Pressure Oscillation in Biomedical Diagnostics and Therapy

Ahmed Al-Jumaily, Lulu Wang

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Table of Contents

List of Tables

List of Illustrations

Wiley-ASME Press Series

Analysis of ASME Boiler, Pressure Vessel, and Nuclear Components in the Creep Range
Maan H. Jawad, Robert I. Jetter

Robust Control: Youla Parameterization Approach
Farhad Assadian, Kevin R. Mallon

Fabrication of Process Equipment
Owen Greulich, Maan H. Jawad

Engineering Practice with Oilfield and Drilling Applications
Donald W. Dareing

Metrology and Instrumentation: Practical Applications for Engineering and Manufacturing
Samir Mekid

Fabrication of Metallic Pressure Vessels
Owen R. Greulich, Maan H. Jawad

Flow-Induced Vibration Handbook for Nuclear and Process Equipment
Michel J. Pettigrew, Colette E. Taylor, Nigel J. Fisher

Vibrations of Linear Piezostructures
Andrew J. Kurdila, Pablo A. Tarazaga

Bearing Dynamic Coefficients in Rotordynamics: Computation Methods and Practical Applications
Lukasz Brenkacz

Advanced Multifunctional Lightweight Aerostructures: Design, Development, and Implementation
Kamran Behdinan, Rasool Moradi-Dastjerdi

Vibration Assisted Machining: Theory, Modelling and Applications

Li-Rong Zheng, Dr. Wanqun Chen, Dehong Huo

Two-Phase Heat Transfer
Mirza Mohammed Shah

Computer Vision for Structural Dynamics and Health Monitoring
Dongming Feng, Maria Q Feng

Theory of Solid-Propellant Nonsteady Combustion
Vasily B. Novozhilov, Boris V. Novozhilov

Introduction to Plastics Engineering
Vijay K. Stokes

Fundamentals of Heat Engines: Reciprocating and Gas Turbine Internal Combustion Engines
Jamil Ghojel

Offshore Compliant Platforms: Analysis, Design, and Experimental Studies
Srinivasan Chandrasekaran, R. Nagavinothini

Computer Aided Design and Manufacturing
Zhuming Bi, Xiaoqin Wang

Pumps and Compressors
Marc Borremans

Corrosion and Materials in Hydrocarbon Production: A Compendium of Operational and Engineering Aspects
Bijan Kermani and Don Harrop

Design and Analysis of Centrifugal Compressors
Rene Van den Braembussche

Case Studies in Fluid Mechanics with Sensitivities to Governing Variables
M. Kemal Atesmen

The Monte Carlo Ray-Trace Method in Radiation Heat Transfer and Applied Optics
J. Robert Mahan

Dynamics of Particles and Rigid Bodies: A Self-Learning Approach
Mohammed F. Daqaq

Primer on Engineering Standards, Expanded Textbook Edition
Maan H. Jawad and Owen R. Greulich

Engineering Optimization: Applications, Methods and Analysis
R. Russell Rhinehart

Compact Heat Exchangers: Analysis, Design and Optimization using FEM and CFD Approach
C. Ranganayakulu and Kankanhalli N. Seetharamu

Robust Adaptive Control for Fractional-Order Systems with Disturbance and Saturation
Mou Chen, Shuyi Shao, and Peng Shi

Robot Manipulator Redundancy Resolution
Yunong Zhang and Long Jin

Stress in ASME Pressure Vessels, Boilers, and Nuclear Components
Maan H. Jawad

Combined Cooling, Heating, and Power Systems: Modeling, Optimization, and Operation
Yang Shi, Mingxi Liu, and Fang Fang

Applications of Mathematical Heat Transfer and Fluid Flow Models in Engineering and Medicine
Abram S. Dorfman

Bioprocessing Piping and Equipment Design: A Companion Guide for the ASME BPE Standard
William M. (Bill) Huitt

Nonlinear Regression Modeling for Engineering Applications: Modeling, Model Validation, and Enabling

Design of Experiments
R. Russell Rhinehart

Geothermal Heat Pump and Heat Engine Systems: Theory and Practice
Andrew D. Chiasson

Fundamentals of Mechanical Vibrations
Liang-Wu Cai

Introduction to Dynamics and Control in Mechanical Engineering Systems
Cho W.S. To

Pressure Oscillation in Biomedical Diagnostics

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In the name of the CREATOR who fashioned humankind as the best of his creations.
To my wife Thana who stands by me in light and dark times.
To my kids, candles of my life.
To my postgraduate students from whom I have humbly learnt.

About the Author

Ahmed M. Al-Jumaily is currently a Professor of Biomechanical Engineering and the Founder of the Institute of Biomedical Technologies at the Auckland University of Technology, Auckland, New Zealand. He holds a PhD and MSc from the Ohio State University, USA, and a BSc from the University of Baghdad, Iraq. He is a Fellow member of the American Society of Mechanical Engineers (ASME) and the Acoustical Society of America in addition, to being a member of 11 more international professional societies. He is the Editor-in-Chief of the ASME Journal of Engineering and Science in Medical Diagnostics and Therapy, the Editor for the ASME monograph series-Biomedical and Nanomedical Technologies, and has been on the editorial and refereeing boards for several international journals. He has published more than 360 papers in international journals and conference proceedings including two ASME books on Vibration and Acoustics in Biomedical Applications and a third one on CPAP devices. He has supervised more than 100 postgraduate students from 35 countries in biomedical applications, vibrations, biomechanics, and electroactive polymers. During his academic career, he has forged strong alliances between academia and industries, in particular, in the medical devices area, which has resulted in many successful grants and contracts with companies and research organizations. Al-Jumaily's current research focuses on biomedical applications, particular interest in the applications of vibration and acoustics to airways constriction therapies, and artery noninvasive diagnostics.

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Preface

This book compiles over 20 years of research and development in applying physiology and engineering principles to designing, modeling, and improving diagnostic and therapy devices and methods to serve the medical community. The fundamental and frontier theories and techniques of low- and high-frequency pressure oscillation are presented as the foundation for these principles. This area is evolving very fast, and documentation of such schemes is essential for various industries and clinical applications. Currently, there is no book with this title available in the open literature.

The book consists of eight chapters. Each chapter has a stand-alone content starting with an introductory material on the subject matter, followed by a review of available technologies to diagnose or treat the diseases with intensive literature survey, and then introducing the significance of pressure oscillation in the diagnostic or therapeutical applications. Each chapter finishes with some clinical applications and voluminous references and bibliography.

The first chapter is an introductory chapter which presents the foundation materials for the rest of the book. It introduces the basic principles of pressure oscillation and how they can be formulated into mathematical equations. The chapter explains how these equations can be converted to practical applications for biomedical diagnostics or therapy. The book is then split into two parts as detailed below.

Part I of the book consists of three chapters focusing on diagnostics, imaging, and characterization. Chapter 2 presents an application of pressure oscillation to develop a diagnostic technique. It briefly describes the basic concepts of arteries, arterial stiffness, arterial blood pressure, and pulse wave. It reviews several methods for measuring these variables. Various new contributions are discussed, including physics-based waveform measurements and human systemic arterial numerical models. Several medical applications of pulse wave analysis are also presented. The basic principles of converting pressure oscillation to a tool in biomedical imaging will be clearly explained in Chapter 3. Two of the methods will be explained in detail: (i) radiation force (RF), which is normally generated by high-frequency pressure oscillation. Several new radiation force-based elasticity imaging (EI) methods were proposed in the past two decades, and these techniques generate radiation force to an object and measure its dynamic displacement response in order to estimate the object's mechanical properties. (ii) Vibro-acoustography (VA) is a speckle-free acoustic radiation force (ARF)-based EI technique, which can visualize healthy and abnormal soft tissue through mapping the acoustic response of the object to a harmonic RF induced by ultrasound. This chapter briefly describes the history of ARF and its applications and provides an overview of ARF-based EI approaches. Examples of ARF-based EI–VA imaging and multifrequency VA techniques and their applications in medical and material evaluation areas are discussed. Several advantages and disadvantages of VA, comparison between VA and pulse–echo systems, as well as future directions are presented.

Respiratory diagnostic and characterization technique are summarized in Chapter 4. The forced oscillation technique (FOT) is a low-frequency-pressure wave technique. It has been used in the measurement of respiratory impedance and has evolved into powerful tools for the assessment of various mechanical phenomena in the mammalian healthy and diseased lung. This chapter briefly reviews the human respiratory system (RS) and its functions, mechanics, and various developed models and measurement methods. An example of the RS measurement method FOT is detailed, including working principles, instrumentation, measurements arrangement, and impedance measurement methods. Finally, clinical applications of FOT are also described.

Part II of the book focuses on respiratory therapies. To be equipped with sufficient knowledge on lung ailments in the upper, central, and lower airways covered in this section, an introductory chapter on the respiratory system is needed. Chapter 5 presents lung mechanics, how each part of the lung is associated with various diseases, and how pressure oscillation can target these parts and help in treating these diseases. In Part II, the following three chapters deal with specific diseases, namely, obstructive sleep apnea (OSA), asthma and respiratory distress syndromes (RDSs).

Chapter 6 briefly describes OSA syndromes, diagnostic methods based on the combined evaluation of clinical manifestations and objective sleep study findings, and currently available treatment methods. Polysomnography represents the gold standard to confirm the clinical suspicion of OSA syndrome, to assess its severity and to guide therapeutic choices. Continuous positive airway pressure (CPAP) is currently the most recommended method for OSA treatments. Some basic working principles of CPAP techniques and their types are discussed. Finally, clinical applications of these devices for the treatment of OSA and benefits are also highlighted. A new technique is introduced and detailed on how pressure oscillation can be used to improve the use of CPAP.

The importance of airway smooth muscle (ASM) in asthma was realized almost 150 years ago. Breathing has a strong relaxing and protective effect on ASM, inhibiting airway constriction. Understanding the behavior of ASM is crucial to understanding the reversible airway obstruction central to asthma. Chapter 7 briefly describes the basic concepts of asthma, ASM, and dynamic behavior of ASM through both experimental data and modeling results. A fading memory model is given to further describe the behavior of contracted ASM for finite duration length steps and longitudinal sinusoidal oscillations. Finally, the potential of pressure waves superimposed on breathing patterns in treating asthma is investigated using experimental research and animal models.

Chapter 8 briefly introduces the common neonatal respiratory diseases with traditional surfactant therapies and respiratory support devices currently used in practice. Various pressure oscillation techniques including high-frequency ventilation (HFV), continuous positive airway pressure (CPAP), and “noisy” ventilation as effective and cheaper methods for respiratory support are discussed. Clinical trials that describe the effectiveness of using such treatments are presented. The concept of stochastic resonance and its application to “noisy” ventilation are introduced. The potential advances in the use of pressure oscillations and “noisy” ventilation to treat both neonatal and adult diseases are presented.

This book can teach students how to turn mathematical equations into medical devices or methodologies, and it also offers an excellent reference for undergraduate and postgraduate students in Physiology, Radiology, Applied Mathematics, Physics, and Biomedical, Mechanical, and Electrical Engineering. The book will also appeal to fellow researchers, practitioners, lecturers, and professionals such as Biomedical Engineers, Clinicians, Medical Doctors, Radiologists, and Researchers in Biomedical Imaging, Diagnostics and Therapies, and medical device industry personnel. It is a helpful compilation that familiarizes the reader with practical modeling approaches to enhance the design process.

Introduction

The primary objectives of this book are to present recent developments, discoveries, and progress made in the implementation of pressure waves in biomedical diagnostics and therapies, with a focus on the arterial and respiratory systems. Based on engineering principles and physiology, the fundamental and frontier theories and techniques of low- and high-frequency pressure waves are applied to develop medical devices and technologies for biological systems imaging, diagnostics, and therapies. It is an interdisciplinary area which utilizes Mathematics, Physics, Chemistry, Engineering, Computer Sciences, Physiology, and other fields for Clinical Applications. As biomedical technologies are evolving very fast, documenting of such schemes are essential for medical industries and clinical applications.

The book is compiled of learning and findings gained in more than 20 years of research and development that I have conducted with my postgraduate students at the Auckland University of Technology. Each chapter summarizes a complete project, which is further detailed in theses cited as references. In this way, I would like to acknowledge the contributions of all my postgraduate students whose works are used as the main reference material for this book. I would also like to acknowledge my appreciation to other authors in the field, whose contributions are evidenced in the voluminous references and bibliography. Further, I would also like to acknowledge the effort of my previous student and postdoc, and current colleague, co-author Dr. Lulu Wang who has helped to compile some of the materials from my team's work during