

Acoustics of Speech Production

R. S. McGowan

CReSS
Books

Published by CReSS Books 2018.

copyright © 2018 by Richard S. McGowan.

ISBN: 978-0-9997574-0-6

Cover silhouette: Paul Dirac and Richard Feynman in discussion.

Cover design by Rebecca McGowan and R. S. McGowan. We gratefully acknowledge the R. P. Feynman Estate for permission to use this image.

Printed by Harvard Book Store.

for Winifred and Rebecca

Table of Contents

Preface	xi
Chapter 1: Air: The Acoustic Material in the Vocal Tract, and Some Physics	
Introduction	1
Properties of air	1
One-dimensional kinematics and dynamics of a point mass	2
Thermodynamic properties of air	8
Geometry	13
Mass-spring systems	15
Conclusion	22
References	23
Appendix to Chapter 1	24
Chapter 2: Acoustic Air Motion in a Straight Tube	
Introduction	25
Preliminaries	25
The conservation equations	27
The wave equation	39
A piston boundary	46
Energy in acoustics	50
Conclusion	57
References	58
Appendix to Chapter 2	59
Chapter 3: Acoustic Air Motion in a Tube of Finite Length	
Introduction	61
An initial brief piston movement	61
Properties of circular functions sine and cosine	69

Sinusoidal piston movement	72
Steadiness	78
The time domain and the frequency domain	86
Conclusion	91
References	92

Chapter 4: Mass-Spring Systems

Introduction	93
Linear mass-spring systems	93
Impulse response functions	96
The simple mass-spring system with a sinusoidal external force	106
The mass-spring system with friction damping	111
Numerical simulations of finite-length tube acoustics with a piston and damping	124
The forced mass-spring system with generalized damping	126
Conclusion	129
References	130

Chapter 5: Standing Waves and Normal Modes

Introduction	131
Trigonometric identities	132
Frequency, wavenumber, period, and wavelength	133
Traveling and standing waves	135
Normal modes	138
Independence of normal modes	150
Conclusion	164
References	165

Chapter 6: Applications of Normal Modes: Acoustic Perturbation Theory and Green's Functions

Introduction	167
Acoustic perturbation theory	167

Green's functions for the acoustics of the finite-length tube	177
Conclusion	190
References	191

Chapter 7: Damped Acoustic Motion in a Finite-Length Tube with Piston Motion

Introduction	193
Energy flow in the sinusoidally forced, damped mass-spring system	194
The finite-length tube with damping and a piston source	199
Source location effects	206
About representations with modes	208
Connection with source-filter theory	210
Conclusion	211
References	213

Chapter 8: Introduction to Complex Variables for Acoustics

Introduction	215
Complex numbers as two-space vectors	215
The algebra of complex numbers	219
Physical quantities in complex notation	223
References	229
Appendix to Chapter 8	230

Chapter 9: Two sub-tubes of unequal cross-sectional area

Introduction	233
Low-frequency acoustics	234
Wave propagation considerations	234
Normal modes with two sub-tubes of unequal cross-sectional area	239
Steady radiation pressure and acoustic perturbation theory	254
The continuity conditions and their amendment	257
Conclusion	265

References	266
 Chapter 10: Multiple Sub-Tubes	
Introduction	267
Multiple sub-tubes with pressure and volume velocity continuity conditions	267
Examples of computing normal modes from area functions	275
Accounting for lumped mass elements	286
Conclusion	302
References	303
 Chapter 11: Damping and Losses	
Introduction	305
Radiation damping	306
Jetting	312
Wall vibration damping	313
Acoustic momentum boundary layer and acoustic thermal boundary layer damping	319
Damping mechanisms that affect phase speed	323
Damping mechanisms that work locally	326
Generalities and comparisons of mode frequency reductions that accompany damping	327
Modifying Green's functions	328
Conclusion	329
References	330
 Chapter 12: Helmholtz Resonators and Side Branches	
Introduction	333
Helmholtz resonators	333
Side branches	347
Conclusion.....	357
References	358

Chapter 13: Fluid Mechanics and Aeroacoustic Sources

Introduction	359
The Euler model	360
Dynamics of rotational air motion	377
Aeroacoustic sources in speech	391
References	410

Chapter 14: Scaling, Curvature, and Speech Development

Introduction	413
Curvature and scaling	414
Hypotheses regarding tongue surface curvature.....	419
If these hypotheses are true, then young children cannot produce strong [ɹ]	420
Sibilant fricatives and tongue curvature	424
Difficulties in velar and alveolar stop releases	426
Conclusion.....	435
References	435

Chapter 15: Layered Structure Model for Vocal Fold Vibration

Introduction	437
The static base configuration	438
Dynamics	441
Simulations	454
Robustness of vibrations	461
Extensions to larger vibration amplitudes with vocal fold collision	465
Conclusion	469
References	469

Index	471
--------------------	-----

Preface

Acoustics is the study of sound. Acoustics, as a part of mathematical physics, is a theory of small disturbances in an otherwise quiescent medium, like air. This means that we take the conservation equations describing air motion, and linearize them. There are other assumptions made in the *acoustic approximation*, but thinking of acoustics in air as linearized fluid mechanics is not far off the mark. While general mechanics of air in the human respiratory system is complex, and often non-acoustic, we can usually make the acoustic approximation for pertinent air motion in most of the supraglottal vocal tract during speech production. When we cannot, the approximation usually breaks down in localized regions, such as at the glottis itself, or in other highly constricted regions. These regions often act as sources of sound for the regions of the vocal tract where pertinent air movement is well described by the acoustic approximation.

We make an important distinction immediately regarding measurable quantities and the various approximations that can be used to describe air motion. This distinction has become clouded when air motion described in the acoustic approximation has been related to the motion described by alternative approximations to the conservation equations, such as the Bernoulli equation. These relations have often been made in an ad hoc manner that seem to make it necessary refer to such things as “acoustic pressure” or “Bernoulli pressure”. When considering the physics of air, we understand air has certain physical, measurable properties, such as density, pressure, particle velocity, volume velocity, and so on. These quantities are defined in such a way that they do not depend on the particular theoretical approximation used to describe their changes in space and time. For instance, there is no such thing as “acoustic pressure” or “Bernoulli pressure”, but there are instances and regions where the behavior of pressure is best described using the acoustic approximation, and others when its behavior is best described by Bernoulli’s equation. The motion of air does not accommodate itself according to the theoretical or mathematical approximations that are intended to describe the air’s motion.

There were several motivations that I had to write this book. I believe, that to make progress in understanding sounds that are

propagated in the atmosphere as a result of speech, the physics of acoustics must be understood by, at least, some researchers. Further, previous books on speech acoustics, such as those of Fant (1960), Flanagan (1965), and Stevens (1998) were written using electrical analogues. Electrical analogues are fine for many calculations, but they assume that the linearized acoustic approximation is valid. It is important to examine acoustics in the broader context of fluid mechanics to understand the use of acoustics for calculation and its connection to fluid motions in the vocal tract that do not conform to the acoustic approximation.

Other motivation came from questions that I have received from linguists, psychologists, and speech clinicians regarding acoustics. One of these questions regarded filter banks used to synthesize speech. If I remember correctly, the question was how is it that frequencies of a source, \mathcal{F} , such as the harmonics of the voice source, drive the filters in a filter bank, but do not follow the relation $\mathcal{F} = c/\lambda$, where c is the speed of sound and λ is the wavelength of the resonance represented by a particular filter in the filter bank? Questions like this made it clear that the way acoustics is traditionally presented to speech researchers is as a computational tool. The physics has often been lost in our understanding when computing outputs from inputs with transfer functions and filter banks. I hold to the idea that “The primary purpose of theory is understanding, not calculation.”

This is a book about settled science, as one of my colleagues has said. Almost all the the material in this book comes from nineteenth and early twentieth century physics. The newest topic that is in the book, other than the two research topics in Chapters 14 and 15, is in Chapter 13, where we discuss how air motion that is not described by the acoustic approximation can serve as a source of acoustic energy for acoustic wave motion. This is the study of aeroacoustics, and its modern beginnings came just after the first half of the twentieth century with the publication of Lighthill’s paper on jet noise in 1952.

The book is divided into four parts. Chapters 1 through 7 provide a thorough explanation of acoustic motion in a tube of finite length and constant cross-sectional area with a moving piston at one end. Some discussion of another type of source is also included. In the first part of the book, almost all of the results are presented in what we consider to be the time domain. This part lays out the fundamental mathematical

physics of the situation, so that further developments in variable-area tubes in Chapters 8 through 12 become more a matter of computation. However, we never switch completely to just computation of physical quantities, but continue to provide physical understanding with the derivation of equations. Much of the second part of the book involves frequency domain considerations. The third part of the book, which is in Chapter 13, is an introduction to fluid mechanics that does not follow the acoustic approximation. This leads to a short study of aeroacoustics and the way that the fluid motions that do not satisfy the acoustic approximation can provide energy for acoustic wave motion in the vocal tract. Finally, Chapters 14 and 15 outline two research projects that have not hitherto been published. The first involves a hypothesized relation between tongue surface curvature constraints applied to young children and their resulting acoustic output during speech. The second work is a proposed model for vocal fold vibration that uses some of the ideas introduced in Chapter 13. It is intended as a replacement for lumped element models, such as the two-mass model. Biomechanical parameters can be more easily related to the proposed model than to lumped element models. This final topic uses advanced mathematical tools.

This book is targeted at people interested in the physical aspects of acoustics that arise during the act of speaking. This includes people involved directly with the science of speech production, but without advanced mathematical knowledge, and those in the physical sciences with some advanced mathematical knowledge. [Here, we consider anything more than a smattering of calculus to be advanced knowledge of mathematics.] It is written to be accessible by those who are not trained in mathematics, while not holding back on presenting important physical ideas that are expressed mathematically. There are many simulations presented in plots and with numerical values to aid understanding. The book is something of a narrative about the physical acoustics encountered during speech production. It is intended to be read in sequence. This is not a text book, or even a reference book, in the traditional sense. For one thing, there are no problems for the student. However, if the reader wishes a more thorough understanding, he or she could derive some of the mathematical expressions presented in the book.

The reader should just forge ahead if he or she finds that some mathematical expressions are too difficult to understand. There is always a discussion or simulation that should still be illuminating. We would also recommend that readers use software to simulate some of the results, and turn to references for more in-depth discussion of topics of interest.

Equations are numbered separately in each chapter. Further, Chapters 1, 2, and 8 have short mathematical appendices with equations numbered as, for example (A1.2), where A1 refers to the Appendix to Chapter 1, and 2 refers to the equation number in that appendix. In some derivations, equation numbers are written in square brackets next to the steps of the derivation, so the reader can justify the step. We do this only for the first few uses of equations in the appendices.

There are numerous people to thank. There are friends, those who I have worked with in speech production research, and those across the United States who have either hosted me or encouraged me on my cross-country treks to teach in the American southwest. The number of people is too great to mention them by name. I want to thank my colleagues at Imperial Valley College, and my friends on both sides of the American-Mexican border in the college's region. All of these people helped me realize that a pedagogical vocation may not be out of reach for me.

Finally, I thank the people who read earlier versions of this book: Michael Howe, Khalil Iskarous, Lynn McGowan, Philip Rubin, and Reiner Wilhelms-Tricarico. They helped to improve this book immensely and are encouraging friends as well.

R. S. McGowan
Lexington, Massachusetts

References

Fant, G. (1960). *Acoustic Theory of Speech Production*. Mouton, The Hague.

-
- Flanagan, J.L. (1965). *Speech Analysis, Synthesis, and Perception*. Springer-Verlag, New York.
- Lighthill, M.J. (1952). On sound generated aerodynamically, Part 1: General Theory. *Proc. Roy. Soc. A.* **211**, 564-587.
- Stevens, K.N. (1998). *Acoustic Phonetics*. MIT Press, Cambridge, MA.

