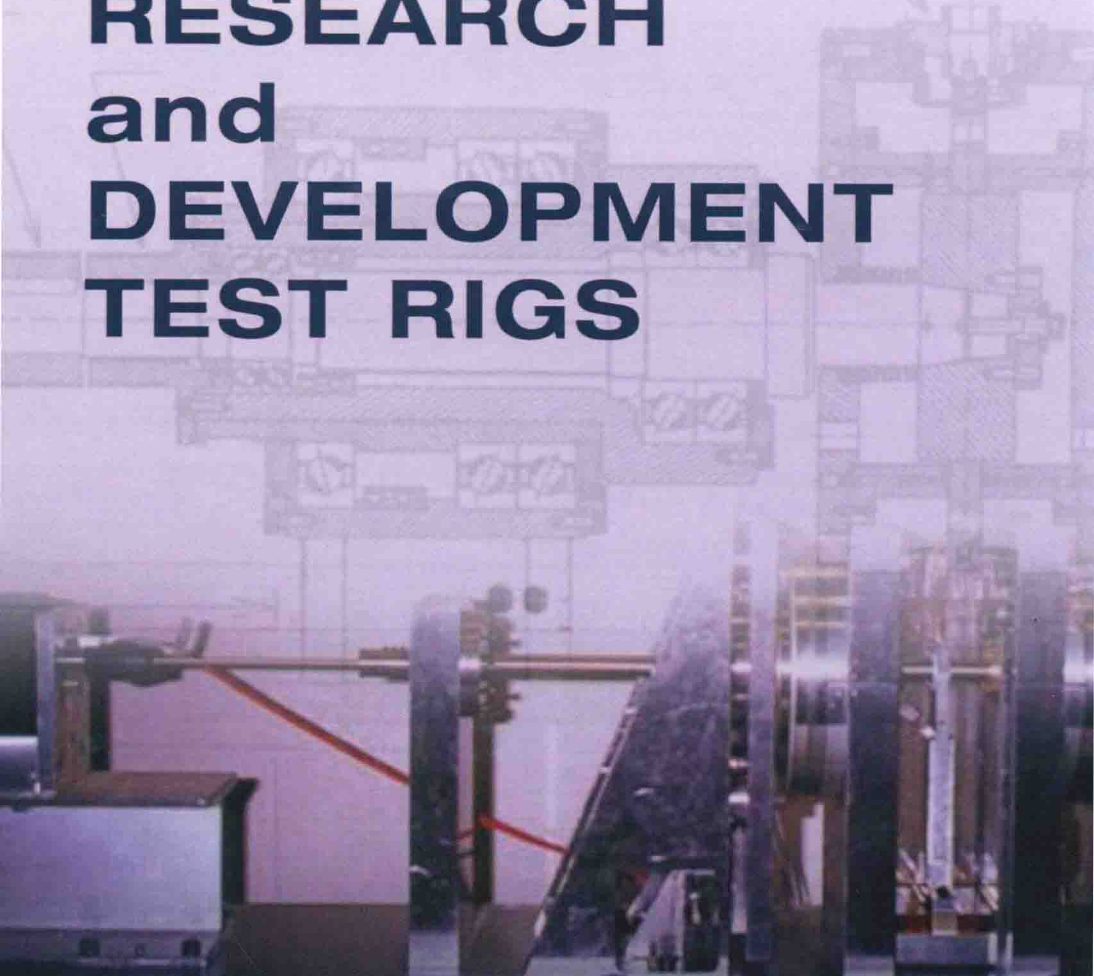
ROTATING MACHINERY RESEARCH and DEVELOPMENT TEST RIGS



MAURICE L. ADAMS, JR.

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The prevalence of rotating parts in machine design and production demonstrates the importance of Rotating Machinery (RM) across multiple disciplines and industries. A deep understanding of rotating machinery design is integral for engineers across all fields, informing the planning, design and production phases of various industries.

This guide presents the development processes for test apparatuses built for research & development in machinery, technology, and product development. Each R & D apparatus is the focus of an entire chapter, with fifteen detailed case studies included from mechanical, aerospace, chemical and biomedical engineering. The author details machinery components, including bearings, seals, power plant pumps, rotors, turbines and compressors. Machinery condition monitoring and product development processes have been integrated, and the specific purposes and results for each test rig are comprehensively presented and explained. This text:

- Explains the advancement of engineering design theory through research testing
- Presents case studies of component improvement for basic machinery components
- Outlines approaches for fostering creativity in development
- Discusses the design of test machines for the R & D process
- Explores R & D testing for improvement of existing machinery

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Rotating Machinery Research and Development Test Rigs

This book is dedicated to my late parents and late brother

Maury, Libby, and George

And to my late wives

Heidi and Kathy

And to my four mechanical engineering sons

Maury, Professor Dr. Mike, RJ, and Nate

Preface

It's hard to think of any machinery type that does not have at least one rotating part. Rotating machinery (RM) is at the heart of the modern world, thus so is RM engineering. The technology of RM is a field of study with considerable depth and breadth, utilizing first principles of all the mechanical engineering fundamental disciplines: solid mechanics, dynamics, fluid mechanics, thermodynamics, heat transfer, and controls. Nearly all industries rely heavily on the reliable operation of RM. These industries include (1) power generation; (2) petrochemical; (3) manufacturing; (4) land, sea, and air transportation; (5) heating, ventilating, and air conditioning; (6) aerospace propulsion; (7) farming; (8) computer disk drives; (9) textiles; (10) home appliances; and (11) a wide variety of military systems.

The ever-present competitive pressures to have machines run faster; be more compact, more powerful, more energy efficient; possess higher power-to-weight ratios; and be less costly have fostered a continuous research and development (R&D) history in the field of RM. That has always necessitated the important component of experimental work to augment the theory-based design analyses. However, modern computer-based analysis tools like finite element analysis (FEA) and computational fluid dynamics (CFD) have significantly impacted on the role of machinery component testing. Prior to such modern computer-based analysis tools, testing was often deemed necessary because of inherent approximations and uncertainties in design methods, and the absence of closed-form solutions to many of the governing theory-based equations, for example, Navier–Stokes equations for 3D fluid flow and the 3D elasticity equations for stress, strain, and deformation in solids. Today, testing is often employed to validate the modern computer software, providing the empirical inputs needed for perfecting the accuracy of those computer codes. Consequently, computer-based analyses are now reliably employed to substitute for some of the pre–computer age product R&D and proof testing. The gas turbine jet engine is one RM high-tech product where this modern engineering approach has provided considerable development cost reductions by making feasible significant reductions in some of the costly development testing of new aircraft engine configurations.

To provide a resource detailing several important rotating machinery R&D test facilities, this book is comprised of 19 chapters describing test rigs pertaining to various types of rotating machinery, including (1) large steam turbine generator sets; (2) power plant, slurry, and heart centrifugal pumps; (3) gas turbines; (4) jet engines; (5) bearings, seals, and rotor dynamics; (6) machine tool spindles; and (7) machinery condition monitoring.

Acknowledgments

Truly qualified technologists invariably acknowledge the shoulders upon which they stand. I am unusually fortunate in having worked for several expert-caliber individuals during my 14 formative years of industrial employment prior to becoming a professor in 1977, especially my four years at the Franklin Institute Research Laboratories (FIRL) followed by my six years at the Westinghouse Corporate R&D Center's Mechanics Department. I am also highly appreciative of many subsequent rich interactions with other technologists. I acknowledge here those individuals, many of whom have unfortunately passed away over the years. They were members of a *now extinct breed of giants* who unfortunately have not been replicated in today's industrial workplace environment.

My work in rotating machinery began (1963–1965) at the Allis-Chalmers Hydraulic Products Division in my hometown York, PA. There, I worked on hydroelectric turbine design. That was followed by employment (1965–1967) at Worthington's Advanced Products Division (APD) in Harrison, NJ. There, I worked under two highly capable European-bred engineers, chief engineer Walter K. Jekat (German) and his assistant John P. Naegeli (Swiss). John Naegeli later returned to Switzerland and eventually became general manager of Sulzer's Turbo-Compressor Division and later general manager of their Pump Division. The APD general manager was Igor Karassik, the world's most prolific writer of centrifugal pump articles, papers, and books and an energetic teacher on centrifugal pumps for all the then-young recent engineering graduates at APD, like me. My first assignment at APD was basically to be "thrown into the deep end" of a new turbomachinery development for the U.S. Navy that even today would be considered highly challenging. That new product was comprised of a 42,000 rpm rotor having an overhung centrifugal air compressor impeller at one end and an overhung single-stage impulse steam turbine powering the rotor from the other end, with water-lubricated turbulent fluid-film bearings. Worthington sold several of these units over a period of many years.

I seized upon an opportunity to work (1967–1971) for an internationally recognized group at the FIRL in Philadelphia. I am eternally indebted to several FIRL technologists for the knowledge I gained from them and for their encouragement for me to pursue graduate studies part time, which led to earning my engineering master's degree at a local Penn State extension near Philadelphia. The list of individuals I worked under at FIRL is almost a *who's who list* for the field and includes the following: Elemer Makay (centrifugal pumps), Harry Rippel (fluid-film bearings), John Rumbarger (rolling-element bearings), and Wilbur Shapiro (fluid-film bearings, seals, and rotor dynamics). I also had the privilege of working with a distinguished group of

FIRL's consultants from Columbia University, specifically Professors Dudley D. Fuller, Harold G. Elrod, and Victorio "Reno" Castelli.

My Franklin Institute job gave me the opportunity to publish in my field. That bit of national recognition helped provide my next job opportunity (1971–1977) at what was truly an internationally distinguished industrial research group, the Mechanics Department at Westinghouse's R&D Center near Pittsburgh. The main attraction for accepting that job was my new boss, Dr. Albert A. Raimondi, leader of the bearing mechanics section, whose famous papers on fluid-film bearings are referenced and reproduced in every undergraduate machine design book. An important insight quite relevant to this book that Al Raimondi imparted to me is paraphrased here: *Design of a unique test rig embodies a caveat differentiating it from other machine design efforts. That is, one usually has spent more than half their budget by the first time they try to operate the rig, and they never work the first time. So when designing a test rig, make a list of all the potential malfunction sources (too numerous to design for all of them) and have a feasible backup redesign modification to correct any couple of these within budget*. In other words, *don't paint yourself into a corner* with the rig design not fixable.

An added bonus at Westinghouse was the presence of the person holding the department manager position, A. C. "Art" Hagg, the company's internationally recognized rotor vibration specialist. My many interactions with Art Hagg were all professionally enriching. At Westinghouse, I was given the lead role on several "cutting-edge" projects, including the nonlinear dynamics of flexible multibearing rotors for large steam turbines and reactor coolant pumps; bearing load determination for vertical multibearing pump rotors; seal development for refrigeration centrifugal compressors; and the turning-gear slow-roll operation of journal bearings, developing both test rigs and new computer codes for these projects. I became the junior member of an elite ad hoc trio that included Al Raimondi and D. V. "Kirk" Wright (manager of dynamics section). They encouraged me to pursue my PhD part time, which I completed at the University of Pittsburgh in early 1977. I express special gratitude to my PhD thesis advisor at Pitt, Professor Andras Szeri, who considerably deepened my understanding of the overlapping topics of fluid dynamics and continuum mechanics.

Since entering academia in 1977, I have benefited from the freedom to publish widely and to apply and extend my accrued experience and knowledge through numerous consulting projects for rotating machinery manufacturers and electric utility companies. I appreciate the many years of support for my funded research provided by the Electric Power Research Institute (EPRI) and the NASA Glenn Research Laboratories.

Academic freedom has also made possible leaves to work abroad with some highly capable European technologists, specifically at the Brown Boveri Company BBC (Baden, Switzerland), Sulzer Pump Division (Winterthur, Switzerland), KSB Pump Company (Frankenthal, Germany), and the Swiss Federal Institute (ETH, Zurich). At BBC, I developed a lasting friendship with

my host Dr. Raimund Wohlrab. At the Sulzer Pump Division, I was fortunate to interact with Dr. Dusan Florjancic (engineering director), Dr. Ulrich Bolleter (vibration engineering), and Dr. Johan Guelich (hydraulics engineering). At the KSB Pump Company, I was fortunate to interact with Peter Hergt (Head of KSB's Central Hydraulic R&D, 1975–1988) and his colleagues. I particularly cherish the interactions with my host and dear friend at the Swiss Federal Institute ETH-Zurich, the late Professor Dr. Georg Gyarmathy, the ETH turbomachinery professor, 1984–1998. This book rests upon the shoulders of all whom I have acknowledged here.

Author

Maurice L. Adams, Jr. is founder and past president of Machinery Vibration Inc. (www.mvibe.com) and is professor emeritus of mechanical and aerospace engineering at Case Western Reserve University. Dr. Adams is an author of more than 100 publications and a holder of U.S. patents; he is a life member of the American Society of Mechanical Engineers. He received his BSME (1963) from Lehigh University, MEngSc (1970) from the Pennsylvania State University, and PhD (1977) in mechanical engineering from the University of Pittsburgh. Dr. Adams worked on rotating machinery engineering for 14 years in industry prior to becoming a professor in 1977.

Since then, he has been retained as a rotating machinery consultant by several machinery manufacturers and users in the United States and abroad, including GE Aircraft Engine Group, InVision Technologies, ABB Corporate Research, Rolls-Royce Power Systems, ABB Large Rotating Apparatus, United Technologies Carrier Group, EPRI, Eaton Corporation Manufacturing Technologies Center, Reliance Electric Motors Group, FIRL, Caterpillar Engine Division, Brown-Boveri Large Steam Turbines, Battelle Research, Sulzer Company Pump Division, Oak Ridge National Laboratories, TRW Aerospace Systems, John Deere Tractor Group, and several electric power plants in the United States and abroad.

Dr. Adams has authored two other Taylor & Francis/CRC Press books: *Rotating Machinery Vibration* (2010) and *Power Plant Centrifugal Pumps* (2017). He has been the MS thesis and PhD dissertation advisor to more than 30 graduate students, three of whom are now endowed-chair professors. He was the recipient in 2013 of the Vibration Institute's Jack Frarey Medal for his contributions to the field of rotor dynamics.