

EXPERIMENTAL EVALUATION OF NONLINEAR INDICES FOR ULTRASOUND
TRANSDUCER CHARACTERIZATIONS

BY

TIMOTHY ALLEN BIGELOW

B.S., Colorado State University, 1998

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2001

Urbana, Illinois

ACKNOWLEDGMENTS

First of all, I would like to thank my adviser, Dr. William O'Brien for his help on this work. I would also like to thank Dr. Andrew Webb for the use of his lab and network analyzer and Dr. Narendra Ahuja for guidance when I first came to the University of Illinois at Urbana-Champaign. I would also like to recognize my coworkers in the Bioacoustics Research Laboratory because of help they provided during the investigation. Last of all, I want to reference Exodus 15:2 and 1 Corinthians 3:11-15.

TABLE OF CONTENTS

CHAPTER	PAGE
1 INTRODUCTION TO THE NONLINEAR INDEX PROBLEM	1
1.1 Background: Extrapolation in Ideal Linear Case	1
1.2 Motivation: Problems Introduced by Acoustical Nonlinear Effects	6
1.3 Approach and Summary of Results	7
2 THEORETICAL ANALYSIS OF ASYMMETRIC DISTORTION	9
2.1 The Modified Ostrovskii/Sutin Method	9
2.2 Some Inherent Problems with the Ostrovskii/Sutin Method	13
2.3 Insights Provided by the Ostrovskii/Sutin Method	17
3 THEORETICAL ANALYSIS OF NONLINEAR ABSORPTION	21
3.1 Acoustical Saturation for Plane Waves	21
3.2 Nonlinear Absorption for a Focused Sound Source	24
4 THEORETICAL ANALYSIS OF PROPOSED INDICES	26
4.1 Absolute Indicators of Nonlinearity	26
4.1.1 Asymmetric ratio	27
1.1.1 Ostrovskii/Sutin's propagation parameter σ_s	28
1.1.3 Bacon's propagation parameter σ_m	30
1.1.4 Field sigma σ_z	35
1.1.5 Second harmonic ratio	35
1.1.6 Absolute spectral index	37

1.2	Relative Indicators of Nonlinearity	38
1.1.1	Relative spectral index	39
1.1.2	Relative focal pressure	39
5	ANALYSIS OF EXTRAPOLATION VOLTAGES	
	41	
5.1	Extrapolation Factor Candidates	41
5.2	Experimental Evaluation of Candidates	47
5.3	Setting the Confidence Measure for each Data Set	
	53	
6	EXPERIMENTAL PROCEDURE	54
6.1	Overview of Experimental System	54
6.2	Analysis of Excitation System	55
6.3	Data Acquisition	61
7	EXPERIMENTAL EVALUATION OF PROPOSED INDICES	
	66	
7.1	Calculation of Indices at Each Applied Voltage	66
7.2	Determination of Threshold Values of Indices	81
7.3	Evaluation of the Different Indices	89
8	CONCLUSIONS AND FUTURE WORK	93
	APPENDIX A: POISSON'S THEOREM	95
	APPENDIX B: THE KLM MODEL	99
	APPENDIX C: THE RLC CIRCUIT MODEL FOR A PIEZOELECTRIC TRANSDUCER	

APPENDIX D: COMPARISON OF THE RLC CIRCUIT MODEL TO THE KLM MODEL	106
APPENDIX E: MATLAB CODE TO DETERMINE THE RLC VALUES FOR THE CIRCUIT MODEL	116
APPENDIX F: MATLAB CODE USED TO DETERMINE EXTRAPOLATION FACTOR	119
APPENDIX G: MATLAB CODE USED TO EVALUATE NONLINEAR INDICATORS	129
REFERENCES	149

LIST OF TABLES

Table	
Page	
5.1: Frequency ranges used to determine RLC parameters	45
5.2: RLC parameters determined for each transducer	47
5.3: Linearity of the “close” pressure waveforms quantified in terms of the mean extrapolation error using p_r as the extrapolation factor	50
5.4: Evaluation of extrapolation factors for p_c quantified in terms of the mean extrapolation error determined from the close pressure waveforms	51
5.5: Evaluation of extrapolation factors for p_r quantified in terms of the mean extrapolation error determined from the close pressure waveforms	51
5.6: Evaluation of extrapolation factors for p_{avg} quantified in terms of the mean extrapolation error determined from the close pressure waveforms	51
5.7: Scores used to select the best extrapolation factor	53
6.1: Values used for the shunt inductance	60
6.2: Step sizes used to find the location of the focus for each transducer	62
6.3: “Close” locations for each transducer	63

LIST OF FIGURES

Figure	Page
1.1: The KLM model of a piezoelectric transducer	2
1.2: Diagram of a typical focused transducer	4
1.3: Plot illustrating asymmetric distortion for a focused source	6
2.1: Diagram illustrating different regions of propagation used in the Ostrovskii/Sutin Method	9
2.2: Results demonstrating pulse asymmetry near the focal region	19
3.1: Plots illustrating shock formation for a propagating plane wave	23
4.1: Typical frequency spectrum at the focus of a spherically focused transducer under two different drive conditions	36
5.1: Equivalent RLC circuit model for a piezoelectric transducer	42
5.2: Comparison of output simulation results from the RLC circuit model and the KLM model under two different load conditions	43
5.3: Example measured admittance curve for one of the transducers	45
5.4: Typical errors in p_c using p_r as an extrapolation factor	49
6.1: Diagram of experimental setup	55
6.2: Pulses generated with matched load and transducer connected to the RAM5000 ...	57
6.3: Voltage pulses after implementation of restoration procedures	60
6.4: Diagram illustrating location of “close” pressure measurement	64
7.1: First six indicators for a 2.8072 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) S_s from P_{asym} (c) S_s from p_r (d) S_m (e) S_z (f) Second harmonic ratio H_{II}	67
7.2: Second six indicators for a 2.8072 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) si from $1.5w_1$ (b) si from $2w_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	68
7.3: First six indicators for a 2.9983 MHz, $f/\#$ of 1, 5.08 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) S_s from P_{asym} (c) S_s from p_r (d) S_m (e) S_z (f) Second harmonic ratio H_{II}	69
7.4: Second six indicators for a 2.9983 MHz, $f/\#$ of 1, 5.08 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) si from $1.5w_1$ (b) si from $2w_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	70
7.5: First six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “one cycle” pulse. (a) Asymmetric ratio P_{asym}	

(b) \mathbf{S}_s from P_{asym} (c) \mathbf{S}_s from p_r (d) \mathbf{S}_m (e) \mathbf{S}_z (f) Second harmonic ratio H_{II}	71
7.6: Second six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “one cycle” pulse. (a) si from $1.5\mathbf{w}_1$ (b) si from $2\mathbf{w}_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	72
7.7: First six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) \mathbf{S}_s from P_{asym} (c) \mathbf{S}_s from p_r (d) \mathbf{S}_m (e) \mathbf{S}_z (f) Second harmonic ratio H_{II}	73
7.8: Second six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) si from $1.5\mathbf{w}_1$ (b) si from $2\mathbf{w}_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	74
7.9: First six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “negative going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) \mathbf{S}_s from P_{asym} (c) \mathbf{S}_s from p_r (d) \mathbf{S}_m (e) \mathbf{S}_z (f) Second harmonic ratio H_{II}	75
7.10: Second six indicators for a 5.4906 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “negative going” “three cycle” pulse. (a) si from $1.5\mathbf{w}_1$ (b) si from $2\mathbf{w}_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	76
7.11: First six indicators for a 5.3574 MHz, $f/\#$ of 2, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) \mathbf{S}_s from P_{asym} (c) \mathbf{S}_s from p_r (d) \mathbf{S}_m (e) \mathbf{S}_z (f) Second harmonic ratio H_{II}	77
7.12: Second six indicators for a 5.3574 MHz, $f/\#$ of 2, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) si from $1.5\mathbf{w}_1$ (b) si from $2\mathbf{w}_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	78
7.13: First 6 indicators for a 8.1517 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) Asymmetric ratio P_{asym} (b) \mathbf{S}_s from P_{asym} (c) \mathbf{S}_s from p_r (d) \mathbf{S}_m (e) \mathbf{S}_z (f) Second harmonic ratio H_{II}	79
7.14: Second six indicators for a 8.1517 MHz, $f/\#$ of 1, 1.905 cm diameter transducer excited by a “positive going” “three cycle” pulse. (a) si from $1.5\mathbf{w}_1$ (b) si from $2\mathbf{w}_1$ (c) rsi (d) P_{ce} (e) P_{re} (f) P_{ae}	80
7.15: Threshold values for the asymmetric ratio	84
7.16: Threshold values for \mathbf{S}_s from p_r	85
7.17: Threshold values for \mathbf{S}_s from P_{asym}	85
7.18: Threshold values for \mathbf{S}_m	86
7.19: Threshold values for \mathbf{S}_z	86
7.20: Threshold values for the second harmonic ratio	87
7.21: Threshold values for si from $1.5\mathbf{w}_1$	87
7.22: Threshold values for si from $2\mathbf{w}_1$	88
7.23: Threshold values for rsi	88
7.24: Threshold values for the relative focal pressure	89
7.25: Direct comparison of pressures at the focus. (a) ~5.5 MHz $f/\#1$ transducer	

(b) ~5.5 MHz $f_{\#2}$ transducer (c) ~8 MHz $f_{\#1}$ transducer	90
B.1: The KLM model of the piezoelectric transducer	99
C.1: The RLC circuit model for a piezoelectric transducer	104
D.1: Input admittance for the KLM model and the RLC circuit model	107
D.2: Transfer function for the KLM model and the RLC circuit model	109