Scherer Marc
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INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3, avenue Circulaire, UCCLE - BRUXELLES 18

AERONOMICA ACTA

A - N° 33 - 1964

Low and very low level DC amplifiers (Part V) Literature and references

by P. VILLE

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3, Ringlaan, UKKEL - BRUSSEL 18

FOREWORD

In Ref.[61] it is stated that "The ability to process these low level d-c voltages to a range suitable for transmission is one of the major problems of modern telemetry".

This text is an attempt to bring together in a clear and orderly manner the basic information about the theory and the design of low level and very low level d-c amplifiers. Two such d-c amplifiers were built and their performance is discussed.

The text is subdivided into five parts :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.

V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Part I and II deal with the basic theory of d-c amplifiers proper. The types of modulators and demodulators used in modulated d-c amplifiers are discussed in Part III. In Part IV we take up the design of a d-c amplifier with characteristics (performance, weight, size, power requirements,...) suitable for space applications. Finally Part V contains the abstracted references to which we refer in the text.

M. Nicolet.

AVANT-PROPOS

Dans la référence[61], on note que : "La possibilité d'adapter ces basses tensions continues à un domaine adéquat pour la transmission est un des principaux problèmes de la télémesure moderne".

Ce texte est un essai pour rassembler, sous une forme claire et ordonnée, les informations fondamentales concernant la théorie et l'utilisation des amplificateurs de tensions continues de faibles et de très faibles niveaux.

Le texte est divisé en cinq parties :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

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V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Les deux premières parties se rapportent à la théorie fondamentale des amplificateurs d-c. Les types de modulateurs et de démodulateurs utilisés dans les amplificateurs d-c modulés sont discutés dans la partie III. L'utilisation d'un amplificateur d-c pour les applications spatiales ainsi que les caractéristiques (performance, poids, forme, puissance, exigences,...) sont discutées dans la partie IV. Finalement, la partie V contient les références citées dans le texte ainsi que leurs résumés.

M. Nicolet.

VOORWOORD

In Ref.[61] wordt gezegd dat "Het beheersen van de technieken die nodig zijn om deze zwakke gelijkspanningen om te zetten in signalen die kunnen overgeseind worden één van de grootste problemen is van de moderne telemeting".

Deze tekst is een poging om op een klare en ordelijke wijze de grondgegevens samen te brengen betreffende de theorie en het ontwerpen van gelijkstroomversterkers voor zwakke en zeer zwakke signalen. Twee zulke gelijkstroomversterkers werden gebouwd en hun eigenschappen worden besproken.

De tekst is onderverdeeld in vijf delen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964,

V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Deel I en II behandelen de basistheorie van de eigenlijke gelijkstroomversterker. De types van modulatoren en demodulatoren, die gebruikt worden in gemoduleerde gelijkstroomversterkers, worden besproken in deel III. In deel IV handelen we over het ontwerpen van een gelijkstroomversterker met eigenschappen (gewicht, afmetingen, voedingsvereisten,...) die hem geschikt maken voor ruimtetoepassingen. Deel V eindelijk bevat de referentiën met korte inhoud, naar dewelke we in de tekst verwijzen.

M. Nicolet.

VOORWOORD

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M. Nicolet.

VORWORT

In Referenz[61] steht geschrieben dass : "Die Möglichkeit dieser schwachen d-c Spannungen zu einem Gebiet nützlich für die Übertragung zu verwenden, ist eines der wichtigsten Problemen der moderne Fernmessung".

Dieser Text ist ein Versuch, um die Grundinformationen über die Theorie und die Benützung der d-c Verstärker für schwachen und sehr schwachen Spannungen in einer klaren und geordneten Weise vorzustellen.

Der Text besteht aus fünf Teilen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.

V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Die zwei ersten Teile haben Bezug auf die Grundtheorie der d-c Verstärker. Die verschiedenen Modulatoren und Demodulatoren die in modulierten d-c Verstärker gebraucht werden, sind im dritten Teil diskutiert. Die Verwendung eines d-c Verstärker für Raumforschung sowie die technischen Daten (Leistung, Gewicht, Form, Kraft, Anforderung,...) sind im vierten Teil diskutiert. Der fünfte Teil enthält die im Text angegebenen Referenzen sowie die Zusammenfassungen.

M. Nicolet.

CONTENTS OF PART V.

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LOW AND VERY LOW LEVEL DC AMPLIFIERS (PART V)

LITERATURE AND REFERENCES

by

Paul VILLE

Centre National de Recherches de l'Espace,
3, Avenue Circulaire
UCCLE - BRUXELLES 18

This last chapter contains a large number of references which we have used in writing this text. In order, however, to give the reader an idea of what is dealt with in each of them, we give a brief summary of what each of them covers. For convenience the references are classified in chronological order.

It is clear that any reference mentioned in the text corresponds, in number, to the one summarized here.

The references mentioned in this chapter are all directly related to the design of d-c amplifiers, modulators and the like. We have not included, for example, such articles in which it is only mentioned that a d-c amplifier is used in a particular device.

Although we have tried to look up as many of the references as possible, there are a few we have not been able to find because of non-availability. For the sake of completeness, however, we do also mention them though without abstract and in a separate list.

CHRONOLOGICAL LIST AND ABSTRACTS OF REFERENCES

1. "Resistance fluctuations in carbon microphones and other granular resistances".
C.S. Christensen and G.L. Pearson
Bell System Technical Journal, Vol. XV, April 1936, pp. 197-223.

Gives mathematical calculations for noise in carbon microphones and other granular resistances.

2. "Magnetic shielding of transformers at audio frequencies"
W.G. Gustafson
Bell System Technical Journal, 17, p. 416, 1938.
Gives mathematical calculations for efficiency of shielding in magnetic fields. Some experimental data is included.

3. "Sensitive d-c amplifier with a-c operation"
S.E. Miller
Electronics, Vol. 14, N° 27, November 1941, p. 27.
Describes special vacuum-tube d-c amplifier (cathode-control amplifier) which is claimed to have low drift by virtue of a special (cathode-) connection. Also emphasizes the regulation of the power supply.

4. "DC/AC converter, a sensitive method of measuring small d-c voltages"
T.A. Ledward
Wireless World, London, England, Vol. 48, August 1943, pp. 230-233.
Gives first basic principles of magnetic-modulated d-c amplifiers. Gives basic vacuum-tube circuits (simple).

5. "Survey of d-c amplifiers"
M. Artzt
Electronics, Vol. 18, p. 112, August 1945.
Discusses many d-c amplifier circuits, direct-coupled as well as others. Gives causes of drift, etc. in tubes.

6. "Crystal driven modulator for d-c amplifiers"
J.A. Williams
Electronics, pp. 128-129, December 1945.
Describes variable resistance method of modulation of a d-c input signal : use of carbon microphone mechanically connected to a vibrating crystal.

7. " A contact modulated amplifier to replace sensitive suspension galvanometers"
M. Liston, C. Quinn, W. Sargeant and G. Scott

Review of Scientific Instruments, Vol. 17, N° 5, May 1946, p. 194.

Says : The idea of modulating DC to AC in order to amplify it was suggested by R. Gunn [Rev. Sci. Inst. 9, 267 (1938)] and A.W. Sear [Electronics 13, 28 (January, 1940)].

Gives some conditions required of the input modulator of modulated d-c amplifiers. Gives some means to keep the input free from drift caused by : temperature, magnetic fields, special transformer.

8. "Electronically balanced recorder for flight testing and spectroscopy"
A.J. Williams, W.R. Clark and R.E. Tarpley
Transactions of the AIEE, 1946, Vol. 65, p. 205-208.

Measures d-c input voltage by comparison. The slider of a potentiometer is moved until its output gives a voltage equal to the voltage to be measured.

9. "DC amplifiers with automatic zero adjustment and input current compensation"
D.G. Prinz
Journal of Scientific Instruments, December 1947, Vol. 24, N° 12, p. 328-331.

Gives principles of avoiding drift in direct-coupled d-c amplifiers by switching the amplifier so that in a first position it corrects itself for drift and in the second one it measures the input.

10. "DC amplifier stablized for zero and gain"
Williams, Jr., Tarpley and Clark
AIEE Transactions, p. 47, 1948, Vol. 67, Part I

Gives general discussion of modulated d-c amplifiers. Considers zero and gain stability. Is considered a basic text for modulated d-c amplifiers.

11. "The design and limitations of d-c amplifiers"
Harris, E.J. and Bishop, P.O.
Electronics Engineering, 1949, 21, p. 332.

Discusses noise in vacuum tubes as well as temperature-dependence of the tube characteristics and the effect of power supply changes.

Considers all this in function of the d-c amplification functions of vacuum tubes.

12. "An electronic DC/AC converter for use in servo systems"
E.E. John
Proc. of IRE, December, 1949, p. 1474-1478.

Describes special circuit for modulation purposes in servo-systems : May be good for high level application (1 Volt) but certainly not for μV applications.

13. "The fundamental limitations of the second-harmonic type of magnetic modulator as applied to the amplification of small d-c signals"
F.C. Williams and S.W. Noble
Proceedings of IEE, London, Vol. 97, Part II, 1950, pp. 445-459.

Gives a basic and complete treatment of the magnetic second-harmonic type modulator in its use as a modulator for d-c amplifiers. Considers the mathematical analysis as well as the sources of noise. Gives appropriate circuits (block diagrams and others).

14. "A d-c amplifier using an electometer valve"
D.H. Pierson
Electronic Engineering, 1950, 22, p. 48, February.

Gives reasons of drift in direct-coupled d-c amplifiers and means to avoid them. (Cause : supply voltage variations and temperature).

15. "DC amplifier using air-coupled chopper"
Shafer
Electronics, March 1950, p. 104.

Discusses air-coupled choppers as used at the input of modulated d-c amplifiers. The noise level is low. The device is however complicated.

16. "Stabilization of wide-band d-c amplifiers for zero and gain"
Goldberg
RCA Review, p. 296, June 1950.

Describes the Goldberg circuit which automatically stabilizes direct-coupled d-c amplifiers against zero offset voltage and voltage

drift. The high-frequency response characteristics of the amplifier are not altered. Primary application has been in the field of analog electronic computers. Gives clear circuits with short though clear mathematical analysis.

17. "A simple magnetic modulator for conversion of millivolt d-c signals"
G. Wennerberg
Electrical Engineering, February 1951, pp. 144-147.

Discusses use of simple magnetic modulator for d-c amplifiers.

18. "Automatic stabilization of high-impedance d-c amplifier"
F.R. Smith
Electronics, February, 1951, p. 124.

Describes an analog computer d-c amplifier. Counteracts drift by periodical standardization by use of a servomotor which moves a potentiometer contact to adjust the bias of the amplifier input in order to have zero output for zero input.

19. "The automatic compensation of zero-drift errors in direct-coupled feedback systems"
F.A. Summerlin
Proceedings of IEE, Part II, February 1951, Vol. 98, N° 61, p. 59-66.

Gives explanation and mathematical treatment of the so-called Goldberg circuit with some extension. Also mentions the Owen-Prinz compensating circuit.

20. "DC amplifier with reduced zero offset"
McAdam, Tarpley and Williams, Jr.
Electronics, August 1951, p. 128.

Is rather complete for offset and noise. Describes a contact-modulated d-c amplifier and considers a) the choice of the appropriate feedback and b) the sources of zero-offset in the amplifier as well as some means to avoid it. Zero offset : 1μV at 1MΩ input impedance and 10^{-12} Amp.

21. "A sensitive instrument converter, the induction galvanometer"
R.W. Gilbert.
Electrical Engineering, Vol. 70, N° 10, p. 893-898, October 1951.

Discusses use of induction type modulator and some of its advantages. Gives complete discussion of F-M-"amplifier" based on that principle.

22. "Universal Direct-Coupled differential amplifier"
Goldberg.
Electronics, October 1951, p. 128.

Describes differential d-c amplifier to be used as a basic amplifier in analog computers. Some possible connections are given with mathematical treatment.

23 "Ueber die Kubischen Verzerrungen am Ringmodulator"
L. Christiansen.
Frequenz, December 5, 1951, p. 298-303.

Gives basic circuits and some mathematical treatment of ring-modulators. Also discusses non-linearity and how to avoid it.

24. "Ein hochempfindlicher Gleichspannungsverstarker mit hohem Eingangswiderstand"
W. Kroebel.
Zeitschrift für Physik, 1952, 133, p. 30.

Describes chopper of which the moving element is made of a bending piezoelectric crystal which drivesthe contacts. This chopper is described as it is used in a d-c amplifier.

25. "Magnetic modulators"
E.P. Felch, V.E. Legg and F.G. Merrill.
Electronics, February 1952, p. 113-117.

Gives basic description of operation of magnetic modulators (called "magnettor"). Also discusses circuit design, excitation source, output filters and the materials as well as the geometry used for magnetic modulators.

26. "Driftless d-c amplifiers"
Bradley and McCoy.
Electronics, April, 1952, p. 144.

Describes d-c amplifier for analog computer use. The basic circuit is a so-called Goldberg circuit (ref.[16])

27. "High-gain d-c amplifiers"
K. Kandiah and D.E. Brown.
Proc. of IEE, August 1952, Part II, p. 314-326.

Discusses simple d-c amplifiers, amplifiers using reflecting galvanometers, contact-modulated amplifiers, magnetic modulators, direct-coupled amplifiers, capacitance-modulated amplifiers, and the limitations in d-c amplifiers due to noise.

28. "The design of a practical d-c amplifier based on the second harmonic type of magnetic modulator"
S.W. Noble and P.J. Baxandall.
Proc. of IEE, August 1952, Part II, p. 327-344.

Is a sequel to "The fundamental limitations of the second-harmonic.." of ref.[13]. It completely discusses a particular magnetic-modulated d-c amplifier. The discussion is very long and elaborate.

29. "Theory of the vibrating condenser converter and application to contact potential measurement"
J.R. Anderson and A.E. Alexander.
Australian Journal of Applied Science, 3, 3 September 1952, p. 201-209.

Gives thorough mathematical treatment of a modulation method using a vibrating capacitor and applies the theory to the measurement of contact potentials.

30. "Ratio meter measures reflection coefficient"
Rosenthal, Potter and Badbyannis.
Electronics, November 1952, p. 136.

Gives practical modulator circuit for dc/ac conversion.

31. "Transistors in switching circuits"
Anderson.
Proc. of IRE, Vol. 40, November 1952, p. 1541-1558.
Discusses properties and characteristics of point-contact type transistors as switches.

32. "An isolating potential comparator"
T.M. Dauphinee.
Canadian Journal of Physics, 31, p. 577, 1953.
Gives discussion and mathematical treatment of a circuit which compares two small d-c voltages without making any direct electrical connection between them. Gives basic operation principles and also discusses the errors involved.

33. "The study of a magnetic invertor for amplification of low-input-power D. C. signals"
E.H. Frost-Smith.
Proceedings of IEE, London, Vol. 100, Part II, 1953, pp. 362-370.
Gives theory of magnetic modulator : physical discussion and some mathematical treatment. Analysis of gain, time-constant, gain drift, zero drift, factors influencing performance of inverter and practical design-details. Practical circuits for the modulator are given.

34. "Dispositif électronique pour la mesure précise des tensions continues par comparaison"
R. Aumont and Jacques Romand.
Revue Générale de l'Electricité, Avril 1953, pp. 210-216.
Gives operation and mathematical treatment of a special circuit used to measure low-level d-c voltages by comparing them to an attenuated known voltage. The method is a null-detecting one : adjust the known voltage until the output is zero.

35. "A survey of the limits of d-c amplification"
C.M. Verhagen.

Proceedings of the IRE, p. 615, May 1953.

Physical consideration of limits in vacuum tubes : heating, etc. Gives a very sophisticated analysis. Considers the vacuum tube as a unit and studies it thoroughly.

36. "Eine Methode zur Verstärkung von extrem kleinen Thermospannurgen"
W. Kroebel.
Zeitschrift für Angewandte Physik, 1953, 5, p. 286.

Is a continuation of the description and the application of crystal-driven choppers as modulators (ref. [24]). Gives complete d-c amplifier built according to the crystal modulator principle.

37. "A new electronic chopper"
R.A. MacMillan and W.G. Field.
Review of Scientific Instruments, October 1953, p. 984.

Gives basics of photoconductor chopper : circuit and advantages. Uses photoconductor chopper in Goldberg circuit.

38. "Magnetic-converter d-c amplifier"
W. Rote.
Electronics, December 1953, pp. 170-173.

Discusses basic magnetic modulator (construction, operation) and its stability problems (zero stability with changing ambient temperature). Takes also up a discussion of output filters. Gives complete circuit of a magnetic-modulated d-c amplifier.

39. "DC amplifiers-Methods of amplifying and measuring small direct currents and potentials"
J. Yarwood and D.H. Le Croissette.
Electronic Engineering, Vol. 26, p. 14, 1954.

Discusses a vacuum-tube direct-coupled d-c amplifier used with a d-c source of high output impedance. Explains sources of errors introduced and means to avoid them (errors result from grid current).

40. "Universal meter for measuring voltages at high impedances, micromicro-amperes and insulation resistance"

Clark, Watson and Mergner.
Electrical Engineering, p. 41, January 1954.

Describes use of modulated d-c amplifier in universal meter.

41. "High sensitivity d-c breaker amplifier"
Liston.
Electronics, January 1954, p. 206.

Describes one specific modulated d-c amplifier with very many precautions. The results are good, however.

42. "Time-shared amplifier stabilized computers"
Slaughter
Electronics, April 1954, p.188.

Gives basic circuit to correct for drift in analog computer d-c direct-coupled amplifiers. The circuit is nothing but the so-called Goldberg circuit (ref.[16]).

43. "Photoelectric d-c chopper for guided missiles"
J. Schwartz and R. Solomonoff.
Electronics, November 1954, pp. 162-163.

Describes photo-modulated d-c amplifier using neon tube which light-modulates photoconductors. Basic modulator circuit is given.

44. "Special purpose relays gain new uses"
Rockett.
Electronics, February 1955, p. 150.

On p. 155 and following are given methods to measure the noise and dwell time of an electromechanical chopper. Also a couple generalities are discussed. The article describes switches and relays in general.

45. "Transistor choppers for stable d-c amplifiers"
R.L. Bright and A.P. Kruper.
Electronics, April 1955, p. 135.

Gives characteristics of transistor choppers in general. Gives advantages of transistor choppers. Gives switch characteristics of

transistor choppers.

46. "Method of reducing zero error and drift in breaker type d-c amplifiers"
T.M. Dauphinee.
Review of Scientific Instruments, Vol. 26, April 1955, p. 401.

Recommends to use input transformers of special design for modulated d-c amplifiers. Gives, however, three circuits to avoid thermal e.m. f.'s in the input transformer.

47. "Feedback stabilized transistor amplifier"
D.W. Slaughter.
Electronics, May 1955, p. 174.

Describes differential d-c amplifier of which the output is amplified by an ordinary d-c amplifier. The final output is fed back to the second side of the differential input stage. The purpose is to stabilize the gain of the transistor amplifier accurately by inverse feedback to avoid drift from aging or temperature change. Use of silicon transistors gives good working despite high ambiant temperatures.

48. "A new circuit for balancing the characteristics of pairs of valves"
R.E. Aitchison.
Electronic Engineering, Vol. 27, May 1955, p. 224.

Discusses circuit used to artificially match two vacuum tubes by controlling their heater supply currents. The circuit consists of a bridge in the heater supply circuitry.

49. "Low level thermocouple amplifier and temperature regulation system"
T. Dauphinee and S. Woods.
The Review of Scientific Instruments, July 1955, p. 693-695.

Claim that they can measure $10^{-2}\mu V$. Careful shielding is necessary and many precautions have to be taken. Describes vacuum-tube modulated d-c amplifier.

50. "The induction modulator"
A. Muller and G. Stolar.
Jet Propulsion, Guided Missile Issue, September 1955, p. 37S.

Gives basic operation of the induction modulator. Also gives design considerations, and a discussion on linearity, damping, phase shift and balance.

51. "Use choppers for control"
F. Rockett.
Automatic Control, November 1955, p. 22-24.

Says : "most common applications for choppers are feedback control of servomechanisms and d-c amplifiers." Gives practical numerical values for choppers. Discusses basics of a certain modulated d-c amplifier without giving formulae. Also explains the working of choppers in feedback circuits.

52. "Operational amplifier has chopper stabilization"
D. Robinson.
Electronics, September 1956, pp. 182-185.

Describes a particular amplifier based on the Goldberg circuit principle (ref. [16]).

53. "Magnetic shielding with multiple cylindrical shells"
W.G. Wadey.
Review of Scientific Instruments, 27, 11, p. 910, November 1956.

Gives formulae for the effectiveness of multiple over single shields in magnetic fields.

54. "Transistorized low-level chopper circuits"
Richard B. Hurley.
Electronics Industries and Tele-Tech., December 1956, p. 42.

Gives mathematical treatment with equivalent circuits of transistor chopper circuits. Some physical explanation is given also.

55. "Transistor circuits and applications".
J. Carroll.
McGraw-Hill Book Company, Inc., 1957.

Textbook about transistors.

56. "A sensitive superconducting 'chopper' amplifier"
A.R. De Vroomen and C. Van Baarle.
Physics XXIII (The Physica Foundation, Amsterdam), 1957, pp. 785-794.
Describes chopper method using superconducting wiring of which the superconductivity is periodically destroyed by a magnetic field.

57. "Silicon diode chopper stabilized d-c amplifier"
L. Fleming.
Electronics, January 1, 1957, p. 178.
Discusses basics of diode chopper. "Input chopper and a-c amplifier and output phase detector" system is investigated.

58. "Properties of some dc-ac chopper circuits"
I.C. Hutcheon.
Institution Monograph N° 218-R, January 1957.
Proc. of IEE, Part C, Vol. 104, 1957, January, pp. 289-298.
Gives mathematical analysis of five basic chopper circuits for low-level d-c to a-c conversion : 3 are capacitance-coupled and two are transformer-coupled. He derives expressions for gain, input resistance and optimum "stopper" resistance in terms of the component values.

59. "Magnetically keyed, phase-sensitive demodulators"
R.B. Mark, W.X. Johnson and P.R. Johannessen.
AIEE Transactions, March 1957, pp. 1 - 6, Part I.
Describes diode demodulator, magnetic-amplifier demodulator, transistor demodulators which are all switched by a magnetic pulse forming circuit.

60. "A study of the transfer function of contact-modulated amplifiers"
Krantz, Salati and Berkowitz.
Transactions of AIEE, March 1957, Part II, pp. 23-28.
Gives mathematical analysis of modulator circuits (transfer functions).

61. "Low level transistorized chopper amplifier"
H.F. Harris and T.E. Smith.
IRE Trans.Telemetry and Remote Control, Vol. TRC-3, N° 1, paper 3.5, April 1957.

Describes a square-wave source, transistor choppers and a corresponding a-c amplifier circuit for use in missiles and the like. 100 μV sensitivity is claimed. Explains physical working of transistor choppers.

62. "Elimination of a-c beats in an isolating potential comparator circuit"
T.M. Dauphinee.
The Review of Scientific Instruments, Vol. 28, N° 6, June 1957, p. 467.

Describes methods using choppers and capacitors to compare two voltages without making direct electrical connection between them.

63. "Servomodulators"

I : Barber
Control Engineering, August 1957, pp. 65-71.

II : Barber
Control Engineering, October 1957, pp. 96-104.

III : Barber and Klivans
Control Engineering, November 1957, pp. 122-131.

IV : Klivans
Control Engineering, December 1957, pp. 90-94.

Gives basic description of modulators :

I : Where and why they are used. Characteristics of the basic types and references.

II : Electromechanical, electronic, and semiconductor-diode units.

III : Semiconductor modulators, magnetic modulators, and tabulated characteristics of commercial units and 84 classified references.

IV : Seven lab-built circuits and their test-obtained characteristics.

64. "A transistor d-c chopper amplifier"
Burton.
Electronic Engineering, August 1957, pp. 393-397.

Gives description of the transistor as a chopper (and a couple chopper circuits) and describes a transistorized d-c amplifier using transistor choppers. Introduces new curves of residual collector-emitter voltage vs. base current for switching transistors.

65. "Drift-corrected d-c amplifier"
M.H. McFadden.
Electronic and Radio Engineer, October 1957, Vol. 34, N° 10, pp.358-364.

Gives discussion of the Goldberg correcting circuit. Gives explanation of need for drift compensation and then explains the Goldberg circuit in simple though clear mathematics. Also an alternative circuit, using feedback is briefly though clearly discussed. Also mentions Owen-Prinz compensating circuit.

66. " A transistor high-gain chopper type d-c amplifier"
G.B. Chaplin, A.R. Owens.
Proc. IEE, Part B 105, 1958, p. 258-266.

Gives complete treatment of transistorized d-c amplifiers using transistor choppers. Discusses the input chopper (operation and temperature effects), the d-c amplifier (basic amplifier, use of negative feedback, high-gain amplifier, frequency response, output stage), the output chopper (operation transient effects, connections) and the chopping-waveform generator. Also stability and performance of the overall amplifier are considered. Plenty of circuits are given.

67. "Direct-coupled amplifiers"
D.S. Martin.
Electronic and Radio Engineer, December 1957, p. 438.

Gives a method to improve the working of direct-coupled d-c amplifiers by matching the effects of heater-supply variations in the tube or tubes of the first stage.

68. "The contact modulator" (8 booklets)
Airpax Electronics, Inc. (1958)

Part 1 : Why use choppers.

Part 2 : Definitions and Measurements.

Part 3 : Modulation methods.

Part 4 : Application and performance.

Part 5 : Noise in chopper circuits.

Part 6 : Chopper amplifier design.

Part 7 : Use of choppers in systems.

Part 8 : Literature and history of choppers and references.

Gives complete discussion of electromechanical (contact-modulated) choppers.

69. "Some transistor input stages for high gain d-c amplifiers"
G.B. Chaplin, A.R. Owens.
IEE, London, England, Vol. 105, Part B, 1958, p. 249

Considers :

a) direct-coupled transistorized d-c amplifiers and drift and its compensation.

b) modulated d-c amplifiers.

Takes up a very extensive discussion of the transistor as a modulator, the associated errors and some means to compensate for them.

70. "Transistor physics and circuits"
R.L. Riddle and M.P. Ristenbatt.
Prentice-Hall, Inc., New York, N.Y., 1958.

Textbook about transistor theory and circuits.

71. "New types of d-c amplifiers
Part I : The cascade-balance system.
Part II : The reflex-monitor system"
D.R. Martin.
Electronic and Radio Engineer, 1958.
Part I : January, p. 2
Part II : February, p. 56

Gives two modifications of the basic Owen-Prinz circuit.

Part I : Briefly describes Owen-Prinz method of drift correction.

Then gives application of this method in a d-c amplifier and gives means to overcome the disadvantage of the method.

Part II : Applies principles of Part I to a direct-coupled differential d-c amplifier of the type using overall drift-correction. "Auxiliary" amplifier stage corrects alternatively its own drift (reflex) and the one of the "main" amplifier stage (monitor).

72. "Noise in Junction Transistors"
A. Van der Ziel.
Proc. IRE 46, pp. 1019-1039, June 1958.

Gives a survey of the problems of shot noise and flicker noise in junction diodes and junction transistors. Discusses different theories of noise.

73. "Voltage feedback and thermal resistance in junction transistors"
J.J. Sparkes.
Proc. IRE, correspondence, Vol. 46, pp. 1305-1306, June 1958.

Gives some explanation of the change of some transistor parameters with temperature and working conditions.

74. "Design and application of a synchronous converter
Part I : Problems of electromechanical design
Part II : Associated equipment and applications"
I.E. Hutcheon.
British Communications and Electronics.
Part I : July 1958, Vol. 5, p. 512
Part II : August 1958, p. 602

Gives detailed discussion on the mechanical contact-modulated chopper.

Part I : Gives discussion about the design, offset, induced e.m.f.'s, thermal e.m.f.'s, stray currents, contact bounce, electrical wear, mechanical wear and contact resistance of contact-modulators.

Part II : Explains about the phase correction in choppers, the operating frequency, the waveform stability of the output, the "input not at ground potential" - problems, the mounting position, the

microphone effects and the waveform of the output. Finally discusses dc-ac conversion (input transformer problem), d-c chopper amplifier techniques and the measurement and multiplication of frequencies.

75. "Performance calculations for d-c chopper amplifiers"
I.E. Hutcheon.
Electronic Engineering, August 1958, p. 476-480.

Gives mathematical calculations of the input resistance to d-c, the overall d-c gain and the output resistance of a chopper amplifier which employs any arrangement of perfect switches, resistors and capacitors in its chopping and rectifying circuits. Discusses chopper amplifiers in general (briefly) and compares them for drift, etc.

76. "Low level d-c amplifier with whole loop feedback"
P.C. Hoell.
Review of Scientific Instruments 29, p. 1120, 1958, December.

Describes ordinary chopper d-c amplifier with negative feedback. Claims to have drift less than 10^{-9} V per hour and less than 2×10^{-9} V per day. Says that the input transformer should be exceptionally well shielded.

77. "Fluctuation phenomena in semiconductors"
A. Van der Ziel.
Butterworths Scientific Publication, London, Academic Press, New York, 1959.

Textbook about noise in semiconductors.

78. "Differential amplifier features d-c stability"
W.T. Matzen and J.R. Biard.
Electronics, January 16, 1959, p. 60.

Gives discussion of special differential d-c amplifier including very many precautions such as thermal matching of first pair and thermal compensation. Includes a few good ideas for temperature compensation of transistorized differential d-c amplifiers.

79. "DC to AC modulators"
G. Sideris.
Electronics, January 23, 1959, p. 47.
Summary of chopper devices with characteristics.

80. "Differential chopper amplifier has high input impedance"
F. Offner.
Electrical Design News, March 1959, p. 38.
Uses a-c feedback from output transformer to input transformer to increase the input impedance of the modulated d-c amplifier.

81. "Transistor a-c and d-c amplifiers with high input impedance"
Middlebrook and Mead.
Semiconductor Products, March 1959, pp. 26-35.
Gives discussion and mathematical treatment of a-c and d-c transistorized amplifiers having high input impedance by virtue of a feedback circuit. Also the gain stabilization and noise figure optimization are considered. Experimental data for a particular circuit is given.

82. "Amplifiers for strain gauges and thermocouples"
R.S. Burwen.
Electronics, p. 43, July 24, 1959.
Gives accurate description and precautions for a particular low-level differential amplifier, which is compensated by the use of a modulated d-c amplifier. The amplifier is very complicated but the results are good. Uses ring demodulator at the output. Positive and negative feedback to a bridge-type transformer-coupled input circuit are used to attain high-impedance differential input in a d-c to 25 kc. amplifier. Bridge balances out common mode signals.

83. "A high-speed, airborne digital data acquisition system"
Cogan and Hodder.
IRE Transactions, Professional Group on Space Electronics and Telemetry, September, 1959, p. 117.

Describes a transistorized airborne PCM/FM data acquisition system. Mentions and briefly describes the modulated d-c amplifier used. Emphasizes the common-mode rejection problem.

84. "Transistor choppers"
Texas Instruments, Inc.
Application notes, September 1959.

Gives equivalent circuit for transistor choppers. Discusses transistor choppers in general and especially the reduction of their noise.

85. "Transistors as switches"
Texas Instruments, Inc.
Application notes, October 1959.

Discusses the characteristics of switching transistors :

1) steady-state values.

2) transient phenomena.

3) parameters and circuit performance.

86. "An analysis of the operation of the magnetic second-harmonic modulator"
B.W. Jalbert.
AIEE Transactions, pp. 268-272, 1960, Vol. 79, Part I.

Gives physical and mathematical analysis of a basic magnetic amplifier circuit.

87. "Theory and operation of a cross-field magnetic modulator"
D.W. Boensel.
AIEE Transactions, pp. 505-510,1960, Vol. 79, Part I.

Describes a magnetic modulator where the a-c winding is perpendicular to the other windings in order to eliminate coupling. Is based on "The application of perpendicularly superposed magnetic fields", R.A. Heartz, H. Buelteman, Jr.,AIEE Transactions, Part I, Vol. 74, November 1955, pp. 655-660.

88. "Stable transistor wideband d-c amplifiers"
H.H. Okada.

Transactions of the AIEE (Communic. and Electronics), March 1960, pp. 26-33.

Discusses generalities (advantages and disadvantages) of transistorized d-c amplifiers. Gives description, analysis and stabilization techniques for chopper amplifiers and differential amplifiers using transistors.

89. "Effect of external base and emitter resistors on noise figure"
J.W. Halligan.
Proc. of the IRE, May, 1960, p. 936.

Derives a couple formulas for the noise figure of transistor amplifiers.

90. "Transistorized data amplifier has high gain-stability"
F. Offner.
Electronics, July 1, 1960, pp. 55-57.

Describes a practical (patented) compensation method for transistor characteristics variations. Gives a circuit for better output performance of modulated d-c amplifiers. Discusses method to lower out-put impedance by use of an output buffer amplifier of unity gain. Compares transistors with vacuum tubes : temperature affects the former more than the latter.

91. "Superconducting contacts"
J.I. Pankove.
IRE Transactions on Electron Devices, July 1960, pp. 137-141.

Contact of two superconducting wires can be used as modulating element : Magnetic field quenches the contact so that the resistance across the latter varies.

92. "Photoconductor chopper stabilizes d-c amplifier"
M.W.P. Strandberg.
Electronics, Spetember 16, 1960, p. 92.

Says : for wide-band applications use dual channel amplifier : a-c amplifier in parallel with modulated d-c amplifier. Mentions

other than mechanical modulators to modulate d-c signals : saturable reactors, diode or vacuum-tube modulators, light-modulated photo-conductors, time varying capacitors. Explains the troubles of photo-modulators and how to overcome them.

93. "Relays and related devices"
Michael F. Tomaino and George J. Flynn.
Electronics, September 30, 1960, pp. 57-61.

On pp. 60-61 are given some characteristics of present contact modulators as for noise levels and drifts. Comparison is made with other modulation methods.

94. "Transistor choppers"
J.A. Ekiss.
Semicinductor Products, October 1960, pp. 23-27.

Discusses how to characterize the transistor for switching applications and which transistor parameters influence the performance. Several simple modulator and demodulator circuits are discussed which illustrate how the transistor is utilized in its chopping application. Also some mathematical treatment is given.

95. "Photomodulator-Miniature size"
Photochron Research, Inc., New York.
Electronics, December 16, 1960, p. 115.

Advertizes a particular miniature-size photo-modulator.

96. "The design of low noise transistor audio amplifiers"
J.W. Halligan.
Journal of the Audio Engineering Society, April 1961, p. 120.

Briefly discusses the dependence of transistor noise figure on various amplifier parameters, on the operating point, the biasing circuitry, the source resistance and the transistor itself. Feedback can improve the input impedance and the gain characteristics.

97. "Elimination of null in modulating and demodulating devices"
Jones.

AIEE Transactions, Communication and Electronics, May, 1961, pp. 135-139.

Achieves lowering of null in phase-sensitive detector by use of feedback. The device described is of the magnetic modulator type.

98. "A theoretical comparison of average and spot noise figure in transistor amplifiers"
J.W. Halligan and J.A. Ekiss.
Proc. of the IRE, July 1961, p. 1216.

Derives a couple formulae for noise in transistors.

99. "Hybrid d-c designing amplifiers to withstand missile environments"
R.L. Konigsberg.
Electronics, August 11, 1961, pp. 157-159.

Describes d-c amplifier using the so-called Goldberg circuit (ref. [16]) and containing many precautions.

100. "Noise aspects of low-frequency solid-state circuits"
A. Van der Ziel.
Proceedings of NEC, Volume XVII, October 1961, pp. 454-460.

A survey of the various ways of characterizing the noise in solid-state circuits. Mathematical treatment is given and the results are applied to several circuits.

101. "Differential amplifier with regulator achieves high stability, low drift"
R.D. Middlebrook and A.D. Taylor.
Electronics, July 28, 1961, p. 56-59.

Gives some advantages of differential amplifiers. Describes special differential amplifier circuit. Drift is 100 μV/hr.

102. "A new d-c transistor differential amplifier"
D.F. Hilbiber.
IRE Transactions on circuit theory, N° 4, December 1961, pp. 434-439.

Describes special d-c amplifier (differential direct-coupled type). Mathematical treatment is given. He uses planar silicon transistors.

The device consists of two differential stages in series the first having special matched transistors and the second being connected so that it helps to reduce remaining changes with temperature of the offset and the drift of the first one.

103. "Solid-state optoelectronic commutator"
R.D. Stewart.
Electronics, February 16, 1962, pp. 38-39.

Explains advantages of photoconductors as modulators. Gives basic photoconductor switching circuit.

104. "Differential amplifier grown in silicon block"
W.F. De Boice and J.F. Bowkev.
Electronics, July 6, 1962, p. 37.

Explains technique of building a d-c amplifier directly into a silicon block.

105. "D-C amplifier uses fluid-state tetrode"
Texas Research and Electronic Corp.
Electronic Products, October 1962, pp. 40-43.

Discusses the use of solion tetrodes to build up a high-performance direct-coupled differential amplifier.

106. "An ultrahigh impedance amplifier"
J. Morrison.
Electronics, October 5, 1962, p. 49.

Explains how to make the input impedance of a measuring device very high. Describes vacuum-tubes using device so designed that variations in component tolerance do not affect the gain.

107. "How to choose transistors for low noise"
John L. Wilkerson.
Electronics, January 11, 1963, p. 50.

Gives a mathematical calculation of the noise figure of a transistor in function of the transistor parameters and the source resistance. From there he derives the emitter current and the source

resistance which give least noise. Also considers the noise as a function of the alpha cutoff frequency.

108. "Amplifying 100-nanovolt low-frequency signals"
Astrodata, Inc., California.
Electronics, January 18, 1963, p. 76.
Advertizes a transistorized d-c amplifier that will operate on signals as low as 100 nv (= 0.1 microvolt).

109. "The design of low noise, high input impedance amplifiers"
Larry Blaser.
Fairchild application data for silicon transistors.
Gives basic requirements of a transistor and associated circuitry for low noise, high impedance amplifier design.

110. "The design of high-stability d-c amplifiers"
P.J. Beneteau.
Fairchild application sheet for silicon transistors.
Describes special transistorized direct-coupled differential d-c amplifier using matched transistors in the input stage and with the second stage so connected that it helps to reduce remaining changes with temperature of the offset and the drift of the first one.

111. "Control system components, Chapter 2, D-C Amplifiers"
J. Gibson and Tuteur.
McGraw-Hill Book Company.
Textbook containing some general information about d-c amplifiers.

SUPPLEMENTARY REFERENCES.

112. "Chopper literature"from
James Electronics, Chicago.

113. "DC-AC choppers, a guide to correct applications"
Stevens-Arnold, Inc., Boston, Mass.

114. "Application notes for transistor choppers"
Airpax Electronics, Inc., Cambridge Division, Cambridge, Maryland.

115. "The synchroverter switch, basic principles and applications"
The Bristol Co., Product data N° P1210.1.9.1-2

116. "Modulation and demodulation with semiconductors"
D.P. Masher.
Technical Report N° 2 (DIC 6986), MIT Servomechanisms Lab.

117. "The requirements and design for a d-c null detector"
Maltby.
AIEE Technical Paper 51-344.

118. "Considerations of relay dynamics with an example of non-linear vibrating reed design"
David A. Robinson.
presented at the Fifth National Conference on Electo- Magnetic Relays, Oklahoma Inst. of Tech., Oklahoma A and M College, Stillwater, Oklahoma.

119. "Electromechanical modulator for an analog computer"
R.A. Gaskill.
M. I. T. Thesis for M. S. degree.

120. "Design criteria for low-level second-harmonic magnetic modulators"
E.J. Kletsky.
Technical Report N° 1, D. I. C. Project N° 6896, MIT.

121. "Carrier-compensation of servomechanisms using synchronous vibrators"
W.I. Cook.
M. I. T. Thesis for M. S. degree.

122. "DC/AC conversion systems"
W.P. Wills.
Electronic Engineering, Vol. 66, January 1947, pp. 39-40.

123. "Electronic DC/AC converter"
Electrical Engineering Abstracts, Vol. 53, N° 1, 683, 1950.

124. "Drift compensation in d-c amplifiers for analog computers"
IRE National Convention, New York, 1951.

125. "Application of transistors to directly-coupled amplifiers"
Franklin.
M. S. Thesis, M. I. T. June, 1952.

126. "The transistor emitter-coupled amplifier"
Slaughter.
Weston Proceedings, 1954.

127. "Zero stabilization of directly-coupled amplifiers"
E. H. Frost-Smith and A.R.B. Churcher.
The Elliott Journal, Vol. 2, N° 1, p. 136, August, 1954.

128. "Switching transistors used as a substitute for mechanical low-level choppers"
A.P. Kruper.
Communications and Electronics, March 1955, N° 17, pp. 55-157 (AIEE).

129. "Chopper-stabilized amplifier"
Royce and Mathews.
Electronic Equipment, May 1955.

130. "A stable diode chopper circuit"
H. Patton.
Paper presented at the IRE Wescon convention in San Francisco, August, 1955.

131. "The magnetic modulator"
Electronic Design, September, 1955, p. 37.

132. "The hushed transistor amplifier"
W.K. Volkers, N.E. Pederson.
Paper presented at the National Electronics Conference, October, 1955.

133. "The selection of triode valves and circuits for direct-coupled amplifiers"

R.E. Aitchison.
Journal of the Institution of Engineers of Australia, Vol. 27, December, 1955, p. 339.

134. "Vibrator amplifiers and their uses in servomechanisms"
I.E. Gukailo, S.M. Fedorov.
Avtomatika i Telemekhanika, Vol. XVII, N° 10, 1956.

135. "A study on the input circuit of the contact modulated amplifier"
N. Kato and J. Ikenoue.
Member Faculty Engineering, Kyoto University, 18 (2), April, 1956, pp. 112-129.

136. "The use of choppers in d-c amplification"
P.T. McCauley.
Research and Engineering, October 1957.

137. "A study of the analytical representation of a system with feedback and modulation"
W.E. Nesbitt (D. E.)
Doctor Thesis, 1958, Johns Hopkins University.

138. "Digital Voltmeters"
Electromechanical Design, June, 1958.

139. "A low level, high accuracy d-c magnetic amplifier"
B. Mazzeo.
Electrical Manufacturing, November 1958.

140. "Low-frequency reactance amplifier"
J.R. Biard.
Digest Tech. Papers, Solid State Circuits, Conf. Philadelphia, pp. 88-89, February 1960.

141. "How to design low-noise transistor circuits"
Paul J. Beneteau.
Electronic Design, August 3, 1960.

142. "High-speed micro-energy switching"
C.D. Simmons.
Solid State Journal, September/October, 1960.

143. "Planar silicon transistors and diodes"
J.A. Hoerni.
Presented at Electron Devices Meeting, Washington D.C., October 27-29, 1960 (Fairchild Semiconductor Corp., TP-14).

144. "A low-drift direct-coupled transistor amplifier for high temperature application"
J.W. Halligan.
Semiconductor Products, April, 1961.