Table 1.2 An example of cause-and-effect matrix
(◎: strong relation, ○: medium relation, △: low relation)

Phenomena / Mechanism	Special term	Self-excited vibration (Natural frequency)		Forced vibration (Excitation frequency)	
		Stabilize	Destabilize	Rotation Ω component	Proportional to rotation vΩ component
Unbalance				◎	
Nonlinear bearing				○	◎
External damping		◎			
Internal damping	Hysteresis whip	○	◎		
Fluid film bearing	Oil whip	◎	◎		
	Oil whirl	◎	◎		
Unsymmetrical shaft	Asymmetric rotor		◎		○
Crack	Cracked rotor		○		◎
Gravity	Secondary critical speed				◎
Blade passing	Blade passing frequency (BPF)				○
Electromagnetic force				○	○
Gear	Mesh frequency			○	◎
Shaft bending	Bowed rotor			◎	
Rotating stall				△	◎
Rubbing	Thermal bending			◎	
	Friction whip		◎	○	○
Ball bearing				○	◎
Misalignment			○	○	○
Cross joint, Joint			△	○	◎
Non-contact seal	Labyrinth whirl		◎		
Impeller shroud			◎		
Fluid containing	Fluid trapped rotor		◎	△	○
Turbine impeller	Thomas force		◎		