DESIGNING ELECTRONIC CIRCUITS

A Manual of Procedures and Essential Reference. Data

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A Word from the Author on the Unique, Practical Value This Book Offers

This forward-looking manual of electronic circuit design techniques, tables, and formulas includes computer programs (with illustrative RUNS) to facilitate preliminary design procedures.

The text starts with an explanation of basic amplifier design procedure with bipolar transistors using hybrid parameters for preliminary device and component evaluation. I give practical examples for the CE, CC, and CB modes of operation. The introductory discussion concludes with a helpful computer program that enables the designer to quickly "punch out" basic amplifier performance figures relative to tentative device and component values.

Procedural topics continue with detailed examination of bias stabilization requirements in basic amplifier design with bipolar transistors. Stabilizing circuitry includes resistor, diode, thermistor, and transistor arrangements. Voltage and current stability factors are derived, and various practical examples are cited. Bias stabilization considerations conclude with effective computer programs for facilitating design analyses.

Amplifier discussion continues with considerations of noise factor and its optimization. I treat audio preamplifier design from an applications viewpoint and optional trade-offs. There are practical examples of preamplifier classes and performance characteristics. I review coupling circuitry for both utility applications and for high-fidelity operation. I examine negative-feedback circuitry and present helpful computer programs to speed up circuit design procedures.

The next examination is of driver and power-amplifier design considerations for bipolar transistor audio circuitry. There is a review of various trade-off options from the standpoint of production economy. I discuss both utility and high-fidelity applications, with various practical examples. I present an introduction to reliability evaluation, pointing out common design pitfalls. These topics conclude with appropriate computer programs to facilitate the design procedure.

Tolerance is a "dirty word" in some areas of design. Admittedly, design tolerances are often difficult (and sometimes impossible) to calculate with a high level of confidence. The text coverage illustrates how a heuristic programming approach can sometimes simplify tolerance calculations for optimal design. There is also a chained graphical technique that facilitates evaluation of tolerance requirements.

Next, I review the basics of tuned-amplifier design with an examination of coupling circuitry characteristics. There is a discussion of various options from the viewpoint of production economy. And, I discuss additional tolerance factors and control of "drift" factors, together with practical examples. There is an outline of gain-control requirements. You will find appropriate computer programs to facilitate coupling-circuit design procedures.

The next description of wide-band bipolar transistor amplifier arrangements includes a review of frequency compensation, direct coupling, RC coupling, negative feedback, and tolerance considerations, all from the standpoint of practical design procedures. You will find typical trade-offs and design options, again with practical examples. A helpful computer program to assist in calculation of design tolerances (worst-case performance characteristics) is part of this section.

The next subsection recaps the foregoing chapters with respect to MOSFET design procedures. There is a detailed description of similarities and differences between bipolar and MOS amplifier circuitry with their relevant advantages and disadvantages. You will read about design procedures, which are exemplified for common-source, common-drain, and common-gate configurations.

I point out applications that are facilitated by very high input resistance, wide dynamic range, and very high forward transconductance.

There are various computer programs with the design procedures to speed up development of prototype models. You will find heuristics to compute optimal parameters in preliminary design procedures. I give practical consideration to worst-case analyses.

Next, I discuss principles of oscillator design with respect to both low-frequency and high-frequency operation. I analyze the RC oscillator in some detail again and provide various computer programs to facilitate preliminary design procedures. I review operating stability, practical production-engineering requirements, and factors relating to harmonic generation.

Up to this point, the focus of attention is directed to basic electronic circuit building blocks and their characteristics. Since a building block such as a parallel-resonant circuit may be energized by a voltage source with significant internal resistance, its parameters are modified accordingly. Again, the resonant circuit may also supply its current demand to a load that has significant conductance. Accordingly, its parameters are further modified. In turn, the focus of attention is redirected to contextual circuit analysis of both RC circuitry and LCR circuitry.

You will find computer programs for calculation of the input and output impedances of unloaded and loaded RC differentiating and integrating circuits. I consider single-section and two-section arrangements; the two-section arrangements include both symmetrical and unsymmetrical configurations. The book contains practical graphs for rapid determination of output/input voltage and phase relations. Survey programs that print out extensive frequency response data supplement the design graphs.

I then discuss basic filter design procedures, insofar as they relate to the needs of the practical design engineer. I review simple RC filters and illustrate the effect of component tolerances. Passive and active tone controls, equalizers, bandpass and loaded bandpass, and low-pass filters with low-frequency cut provisions are described and illustrated. Computer programs are provided to speed up preliminary design procedures.

The next chapter is concerned with the principles of transient circuit design. Nonsinusoidal oscillator circuitry is included. Emphasis is placed on mathematical treatment of transient circuit operation and the effects of component tolerances. I provide various computer programs to ease the task of mathematical analysis.

You will find an example of creative design procedure in the final chapter, entitled Elements of Linear RC Voltage Bootstrap Circuitry. It shows step by step, with practical examples, how to design an RC-integrating or differentiating network that develops an output voltage greater than its input voltage. Then, I show cascaded arrangements that produce an output voltage that approaches a limiting value, followed by cascaded configurations that develop an output voltage that approaches infinity as the number of RC sections is indefinitely increased. This is more of a tutorial chapter focusing on the creative process than on practical applications of known network theory.

The book includes useful appendices for explanation of program conversions among the more popular types of personal computers, for ready reference to most-often-used mathematical relations, and for speedy retrieval of electronic circuit data. The cross-referenced index facilitates localization of any topic that the designer may need to look up.

Professional electronic designers and troubleshooters know that time is money and that knowledge is power. Your success in practice of your profession is limited only by the horizons of your technical know-how. The unique and practical design approaches, application techniques, procedural data, examples, computer-aided design procedures, and technical reference data in this manual provide key stepping stones to your goal.

ROBERT G. MIDDLETON

Contents

1

BASIC AMPLIFIERS

COMMON-EMITTER AMPLIFIER

The simplest practical common-emitter amplifier arrangement is shown in Figure 1–1. To calculate the voltage gain, power gain, current gain, input resistance, and output resistance for this configuration, it may be skeletonized, as depicted in Figure 1–2. Since the transistor is a nonlinear device, small-signal class-A operation is discussed at this time. Calculations are made with respect to the equivalent circuit shown in Figure 1–3.

Voltage gain is calculated from the formula:*

$$A_v = \frac{-\alpha_{fe}R_L}{(h_{ie}h_{oe} - \alpha_{fe}\mu_{re})R_L + h_{ie}}$$

EXAMPLE:

R_L = 15 kilohms h_{ie} = 1500 ohms $h_{oe} = 20 \times 10^{-6}$ Siemens

$\alpha_{fe} = 50$ $\mu_{re} = 5 \times 10^{-4}$

$A_v = -476$

*A short computer proram for rapid calculation of amplifier parameters is provided at the end of this chapter.

Current gain is calculated from the formula:

$$A_i = \frac{-\alpha_{fe}}{h_{oe}R_L + 1}$$

EXAMPLE:

R_L = 15 kilohms $h_{oe} = 20 \times 10^{-6}$ Siemens

$\alpha_{fe} = 50$

$A_i = -38.4$

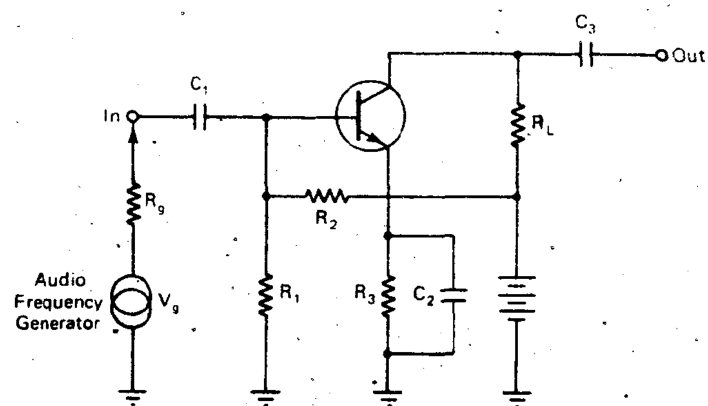


Figure 1–1. Simplest practical common-emitter amplifier arrangement.

NOTE: The hybrid parameters are frequency-dependent in this example, because R3 is bypassed by C2. At zero frequency (dc), C2 is effectively open; at high frequencies, C2 is effectively a short circuit for ac. The hybrid parameters are unaffected by the values of C1 and C3.

In preliminary design procedures, it is usually helpful to keep the requirements in mind for a low noise figure. Thus, a collector-supply voltage less than two volts, an emitter current less than one milliampere, and a generator (source) internal resistance in the 300- to 3,000-ohms range are practical guidelines for an audio-input stage.

Transistor data sheets ordinarily specify hybrid-parameter values for average values of collector voltage and current. Accordingly, adjusted values of hybrid parameters should be used when calculating amplifier performance at low values of collector voltage and current.

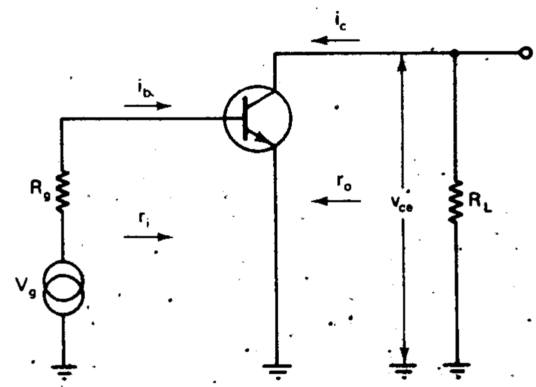


Figure 1–2. Skeletonized version of the configuration in Figure 1–1.

NOTE: In some circumstances, the designer has no choice of generator resistance. If R_g is very high, the proper procedure is to reduce the emitter current to the lowest practical level and to select a transistor type that has a maximum forward current-transfer ratio (h_{fe}). These considerations will minimize the noise figure in an audio-input stage, for example.

The input resistance r_i is the e/i ratio that the generator "sees," looking into the base of the transistor. The output resistance r_o is the e/i ratio that the load "sees," looking back into the collector of the transistor.

The predominant design goal for small-signal audio amplifiers is generally maximized power gain. However, the designer seldom has a "free hand" and must make judicious trade-offs with respect to production costs and product "price tag."

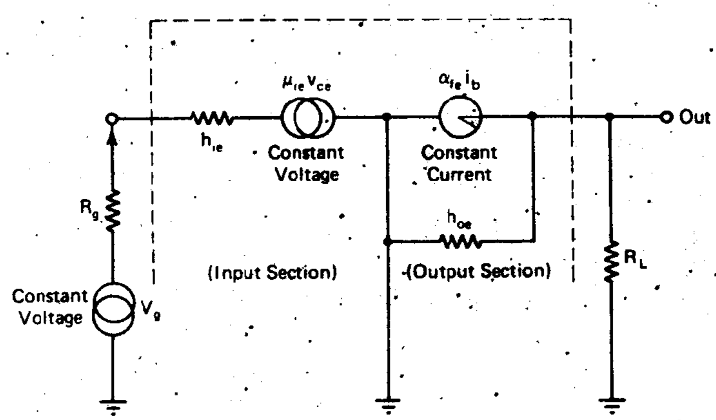


Figure 1–3. Equivalent circuit for the arrangement in Figure 1–2.

NOTE: The hybrid parameter h_{ie} is equal to the input impedance of the transistor with output short-circuited. The hybrid parameter μ_{re}, or h_{re}, is equal to the reverse open-circuit voltage amplification factor. The hybrid parameter α_{fe}, or h_{fe}, is equal to the forward short-circuit current amplification factor. The hybrid parameter h_{oe} is equal to the output admittance of the transistor with open-circuit input. V_{ce} is the collector-to-ground voltage, and i_b is the base current of the transistor.

Power gain is calculated from the formula:

$$G_p = A_v A_i$$

or,

$$G_p = \frac{(\alpha_{fe})^2 R_L}{(h_{oe}R_L + 1)\left[(h_{ie}h_{oe} - \alpha_{fe}\mu_{re})R_L + h_{ie}\right]}$$

> EXAMPLE:
>
> $A_v = -476$ $A_i = -38.4$
>
> $G_p = 18{,}278$
>
> $R_L = 15$ kilohms $\alpha_{fe} = 50$ $h_{oe} = 20 \times 10^{-6}$ Siemens
>
> $h_{ie} = 1500$ ohms $\mu_{re} = 5 \times 10^{-4}$
>
> $G_p = 18{,}315$ $G_p(\text{dB}) = 10 \log 18{,}315 = 10 \times 4.26 = 42.6$ dB

Input resistance is calculated from the formula:

$$r_i = \frac{h_{ie} + (h_{oe}h_{ie} - \alpha_{fe}\mu_{re})R_L}{1 + h_{oe}R_L}$$

> EXAMPLE:
>
> $R_L = 15$ kilohms $\alpha_{fe} = 50$ $h_{oe} = 20 \times 10^{-6}$ Siemens
>
> $h_{ie} = 1500$ ohms $\mu_{re} = 5 \times 10^{-4}$
>
> $r_i = 1212$ ohms

Output resistance is calculated from the formula:

$$r_o = \frac{h_{ie} + R_g}{h_{oe}h_{ie} - \mu_{re}\alpha_{fe} + h_{oe}R_g}$$

> EXAMPLE:
>
> R_g 1500 $h_{oe} = 20 \times 10^{-6}$ Siemens
>
> $h_{ie} = 1500$ ohms $\mu_{re} = 5 \times 10^{-4}$ $\alpha_{fe} = 50$
>
> $r_o = 85{,}714$ ohms

Observe in the foregoing examples that A_v is negative because the output voltage has reversed phase compared to the input voltage. A_i is negative because the output current has reversed phase compared to the input current.

HYBRID PARAMETERS

Hybrid parameters are employed in the foregoing examples. The hybrid parameters for the common-emitter configuration are:

h_{ie} or h_{11e} = Input impedance with output short-circuited
h_{oe} or h_{22e} = Output admittance with open-circuit input
h_{re} or h_{12e} = Reverse open-circuit voltage amplification factor
h_{fe} or h_{21e} = Forward short-circuit current amplification factor

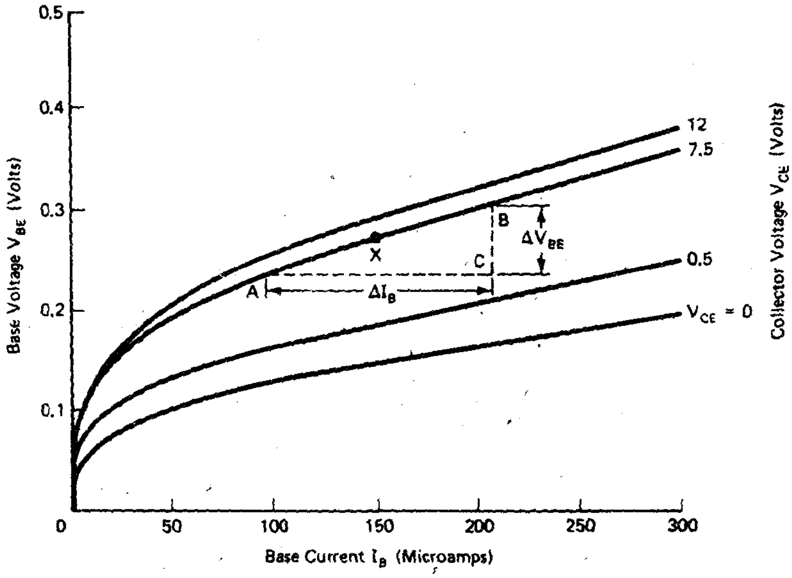
Note that h_{re} is also called μ_{re} and h_{fe} is also called α_{fe}.

As shown in Figures 1–2 and 1–3, R_g denotes the generator resistance or the internal resistance of the signal source.

HYBRID PARAMETER DEFINITIONS

The input impedence of a transistor with its output short-circuited (h_{ie}) is defined as shown in Figure 1–4. This is a plot of base voltage versus base current, with collector voltage as the running parameter, for a typical bipolar transistor. Since the V_{BE}/I_B characteristics are nonlinear, the value of h_{ie} will depend on choice of the operating point. The operating point in this example is indicated by X. The corresponding value of h_{ie} is equal to the limiting ratio of $\Delta V_{BE}/\Delta I_B$ for a chosen value of collector voltage (in this example, V_{CE} = 7.5 volts). This ratio has a value in the limit of 608 ohms for the particular transistor and for the specified operating (quiescent) point.

The reverse open-circuit voltage amplification factor of a transistor is defined as shown in Figure 1–5. This is a plot of base voltage versus collector voltage, with base current as the running parameter, for a typical bipolar transistor. Inasmuch as the V_{BE}/V_{CE} characteristics are nonlinear, the value of h_{re} depends on choice of the operating point. In this example, the operating point is indicated by X.



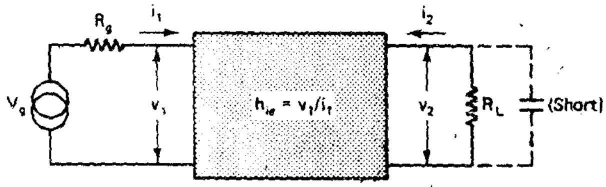


Figure 1–4. Definition of the input impedance of a transistor with its output short-circuited (h_{ie}).

NOTE: H parameters are slopes of the static characteristic curves for the particular transistor.

In turn, the corresponding value of h_{re} is equal to the slope of the tangent at point *X* on the 150-μA curve. This slope has a value of 14×10^{-4} for the particular transistor and for the specified operating point. Note that the diagram in Figure 1–5 depicts reverse transfer (feedback) characteristic curves for the common-emitter configuration. Stated otherwise, a collector-voltage variation ΔV_{CE} will appear at the input as a base-voltage variation ΔV_{BE}.

The forward short-circuit current amplification factor (h_{fe}) for a transistor is defined as shown in Figure 1–6. This is a plot of