Broadband Feedback Amplifiers

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Editor's Foreword

This is the first monograph to be published in the R.S.P. Series on Electronic Circuits and Systems. These volumes are intended to encourage the early dissemination of high-quality work in specific subjects with more background and perspective than can be included in reputable engineering journals. The titles reflect areas of research having originality and high contemporary relevance as well as direct implications in the evolution of electronics.

It is particularly fitting that the opening text by Douglas Maclean should combine theoretical rigour with practicality. Starting from the foundations laid by Black and Nyquist, new light is shed on the concepts of loop gain leading to a distinctly useful method for assessment of total feedback in multiloop systems. This exploits modern computer and measurement techniques to full advantage providing broadband representations of transistor amplifiers which are likely to find wide application. Some of the contents have already been well received in a number of research papers by the author, one of which gained the Electronics Division Premium Award of the Institution of Electrical Engineers (London) in 1980. The author has harnessed both his considerable analytical understanding and his extensive industrial experience to present a work of considerable interest to practising engineers in many areas of modern telecommunications.

P. Bowron

Preface

"I do not know what I may appear to the world, but to myself I seem to have been only a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me".

(Sir Isaac Newton, 1642-1727)

The stability margins of broadband feedback amplifiers have, until recently, been assessed by conventional methods of loop-gain analysis. This monograph unifies and expands a more realistic approach first presented in a number of journals published in America, Britain, and West Germany. Advances in both theoretical and practical aspects of feedback are described for use by those responsible for the design, development, testing, or specification of wideband feedback amplifiers. Such staff are employed in the engineering, manufacture, operation and administration of point-to-point communications (civil and military), television broadcasting and distribution, radar and satellite systems, among others. It is also likely to be of considerable interest professionally to staff in University departments or Institutes devoted to telecommunications and related subjects.

The new approach can provide more realistic stability margins and some of their sensitivities than loop-gain analysis can ever achieve. The present monograph is a comprehensive and practical description of the method. Unlike most textbooks including material on feedback in amplifiers, it is intended to have a significant impact on the design and performance of broadband amplifiers, because the technique is based upon a practical and realistic description of such circuits. Again, unlike other such books, the material is new and has grown from experience in research and development laboratories within the telecommunications industry.

The improved method of assessment rests on the sure foundations provided by the mathematical theory of feedback due to H.W. Bode, and modern computer-controlled measurements. The latter are normally performed by network analyzers, especially those which give s-parameters directly. Such instruments cover an enormous band of frequencies, within which lie almost all present-day high-capacity carrier systems and their traffic basebands. Even in optical-fibre communications, the intermediate and multiplex-baseband frequencies are, of course, within the present scope. Either in custom-built form (such as the largest organizations possess) or as commercially available equipment, network analyzers provide an exceedingly costeffective means of obtaining accurate measurements. Bode's theory is unrivalled by any other, and can be expressed in terms of straightforward nodal analysis. This basis is particularly appropriate because it is so widely used in computer-aided design and analysis. Regardless of which two-port parameters are actually measured, the software algorithms based on the theory manipulate admittance matrices stored as data banks.

Significant points of the new method are:

- it provides more realistic and meaningful predictions of stability margins and sensitivities of amplifiers under test than is possible using the original loop-gain concept;

- it does not depend upon identifying individual loops, nor upon the number of positive and negative loops present, and does not require the provision of a special break point in a single external loop;

- it is more likely to be applicable to amplifiers realized in modern technologies such as hybrid or integrated-circuit construction, or using modern devices such as GaAs MESFETs in microwave amplifiers or optical receivers;

- the viewpoint is closer to modern methods of measuring and representing noise and distortion in high-performance amplifiers for operational systems.

Except for the first chapter, which is intended to summarize the concepts and properties in a realistic modern setting, the remainder of the monograph is mainly devoted to an explanation of means of overcoming difficulties and problems in the theory and practice of feedback assessment. Because the author's experience suggests that most practising engineers are reluctant to use algebra and other mathematical tools, these aids have been kept to a minimum. Indeed, to avoid their intrusion into the text and the consequent interruption to the flow, they are often relegated to an appendix. Node-datum (nodal) analysis and admittance matrices, together with determinants and cofactors thereof, provide very elegant means of expressing the theoretical results. Moreover, because the matrices are of low order, formulae can easily be derived using literal rather than numerical matrix elements, which is a distinct advantage for the reader, who can thus follow the derivation of the results readily and, if desired, verify them algebraically. This approach is unlike that of many books on active networks and feedback amplifiers, where the theory tends to be complicated and impractical, and based upon unrealistic circuit diagrams.

The professional level of the text is enhanced by the use of drawings which, in general, conform to British Standard or IEC practice. Whenever possible, so do the symbols and notation. The choice of the letter p for the complex frequency, rather than s, is made to prevent confusion with the use of s to denote small-signal scattering parameters which lie at the heart of the method. Each chapter concludes with a summary, and many recent references chosen for their usefulness to designers and others concerned with feedback amplifiers. An attempt has been made to provide a wide geographical spread of literature citations although, unfortunately, few Russian contributions have been included owing to the unsatisfactory nature of most translated articles. Within the text, italics are freely used to highlight important points. Indented lists are also provided for ease of use; the more significant lists being identified by Roman numerals, the less significant by letters. A glossary of notation and an extensive index have been compiled to increase the value of the book as a work of reference.

A brief overview of each chapter is now presented.

First the principle of negative feedback in amplifiers is introduced by a brief discussion of the two inventions from which it arose, followed by enumeration of the changes it causes in amplifier properties. In contrast to most previous texts, the assumptions underlying single-loop theory are stated in detail, then aspects of this theory are considered. In particular, the effects on noise and dynamic range are treated in a manner appropriate to repeater amplifiers carrying FDM telephone traffic.

Chapter 2 presents a detailed mathematical examination of an old and familiar concept in a novel manner. The possibility of loop gain failing to predict instability in a closed-loop amplifier is discussed and illustrated by the results of computations based upon real amplifiers. It emerges clearly that loop gain is, indeed, "a rickety old concept". However, many old problems can be answered with the help of a simple but absolutely basic mathematical identity. To conclude this chapter, the most practical form of loop-gain expression in terms of scattering parameters is fully explored.

In order to obtain realistic margins, all of the feedback (loop, local and internal) around a controlled source must be included. Chapter 3 explains how this is best done from scattering-parameter measurements on a transistor and on the remainder of the amplifier at the shared terminals. The measurement arrangements for the amplifier part are described in detail.

Foundations are laid for the corresponding theory in a review of Bode's treatment. The link between his approach in terms of admittance matrices of multinode circuit diagrams and that of matrices derived solely from the scattering-parameter measurements is forged in Chap. 4. The formulae for return difference and ratio can thereby be expressed in terms entirely of quantities derived from measurements, giving the fundamental relationships of a technique termed the embedding network method (ENM). The important matter of the choice of a unique, broadband representation for a transistor is fully discussed and its physical significance noted.

Chapter 5 is devoted to confirmations of the new method; firstly by computing the value of an add-on component which should cause self-oscillation at about 500 MHz, then by demonstrating this instability on a test amplifier. Further corroborations result from numerical analyses of an increasingly realistic set of circuit diagrams. Examination of two different submarine repeater-type amplifiers fully demonstrates the power and scope of the method, as well as its ability to uncover behaviour which older techniques fail to reveal.

The impact on design is considered in Chapter 6, where it is shown that the new method can be exploited profitably before construction starts. It can also be used in shaping gain and phase margins during development on the bench. Certain sensitivities of interest to designers are considered in depth.

A practical form of Nyquist stability criterion for multiloop amplifiers is formulated as a Bode Set early in Chap. 7. Behaviour at relatively high frequencies is of some importance in this context. The question of maximum available feedback for a given structure is also discussed. In some circumstances, a method of stability assessment based on measurements of insertion gains may be preferred, and one useful technique is presented. Extensions of the ENM to microwave amplifiers and to almost-linear amplifiers are presented.

Chapter 8 deals first with modern representations of noise in two-parts based on sets of four suitable noise quantities which are accurately measurable. The power and scope of this approach is comparable to the use of s-parameters and, like the ENM, can provide more realistic noise performance. Another modern development is the application of feedback amplifiers in receivers for optical communication systems. In this context, detailed results are presented for the first time for bipolar and GaAs MESFET input stages.

The last chapter opens with a broad review of the results obtained, highlighting some of the important topics and drawing attention to economies of effort inherent in the ENM. A number of specific applications which may be of considerable interest in certain circumstances are outlined. Potential uses in receivers for optical fibre systems, microwave amplifiers and multichannel cable television are noted. Integrated circuits play an increasingly important and pervasive rôle in electronics and Chapter 9 ends by tentatively discussing ways in which the ENM might be exploited in this technology.

The chapters are succeeded by a number of appendices, of which the second is probably of most interest to amplifier designers, being an introduction to s-parameters and their relationships to y-parameters. It also contains an extensive set of graphs which illustrate the frequency dependence of s-parameters and admittances for several transistors. In addition, the effect of different bias currents are shown, together with results taken from a batch of transistors of the same type. The information on the admittances of the broadband representations (Chap. 4) for these transistors are thought to be the first such ever to be published. They should be of great interest to many readers.

Analysis of amplifiers requires that the small-signal properties of transistors must be described appropriately. Three types of description are in use: a circuit diagram, a 2-port representation, or 2-port scattering parameters. This last is relatively uncommon because only a few computer programs can use s-parameters directly, at present. In this monograph, the first type of description is called a *circuit model (or model, for brevity)*, and always means a circuit diagram comprising conventional lumped elements and one or more controlled sources. The circuit topology and element values are often related to the physical and geometrical properties of the device. The preferred description in this book is a *2-port representation* consisting of three 1-port admittances and a controlled source corresponding to the 2-port y-parameters. The distinction between model and representation should be borne in mind by the reader.

It was as an undergraduate (on a 'sandwich' course) working on amplifiers for the London-to-Birmingham television microwave-radio link that I first used Dr. Bode's book. Subsequently, I have returned to it again and again. During my career, there have been three periods when I was involved with the design or assessment of feedback amplifiers. It may be said that the seeds sown in earlier years have now borne fruit in this present monograph. By pure coincidence, I was born between the two dates in August, 1927, when H.S. Black had the flashes of insight which crowned several years of hard work, and led to the negative feedback amplifier.

Douglas J.H. Maclean,
Bishop's Stortford,
December, 1981

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Glossary of Notation

1. Preliminaries

In general, the symbols used in the text, tables, and figures follow national standards such as British Standard BS3939 and the German DIN 41785, which in many cases are the same as the IEC standard.

Considering voltage, current and power symbols first; capital (upper case) letters are used to denote constant quantities, particularly d.c. values, or r.m.s. values of a.c. quantities. These are distinguished by capital and lower case (small) subscripts respectively. In a few places, instantaneous quantities are used and these are denoted by small letters, associated with lower case subscripts for a.c. or noise quantities.

The admittances, resistances, inductances (but not capacitances) pertaining to small-signal properties of transistors are denoted by lower case letters and subscripts, e.g. $r_{bb'}$, y_a, $C_{b'e}$. Capital letters are used for elements representing passive components, and for the parasitics and strays associated with such components, transistor packages, and circuit boards.

Square brackets are used to denote matrices, and also parts of the complex frequency plane; these different uses will be clear from the context. Two vertical lines thus, $| \, |$, signify the determinant of the enclosed quantity, or the magnitude; again, the meaning will be clear from the context. The elements (entries) in an array (matrix, determinant, or cofactor) will be denoted by lower case or upper case letters with one or two numerical subscripts as required by the text, e.g. b_1 or Y_{32}.

To provide the reader with ready access to the meanings of the main symbols, the list of notation has been compiled in order of first appearance, by chapters, grouping symbols of like kind.

Chapter 1

H1, H2	hybrid circuit
θ	loss or gain (nepers), phase (radians)

The next group denotes gains (in general, complex) of unilateral amplifiers.

$\mu 1$	main amplifier
$\mu 2$	compensating amplifier
μ	forward-path amplifier
μ_1	first amplifier
μ_2	second amplifier
μ_c	comparison amplifier

The next group represent r.m.s. values of currents or voltages:

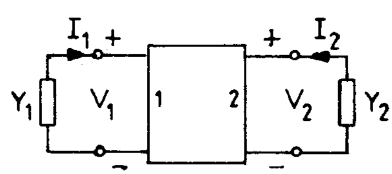
S	signal
S_1	line-input signal
S_2	line-output signal
βS_2	returned signal
$S_1 \mp \beta S_2$	net (error) input signal to forward path
$\mu\beta$	loop gain of single-loop amplifier
$1-\mu\beta$	feedback of single-loop amplifier
D	distortion (function of S_2)
D_2	distortion at line output
D_{20}	distortion at output of comparison amplifier
N	additive noise (independent of signal)
N_2	noise at line output from N in second amplifier
N_2'	noise at line output from N in first amplifier
N_{20}	noise at output of comparison amplifier

Other symbols:

e^{θ}	external gain, S_2/S_1, of feedback amplifier
β	'transmission' through return path (note: dimension of βS_2 must be the same as that of S_1)
k	number, $1<k<\mu_1$
f_A, f_B, f_C	frequencies of test signals used to measure intermodulation

Chapter 2

The first group concerns two-port parameters, and r.m.s. port variables with sign conventions shown in the figure.



$y_{11}, y_{12}, y_{21}, y_{22}$	short-circuit admittance parameters
$a_{11}, a_{12}, a_{21}, a_{22}$	chain-matrix or cascade parameters
$s_{11}, s_{12}, s_{21}, s_{22}$	scattering parameters (defined in App. B)

The next group consists of:

J_1, J_2	independent current generators (excitations, driving forces) with r.m.s. values
Y_1, Y_2	admittances of terminations at ports 1, 2 respectively
Y_{D1}, Y_{D2}	driving-point admittances at ports 1, 2 respectively.

The determinants and cofactors of multinode admittance matrices of unterminated open-loop amplifier (1 input, 2 output nodes)

Δ_{ij}; i=1,2	cofactors of matrix elements
Δ_{1122}	cofactor obtained by deleting rows 1 and 2 and columns 1 and 2

The (principal) determinants of the reduced admittance matrix for the two-port are:

$\Delta = y_{11}y_{22} - y_{12}y_{21}$, unterminated
$\Delta' = y_{11}(y_{22}+Y_2) - y_{12}y_{21}$, with load termination
$\Delta'' = (y_{11}+Y_1)(y_{22}+Y_2) - y_{12}y_{21}$, doubly terminated

The principal determinant of the multinode admittance matrix of the corresponding closed-loop amplifier is

$^c\Delta$	(or simply Δ where there can be no confusion with open-loop quantities)
MAM	multinode admittance matrix

Other symbols are

G	conductance of test equipment of characteristic resistance G^{-1}
$Y_{ij}, Y'_{12}, Y''_{12}$	elements (entries) in a multinode admittance matrix
g_1, g_2, g_3, g_4	factors of identity for $^c\Delta$
$p = \sigma + j\omega$	complex frequency
[L]	left-hand side of p plane, $\sigma < 0$,
[R]	right-hand side of p plane, $\sigma > 0$,
[B]	boundary between them, $\sigma = 0$
LG	loop gain of multiloop amplifier

Chapter 3

The first group concerns quantities relating to stability margins:

x	gain margin
y	phase margin
f_1	phase margin frequency
f_2	gain margin frequency

Other quantities are denoted by

RD	return difference (analogue of $1-\mu\beta$)
RR	return ratio (analogue of $-\mu\beta$)
Δ^o	principal determinant of closed-loop amplifier matrix when one circuit element is set to zero

Chapter 4

Grouping matrices and related symbols gives

X_{ij}; i,j=1,2,3	elements (entries) in the reduced admittance matrix (3x3)
[0]	submatrix all of whose elements are zero
[LT]	lower triangular submatrix
[4]	submatrix (not required in calculations)
$[Y_{11}Y_{22} \cdots Y_{NN}]$	multinode admittance matrix of order N
$\lvert Y_{11}Y_{22} \cdots Y_{NN}\rvert$	determinant of above matrix
$[EN] = [a_1b_2c_3]$	embedding network admittance matrix
$[AT] = [a'_1b'_2c'_3]$	indefinite admittance matrix of accessible transistor
$[CA] = [A_1B_2C_3]$	matrix of computer amplifier = [AT] + [EN]
$D(jf_m) = \lvert A_1B_2C_3\rvert$	determinant of [CA] at frequency f_m
$D(jf_m, y_m = 0) = \lvert A_1B_2C_3\rvert_{y_m=0}$,	determinant D when y_m is set to zero
$[y_m]$	indefinite admittance matrix of controlled source (CS)
$[\pi]$	indefinite admittance matrix of reciprocal transistor (RTR)

The second group lists network functions expressed in determinant notation:

$J_i/V_i = \Delta/\Delta_{ii} = D/D_{ii}$, driving-point admittance at node i

$V_j/V_i = \Delta_{ij}/\Delta_{ii} = D_{ij}/D_{ii}$, voltage ratio (output/input)

$J_i/V_j = \Delta/\Delta_{ij} = D/D_{ij}$, transfer admittance (input/output)

The third group is associated with the broadband representation for transistors:

y_m (or m)	transadmittance of controlled source (nonreciprocal part of transistor)
y_c (or c)	coupling admittance between base (gate) and collector (drain)
y_a (or a)	1-port admittance between base and emitter
y_b (or b)	1-port admittance between collector and emitter

Other symbols are

$g_{11} = \text{Re } y_{11}$

$g_{22} = \text{Re } y_{22}$

$g_{12} = \text{Re } y_{12}$

$g_{ij} + jb_{ij} = y_{ij}$; $i,j = 1,2$

k — reference value for y_m which makes a specific LG vanish (=0)

The last group in this chapter relates to the transformation of [EN] to the indefinite admittance form

$\Sigma 1 = a_1+b_1+c_1$	sum of entries in first row
$\Sigma 2 = a_2+b_2+c_2$	second row
$\Sigma 3 = a_3+b_3+c_3$	third row
$\Sigma a = a_1+a_2+a_3$	sum of entries in first column
$\Sigma b = b_1+b_2+b_3$	second column
$\Sigma c = c_1+c_2+c_3$	third column
w =	summation of all rows or all columns = $\Sigma a_i+\Sigma b_i+\Sigma c_i$
p	admittance of branch between base and collector
q	admittance of branch between emitter and ground (datum)
$\tilde{w}$ =	w−q

Second subscript o denotes admittance connected from appropriate accessible node to datum; second subscript c denotes sum of admittances connected from this accessible node to other accessible, or concealed, nodes, e.g. $a_{10}+a_{1c} = a_1$

Chapter 5

B,C,E	letters symbolizing base, collector and emitter terminals; numerical subscripts indicate transistor (TR) number
RT	return transmission from controlled node-pair to control node-pair

The next group of symbols are associated with 2x2 matrices of transistor and embedding network:

$[a_1'b_2']$	definite admittance matrix of accessible transistor
$[a_1^*b_2^*]$	reduced admittance matrix of embedding network
$[A_1^*B_2^*]$	corresponding matrix of computer amplifier
D*	determinant of this matrix
D_k^*	determinant when y_m = k (reference value)
L	magnitude and phase of a specific loop gain

Chapter 6

Mbd	megabaud, symbol rate in digital transmission
NF	noise factor (or figure)
IM3	third-order intermodulation margin, dB
det[CA]	determinant of computer amplifier

$\det[CA^{o}]$	determinant when $y_m = 0$
[ET]	indefinite admittance matrix of an embedded transistor
[MAM]	multinode admittance matrix

The next group deals with sensitivities:

$e^{\theta} = \frac{\Delta_{12}}{\Delta} Y_L$	external gain
Y_L, Y_S	load and source admittances respectively
q	general variable element or component
dq	change in q
F	general network function, e.g. e^{θ}, RR
dF	change in F due to change in q
DS	differential sensitivity of F with respect to q
$\Delta q = q_2 - q_1$	change from initial (q_1) to final (q_2) values of q
$\Delta F = F_2 - F_1$	corresponding change in F
ES	exact (large-change) sensitivity of F with respect to q

Chapter 7

R	revolutions of phase = $(B_2-B_1)/360^{o}$
(B_2-B_1)	total change in phase angle between initial and final values of frequency
P	number of poles in [R] of a network function
P_k	number of poles in [R] of the kth return difference
Z	number of zeros in [R] of a network function
Z_k	number of zeros in [R] of the kth return difference
W	1-port admittance of a passive component
W_o	reference value of W which causes a specified transmission to vanish
θ_{∞}	value of θ when W is replaced by a short circuit
D'	value of D when W is replaced by W_o
e^{θ_F}	fractionated gain, or gain before feedback

Chapter 8

J_{n1}, J_{n2}	noise current generators (Fig. 8.1)
E_n, J_n	noise e.m.f. and current generator (Fig. 8.2)
i_s	instantaneous value of signal current
i_n	equivalent noise current of photodiode
i_a	equivalent noise current of amplifier
G_{eq}	equivalent noise conductance
R_{eq}	equivalent noise resistance
ζ κ	real and imaginary parts of normalized complex correlation coefficient
TZA	transimpedance amplifier

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