

Contents

Foreword	vii
Preface	ix
Acknowledgments	xi
1 Introduction	1
1.1 The Sound of Horns	1
1.2 A Hundred Years of Progress?	2
1.3 Remarks on Writing the History of Horn Loudspeaker Technology	3
1.4 Remarks on Language, and the Process of Writing	4
1.5 Available Literature	4
1.6 About the Contents	5
1.6.1 The History Section	5
1.6.2 The Theory Section	5
1.6.3 The Design Section	6
1.6.4 The Appendix	6
I History	9
2 Origins of Electroacoustics	11
2.1 Early use of Horns	11
2.1.1 Early Mathematical Analysis	12
2.2 Early Electroacoustics	13
2.2.1 The telephone and the Rise of AT&T	13
2.2.2 Early Telephonic Transmission of Musical Performances	19
2.2.3 Early Moving-Coil Transducers	21
2.2.4 Other Transducer Mechanisms	23
2.3 The Evolution of Electrical Transmission Theory	23
2.3.1 Lord Kelvin and the KR Law	24
2.3.2 The Transatlantic Telegraph Table	24
2.3.3 Loaded Lines and Wave Filters	24
2.4 The Phonograph	30
2.5 From de Forest's Audion to High Vacuum Triode	32
2.5.1 Fleming's Vacuum Diode	33
2.5.2 The Earliest Three-Element Vacuum Tubes	33
2.5.3 The Audion Evolves	35
2.6 Radio Broadcasting	37
2.7 The Stage is Set	38
3 Loudspeaker Technology 1915-1925	41
3.1 Pridham and Jensen - the "Magnavox" loud speaker	41
3.2 The "Rebirth" of Horn Theory	44
3.3 Horn Research in the Early 1920s	45
3.3.1 Investigations of Conical Horns	45
3.3.2 The Contributions to Horn Theory by Hanna and Slepian	46
3.3.3 The Investigations of Goldsmith and Minton	46

3.4	Radio and General Purpose Horn Speakers	47
3.5	The Loud Speaker Problem	51
3.5.1	Armature Loudspeakers	51
3.5.2	Early Cone Type Loudspeakers	53
3.6	Outlook	56
4	The Birth of Sound Pictures	59
4.1	Introduction	59
4.2	Phonofilm and Movietone	60
4.3	Tri-Ergon and Klangfilm	61
4.4	Western Electric and BTL	62
4.5	The Vitaphone	63
4.6	RCA Photophone	64
5	Developments at AT&T	69
5.1	The AT&T	69
5.2	Notes on Terminology	70
5.2.1	Transducers	70
5.2.2	Transmission Units, decibels	71
5.3	Early Acoustics Research	71
5.4	Matched Impedance Transmission	74
5.4.1	Characteristics of Matched Impedance Systems	74
5.4.2	Matching of Impedances in Horns	75
5.5	Measurement Capabilities	75
5.5.1	Impedance and Transmission Loss Measurement	75
5.5.2	Loudspeaker Measurements	76
5.5.3	Introduction of the Plane Wave Tube for Response Measurements	77
5.6	Vacuum Tube Amplifiers for Loud Speaking Telephones	80
5.6.1	Audio Transformer Developments	80
5.7	Public Address Systems 1920–1925	82
5.7.1	Horns and Transducers	82
5.8	The development of the Orthophonic Phonograph System	83
5.8.1	The Orthophonic Soundbox	90
5.8.2	The Orthophonic Horns	94
5.9	Development of the Vitaphone Loudspeakers	100
5.9.1	Theoretical Foundations and Experimental Investigations	100
5.9.2	The Initial Loudspeaker Tests	107
5.9.3	Production of 12-A and 13-A	111
5.9.4	Theatre Installations	113
5.9.5	The Western Electric 555-W, From Laboratory Model to Commercial Product	113
5.9.6	555-W In Use	114
5.9.7	Variants of 12- and 13-Type Horns	117
5.9.8	Loudspeaker Development 1926–1929	117
5.10	The Type 15 Horn	120
	Typw 15 Horn Manufacturing	128
5.10.1	Type 17	137
5.11	Further Work on Type 15 Horns	137
5.11.1	The Slit Mouth 15-A	138
5.11.2	Type 19	144
5.12	Shallow Horns	144
5.12.1	KS-6575 and KS-6576	145
5.12.2	Type 16 Horn	145
5.13	Who Designed the Horns?	151
5.14	Public Address Systems 1926–1932	152
5.14.1	36-Hz Horns: KS-6256 and Variants	154
5.14.2	The 1928 Laboratory Rooftop Experiment	154
5.14.3	Madison Square Garden upgraded Public Address system (1929)	155
5.14.4	Atlantic City Convention Hall PA System	158
5.14.5	Racon Fabric Horns	159

5.15	Proposed Improvements in Reproducers and Horns by E.L. Norton	160
5.16	Improvements of the W.E. 555	162
5.17	The Type 596/597 High-Frequency Unit	162
5.17.1	Manufacturing	164
5.17.2	Reliability Issues	167
5.17.3	Coaxial Loudspeaker	168
5.17.4	Permanent Magnet Versions	168
5.18	British Western Electric horns and receivers	168
5.18.1	The 30150 Receiver	168
5.18.2	The 30154 Horn	168
5.18.3	The 30411 High-Frequency Receiver	170
5.19	Towards the Wide Range System	170
5.19.1	The Gotham Theatre Tests	172
5.19.2	595/596 Two-Way Systems	177
5.20	The Wide Range System	183
5.21	Types 21 and 22 Horns	186
5.22	The Fletcher System	186
5.22.1	The Stokowski Connection	187
5.22.2	Initial Experiments	187
5.22.3	The System	187
5.22.4	The Demonstrations	196
5.22.5	Later Use	196
5.23	ERPI's New Theater System	196
5.23.1	Bostwick's 3-Way System	200
5.23.2	The Blattner 200-10000 cycle loud speaker	203
5.23.3	594-A	204
5.23.4	The Multicell Horns	208
5.23.5	Work on Bass Horn and Driver	210
5.24	The Mirrophonic System	213
5.25	Later Horns and Drivers	218
5.25.1	Radial Horns 31A and 32A	218
5.25.2	Post-War Theater Systems	218
5.26	Stereophonic Tests	219
5.27	Summary	220
6	Loudspeaker Work at RCA	229
6.1	Acoustic Research	229
6.2	The First Photophone System	231
6.3	Photophone Horns	232
6.4	The "High Fidelity" Range	234
6.5	Compound Horns	236
6.6	Multicell and Multi-Flare Horns	237
6.6.1	Multi-Flare Technology	239
6.6.2	Single-Channel Multicell Horn	240
6.7	Low-Frequency Horns	242
6.8	A Coaxial Two-Way System	242
6.9	RCA High-Frequency Drivers	243
6.9.1	The MI-1428 HF driver	243
6.9.2	MI-1429 and MI-1435	244
6.10	RCA Systems	244
6.11	Fantasound	244
6.11.1	The Speaker Systems of Fantasound	250
6.12	Summary	254
7	Other Horn Loudspeaker Developments 1925-1940	259
7.1	Theory and Research	259
7.1.1	William M. Hall's Horn Studies	260
7.1.2	Studies of the Hyperbolic Horn	262
7.2	P.G.A.H. Voigt's Contributions to the Art	263

7.2.1	Voigt and the Tractrix Horn	265
7.2.2	Voigt's Corner Horn	266
7.2.3	The Lowther-Voigt Association	268
7.3	Percy Wilson's Contributions to the Art	269
	The Fitzpatrick "Acoustical Ethereal" Gramophone	272
7.4	R.P.G. Denman and His Horns	274
7.4.1	The Denman/Benson 25-Foot Horn	274
7.4.2	The Science Museum horn	277
7.5	The Marconi Company	279
7.6	British Thomson-Houston	280
7.6.1	B.T.H. Type D and E5A horn drivers	282
7.7	Jensen Radio Manufacturing Company	283
7.7.1	The SE-7015/XP-101 horn drivers	283
7.7.2	The Hypex horn	285
7.8	Vitavox Acoustics/	
	Vitavox Ltd. 1931-1940	288
7.9	Developments in Germany	293
7.9.1	Early Public Address Loudspeaker Developments at Siemens & Halske and Tele-funken	293
7.9.2	Horn Research and Developments at AEG	295
7.9.3	Walter Schottky of Telefunken G.m.b.H.	297
7.9.4	Klangfilm	298
7.10	Various Manufacturers	302
7.10.1	Racon	302
7.10.2	Fox	304
7.10.3	Amplion	305
7.10.4	The Electrophone Corporation and their Piezoelectric Horn Speakers	305
7.11	The Shearer System	309
7.11.1	RCA's Involvement	310
7.11.2	The Final System	312
7.12	Lansing MFG Co.	315
7.12.1	Shearer-Lansing Theatre Speakers	316
7.12.2	Lansing MFG. Co. Monitoring Speakers	317
7.13	Multicell Horns	320
7.13.1	An Early Multicell Horn	320
7.13.2	The Origin of the Classical Multicellular Horn	323
7.13.3	RCA Multicell Horns	323
7.13.4	RCA experimental Multicell Style Horn Arrays	325
7.13.5	Multicell HF Horns Established as Standard Practice	325
7.14	From ERPI to Altec	328
7.15	Summary	333
8	Post-War Developments	343
8.1	Altec Lansing Corporation	343
8.1.1	The Duplex Loudspeaker	344
8.1.2	New Line of Theatre Systems	345
8.1.3	Later Altec Lansing Company History	346
8.2	Paul W. Klipsch	348
8.3	James B. Lansing Sound, Incorporated	352
8.3.1	JBL Hartsfield	353
8.3.2	The 375	354
8.3.3	The "Ultra High Frequency" Drivers	355
8.3.4	The Paragon	355
8.3.5	JBL Enters the Professional Market	355
8.3.6	Home Audio	358
8.3.7	JBL Horn and Driver Technology	359
8.4	Various Manufacturers	360
8.4.1	Klangfilm	360

8.4.2	Vitavox Ltd.	361
8.4.3	RCA	364
8.4.4	Westrex	365
8.4.5	University Loudspeakers	366
8.4.6	Community Light & Sound	369
8.4.7	Electro-Voice	370
8.4.8	Celestion	372
8.5	Miscellaneous Horn Loudspeaker Developments	377
8.5.1	Sectoral Horns	377
8.5.2	Acoustic Lenses	377
8.5.3	Diffraction Horns	377
8.5.4	Columns and Line Arrays	378
8.5.5	Other Approaches	381
8.5.6	Piezoelectric Tweeters	382
8.5.7	Compression Drivers	382
8.6	Home Audio Systems	382
8.6.1	Rebirth of High Efficiency Domestic Speakers	384
8.6.2	The work of Dr. Bruce Edgar	385
8.6.3	The work of Jean-Michel Le Cléac'h	385
8.6.4	Horn Loudspeakers, Big in Japan	386
8.7	Horn Theory and Simulation	390
8.7.1	Horn Theory 1940-1950	391
8.7.2	1950-1960	391
8.7.3	1960-1970	392
8.7.4	1970-1980	392
8.7.5	1980 and onward	393
8.7.6	Outlook	395
8.8	Conclusion	395

II Theory 411

9	Horn Loudspeakers – an Introduction	413
9.1	Efficiency	413
9.2	Impedance Transformation	416
9.3	The Horn Loudspeaker	418
9.4	Directivity	422
9.5	Basic Topologies	423
9.5.1	Front-Loaded Horns	423
9.5.2	Rear Loaded Horns	424
9.5.3	Full Range Systems	424
9.5.4	Multi-Way Systems	424
9.6	Summary	424
10	Symbols	427
10.1	Symbols	427
11	Basic Theory	429
11.1	Peak and RMS values	429
11.2	Complex Numbers	429
11.3	Dynamical Analogies	430
11.3.1	Impedance and Admittance	430
11.3.2	Acoustic Impedance	431
11.3.3	Sources	432
11.3.4	Resistive Elements	432
11.3.5	Inductive Elements	432
11.3.6	Capacitive Elements	433
11.3.7	Acoustic Transformers	433
11.3.8	Coupling Between Domains – Transducers	435

11.4	Linear Time-Invariant Systems	436
11.4.1	Minimum Phase and All-Pass	436
11.4.2	Transient Response and Delay	437
11.5	Filters	439
11.5.1	Image-parameter Method	439
11.5.2	Modern Filter Synthesis	440
11.6	Transmission Lines	440
11.7	Resonant Circuits	441
11.7.1	Resonance	441
11.7.2	Q	441
11.8	Impedance Matching	442
11.8.1	Maximum Power Transfer	442
11.8.2	Efficiency	442
11.9	Two-Port Networks	443
11.9.1	Transmission Matrix	443
11.9.2	Impedance Matrix	444
11.9.3	T , π and Lattice Networks	444
11.10	Principles of Sound Propagation	445
11.10.1	The Wavenumber	446
11.10.2	The Wave Equation – Simple Derivation	446
11.10.3	Velocity Potential	447
11.10.4	The Wave Equation – More Detailed Derivation	447
11.10.5	Sound Intensity	449
11.10.6	Sound Power	449
11.11	One-Dimensional Solutions to the Wave Equation	449
11.11.1	Plane Waves	449
11.11.2	Spherical Waves	449
11.11.3	Cylindrical Waves	450
11.12	Simple Sources	451
11.13	Modal Description of the Sound Field	451
11.13.1	Modes in Rectangular Coordinates	452
11.13.2	Cylindrical Coordinates	454
11.13.3	Spherical Coordinates	454
11.14	Air Nonlinearity	454
11.15	Summary	455
12	Horn Theory	459
12.1	Wave Propagation in Horns	459
12.1.1	The Assumptions of Classical Horn Theory	460
12.1.2	One-Parameter Horns	460
12.2	The Horn Equation	461
12.2.1	Validity Range of the Horn Equation	462
12.2.2	Generalized Horn Theory	464
12.3	Solutions to the Horn Equation	464
12.3.1	Using the T-Matrices	465
12.3.2	Z-Matrices – Flanders's Method	466
12.3.3	Infinite Horns	467
12.3.4	The Resistance–Reactance Coupling	467
12.3.5	Horn Synthesis	467
12.3.6	Duality Principle	467
12.4	Evaluation of Horn Performance	467
12.4.1	Throat Impedance	468
12.4.2	Power Factor	468
12.4.3	Reflection Factor	468
12.4.4	Matched Source Method	469
12.4.5	Effective Length	469
12.5	The Uniform Pipe	469
12.5.1	Infinite Pipe	470

12.5.2	Finite Pipe	470
12.6	Parabolic (Cylindrical) Horn	471
12.7	Conical Horn	471
12.7.1	Infinite Conical Horn	472
12.7.2	Finite Conical Horn	472
12.8	Exponential Horn	473
12.8.1	Infinite Exponential Horn	474
12.8.2	Finite Exponential Horn	475
12.8.3	Z-Matrix for the Exponential Horn	475
12.8.4	Exponential Horn with Wall Losses	477
12.8.5	The Cutoff Phenomenon	477
12.8.6	Cutoff in Finite Horns	478
12.9	The Family of Hyperbolic-Exponential Horns	478
12.9.1	Infinite Horns	479
12.9.2	Finite Horns	480
12.9.3	Catenoidal Horns	480
12.10	Bessel Horns	481
12.10.1	Infinite Bessel Horns	482
12.10.2	Finite Bessel Horns	483
12.10.3	Bessel Horns with Negative Exponent	483
12.11	Other Horn Types	484
12.11.1	Tractrix Horn	485
12.11.2	Other Solutions	486
12.11.3	Multi-Segment Horns	487
12.12	Discussion	488
12.13	Horns with Losses	489
12.14	Horn Termination	490
12.14.1	Throat End	490
12.14.2	Mouth End	491
12.14.3	Mouth Size	491
12.14.4	Mouth Aspect Ratio	493
12.14.5	Horn Length	493
12.14.6	Radiation Solid Angle	493
12.14.7	Mirror Images and Mutual Impedance	495
12.14.8	Constant Mouth Size, Varying Distance	495
12.14.9	Varying Mouth Size	497
12.14.10	Varying Distance	498
12.15	Time Domain	499
12.15.1	Horn Phase Distortion	500
12.16	Nonlinear Distortion in Horns	503
12.16.1	Mouth Reflections	505
12.16.2	Actual Distortion Levels	505
12.17	Theory of Curved and Folded Horns	506
12.17.1	Low-Frequency Models	506
12.17.2	Right-Angle Bends	507
12.18	Summary	509
13	Advanced Horn Theory	515
13.1	Measured Wave Fronts in Real Horns	515
13.2	Horn Theory: A Step Further	516
13.2.1	The Sound Field in a Horn	518
13.2.2	Flaring Horns	519
13.2.3	Waveguides	520
13.3	Corrections to the Horn Equation	521
13.4	Simple Coordinate Systems	522
13.4.1	Uniform Duct	522
13.4.2	Conical Horn	523
13.4.3	Cylindrical Horn	524

13.5	Other Separable Coordinate Systems	525
13.5.1	The Oblate Spheroidal Waveguide	525
13.6	Orthogonal Coordinate Systems	527
13.6.1	Exponential Horn	529
13.7	Modal Coupling	530
13.7.1	Modal Coupling Mechanics	530
13.7.2	Modal Coupling Impedance	532
13.8	Modal Group Delay	532
13.9	Modal Propagation in Bends	534
13.9.1	Propagation through rectangular bends	534
13.9.2	The dispersion relation	535
13.9.3	Coupling to straight rectangular ducts	535
13.10	Summary	536
14	Radiation of Sound	541
14.1	Radiation Impedance	541
14.2	Radiation from Vibrating Bodies	542
14.2.1	The Kirchhoff-Helmholtz Integral	542
14.2.2	The Far-Field	542
14.3	Superposition	542
14.4	Radiators in an Infinite Baffle	543
14.4.1	Rayleigh Integral	543
14.4.2	The Radiation Impedance	543
14.4.3	Time Domain Representation	544
14.4.4	Circular Piston	544
14.4.5	Rectangular Piston	545
14.5	Mutual Radiation Impedance	546
14.6	Sources in Fractional Space	547
14.6.1	Radiation Impedance for a Piston near One or Two Walls	547
14.7	Diffraction	548
14.7.1	Edge Source Method	548
14.7.2	Distributed Edge Dipole Method	550
14.8	Unbaffled Sources	550
14.8.1	Unflanged Duct	550
14.8.2	Spherical Cap in Sphere	551
14.9	More Advanced Radiation Models	552
14.9.1	Radiation Modes	552
14.9.2	Cylindrical Geometry	553
14.9.3	Rectangular, Quarter Symmetric Geometry	553
14.9.4	Rectangular, Asymmetric Geometry	554
14.10	Generalized Modal Radiation Impedance	554
14.11	Physical Meaning of the Modal Radiation Impedance	555
14.12	Radiation Impedance, Axisymmetric Duct	557
14.13	Radiation Impedance, Rectangular Duct	558
14.14	Sources Near Walls	560
14.15	Horns in Rooms	560
14.15.1	Method 1	560
14.15.2	Method 2	562
14.15.3	Method 2: Basic Equations	562
14.15.4	Method 2: Impedance	563
14.15.5	Example	564
14.16	Summary	564
15	Directivity	569
15.1	Definitions	569
15.2	Directivity Metrics	569
15.2.1	Polar Plot and Balloon Plot	569
15.2.2	Beamwidth or Coverage Angle	570
15.2.3	Directivity Factor and Directivity Index	570

15.2.4	Directivity Figure of Merit	571
15.2.5	Polar Map — Sonogram	571
15.2.6	Altec “Mercator” Projection	571
15.2.7	Constant Directivity Metrics	572
15.3	Beaming	573
15.4	Principles of Directivity Control	573
15.4.1	Lower Control Frequency	574
15.4.2	Interdependence of Intercept Frequencies	575
15.4.3	Upper Control Frequency	576
15.4.4	Midrange Narrowing	577
15.5	Theory of Directivity Control	577
15.5.1	Velocity Distribution	578
15.5.2	Constant Beamwidth Transducers	579
15.5.3	Baffled Source Velocity Distribution	579
15.5.4	Designing the Polar Pattern	580
15.5.5	Independence of Directivity Planes	580
15.5.6	Non-Ideal Behavior	580
15.5.7	The Finer Points	582
15.6	Axisymmetric Horns for Directivity Control	582
15.6.1	Mouth Flare	584
15.6.2	Conical-Exponential Horns	584
15.6.3	OS Waveguides	585
15.7	Non-Axisymmetric Horns	585
15.7.1	Multicellular Horns	585
15.7.2	Sectoral Horns	589
15.7.3	Acoustic Lenses	590
15.7.4	Reverse Flare Horns	592
15.7.5	Diffraction Horns	593
15.7.6	Limitations of the Single Surface CD Horn	594
15.7.7	Throat Impedance of Horns for Directivity Control	594
15.8	Arrays	595
15.8.1	Splaying	596
15.9	Summary	596
16	Transducer Basics	601
16.1	Generalized Small Signal Model	601
16.2	The Moving Coil Transducer	601
16.3	The Electrical Side	602
16.3.1	Modeling Voice Coil Inductance	603
16.3.2	The Electromagnetic Coupling	604
16.3.3	Motional Impedance	605
16.4	The Mechanical System	605
16.4.1	Creep	606
16.5	The Acoustical Side	606
16.6	The Complete Model	606
16.7	Thiele-Small Parameters	608
16.8	Direct Radiator Basics	609
16.8.1	Mass Control vs. Resistance Control	610
16.9	Other Transducer Mechanisms	610
16.9.1	Electrostatic Transducer	610
16.9.2	Armature Transducer	611
16.9.3	Piezoelectric Transducer	612
16.10	Driver Scaling	612
16.11	Nonlinearity	613
16.11.1	Motor System	613
16.11.2	Diaphragm/radiator	614
16.11.3	Suspension	614
16.12	Reducing Nonlinear Distortion	614

17 The Moving Coil Motor System	617
17.1 Magnetism	617
17.1.1 The Hysteresis Loop	618
17.2 Magnetic Circuits	619
17.2.1 Basic Calculations	620
17.2.2 Calculations with Leakage	620
17.3 Gap Geometries	622
17.4 The Gap at Saturation	623
17.5 Motor Topologies	623
17.6 Voice Coils	624
17.6.1 Voice Coil Calculation	625
17.7 Permanent Magnets	625
17.7.1 Recoil	626
17.7.2 Temperature Stability	627
17.7.3 Magnet Types	627
17.8 Soft Magnetic Materials	629
17.8.1 Materials	629
17.8.2 Annealing	630
17.9 Nonlinear Distortion Mechanisms	631
17.9.1 Symptoms	632
17.9.2 The Fundamental Mechanisms	633
17.9.3 Flux Modulation	635
17.9.4 Permeability Modulation	637
17.9.5 Thermal Compression	637
17.10 Reducing Nonlinear Distortion	639
17.10.1 Non-Uniform B_l	640
17.10.2 Flux and Permeability Modulation	640
17.10.3 Thermal Compression	641
17.11 Summary	641
18 The Horn Driver	645
18.1 Initial Efficiency	645
18.1.1 Conversion efficiency	646
18.1.2 Nominal efficiency	647
18.1.3 Reference Power Available Efficiency	647
18.1.4 Sensitivity	648
18.1.5 Rear Side Losses	648
18.2 Corner Frequencies	649
18.3 Efficiency-Bandwidth Trade-offs	650
18.3.1 Overall Efficiency	651
18.3.2 EBP and Coil Properties	651
18.4 Compression Drivers	652
18.4.1 Types of Compression Drivers	652
18.4.2 Lumped Parameter Model	653
18.4.3 Driver Impedances	654
18.4.4 Performance Analysis	654
18.4.5 Leaks and Cavity Resonances	657
18.4.6 Diaphragms	658
18.4.7 Diaphragm Geometries	659
18.4.8 Breakup Modes	660
18.4.9 Suspension	662
18.4.10 The Phase Plug	665
18.4.11 High-Frequency Performance	669
18.4.12 Phase Plug Analysis	669
18.4.13 Phase Plug Channels	680
18.5 High-Frequency Units	681
18.6 The Gramophone Soundbox – a Purely Mechanical Compression Driver	682
18.6.1 Classical Method	684

18.6.2	Modern Filter Method	685
18.6.3	Discussion	685
18.7	Nonlinear Distortion Particular to Horn Drivers	686
18.7.1	Adiabatic Compression	686
18.7.2	Front Chamber Volume Modulation	686
18.7.3	Distortion due to Nonlinear Acoustic Load	687
18.7.4	Distortion due to Other Mechanisms	687
18.7.5	Distortion Levels	688
18.7.6	Reducing Nonlinear Distortion	688
18.8	Summary	689
19	Horn Loudspeaker Combinations	695
19.1	Front-Loaded Horns	695
19.1.1	Analysis, Mid-Frequency Range	695
19.1.2	Impedance Matching Factor	696
19.1.3	Analysis, High-Frequency Range	697
19.1.4	High-Frequency Range with Inductance Included	698
19.1.5	Analysis, Low-Frequency Range	699
19.1.6	The Electrical Impedance	703
19.1.7	Choosing S_d/S_t Ratio	704
19.1.8	Finite Horns	705
19.1.9	Large-Signal Analysis	705
19.1.10	Parameter Sensitivity	707
19.1.11	System Design	707
19.1.12	System Design With Driver	707
19.1.13	System Design from Specifications, General	710
19.2	Horns with Vented Rear Chamber	711
19.3	Rear Loaded Horns	712
19.4	Compound Horns	715
19.5	Quarter Wave Horns	715
19.6	Tapped Horns	716
19.6.1	Simple Tapped Horn	716
19.6.2	General Tapped Horn	718
19.6.3	Tapped Horn Performance	719
19.7	Multiple Entry Horn Loudspeakers	721
19.8	Summary	722
20	Overview of Horn Simulation Methods	729
20.1	Analysis Approaches	729
20.2	Analytical Methods	729
20.2.1	The Horn Equation	730
20.2.2	Three-Dimensional Solutions	730
20.3	General Numerical Models	730
20.3.1	Lumped Parameter Models	731
20.3.2	The Finite Difference Method	731
20.3.3	The Finite Element Method	732
20.3.4	The Boundary Element Method	733
20.3.5	The Boundary Element Rayleigh Integral Method	735
20.3.6	Fast Multipole BEM	735
20.3.7	Other Methods	736
20.3.8	Numerical Efficiency	737
20.4	Semi-Analytical Models	738
20.4.1	Transmission Line Elements	738
20.4.2	Advanced One-Dimensional Models	739
20.4.3	Mode Matching Methods	739
20.5	Summary	741
21	One-Dimensional Horn Modeling	747
21.1	Transmission Matrix Method	747

21.1.1	Using the T_{12} Matrices	748
21.1.2	Using the T_{21} Matrices	748
21.1.3	Wave Front Areas	748
21.1.4	Isophase Model 1 (IP1)	749
21.1.5	Isophase Model 2 (IP2)	750
21.2	Radiation Impedance	750
21.2.1	Infinite Baffle	751
21.2.2	4π Space	752
21.2.3	Fractional Space	753
21.3	Examples	753
21.3.1	Infinite Baffle	753
21.3.2	4π Space	753
21.4	Directivity Models	755
21.5	Folded Horns	756
21.6	Distortion	757
21.7	Summary	757
22	The Mode-Matching Method	761
22.1	Basic Principles	761
22.2	Mode Functions	762
22.2.1	Cylindrical Geometry	762
22.2.2	Annular Geometry	763
22.2.3	Rectangular, Quarter Symmetric Geometry	764
22.2.4	Rectangular, Asymmetric Geometry	764
22.3	Propagation Along a Uniform Duct – General	764
22.4	Propagation Across a Discontinuity – General	765
22.5	F -Matrices	766
22.5.1	Cylindrical Geometry	766
22.5.2	Annular Cylindrical Geometry	766
22.5.3	Rectangular, Quarter Symmetric Geometry	768
22.5.4	Rectangular, Asymmetric Geometry	769
22.5.5	Complex Discontinuities	769
22.6	Radiation and Radiation Impedance	770
22.6.1	Aspect Ratio Transformation	770
22.6.2	Mutual Radiation Impedance	771
22.6.3	Radiated pressure	772
22.7	Summary of the Mode Matching Method	772
22.7.1	Practical Notes	773
22.8	An Alternative Formulation	773
22.9	Curved Horns	773
22.10	The Mode-Matching Boundary Element Method (MMBEM)	775
22.10.1	BEM as Load	775
22.10.2	MMM as Load	776
22.10.3	MMBEM	777
22.11	Accuracy of the MMM	777
22.12	Summary	779
23	Horn Loudspeaker Modeling	783
23.1	The Driver	783
23.1.1	Parasitic Elements	783
23.2	Combining Driver and Horn	784
23.3	Box Models	785
23.3.1	Lumped Parameter Models	785
23.3.2	Lined Box	786
23.3.3	Vented Rear Chamber	787
23.4	Front Chamber	787
23.5	Power Response and Efficiency	788
23.6	Sound Radiation	788

III Design	791
24 System Considerations	793
24.1 Nature of Musical Sounds	793
24.2 The Auditory System	794
24.3 Psychoacoustics	795
24.3.1 Masking and Critical Bands	796
24.3.2 Pitch and Loudness	798
24.3.3 Phase and Polarity	799
24.3.4 Just-Noticeable Differences	800
24.3.5 Distortion	800
24.3.6 Distance and Proximity	800
24.3.7 Spatial Hearing	801
24.4 Required Frequency Range	801
24.5 Required Dynamic Range	802
24.6 Distortion	804
24.6.1 Linear Distortion	805
24.6.2 Nonlinear Distortion	811
24.6.3 Dynamics Distortion	812
24.7 Reproduction of Transients	813
24.7.1 Impulse Response	813
24.7.2 Envelope Transient Response	814
24.7.3 Bass Transient Response and “Fast” Bass	814
24.7.4 Krokstad’s “Music Transmission Index”	815
24.8 Room Acoustics	815
24.8.1 Statistical Room Acoustics	815
24.8.2 Reflections and their Perception	816
24.8.3 The Modal Region	816
24.9 Mono, Stereo and Multi-Channel	818
24.9.1 How Stereo Works	818
24.9.2 Stereo Shortcomings	819
24.9.3 Mono versus Stereo	820
24.9.4 Is Multichannel Important?	820
24.10 Directivity	821
24.10.1 Control of First Reflections	821
24.10.2 Image Stabilization	822
24.11 The Difficult Midrange	822
24.11.1 Defining the midrange	823
24.11.2 Energy Distribution	823
24.11.3 Harmonic Phase Coherence	823
24.11.4 Linear Phase – Is it Worth the Trouble?	823
24.11.5 Summary	824
24.12 Design Objectives	824
24.12.1 Efficiency	824
24.12.2 Bandwidth	824
24.12.3 Horn Loading	824
24.12.4 Directivity	825
24.12.5 Nonlinear Distortion	825
24.13 The Design Process	825
24.14 Selection of Topology	826
24.14.1 Full-Range	826
24.14.2 Two-Way	826
24.14.3 Three-Way	827
24.14.4 Sub-Woofers and Super-Tweeters	827
24.14.5 Four-Way and Beyond	827
24.14.6 Partly Horn-Loaded Systems	827
24.15 Summary	828
25 Practical Horn Design: Straight Horns	833

25.1	Mouth Geometry and Termination	833
25.2	Mouth Diffraction	833
25.3	Choice of Expansion	834
25.4	Wave Front Expansion Correction	835
25.4.1	The Western Electric Method	835
25.4.2	The Tractrix Horn	836
25.4.3	The Wilson Method	837
25.4.4	Spherical Wave Horn	839
25.4.5	Isophase Wave Fronts	840
25.4.6	The Le Cléac'h Method	841
25.4.7	Comparisons	842
25.4.8	Iwata Horns	843
25.4.9	Non-Axisymmetric Le Cléac'h Horn	845
25.5	Horns for Directivity Control	845
25.5.1	Multicell Horns	846
25.5.2	Sectoral Horns	847
25.5.3	Conical-Exponential Horns	848
25.5.4	Manta-Ray Horns	849
25.5.5	Bi-Radial Horns	849
25.5.6	Variable Dispersion Bi-Radial Horn	850
25.5.7	Waveguides	852
25.6	Round to Rectangular	852
25.6.1	Round Corners	852
25.6.2	Superellipse	852
25.6.3	Eye-Form	853
25.7	The Horn Wall	854
25.7.1	Wall Vibration	854
25.7.2	Wall Absorption	855
25.7.3	Leaks	856
25.8	Construction Methods	857
25.8.1	Solid Wood	857
25.8.2	Plywood	857
25.8.3	Sheet Metal	861
25.8.4	Casting	862
25.8.5	Other Methods	863
25.9	Summary	863
26	Practical Horn Design: Folding and Curving	867
26.1	Bend Behavior	868
26.2	Types of Bends	868
26.3	Bend Acoustic Length	869
26.4	Folding	869
26.4.1	Example Reference Horn	872
26.4.2	180° Folds	872
26.4.3	90° Folds	873
26.4.4	W-Fold	873
26.5	Corner Horns	873
26.6	Curved Horns	876
26.7	Curving Methods	876
26.7.1	Constant Radius	877
26.7.2	Constant Ratio - Voigt's Method	878
26.7.3	The Cord	879
26.7.4	Other Methods	879
26.7.5	Wilson's Method	879
26.7.6	Examples	880
26.8	Bifurcation	883
26.8.1	Bifurcation Examples	884

26.8.2	Path Equalization	885
26.9	Summary	886
27 Practical Horn Drivers		889
27.1	Compression Driver Paradigms	889
27.2	W.E. 555W	890
27.2.1	Diaphragm and Suspension	891
27.2.2	Damping of the 555 Diaphragm	892
27.2.3	Voice Coil	892
27.2.4	Magnetic Structure and Proposed Improvements	895
27.2.5	Proposed Improvements: Low-Frequency Response	897
27.2.6	Proposed Improvements: High Frequency Response	901
27.3	Fletcher HF Unit and W.E. 594A	901
27.3.1	Electromechanical Constants	902
27.3.2	Diaphragm Assembly and Phase Plug	902
27.3.3	Magnetic Structure and Gap	903
27.4	LF driver for the Fletcher System	903
27.5	RCA MI-1428	907
27.6	TAD Compression Drivers	911
27.7	Community M4	911
27.8	BMS Coaxial Drivers	912
27.9	JBL Dual Diaphragm Drivers	913
27.10	Celestion Axiperiodic Drivers	914
27.11	Selecting a Compression Driver	915
28 Low-Frequency Horn Speaker Design		921
28.1	Bass Horn Driver Selection	921
28.1.1	Small Signal Metrics	921
28.1.2	Large Signal Metrics	922
28.1.3	Using the Metrics	923
28.2	Bass Horn Design	923
28.2.1	Choice of Solid Angle and Mouth Size	927
28.2.2	Methods to Reduce Size	928
28.2.3	Worked Example	928
28.3	Midbass Horns	931
28.3.1	Worked Example	931
28.4	Horn Sub-Woofers	932
28.4.1	Worked Example	932
28.5	Horns in Rooms	933
28.5.1	Examples	933
28.5.2	Closed Box Reference	934
28.5.3	Large Horn	934
28.5.4	Smaller Horn	935
28.5.5	Multiple Direct Radiators	935
28.5.6	Impedances	935
28.5.7	Discussion	936
28.6	Summary	936
29 Crossovers and System Integration		941
29.1	Crossovers	941
29.2	Active and Passive Systems	941
29.3	Crossover Objectives	942
29.4	Crossover Types	943
29.4.1	All-pass Crossovers	943
29.4.2	Phase Linear Crossovers	944
29.5	Crossover Performance	945
29.5.1	Polar Responses	945
29.6	Horn Challenges	945
29.7	Amplifier Interface	949

29.7.1	Current Feedback Methods	950
29.7.2	Current Drive	951
29.7.3	Current Feedback Performance	952
29.7.4	Loudspeaker Cables	952
29.8	System Integration	954
29.8.1	Time Alignment	954
29.8.2	Time Alignment Methods	956
29.8.3	Know What You are Phasing	956
29.9	Summary	957
30 Measurements		963
30.1	Impulse response	963
30.2	Frequency Response	964
30.3	Power Response	964
30.4	Directivity	965
30.5	Plane Wave Tube Measurements	965
30.5.1	Low-Frequency Limitations	967
30.5.2	Microphone Placement	967
30.6	Distortion	968
30.7	Acoustic Impedance	968
30.7.1	Standing Wave Tube	969
30.7.2	Two-Microphone Method	969
30.7.3	Single Microphone Method	971
30.7.4	Velocity Probe Method	972
30.7.5	Impedance Bridge Method	972
30.8	Driver T-Matrix	972
30.9	Flux Measurement	974
30.9.1	Gap Flux	974
30.9.2	BH-Curve	974
30.10	Summary	975
IV Appendix		979
A Harrison's Patent 1,730,425		981
B Useful Formulae		1003
B.1	Complex Numbers	1003
B.1.1	Basic Operations	1003
B.1.2	Trigonometric Functions	1003
B.1.3	Logarithms and Powers	1004
B.2	Matrices	1004
B.2.1	Basic Operations	1004
B.2.2	2×2 Matrices	1004
B.3	Thiele-Small Parameter Conversion	1005
B.3.1	Conversion from Electromechanical to T/S-Parameters	1005
B.3.2	Conversion from T/S to Electromechanical Parameters	1005
B.4	Horn Transmission Matrix Coefficients	1005
B.4.1	Uniform Pipe and Conical Horn	1005
B.4.2	Exponential Horn	1006
B.4.3	Hyperbolic-Exponential Horn	1006
B.4.4	Bessel Horn	1006
B.4.5	90° Bend	1007
B.5	Room Modal Impedance Expressions	1007
C Western Electric Manufacturing Information		1011
C.1	Apparatus Specifications	1011
C.1.1	"M" Specifications	1011
C.1.2	"D" Specifications	1011

C.1.3	"KS" Apparatus Specifications	1011
C.1.4	"KS" Conversion Specifications	1011
C.1.5	"KS" Repair Specifications	1011
C.1.6	"KS" Testing Specifications	1011
C.1.7	"ES" Drawings – Principal Purposes	1011
C.2	Varnish	1012
D	Service of the 555W Receiver	1015
D.1	Structure and Maintenance of Sound-Picture Speakers by Jesse A. Cook	1015
D.1.1	Retaining Plate Pressure	1015
D.1.2	Simple Checking Aids	1016
D.1.3	Replacement of Diaphragms	1017
D.1.4	Polarity, Poling and Phasing	1017
E	Glossary	1019