Preface

This book is based on the author's many years of industrial experience in designing rotor and bearing systems. It is a living document, since the author is still learning more about this exciting field. Even as these guidelines and criteria are being established, creative new bearing designs, new alloy materials, and new synthetic lubricants are introduced nearly every day; therefore the limitations are constantly being removed or further relaxed. What this book does is provide the basic theory, design principles, and guidelines – and enough detailed examples – to let practical engineers can perform their own design work to achieve their needs. The emphasis is on the practical design rather than the derivations of the equations. In the practical field, understanding of the nature of the analytical results and the physical insights behind a solution are more significant than knowing the exact solution itself at the start.

Every application is unique, and these guidelines should not be applied without utilizing engineering judgment and practical operating experience. Many companies have established their own design guidelines and handbooks, based on their years of operating experience. Some of them are extremely useful while some may be out of date. Engineers should always carry out their designs with flexibility, as long as the laws of physics are followed.

One attempt in this text is to bridge the knowledge bases of rotor dynamics and bearing design. The rotor and bearings are essentially two halves of one whole, and are inseparable in the rotating machinery design process. In rotor design, the emphasis is on dynamics such as the positions of critical speeds, rotor response due to excitations, and rotor stability. In bearing design, the emphasis is on the lubrication, such as minimum film thickness, power loss, temperature rise, peak film pressure, and flow rate. However, the rotor's dynamic behaviors are strongly influenced by bearings; the rotor will not run well if the bearings do not perform as desired. Therefore, engineers working in this field should have knowledge of both rotor dynamics and bearing lubrication. All too often, rotordynamicists and bearing analysts work in different design groups or departments. Vibration problems and bearing failures occur frequently when the design engineers only perform the rotordynamics without knowledge of bearings and how the bearing dynamic coefficients are calculated, and/or the bearing analysts focus on the bearing performance without a strong knowledge of general vibration.

Although it is far from complete, the body of work presented by many researchers and practical engineers regarding the design of rotor and bearing systems is truly impressive. Many early publications in the bearing design and development field are extremely valuable, and many talented engineers working in this field have also advanced bearing technology. The American Petroleum Institute (API) and the International Organization for Standardization (ISO) have documented many publications about acceptable criteria for rotating machinery vibration, bearing performance inspection methods, balancing specifications, etc. These specifications have served as general guidelines for many decades, and they are updated frequently to meet today's challenging

technology advances. We have built upon the work of other people and organizations, and benefit from their insights and innovations.

Chapter 1 contains discussion of the forms of basic vibration, vibration measurements, various specifications and design considerations, and the vibration characteristics of common machinery problems. Vibration data are always taken in the time domain, but the diagnosis and verification usually require vibration data presented in the frequency domain. The vibration amplitude in different forms, such as zero-to-peak, peak-to-peak, average, root-mean-square (RMS), and Decibel (dB), is addressed. Different vibration transducers used in vibration measurements and their selection are discussed. Machine vibration acceptability and severity criteria published by the API, ISO, and other engineering firms are also summarized for reference. Vibration characteristics of common rotating machinery faults are presented and discussed in detail in this chapter.

Chapter 2 introduces some basic concepts, definitions, and nomenclatures commonly presented in rotordynamics and vibration literatures. Two primary considerations in the design of rotor-bearing systems – rotor forced response and stability – are fully discussed. The characteristics of the free and forced vibrations are presented; this knowledge is crucial for test data interpretation, machine diagnosis, and malfunction correction. The amplitude and phase angle for the common steady-state response caused by the mass unbalance and shaft bow are discussed in detail by using Bode and polar plots. The relationship between the rotor response direction of precession (forward and backward) and bearing properties, destabilizing force (circulatory force) present in the fluid film bearings and aerodynamic cross-coupling are all discussed. The concepts presented in the text are reinforced by many examples with parametric studies and illustrative figures.

Chapter 3 begins with the introduction of the principles and operating regimes of hydrodynamic bearings. The governing Reynolds equation is valid only in the full film lubrication regime. This chapter covers classification of oil whirl and shaft whip, bearing static and dynamic performance, and the importance of relevant parameters. Several commonly-used hydrodynamic journal bearings are presented and studied extensively. Parametric study on the operating parameters and bearing geometric data is illustrated in dimensional and non-dimensional forms. Whenever possible, the parametric sensitivity is presented in the non-dimensional form, which can be a useful tool in bearing design. Optimal values for some bearing parameters are recommended when applicable. This chapter ends with the discussion of hydrodynamic thrust bearings. Although thrust bearings are not the focus of most rotordynamics books, they are essential components in rotating machinery. Many machine failures and high vibrations are caused by poorly-designed thrust bearings.

Chapter 4 deals with hydrostatic fluid film bearings. This topic could fill its own book. Only the important concepts and design procedures are presented here. The design of hydrodynamic and hydrostatic fluid film bearings can be very different; their characteristics are compared and presented. Most applications for hydrostatic bearings are very low-speed and high-load. However, if the speed effect cannot be neglected and the power ratio (ratio of the frictional power loss to the pumping loss) is greater than 1, then the hydrodynamic effect must be included. An example with extensive parametric studies is presented at the end of this chapter.

Chapter 5 summarizes the bearing and lubrication design considerations – from lubricants and bearing material selection to the bearing operating ranges and limits, and the determination of bearing parameters. Bearing temperature measurements and temperature sensitivity to the operating conditions are also presented. The bearing temperature is very sensitive to change in operating conditions and vibration levels; therefore, it can be a very useful tool for machine protection. Lubrication system considerations and common bearing manufacturing tolerances are also discussed.

Chapter 6 reviews the analytical modeling techniques and common mistakes made in the modeling and analysis. The typical analysis performed during the design stage is also reviewed. For linear systems, the analyses include critical speed analysis, steady-state synchronous response analysis, whirl speed and stability analysis, and time-transient analysis. However, for nonlinear systems, the analyses include time-transient analysis and steady-state synchronous response analysis if a centered circular orbit is assumed. If the rotor speed exceeds the instability threshold and/or the response amplitude is large, then nonlinear analysis becomes necessary. The emphasis is on the interpretation of the results and the design considerations, not the derivation of the equations and the solution techniques. Understanding the system's dynamic behaviors and the effects of the components are critical for a robust design.

Chapter 7 is devoted to some practical design considerations. Rigid and flexible rotors are quantitatively defined and discussed. Design considerations for both are addressed. For a specified bearing stiffness and rotor system, there is an optimal damping value for rotor response and stability. Damping values outside this range, large or small, aggravate the system's dynamic behaviors. Gyroscopic effect and disk flexibility are also discussed in detail here, although they have been presented throughout this text. The effect of flexible support is also discussed. Flexible support underneath a bearing without damping can significantly degenerate the total effective damping, while bearing support with proper damping can improve the bearing's performance. Design considerations of vertical rotors are presented. Examples are used throughout this chapter to illustrate the concepts and effects.

Chapter 8 discusses the coupled vibration of a geared system with multiple rotors. The lateral-torsional-axial motions are coupled through gear meshes and thrust collars. Since the rotors rotate in different directions, special considerations must be made regarding the directions of rotor rotation and the bearing dynamic coefficients. Purely torsional vibration for a simple geared system is briefly discussed here for reference. This chapter includes four comprehensive examples with various purposes and illustrations.

Chapter 9 uses an industrial-geared compressor as an example to demonstrate the design considerations and procedures discussed in this text. Although this example is a geared system, many design concepts and considerations are the same as for other non-geared systems. The steps that are not applicable to other rotor systems can be skipped in the design procedures. The book concludes with some practical design compromises and considerations.

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