Cochlear Mechanics

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Introduction to a Time Domain Analysis of the Nonlinear Cochlea

Springer

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ISBN 978-1-4419-6116-7 e-ISBN 978-1-4419-6117-4
DOI 10.1007/978-1-4419-6117-4
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011944505

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Interest in cochlear mechanics (CM) and particularly in the role of nonlinear cochlear processes expanded significantly during the 1970s. For me it was stimulated particularly through contacts with Jont Allen—a contact that remained important after his visit to Eindhoven—and Egbert de Boer, who was—amongst others—active within the Dutch Auditory Biophysics community.

My move to the University of Groningen in 1980, in combination with international developments, such as the discovery of otoacoustic emissions, led to an immediate increase in interest in CM. We followed up a proposal by Peter Johannesma [International Symposium on Hearing (ISH)—1980] stating that a Van der Pol-oscillator might be a proper model for spontaneous emissions.

At the same time significant theoretical contributions were given by John W. Matthews (1980) and Stephen T. Neely (1981) in their doctoral theses presented at Washington University. They also contributed to the ISH-1980 conference mentioned above. They started to explore nonlinear cochlea models in the frequency and time domain.

As a result, 1980 became a pivotal point in this book!

This book strongly rests on work from the Groningen biophysics department, which was largely performed by graduate students, both at master's (Sietse van Netten, Berk Hess, Johan Kruseman) and PhD levels (Marc van den Raadt, Peter van Hengel) and by postdocs (in particular Peter van Hengel). In addition, national (Max Viergever, Rob Diependaal: Delft University of Technology) and international cooperations have been essential (Bastian Epp: Carl von Ossietzky University of Oldenburg).

Within the University of Groningen we cooperated with mathematicians (Hendrik Hoogstraten, Henk Broer) and with audiologists from the ENT-department at the University Medical Center Groningen (Roel Ritsma, Hero Wit, Pim van Dijk).

Disputes and collaborations with the international community have quite effectively been controlled through the international journals as well as through meetings such as the Mechanics of Hearings conference series (started in 1984).

After formal retirement from the University of Groningen faculty, I was in the position to put our developments together in the underlying book format.[1]

The book is intended for use at the graduate or postgraduate level for students with a background in (bio)physics, (electrical) engineering, applied mathematics, or related specializations and multidisciplinary interest. It is somewhat related to Dallos's *The Auditory Periphery* (1973), but much narrower in scope, and updated with respect to otoacoustic emission data and to nonlinear modeling.

The contents is divided in three parts. Part I contains a historical introduction and deals with developments of linear CMs, up to approximately 1980. Part II presents a selection of experimental nonlinear phenomena, and the time domain study of some global nonlinear models. Part III presents results and open issues. Finally, Part IV contains useful general tools and example results.

The introductory Chap. 1 relies heavily on input from Peter van Hengel. His role in the development of the program and applications is also appreciated.

The final form of this book was significantly improved by the reviewers Bastian Epp, Hero Wit, and in particular Michael Rapson.

Groningen Hendrikus Duifhuis

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Matthews JW (1980) Mechanical modeling of nonlinear phenomena observed in the peripheral auditory system. PhD thesis, Washington Univ. Sever Institute of Technology, St. Louis

Neely ST (1981) Fourth-order partition dynamics for a two-dimensional model of the cochlea. PhD thesis, Washington Univ. Sever Institute of Technology, St. Louis

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[1] Additional material referred to in the text by unspecified URLs is accessible through the following Springer link: http://www.springerextras.com.

Contents

Part I Anatomy and Function of the Linear Cochlea

Part II Anatomy and Function of the Nonlinear Cochlea

Part III Results and Open Issues

Part IV Basic Linear and Nonlinear Tools and a PTPV Response Collection

List of Acronyms and Symbols

ABCD	Residual time technique (Brass, Kemp)
AC	Alternating current
AN	auditory nerve, N VIII (eighth nerve)
ANSI	American National Standards Institute
ASA	Acoustical Society of America
ASR	Automatic Speech Recognition
BCE	Before the Common Era (Before Christ)
BM	Basilar Membrane
BPNL	Bandpass Nonlinear
CB	Critical Band(width)
CDT	Cubic Difference Tone[1]
CEOAE	Click Evoked OtoAcoustic Emission
CP	Cochlear Partition
CT	Combination Tone
CTCF	Constant Tone at CF, level and frequency
DE	Differential Equation
DP	Distortion Product
DPOAE	Distortion Product OtoAcoustic Emission
ECFB	Equivalent LTI Cochlear Filterbank
EM	Electron Microscopy
ENT	Ear- Nose- Throat-
ERB	Equivalent Rectangular Bandwidth
EOAE	Evoked OtoAcoustic Emission
(F)FT	(Fast) Fourier Transform
IHC	Inner Hair Cell
ISH	International Symposium on Hearing
ISI	Inter-Spike Interval
ISO	International Organization for Standardization

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[1] A misnomer.

LCR	Inductance, Capacitance and Resistance
LG	Liouville, Green
LTI	Linear Time-Invariant (system)
NL	Nonlinear, Nonlinearity
OAE	OtoAcoustic Emission
OC	Corti's Organ
ODE	Ordinary Differential Equation
OHC	Outer Hair Cell
OW	oval window
PSTH	Post Stimulus Time Histogram
PTPV	Primary-Tone Phase Variation
RK4	Runge-Kutta 4 method
RW	round window
SEM	Scanning Electron Microscopy
SFOAE	Stimulus Frequency Evoked OtoAcoustic Emission
SOAE	Spontaneous OtoAcoustic Emission
SPL	Sound Pressure Level
TEM	Transmisson Electron Microscopy
TeM	Tectorial Membrane
TM	Tympanic Membrane
vdP	van der Pol-oscillator
WKB(J)	Wentzel, Kramers, Brillouin (Jeffreys)

List of Symbols

Symbol	Description	Value	Units	Dimensions
0	As subscript index: initial or average value			
δ	Damping coefficient		–	0
ε	NL-parameter		–	0
η	Dynamic viscosity		Pa s	$\mathrm{L^{-1}MT^{-1}}$
γ	Ratio of heat capacities (C_p/C_V)		–	0
ν	Kinematic viscosity		$\mathrm{m^2/s}$	$\mathrm{L^2T^{-1}}$
ρ	Fluid density (water, lymph)	1,000	$\mathrm{kg/m^3}$	$\mathrm{ML^{-3}}$
Φ	Heat source		J	$\mathrm{L^2MT^{-2}}$
a	As subscript: acoustic			
a	Acceleration		$\mathrm{m/s^2}$	$\mathrm{ML^{-2}}$
A	Area		$\mathrm{m^2}$	$\mathrm{L^2}$
d_a	Acoustic damping (resistance)		$\mathrm{Pa\ s/m^3}$	$\mathrm{ML^{-4}T^{-1}}$
e	AC voltage		V	$\mathrm{I^{-1}L^2MT^{-3}}$
E	Energy		J	$\mathrm{L^2MT^{-2}}$
F	Force		N	$\mathrm{LMT^{-2}}$
$FT\{s(t)\}$	Fourier transform, operator			$[s(t)].\mathrm{T}$
$FT^{-1}\{S(\omega)\}$	inverse Fourier transform, operator			$[S(\omega)].\mathrm{T^{-1}}$
g	Gravitational acceleration		$\mathrm{m/s^2}$	$\mathrm{ML^{-2}}$
i	AC current		A	I
I	Sound intensity		$\mathrm{W/m^2}$	$\mathrm{MT^{-3}}$
J	Sound-energy flux		W	$\mathrm{L^2MT^{-3}}$
m	Mass, general physical		kg	M
$m(x)$	Partition mass per area	0.5	$\mathrm{kg/m^2}$	$\mathrm{ML^{-2}}$
m_a	Acoustic mass (inductance)		$\mathrm{kg/m^4}$	$\mathrm{ML^{-4}}$
$p(\mathbf{x}, t)$	Sound pressure at **x** and *t*		Pa	$\mathrm{L^{-1}MT^{-2}}$
$\mathbf{q}$	Heat flux density		Pa	$\mathrm{L^{-1}MT^{-2}}$
s	Specific entropy		J/kg.K	$\mathrm{L^2T^{-2}\Theta^{-1}}$
S	Entropy		J/K	$\mathrm{L^2MT^{-2}\Theta^{-1}}$
s_a	Acoustic stiffness (1/capacitance)		$\mathrm{Pa\ /m^3}$	$\mathrm{ML^{-4}T^{-2}}$
$s(x)$	Partition stiffness per area		Pa /m	$\mathrm{ML^{-2}T^{-2}}$
t	Time		s	T
T	Temperature		K, (°C)	Θ
$u(t), v(t), w(t)$	x-,y-,z-velocity at t		m/s	$\mathrm{LT^{-1}}$
u	Specific internal energy		J/kg	$\mathrm{L^2T^{-2}}$
U	Internal energy		J	$\mathrm{L^2MT^{-2}}$

List of Symbols (continued)

Symbol	Description	Value	Units	Dimensions
$U(\mathbf{x},t)$	volume velocity $\mathbf{x}$–direction at t		m^3/s	$\mathrm{L^3T^{-1}}$
$U_{\mathrm{st}}(t)$	volume velocity stapes at t (positive: inward)		m^3/s	$\mathrm{L^3T^{-1}}$
V, V_0	volume		m^3	$\mathrm{L^3}$
$\mathbf{x}$	3-D x-vector		m	L
x, y, z	length, width, height		m	L
Z, Z_{e}	electrical impedance V/I		Ω	$\mathrm{L^2MT^{-3}I^{-2}}$
Z_{m}	mechanical impedance F/v		N s/m	$\mathrm{MT^{-1}}$
Z_{a}	acoustic impedance p/U		Pa s/m^3	$\mathrm{L^{-4}MT^{-1}}$
Z_{sa}	specific acoustic impedance p/v		Pa s/m	$\mathrm{L^{-2}MT^{-1}}$