Tutorial Guides in Electronic Engineering

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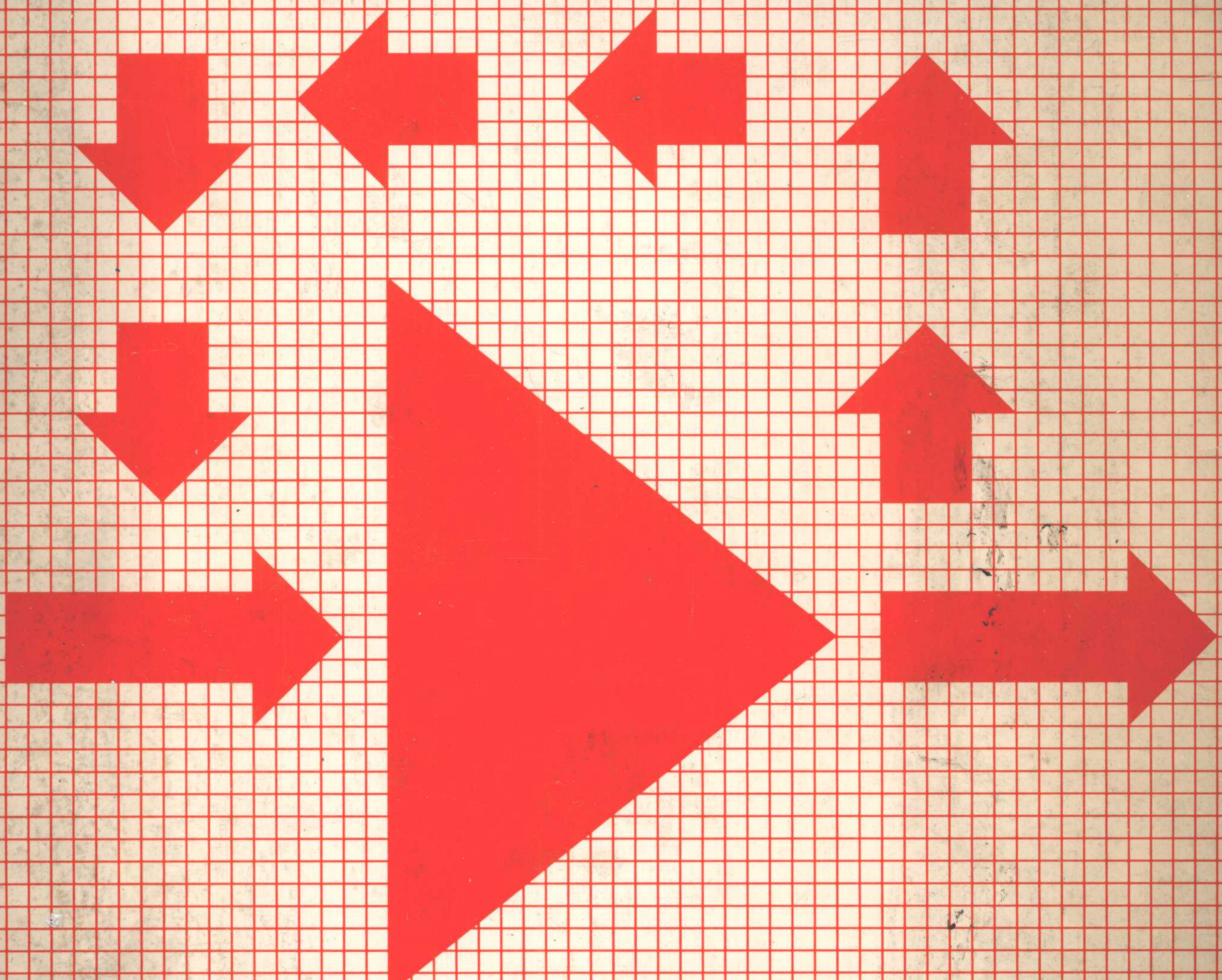
Feedback Circuits and Op. Amps.



D. H. Horrocks

Van Nostrand Reinhold (UK)

Feedback Circuits and Op. Amps.

D.H. Horrocks
Department of Electrical and Electronic Engineering
University College Cardiff

Van Nostrand Reinhold (UK) Co. Ltd

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Feedback Circuits and Op. Amps.

TUTORIAL GUIDES IN ELECTRONIC ENGINEERING

Series editors
Professor G.G. Bloodworth, *University of York*
Professor A.P. Dorey, *University of Lancaster*
Professor J.K. Fidler, *Open University*

This series is aimed at first- and second-year undergraduate courses. Each text is complete in itself, although linked with others in the series. Where possible, the trend towards a 'systems' approach is acknowledged, but classical fundamental areas of study have not been excluded, neither has mathematics, although titles wholly devoted to mathematical topics have been eschewed in favour of including necessary mathematical concepts under appropriate applied headings. Worked examples feature prominently and indicate, where appropriate, a number of approaches to the same problem.

A format providing marginal notes has been adopted to allow the authors to include ideas and material to support the main text. These notes include references to standard mainstream texts and commentary on the applicability of solution methods, aimed particularly at covering points normally found difficult. Graded problems are provided at the end of each chapter, with answers at the end of the book.

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Preface

Feedback circuits in general, and op. amp. applications which embody feedback principles in particular, play a central role in modern electronic engineering. This importance is reflected in the undergraduate curriculum where it is common practice for first year undergraduates to be taught the principles of these subjects. It is right therefore that one of the tutorial guides in electronic engineering be devoted to feedback circuits and op. amps.

Often general feedback circuit principles are taught before passing on to op. amps., and the order of the chapters reflects this. It is equally valid to teach op. amps. first. A feature of the guide is that it has been written to allow this approach to be followed, by deferring the study of Chapters 2, 4 and 5 until the end.

A second feature of the guide is the treatment of loading effects in feedback circuits contained in Chapter 5. Loading effects are significant in many feedback circuits and yet they are not dealt with fully in many texts.

Prerequisite knowledge for a successful use of the guide has been kept to a minimum. A knowledge of elementary circuit theory is assumed, and an understanding of basic transistor circuits would be useful for some of the feedback circuit examples.

I am grateful to series editor Professor G.G. Bloodworth for many useful discussions and suggestions. I am also grateful for the expert typing of Mrs. B. Richards and for help in preparing solutions to the problems given by Mr. R. Hor. Finally, I thank my wife, Chris, and son, Jim, for their forbearance.

Contents

Preface v

1 Introduction 1

2 General Properties of Feedback Amplifiers 4
Basic definitions and equations 4
Positive and negative feedback 7
Reduced sensitivity to gain variations 11
Reduction of noise and distortion 13
Multiple-loop feedback 15

3 Amplifiers Without Feedback 21
Amplifier models 21
Connection of signal-source, amplifier and load 26
Frequency response effects 29
Differential amplifiers 39

4 Feedback Amplifier Circuits 47
The four feedback circuit configurations 47
Effect of feedback on input and output impedance 49
Shunt-voltage feedback circuit example 56
Series-voltage feedback circuit example 59
Series-current feedback circuit example 61
Shunt-current feedback circuit example 64

5 More About Feedback Amplifiers 69
Loading effects between forward amplifier and feedback block 69
Effect on feedback amplifier of source and load impedances 82
Frequency response of feedback amplifiers 88
Instability 90

6 The Op. Amp. — Basic Ideas and Circuits 97
What is an operational amplifier? 97
Inverting voltage amplifier 100
Circuits based on the inverting voltage amplifier 105
Non-inverting voltage amplifier 109
Power supply connections to the op. amp. 111

7 Op. Amp. Non-idealities 115
The importance of op. amp. non-idealities 115
Offset voltages 115
Bias currents and offset currents 120
Op. amp. frequency response 124
Slew rate and full-power bandwidths 126

8 Further Op. Amp. Circuits 131
Precision difference and instrumentation amplifiers 131
Analogue computation 135
Wein Bridge Oscillator 139
The inverse function principle 142
Triangle wave/square wave generator 145

Answers to Numerical Problems 149

Index 151

Introduction 1

Many examples of feedback can be found in everyday life. One example is the temperature regulation of a heated room, shown schematically in Fig. 1.1. The heater supplies heat to the room and the temperature of the room, T_m, is sensed. This is fed back and compared with the desired temperature, T_D. The difference, $T_E = T_D - T_M$ (called the *error signal*), is passed to the regulator. The regulator uses the error signal to control the heater to maintain the room temperature close to the desired temperature. This automatic control technique is an example of *negative feedback*, so called because, in generating the error signal, the function of the comparator is to *subtract* the measured temperature from the desired temperature.

The subject of this tutorial guide is the application of feedback principles to electronic amplifying circuits containing active devices such as transistors. The use of integrated circuit transistor amplifiers, called *op. amps.* (an abbreviation of *operational amplifiers*), is particularly important and is considered in some detail.

The elements of a negative feedback amplifier system are shown in Fig. 1.2. The amplifying circuit uses active devices, normally transistors, to increase the magnitude of the electronic signal applied to its input. The input signal to the amplifier comes from a comparator which subtracts from the external input signal a fraction β of the amplifier output signal. If the amplifier has high gain it requires only a small signal at its input. Therefore the external input signal is approximately equal to the fraction β of the output signal. It follows that the output signal must be approximately equal to the input signal divided by β. This technique gives a system with a stable overall gain if the components in the feedback circuit have stable values. This is relatively easy to achieve using passive components such as resistors. The amplifying circuit itself does not need to have stable gain (but the gain must be high). This is of importance because the stable and predictable gain of systems is highly desirable for most electronic systems, but active devices so far invented do

A very significant result.

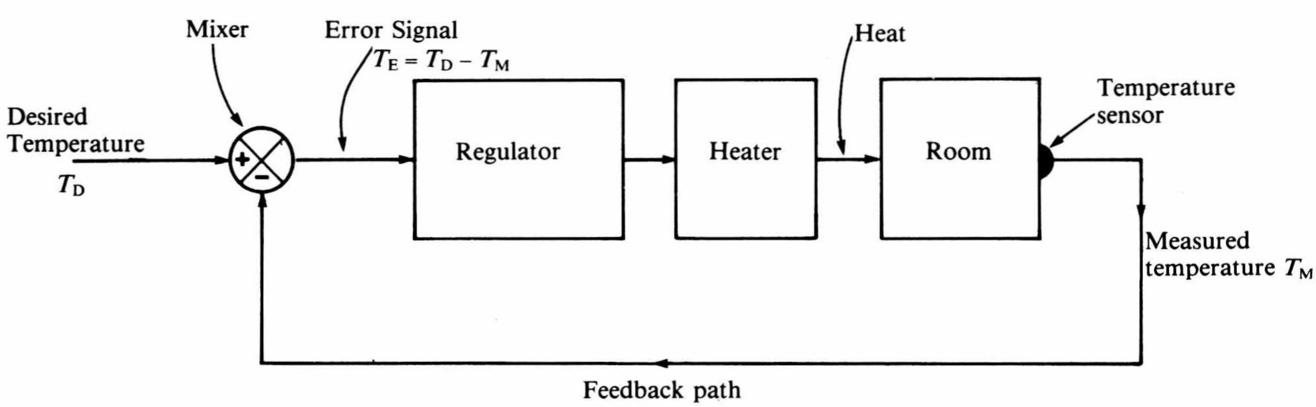

Fig. 1.1 Temperature regulation of a heated room.

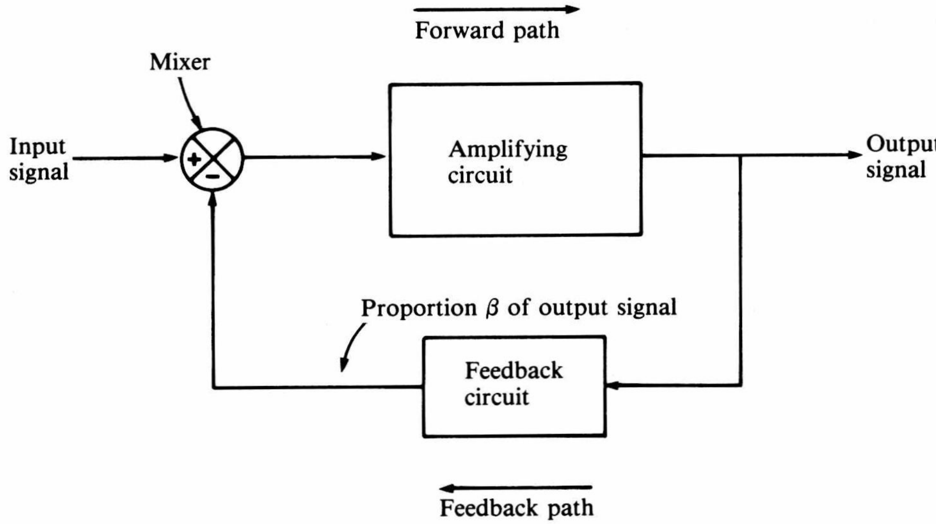

Fig. 1.2 Operating principle of a negative feedback amplifier system.

not have stable characteristics. Fortunately the requirement for the feedback system that the amplifier should have high gain is readily and cheaply achieved nowadays with transistors, particularly in integrated circuit form.

It should be noted that the stability of gain provided by negative feedback is not merely stability with the passage of time. Negative feedback also reduces the variations of gain with environmental conditions such as temperature, with manufacturing component spreads, and with the frequency and amplitude of the signals.

From Fig. 1.2 it is apparent that if a fraction β of the output signal is *added* to the input signal the overall gain is increased. This is called *positive feedback*.

During the early development of thermionic valve amplifiers positive feedback was used to increase the gain because valves were expensive and had low performance.

Non-linearities are also present in modern transistors.

Black conceived the idea 'in a flash' while commuting to work on a ferry across the Hudson river, *IEEE Spectrum*, December 1977, pp. 56–60.

A serious problem of valve amplifiers was distortion of signals caused by non-linearities, that is to say variation of gain with signal amplitude in the valves. In 1927 H.S. Black proposed the use of negative feedback for the first time, to reduce distortion in valve amplifiers. This discovery is seen in retrospect to have been one of the most significant ideas in the 20th century and has led to important advances in engineering. From it has grown whole disciplines such as control engineering, and the idea has been used by biologists, economists and others, to understand and model the operation of systems in their disciplines. However, it is particularly in electronic engineering that the idea is all-pervasive as transistors can provide high gain very cheaply, but cannot provide stable gain. This book shows that negative feedback not only stabilizes gain but also has other advantages such as enabling input and output impedances to be controlled, and bandwidth to be extended.

In Chapter 2 the general properties of feedback amplifiers and some of the main advantages of negative feedback are analysed. An introduction to the analysis of multi-loop systems is also included.

Before applying these ideas to amplifier circuits in Chapters 4 and 5, a description is given in Chapter 3 of the relevant properties of amplifier circuits without feedback. This includes calculation of voltage and current gains, multiple stages, input and output impedances and frequency response.

In Chapter 4 the four basic ways to apply negative feedback to an amplifier are explained and some examples are analysed. The simple treatment given in this chapter covers cases where loading effects can be neglected.

The methods of taking these effects into account are explained in Chapter 5, which also deals with the frequency response of feedback amplifiers. This material is more advanced and may be omitted from a first reading.

The remainder of the book deals with operational amplifier circuits. The name arises from the use of this type of amplifier in the early development of analogue computers to perform various mathematical *operations* on analogue voltages. The early op. amps. were constructed from thermionic valves, but since they were expensive their application was limited. The development of the silicon integrated circuit in the nineteen sixties enabled cheap high-gain op. amps. to be mass-produced. Nowadays they are widely used as components with negative feedback to perform many functions in analogue instrumentation, communications, etc.

The subject of analogue computers is briefly covered in Chapter 8.

Chapter 6 explains the characteristics of op. amps. and their use in voltage amplifiers. Use is made of the concept of the ideal op. amp.

Although op. amp. characteristics do approach this ideal they have some limitations which can be significant. In Chapter 7 the nature of the more important non-idealities are described and methods for allowing for them are explained.

In Chapter 8 some more advanced op. amp. circuits are described which have a range of useful applications and illustrate some further principles.

The chapter sequence adopted here follows one of the logical ways of developing and studying the subject at an introductory level. However, an equally logical and valid method of approach is to study op. amp. circuits before studying discrete transistor circuits. A reader following the latter method of study should defer a reading of Chapters 2, 4 and 5 until the end.

2 General Properties of Feedback Amplifiers

Objectives

- ☐ To calculate the gain of an amplifier after feedback has been applied.
- ☐ To distinguish between positive and negative feedback.
- ☐ To explain loop-gain and feedback factor.
- ☐ To explain how reduced sensitivity to component variations can be obtained by negative feedback.
- ☐ To describe how to use negative feedback to reduce noise and distortion.
- ☐ To simplify and analyse simple multiple-loop systems.

Basic Definitions and Equations

Feedback is a general idea.

Do not confuse β here with the current amplification of a transistor.

Fig. 2.1 shows a feedback system, with the various signals indicated. In this text the system is assumed to be electrical and the signals marked represent currents or voltages; however, it should be remembered that feedback can be applied to other systems, in which case the signals may represent velocity, cash flow, production output and so on. In the forward path, block A represents an amplifier whose output X_o is equal to the amplifier input signal X_{ia} multiplied by the *forward-path gain* constant A. The gain constant is usually large and can be positive or negative (the latter causing phase reversal of a sinusoidal signal). In general though, as explained later, it can be a complex number which is a function of signal frequency. The output of the amplifier X_o, which is also the output of the feedback system, is sensed by the feedback block. This block provides a feedback signal X_f equal to the

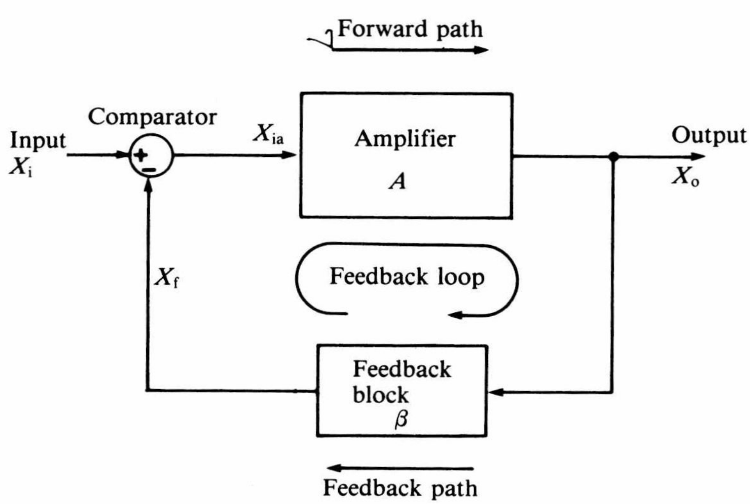

Fig. 2.1 Signals in a feedback system.

system output multiplied by the *feedback fraction* β. The feedback fraction is usually quite small and like the constant A it can be positive, negative or a complex number which is a function of signal frequency. The feedback signal X_f is subtracted from the system input X_i by the *comparator* to give the amplifier input X_{ia}.

In practice an electronic amplifier could be made from a simple amplifying circuit containing a single amplifying device such as a bipolar junction transistor or a field-effect transistor. Or it could be made from a combination of such simple circuits, possibly in integrated circuit form. There is a wide range of possible amplifier circuits and a number of different networks for the feedback block are available. In addition, there is more than one way to compare the feedback signal and the system input signal. These possibilities are explored later in Chapter 4. These details are not required in this chapter as only the general properties of systems with feedback are being considered.

When analysing feedback systems the relationship between input signal X_i and signal output X_o, after feedback has been applied is found first. From this other properties of a feedback system can be discovered.

From Fig. 2.1 it can be seen that the following three equations define the signal inter-relationships.

For the feedback block

$$X_f = \beta X_o \tag{2.1}$$

For the comparator

$$X_{ia} = X_i - X_f \tag{2.2}$$

For the amplifier block

$$X_o = A\,X_{ia} \tag{2.3}$$

To obtain the overall relationship between input X_i and output X_o the internal signals X_f and X_{ia} need to be eliminated from this set of equations. One way is to substitute the first equation into the second to give, for the comparator,

There are three equations in four variables; they can be reduced to one equation in two variables.

$$X_{ia} = X_i - \beta X_o \tag{2.4}$$

and then to substitute this equation into Equation 2.3 to give:

$$X_o = A(X_i - \beta X_o)$$

Hence

$$X_o(1 + A\beta) = A\,X_i$$

and from this

$$X_o = \frac{A}{1 + A\beta} \cdot X_i$$

The ratio X_o/X_i is called the gain with feedback, A_f. It is also called the *closed-loop gain*, and from the last equation is given by

$$A_f = \frac{X_o}{X_i} = \frac{A}{1 + A\beta} \tag{2.5}$$

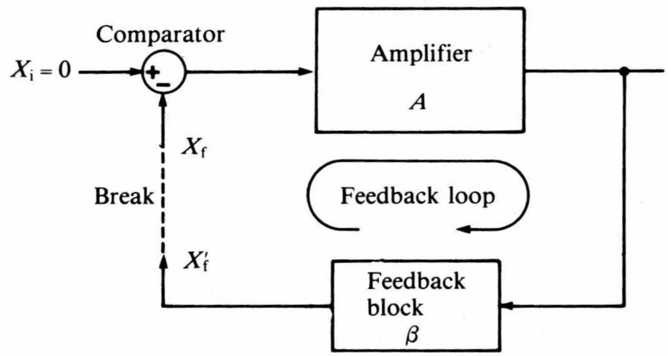

Fig. 2.2 Breaking the feedback loop to obtain loop gain.

This is the *fundamental feedback relationship*. The gain A without feedback is known as the *open-loop gain*.

It can be seen that the effect of feedback is to cause the gain in the forward path to be divided by the factor $1 + A\beta$.

Exercise 2.1 Derive the following expressions for the internal signals in terms of the system input;

$$X_f = \frac{A\beta}{1 + A\beta}. X_i \text{ and } X_{ia} = \frac{1}{1 + A\beta}. X_i \tag{2.6}$$

Now consider again the feedback loop in Fig. 2.1 comprising the forward-path amplifier, the feedback block and the comparator. Suppose the system input is not present, $X_i = 0$, and also suppose the feedback loop is temporarily broken at any point, say at the output of the feedback block, as shown in Fig. 2.2. If a hypothetical signal is inserted at point X_f, then the output of the comparator is equal to $-X_f$, (see Equation 2.2 and set $X_i = 0$). This signal passes through the forward amplifier with gain A and emerges at the output with a value $-AX_f$. Then it passes into the feedback block which multiplies the signal by β to give the open-loop feedback signal $X_f' = -A\beta X_f$. Notice that in passing round the loop the hypothetical injected signal, X_f, has been multiplied by the factor $-A\beta$. This factor is called the *loop gain*, thus

This is a *thought experiment*, carried out to understand a concept rather than to do something in practice.

$$\text{Loop-gain} = -A\beta \tag{2.7}$$

A very important property.

At this point it may be noted that if the magnitude of $A\beta$ is much greater than unity then the closed-loop gain is approximately equal to $1/\beta$, and therefore becomes independent of the properties of the forward amplifier.

Exercise 2.2 Verify that the above argument provides the same formula for loop-gain no matter at what point the loop is broken.

To conclude this introduction we restate the most important result,

The fundamental feedback formula.

$$\text{Closed-loop gain} = \frac{\text{Forward gain}}{1 - \text{Loop gain}}$$

i.e.

$$A_f = \frac{A}{1 + A\beta} \qquad (2.8)$$

Positive and Negative Feedback

We are now ready to define the terms *negative feedback* (NFB) and *positive feedback* (PFB). As stated in the introductory chapter, if the input signal to the system is reduced in magnitude when the feedback signal is subtracted from it then the feedback is negative. Looking at Equation 2.6 for the output from the comparator, X_{ia}, in terms of the signal input, X_i, negative feedback occurs when $|1 + A\beta|$ is greater than unity. This fact, when applied to the fundamental feedback relationship (2.8), shows for negative feedback that the magnitude of the gain, with feedback, is less than the forward gain. Converse statements can be made about positive feedback. Therefore the equivalent definitions of NFB and PFB can be written in terms of the magnitudes of the various quantities, as shown in Table 2.1.

Despite the name, negative feedback has very positive benefits!

Table 2.1 Equivalent Definitions of Negative and Positive Feedback

Negative feedback	Positive feedback
$\lvert X_{ia}\rvert < \lvert X_i\rvert$	$\lvert X_{ia}\rvert > \lvert X_i\rvert$
$\lvert 1 + A\beta\rvert > 1$	$\lvert 1 + A\beta\rvert < 1$
$\lvert A_f\rvert < \lvert A\rvert$	$\lvert A_f\rvert > \lvert A\rvert$

The vertical bars | | mean absolute value for real numbers, or modulus for a complex number.

From the formula $(1 + A\beta)$, it can be seen that the presence of negative or positive feedback depends on the particular values of forward gain A and feedback fraction β. A variety of conditions are possible. Consider what happens to the closed-loop gain A_f when, for some particular value of forward-gain A, the feedback fraction β is varied over positive and negative values. The fundamental feedback equation (2.8) is expressed graphically in Fig. 2.3. Although the curve is drawn for A positive, consider five regions of the curve for both positive and negative A.

Region (i) ($A\beta > 0$) (negative feedback). In this region, the loop gain $(-A\beta)$ is negative and so $|1 + A\beta| > 1$, thus showing that the feedback is negative. As β is increased the factor $|1 + A\beta|$ is also increased, the negative feedback strengthened and so the closed-loop gain is reduced. As β decreases towards zero, the closed-loop gain increases in magnitude until at $\beta = 0$, the factor $|1 + A\beta|$ is unity and the fundamental feedback relationship indicates that the closed-loop gain equals the open-loop gain, $A_f = A$. This is to be expected since if $\beta = 0$ it is equivalent to having no feedback at all.

Splitting the curve into smaller parts

Region (ii) ($-1 < A\beta < 0$) (positive feedback). In this region the loop-gain $(-A\beta)$ is positive and $|1 + A\beta| < 1$, thus showing that the feedback is positive. The fundamental feedback relationship shows that the magnitude of the closed-loop gain is greater than that of the open-loop gain. If β is varied to make $A\beta$ approach -1 then $|1 + A\beta|$ becomes very small and the closed-loop gain increases without limit.

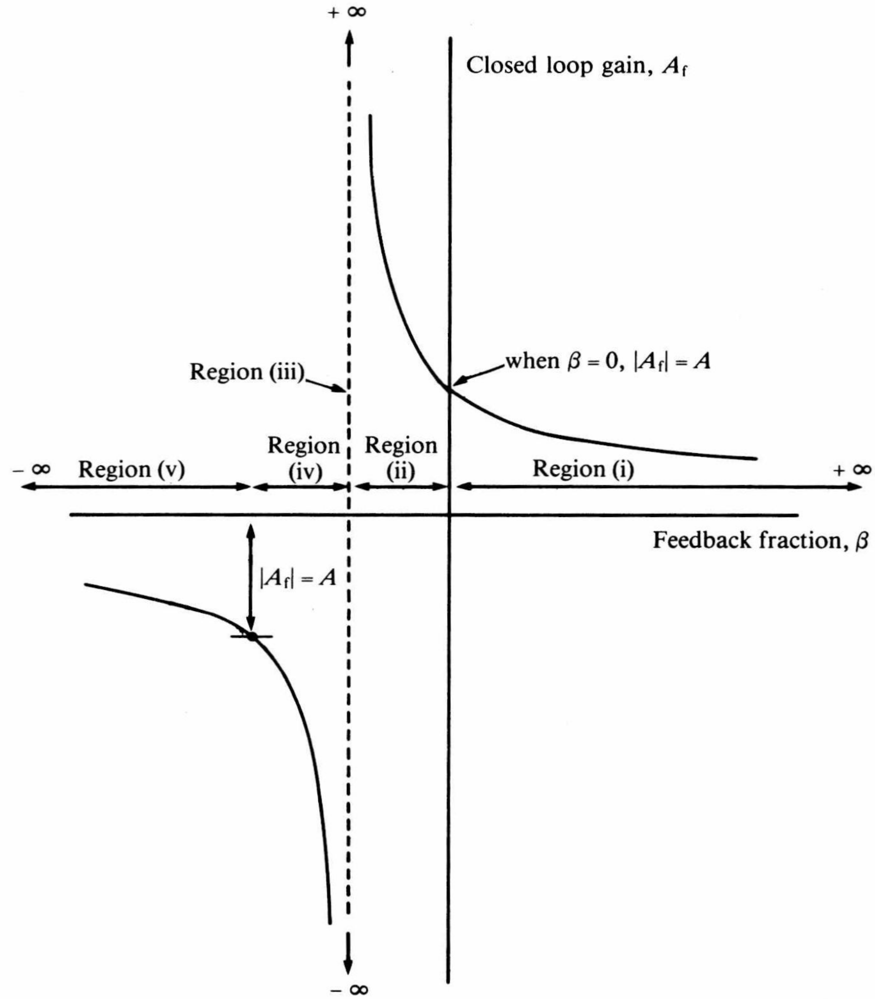

Fig. 2.3 Graph of fundamental feedback equation showing various feedback regions.

We have hit a *pole* of the function for closed-loop gain.

Region (iii) ($A\beta = -1$) (infinite gain, positive feedback). At this point the loop gain equals $+1$ and $|1 + A\beta| = 0$. The fundamental feedback relationship indicates a value of $A_f \rightarrow \infty$. Turning the gain relationship $X_o = A_f.X_i$ around, then $X_i = (A_f)^{-1}.X_o$. Thus $A_f \rightarrow \infty$ shows that a finite output X_o can be sustained for zero input signal. Consider again Fig. 2.2. A loop gain of exactly $+1$ means that $X_f' = X_f$. Thus once the loop is closed any signal in the system goes round the loop for ever with sustained amplitude. In effect the feedback system is not an amplifier of signals but a generator of signals. This is a special case of a feedback amplifier which can be exploited in the design of sinewave oscillators (see Chapter 8).

Region (iv) ($-2 < A\beta < -1$) (positive feedback, usually unstable). Increasing $A\beta$ negatively below -1 further increases the loop-gain beyond $+1$. Thus signals circulate round the feedback loop and usually increase in amplitude in an unstable way without limit until stopped by the inability of the amplifier to handle the large signals thus generated. This behaviour in amplifiers is called *instability* and is undesirable.

Region (v) ($A\beta < -2$) (negative feedback, usually unstable). In this region $(1 + A\beta) < -1$ and so $|1 + A\beta| > 1$ thus showing the feedback to be negative (see Table 2.1). However, as in the previous region (iv) because the loop-gain is greater than $+1$ in this region the system can be expected to be unstable.

Note that from the last two regions the conclusion can be drawn that a positive loop gain, greater than one is expected to result always in an unstable feedback system owing to signals circulating round the feedback loop and growing. However, under special circumstances stable operation is possible (but rarely used in practice). Discussion of this is left until Chapter 5.

In the discussion so far the parameters A and β of the feedback system have been assumed to have positive or negative real values. Signals X_i, X_o and X_f would all be in- or anti-phase if sinusoidal. In practice, the output signal of amplifiers and linear circuits generally are changed in phase as well as in magnitude when compared with the input signal. Both changes are functions of frequency. (The reason is discussed in the next chapter but need not concern us here.) Thus the amplification A_f is now written as the complex variable $\hat{A}_f$ which can be expressed in modulus and angle form or in terms of real and imaginary parts.

These concepts are explained in introductory circuit-theory books, e.g. Fidler, J.K. *Introductory Circuit Theory* (McGraw-Hill, 1980).

Nearly all the analysis derived, so far, for feedback systems with real quantities can be used equally well for complex quantities by merely interpreting the various parameters as complex variables and applying the usual rules for manipulation of complex numbers. For example the fundamental feedback equation (2.8) becomes

$$\hat{A}_f = \frac{\hat{A}}{1 + \hat{A}\hat{\beta}} \tag{2.9}$$

and the definitions of negative and positive feedback become

$$|1 + \hat{A}\hat{\beta}| > 1 \text{ for NFB}$$

and

$$|1 + \hat{A}\hat{\beta}| < 1 \text{ for PFB} \tag{2.10}$$

where the vertical bars are now taken to mean modulus of the complex quantity within.

The only part of the previous discussion which does not completely fit the general case of complex quantities is the discussion of the various stability regions of Fig. 2.3. In this figure A and β are assumed to be positive or negative real quantities, with phase shifts of 0° or 180°. The figure does not exist for complex values of $\hat{A}$ and $\hat{\beta}$ and a different approach is required to examine amplifier stability and instability (see Chapter 5).

Worked Example 2.1

An amplifier-block having a nominal gain of $A = 1000$ is to be used in a feedback circuit to provide a closed-loop gain having a magnitude equal to 10. Calculate a suitable value for feedback fraction β. If in practice the amplifier block turns out to have $A = 900\underline{/-30}°$ then calculate the closed-loop gain actually obtained.