MACHINERY CONDITION MONITORING

PRINCIPLES AND PRACTICES

AMIYA R. MOHANTY

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Dedicated to the memory of my father.

Professor Aswini Kumar Mohanty

(1941–1995)

Preface

While teaching the subject of machinery fault diagnostics and signal processing, and conducting short courses for industry professionals for more than fifteen years to the senior year and graduate students at the Indian Institute of Technology, Kharagpur, I have always had a problem locating a single book on the subject. Though there are excellent research journals and trade magazines on the subject, I have failed to locate a book without bias toward the equipment used or process followed for detecting faults in machines in general, and rotating machines in particular. With this preamble I began to write this book, drawing on my experience with machinery condition monitoring while consulting for many industries in India and abroad over the last two decades.

In many of my fault-detection exercises in the industries where I have consulted, I have come across technicians and engineers who wonder what fast Fourier transform (FFT) is, and I have been provided with a table full of numbers and asked to find the fault in the machines. Many engineers in the field learn this subject from the technical brochure of the equipment they use, without understanding their limitations. They feel that since they have a piece of costly equipment at their disposal, they can detect and diagnose the fault in any machine. One of the purposes of this book is to eliminate such myths. No offense intended. There are many commercial software packages available in the market to do diagnostics, but with an understanding of the subject, an engineer can better appreciate the diagnostic routines, because garbage in is garbage out.

This book can be used as a textbook in universities for a forty-hour lecture class. Much of the material in this book has been time tested in my class at the Indian Institute of Technology Kharagpur. I have found MATLAB® to be a very easy way to introduce students to the basics of signal processing, a very important component in machinery condition monitoring. A few MATLAB codes for signal processing are provided in this book.

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Various techniques of machinery maintenance are available today, and after a brief overview of the maintenance techniques in Chapter 2, I focus on the fundamentals of machinery vibration and rotor dynamics in Chapters 3 and 4. A majority of the condition monitoring techniques in the world involve monitoring machine vibrations. Signal processing is a very important component in diagnosing the fault in a machine. Thus Chapters 5 and 6 are focused on the basics of signal processing and instrumentation, which are essential for monitoring the health of machines. Discussions of the requirements of vibration monitoring and noise monitoring are presented in Chapters 7 and 8. Lately, motor current signature analysis has developed into one of the major techniques of fault detection in machines. For example, how does one monitor the condition of a submersible pump buried in the ground, where a vibration transducer cannot be mounted? Further, electric motors are used in a majority of situations in the industry as prime movers, so monitoring their condition is of paramount importance. Chapter 9 focuses on electrical machinery faults. Infrared temperature detection has emerged as a cheap and convenient way to detect hot spots, so Chapter 10 describes the thermography for condition monitoring. Chapters 11 and 12 discuss the techniques of wear debris analysis and some of the nondestructive test (NDT) techniques for condition monitoring like ultrasonics, radiography, and so on. In manufacturing industries, the information regarding a cutting tool, in particular when the tool should optimally be changed, is a matter of concern. Chapter 13 discusses machine tool condition monitoring. In spite of our best maintenance efforts, machines do fail for reasons beyond our control. After a machine fails, we are called to do a postmortem. So, I have added a chapter on engineering failure analysis (Chapter 14). In Chapter 15 I discuss several case studies, mostly on failure analysis, from my consulting experience. After going through all the earlier chapters, I sincerely hope that readers will be able to diagnose the faults in machines on their own. I have done my job if readers can do that. This book concludes with a bibliography for those interested in learning more about the subject, and a set of appendices on standards, balancing, misalignment techniques, and the use of MATLAB®.

I hope this book will be on the desk of every practicing maintenance engineer, student studying the subject, and my colleagues from academia who are teaching and doing research in the areas of machinery condition monitoring.

A. R. Mohanty
Kharagpur
June 2014

Acknowledgments

Writing a book is not an easy thing. At the outset I must thank all of the students in my machinery condition monitoring and signal processing class for their intriguing questions, which initially led me to believe that a single source book on this subject needed to be written—and the sooner the better. A course on machinery condition monitoring cannot be taught from research papers and fundamental engineering books. A lot of field experience needs to be brought into the classroom. I thus thank my many industry sponsors in India and some in the United States, who gave me several opportunities to do field measurements and then provide solutions to fix problems. Such experience was very helpful to me as a consultant and then as an author of this book. I have tried to bring many such field topics into this book.

Of course, my training as a mechanical engineer, with close to thirty years of experience in machinery condition monitoring, would not have been possible without the care and guidance of my teachers, mentors, and colleagues. I wish to acknowledge my undergraduate engineering teachers at NIT Rourkela, Professors T. N. Subramanian and A. K. Behera, who introduced me to vibrations. I thank Professor Amalendu Mukherjee, my teacher and master's guide at the Indian Institute of Technology Kharagpur who, on the very first day I met him, introduced me to fast Fourier transform (FFT), and of course then many other rudiments and aspects of data acquisition, signal processing, and controls. My PhD supervisor Professor Andy Seybert at the University of Kentucky taught me, among many other things that I will always cherish, how to do correct measurements, and actually taught me the rudiments of acoustics and noise control and how to be a successful engineering consultant. I thank Professor Seybert for instilling in me the confidence to do experiments. Professor Bob Bernhard, my postdoctoral guide at Purdue, introduced me to the noise vibration harshness (NVH) chassis dynamometer at Herrick Labs, where we did sponsored research on active control of road noise.

I have also had a few mentors in the industries where I have worked. Mr. R. A. Noras and Mr. Amitabh Nath at Larsen Toubro Limited, Mumbai, gave me many of my first opportunities to conduct machinery field vibration measurements, machinery failure analyses, and experimental modal analyses. My experience at Ford Motor Company was very rewarding and allowed me to do many vehicle noise and vibration measurements at the Dearborn Proving Ground and do computer-aided engineering (CAE) simulations. For these experiences, I owe a debt of gratitude to my supervisors, managers, and colleagues at Ford, especially Dr. Farhang Aslani, Dr. Randy Visantainer, Dr. P. Suruli-Naryansami, Mr. Tom Martin, Mr. Bruce Bonhard, Mr. Barry St. Pierre, and Ms. Stacey McCreery.

This book was made possible by the research in machinery condition monitoring being done by my group at the Indian Institute of Technology Kharagpur. A few of the examples in this book are based on the results of my past and present PhD students. I wish to acknowledge my past students, Dr. S. Prabhakar, Dr. C. Kar, Dr. A. K. Jalan, Dr. (Cdr) V. K. Rai, and Dr. P. K. Pradhan. I also want to thank my present students, S. Fatima, S. K. Roy, T. Bose, P. Bansod, Marxim, and Bhartendra for their help in conducting a few experiments on the rigs.

While working as a faculty member at the Indian Institute of Technology, I get to interact with other academic and nonacademic institutes throughout the world. I would like to acknowledge my interactions with Professor M. L. Munjal from the Indian Institute of Science Bangalore; Professor S. Narayanan, Professor C. Sujatha, Professor P. Chandramouli, Professor A. S. Sekhar, and Professor B. V. A. Rao from the Indian Institute of Technology Madras; Professor D. N. Manik from the Indian Institute of Technology Bombay; Professor N. Tandon from the Indian Institute of Technology Delhi; Professor N. Tiwari from the Indian Institute of Technology Kanpur; Professor R. Tiwari from the Indian Institute of Technology Guwahati; Professors A. B. Chattopadhyay, C. S. Kumar, Siddhartha Das, Karabi Das, A. Routray, A. Patra, S. Mukhopadhyay, S. Paul, V. N. A. Naikan, and K. Pathak from the Indian Institute of Technology Kharagpur; and Dr. V. Bhujanga Rao from the Defence Research Development Organization and the founder president of the Condition Monitoring Society of India.

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Of course, I thank all the members of my family and close friends, who have been very supportive during my book-writing sessions. I thank my wife, Bithika, and my two sons Saurav and Siddarth, who kept reminding me of the target at hand and the much awaited vacation after I completed the manuscript. I must thank Dr. Gagandeep Singh, acquisitions editor at CRC Press, for the timely reminders and bearing with me when I exceeded the deadlines. This book just would not have been possible without my interactions with all the persons I have mentioned above. I owe each one of them my sincere thanks and gratitude. Please excuse me if I inadvertently missed anyone.

About the Author

Amiya Ranjan Mohanty has been a faculty member at the Indian Institute of Technology Kharagpur, India, since 1996, where he is currently a professor of Mechanical engineering. Professor Mohanty has a B.ScEngg (Hons) degree in mechanical engineering from the National Institute of Technology, Rourkela (formerly the Regional Engineering College). He holds a master's degree in machine design specialization from the Indian Institute of Technology, Kharagpur, and a PhD in the area of noise control from the University of Kentucky in the United States.

At the Indian Institute of Technology, Kharagpur, he established a state-of-the-art laboratory for acoustics and condition monitoring. He teaches courses in machine design, instrumentation, automobile engineering, acoustics and noise control, machinery fault diagnosis, and signal processing. He regularly conducts short-term courses in the areas of noise control and condition monitoring. He has been a consultant to more than 50 companies in the areas of noise control and machinery condition monitoring.

Professor Mohanty has worked in the R&D divisions of Larsen Toubro Limited, Mumbai, and Ford Motor Company at Dearborn, Michigan, in the United States. Professor Mohanty has collaborated in research on noise control and machinery condition monitoring with many leading universities around the world in the United States, France, Sweden, the United Kingdom, and Singapore, and was a postdoctoral Fellow at the Ray W. Herrick Labs at Purdue University in the United States.

Professor Mohanty is a Fellow of the Acoustical Society of India and a member of ASME and SAE. He received the Chancellor's Award for outstanding teaching at the University of Kentucky, the Rais Ahmed Memorial Award of the Acoustical Society of India, and the best research paper in underwater acoustics from the Acoustical Society of India. He has published more than 100 journal articles in the areas of noise control and machinery condition monitoring. His research projects are sponsored by several private and government agencies.

Contents

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Introduction

1.1 Machinery Condition Monitoring

Different types of machinery are present in industry. The majority of these machines have rotating components. For an industrial plant to have high production rates, the machines must perform as per their designed specifications and installed capacity. In order to ensure that these machines run without any significant downtime, the machine must be in proper condition. The maintenance personnel in a plant take necessary steps to ensure that the machines run for their designed life without any significant failure.

Machinery condition monitoring deals with the maintenance aspects of these machines based on the present and past condition of the machine. In order to know the machine's condition, sensors are installed around the machine so that relevant information about the machine's health condition can be collected, analyzed, and decisions made regarding the appropriate maintenance or corrective actions to be taken so that the machine is able to perform as per its original design objectives. In a plant without a proper protocol in place for machine maintenance, the end result could be an eventual loss for the plant. Machinery maintenance is dependent on the type of machine, the severity of the defects in the machines, and the downstream consequences they may have on the overall operation of the plant. The different aspects of maintenance will be dealt with in the next chapter. Machinery condition maintenance is a scheme in which appropriate maintenance is done based on the condition of the machine.

During operation, machines give out information or signals in the form of noise, vibration, temperature, lubricating oil condition, quality and quantity of the motor current drawn, and the like. These signals from the machine are acquired by installing transducers to measure the mechanical parameters of the machine. The signals thus obtained are usually analog and they exist at all times. In order to create meaningful information from these signals, the signals are converted into the digital domain by analog-to-digital converters. The discrete digital data corresponding to the analog signal thus obtained is analyzed on computers. Software is available to efficiently store and handle