Contents

DEFINITIONS 1

1 INTRODUCTION 9
1.1 Aim of this book 9
1.2 Application area of electron tubes 10
1.3 Audio amplifiers versus instrumental amplifiers 10
1.4 Short history 11
1.5 Coding of electron tubes 13
1.6 Bibliography for chapter 1 13

2 PRINCIPLES OF ELECTRON EMISSION 14
2.1 Types of electron emission 14
2.2 Space charge 15
2.3 Emission efficiency 16
2.4 Bibliography for chapter 2 17

3 DIODE 18
3.1 The construction of diodes with directly and indirectly heated cathodes 18
3.2 Operation of diodes 19
3.3 Types of diodes and their application 20
3.4 Measuring of diode characteristics 21
3.5 Application of the diode as rectifier 31
3.5.1 Half-wave rectifier with buffer capacitor 31
3.5.2 Full-wave rectifier with buffer capacitor 33
3.5.3 Matching the diode rectifier with the supply transformer 35
3.5.4 Smoothing filters 40
3.5.4.1 π-filter C-R-C 40
3.5.4.2 π-filter C-L-C 42
3.5.5 Full-wave rectifier without buffer capacitor 46
3.5.6 Measurement of tube rectifier circuits 51
3.5.6.1 The practical test circuit 51
3.5.6.2 Analysis of the ripple voltage and output voltage as a function of the current in relation to the buffer capacitor and full/half-wave rectification 55
3.5.6.3 Analyses of the ripple voltage as function of the values of the π-filter C-R-C 65
3.5.6.4 Analyses of the ripple voltage as a function of the values of the π-filter C-L-C 68
3.5.6.5 Analyses of the ripple voltage and output voltage as a function of the values of the full-wave tube rectifier circuit without buffer capacitor 70
3.5.6.6 Measurement of some rectifier circuits 73
3.6 Heater and negative bias supplies 80
3.7 Practical advice 85
3.8 Bibliography for chapter 3 88

4 TRIODES 89
4.1 The construction of triodes with directly and indirectly heated cathodes 89
4.2 Operation of triodes 90
4.3 Static triode characteristics and triode quantities 98
4.3.1 Static triode characteristics 98
4.3.2 Anode static steepness 99
4.3.3 Anode amplification factor 100

4.3.4 Anode AC internal resistance 102
4.3.5 Control grid base 104
4.3.6 Barkhausen formula 104
4.3.7 Triode quantities versus anode current 105
4.3.8 Dissipation and power 108
4.3.9 Measured static triode characteristics for the electron tubes ECC81, ECC82 and ECC83 108
4.3.10 Calculated examples of static triode quantities 114
4.4 Dynamic triode characteristics with anode resistor 120
4.4.1 The theory of the dynamic triode characteristics with anode resistor 120
4.4.2 The practice of the dynamic triode characteristics with anode resistor 132
4.5 Observations on heater supplies for triodes 136
4.5.1 Heater supply observed for directly heated triodes 137
4.5.2 Heater supply observed for indirectly heated triodes 139
4.6 Low frequency amplification with resistor coupling 142
4.6.1 Automatic negative bias voltage 142
4.6.2 Control grid current 145
4.7 The theory and practice of the basic triode circuits 148
4.7.1 The theory of the basic cathode circuit 148
4.7.2 The theory of the basic anode circuit or cathode follower 150
4.7.3 The theory of the basic negative feedback circuit 152
4.7.4 The theory of the basic control grid circuit 159
4.7.5 The theory of the basic cascode circuit 162
4.7.6 The theory of the basic Series Regulated Push Pull circuit 165
4.7.7 Summary of basic triode circuits 168
4.7.8 The practice of basic triode circuits 170
4.8 Phase shifter circuits in both theory and practice 186
4.8.1 The transformer phase shifter 186
4.8.2 The cathodedyne phase shifter 188
4.8.3 The cascade phase shifter 195
4.8.4 The differential amplifier phase shifter 196
4.8.5 The inverting stage phase shifter 202
4.8.6 The self-adjusting phase shifter 204
4.8.7 Summary of the phase shifters 206
4.9 The driver stages in both theory and practice 207
4.9.1 The cathode follower driver stage 207
4.9.2 The differential amplifier driver stage 209
4.9.3 The Series Regulated Push Pull driver stage 212
4.10 The triode power amplifiers 216
4.10.1 Classifications of triode power amplifiers 216
4.10.1.1 Classification of triode power amplifiers by classes 216
4.10.1.2 Classification of triode power amplifiers by negative bias voltage 217
4.10.1.3 Classification of triode power amplifiers by control grid current 218
4.10.1.4 Classification of triode power amplifiers by single ended and push pull 219
4.10.2 Output transformers for the audio frequency range 221
4.10.3 Loudspeaker impedance and damping factor 225
4.10.4 Resistive and inductive load lines 230
4.10.5 The theory of single ended triode power amplifiers 234
4.10.5.1 Probable maximum delivered power and probable efficiency 235
4.10.5.2 Powers and efficiency as functions of the control grid cathode AC voltage 241
4.10.5.3 Parallel operation of power triodes 244
4.10.5.4 Real maximum delivered power and real efficiency 246
4.10.6 The practice of single ended triode power amplifiers 259

4.10.6.1 Real maximum power and efficiency as functions of r_a/r_i for fixed control grid cathode AC voltage ... 262
4.10.6.2 Real maximum power and efficiency as functions of r_a/r_i for variable control grid cathode AC voltage ... 264
4.10.6.3 Measured power and measured efficiency as functions of the control grid cathode AC voltage ... 266
4.10.6.4 Power balance and efficiency at maximum delivered power ... 268
4.10.6.5 Measured resistive and inductive load lines ... 270
4.10.6.6 Design examples of single ended triode power amplifiers ... 272
4.10.7 The theory of push pull triode power amplifiers ... 280
4.10.7.1 The B.J. Thompson method ... 281
4.10.7.2 Push pull class A triode power amplifiers ... 285
4.10.7.3 Push pull class B triode power amplifiers ... 286
4.10.7.4 Push pull class AB triode power amplifiers ... 296
4.10.7.5 Advanced topics of triode power amplifiers which are difficult ... 298
4.10.8 The practice of push pull triode power amplifiers ... 303
4.10.8.1 Application of the B.J. Thompson method for classes A, B and AB ... 306
4.10.8.2 Measured powers and efficiency as functions of the control grid cathode AC voltage for classes A, B and AB ... 319
4.10.8.3 Power balance and efficiency at maximum delivered power for classes A, AB and B ... 325
4.10.8.4 Design examples of push pull triode power amplifiers ... 329
4.10.9 Summary of triode power amplifiers ... 339
4.10.10 Other power triodes ... 341
4.11 Bibliography for chapter 4 ... 344

5 TETRODE ... 345
5.1 The construction of tetrodes ... 345
5.2 Why the tetrode was developed ... 346
5.3 Operation of tetrodes ... 346
5.4 Beam Power tetrode ... 350
5.5 Circuits and calculations applied to tetrodes ... 353
5.6 Bibliography for chapter 5 ... 354

6 PENTODE ... 355
6.1 Introduction ... 355
6.2 The construction of pentodes ... 356
6.3 Operation of pentodes ... 358
6.4 Static pentode characteristics and pentode quantities ... 364
6.4.1 Static pentode characteristics ... 364
6.4.2 Anode static steepness ... 365
6.4.3 Anode amplification factor ... 368
6.4.4 Anode AC internal resistance ... 369
6.4.5 Screen grid static steepness ... 371
6.4.6 Screen grid amplification factor ... 372
6.4.7 Screen grid AC internal resistance ... 374
6.4.8 Barkhausen formulae ... 376
6.4.9 Control grid bases ... 377
6.4.10 Pentode quantities versus anode current ... 379
6.4.11 Dissipation and power at the anode and screen grid ... 385
6.4.12 Measured static pentode characteristics of the EF86 electron tube ... 387
6.4.13 Calculation examples of static pentode quantities ... 395
6.5 Dynamic pentode characteristics with anode external resistor ... 402

6.5.1 The theory of the dynamic pentode quantities with anode external resistor 402
6.5.2 Additional draft of the theory of the dynamic pentode 414
6.5.3 The practice of the dynamic pentode quantities with anode external resistor 420
6.6 First interim comparison between triodes and pentodes 428
6.7 Low frequency amplification with resistor coupling 430
6.7.1 Realization of the screen grid cathode DC voltage 430
6.7.2 The basic cathode circuit with automatic negative bias DC voltage in theory and practice 433
6.8 The MU-stage 442
6.8.1 The theory of the MU-stage 442
6.8.2 A practical example of the MU-stage 444
6.9 Pentode power amplifiers 452
6.9.1 The theory of single ended pentode power amplifiers 452
6.9.1.1 Probable maximum delivered anode power and probable anode efficiency 453
6.9.1.2 Powers and efficiency as functions of the control grid cathode AC voltage 460
6.9.1.3 Real maximum delivered power and real efficiency 462
6.9.2 The practice of single ended pentode power amplifiers 466
6.9.2.1 Real maximum power and anode efficiency as function of r_a/R_i 468
6.9.2.2 Measured power and efficiency as functions of the control grid cathode AC voltage 470
6.9.2.3 Power balance and efficiency at maximum delivered power 472
6.9.2.4 Design examples of single ended pentode power amplifiers 475
6.9.3 Second interim comparison between triodes and pentodes 480
6.9.4 The theory of push pull pentode power amplifiers 481
6.9.4.1 Push pull class A pentode power amplifiers 484
6.9.4.2 Push pull class B pentode power amplifiers 484
6.9.4.3 Push pull class AB pentode power amplifiers 495
6.9.4.4 Advanced topics of pentode power amplifiers which are difficult 496
6.9.5 The practice of push pull pentode power amplifiers 500
6.9.5.1 Design examples of a push pull pentode power amplifier 503
6.9.5.2 Real powers and efficiency as functions of control grid cathode AC voltage for classes A, B and AB 511
6.9.5.3 Power balance and efficiency with maximum delivered power for classes A, B and AB 518
6.9.6 Third interim comparison between triodes and pentodes 523
6.10 The ultra-linear power amplifier 525
6.10.1 The theory of ultra-linear power amplifiers 525
6.10.1.1 An adventure between triode and pentode 525
6.10.1.2 Powers and efficiency of ultra-linear power amplifiers 531
6.10.1.3 A network analysis of the ultra-linear power amplifier 534
6.10.2 The practice of ultra-linear power amplifiers 545
6.10.2.1 Determination of the screen grid primary transformer tap *x* 545
6.10.2.2 The anode amplification and the AC output impedance as a function of the screen grid primary transformer tap *x* 551
6.10.2.3 Practical comparison of a triode, an ultra-linear and a pentode power amplifier 557
6.10.2.4 The contributions of anode AC current and screen grid AC current to ultra-linear power 560
6.11 Summary of the pentode and the ultra-linear power amplifier 562
6.12 Bibliography for chapter 6 563

7 FREQUENCY DEPENDENT BEHAVIOUR 564
7.1 Definition and concepts 564
7.2 Frequency dependent behaviour of the amplifier components 575
7.2.1 Frequency dependent behaviour of the output transformer 575
7.2.2 Frequency dependent behaviour of the passive components 580
7.2.3 Frequency dependent behaviour of the triode 586

7.2.4 Frequency dependent behaviour of the pentode ... 595
7.3 Amplification at low frequency signals ... 598
7.4 Amplification at high frequency signals ... 609
7.5 Amplification of low and high frequency signals ... 620
7.6 The practice of frequency dependent behaviour ... 632
7.6.1 Measurement of frequency characteristics ... 632
7.6.2 Checking a practical situation ... 637
7.7 Afterthought ... 649
7.8 Bibliography for chapter 7 ... 652

8 NON-LINEAR DISTORTION AND NOISE ... 653
8.1 The sound from electron tube amplifiers ... 653
8.2 Non-linear distortion already discussed ... 654
8.3 Harmonic analysis ... 656
8.4 Applied harmonic analysis ... 658
8.4.1 Harmonic analysis of the output transformer ... 658
8.4.2 Harmonic analysis of electron tubes ... 659
8.4.2.1 The curvature of the anode steepness characteristics ... 659
8.4.2.2 The algebraic determination of the coefficients of the power series ... 666
8.4.2.3 The graphical determination of the second and third harmonics ... 672
8.4.2.4 InterModulation Distortion IMD ... 681
8.4.3 Harmonic analysis of passive components ... 683
8.5 Prevention of non-linear distortion without feedback ... 685
8.5.1 The anode resistor against non-linear distortion ... 685
8.5.2 The push pull power amplifier against non-linear distortion ... 686
8.6 The practice of non-linear distortion ... 688
8.6.1 The spectrum analyzer, the pure signal source and the measurement in cascade ... 688
8.6.2 Non-linear distortion of passive components ... 692
8.6.3 Determination of the coefficients of the power series of the second and third harmonic ... 694
8.6.4 The impact of the anode resistor on non-linear distortion ... 700
8.6.5 The basic cathode circuit versus the basic SRPP circuit versus the MU-stage circuit ... 702
8.6.6 The basic cascode circuit versus the basic pentode circuit ... 705
8.6.7 Measured non-linear distortion of some known electron tube amplifiers ... 707
8.7 Afterthoughts on non-linear distortion ... 712
8.8 Noise ... 713
8.8.1 Thermal noise ... 713
8.8.2 Noise in electron tubes ... 715
8.8.3 Signal to noise ratio and noise factor ... 717
8.8.4 A little more about the practice of noise ... 718
8.9 Bibliography for chapter 8 ... 721

9 NEGATIVE FEEDBACK ... 722
9.1 Types of negative feedback ... 722
9.1.1 Negative parallel-serial feedback ... 722
9.1.2 Negative serial-serial feedback ... 723
9.1.3 Negative parallel-parallel feedback ... 724
9.1.4 Negative serial-parallel feedback ... 724
9.1.5 Negative voltage feedback ... 725
9.1.6 Negative current feedback ... 725
9.1.7 First summary of negative feedback ... 726
9.2 The impact of negative feedback ... 727
9.3 The impact of negative feedback on gain and input and output impedances ... 730

9.3.1 Calculations for negative parallel-series feedback ... 730
9.3.2 Calculations for negative serial-serial feedback ... 732
9.3.3 Calculations for negative parallel-parallel feedback ... 733
9.3.4 Calculations for negative serial-parallel feedback ... 735
9.3.5 Second summary of negative feedback ... 737
9.4 Calculations for application examples ... 738
9.5 The impact of negative feedback on disturbances and noise ... 752
9.6 The impact of negative feedback on the frequency characteristics ... 754
9.6.1 The impact of negative feedback at lower frequencies ... 754
9.6.2 The impact of negative feedback at higher frequencies ... 755
9.6.3 The impact of negative feedback at lower and higher frequencies ... 757
9.6.4 The impact of negative feedback on a cascade of amplifier stages ... 758
9.6.5 Frequency independent and frequency dependent negative feedback parts ... 762
9.6.6 Discussion of the emergence of a new theory for negative feedback ... 763
9.6.7 Stability and the Nyquist diagram ... 770
9.7 Negative feedback between power tubes and the output transformer ... 772
9.8 The impact of negative feedback on the quantities of the sound ... 774
9.9 The practice of negative feedback ... 774
9.9.1 The practical test circuits ... 774
9.9.2 Negative-feedback amplification as a function of the negative-feedback voltage ratio ... 778
9.9.3 The crossover points as a function of the negative-feedback voltage ratio ... 781
9.9.4 Harmonic distortion visually observed as a function of the negative-feedback voltage ratio ... 782
9.9.5 The harmonics as a function of the output power versus negative-feedback voltage ratio ... 783
9.9.6 Total Harmonic Distortion as a function of negative-feedback voltage ratio mathematically ... 786
9.9.7 The reduction of the crossover distortion for class B push pull amplifiers ... 787
9.10 Bibliography for chapter 9 ... 789

10 THE CONSTRUCTION OF ELECTRON TUBE AMPLIFIERS ... 790
10.1 Introduction ... 790
10.2 Electronic components ... 790
10.3 Connection and assembly materials ... 792
10.4 Electrical construction methods ... 796
10.4.1 Construction on tagboards ... 796
10.4.2 Construction ‘in the air’ ... 799
10.4.3 Construction on breadboard print ... 801
10.4.4 Construction on printed circuit board ... 804
10.5 Experimental set-ups ... 805
10.6 Electro Magnetic Compatibility EMC ... 807
10.6.1 Crosstalk ... 807
10.6.2 Supply distribution ... 811
10.6.3 Grounding ... 812
10.6.4 Shielding ... 812
10.7 Safety ... 813
10.8 Cooling ... 814
10.9 Vendors for components and sources of knowledge ... 815
10.10 Design strategies ... 816
10.11 Bibliography for chapter 10 ... 818

INDEX ... 819