OPERATIONAL AMPLIFIERS

Theory and Design

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CONTENTS:

SUMMARY

A systematic circuit design of operational amplifiers is presented. It is shown that the topology of all operational amplifiers can be divided in nine main overall configurations. These configurations range from one gain stage up to four or more gain stages. Many famous designs are completely evaluated.
High-frequency compensation techniques are presented for all nine configurations. Special focus is on low-power low-voltage architectures with rail-to-rail input and output ranges.
The design of fully differential operational amplifiers and operational floating amplifiers is being developed. Also, the characterization of operational amplifiers by macromodels and error matrices is presented, together with measurement techniques for their parameters.
Problems and simulation exercises have been supplied for self-evaluation.

INTRODUCTION

The goal of this book is to equip the circuit designer with a proper understanding of the theory and design of operational amplifiers (OpAmps). The core of the book presents the systematically design of operational amplifiers. All operational amplifiers can be classified into a periodic system of nine main overall configurations. This division enables the designer to quickly recognise, understand, and choose optimal configurations.

Chapter 1 defines four basic types of operational amplifiers on the basis of the external ground connections of the input and output ports of generalized linear active network elements. Whether an input or output port needs to be isolated from ground has a big impact on the circuit design of the input and output stages, as will be shown in later chapters.

A complete set of linear parameters, by which each of the above four basic types of operational amplifiers can be quantified, is given in Chapter 2. This provides the reader with a sense of which parameters are most important. Chapter 2 also presents macromodels and measurement techniques for OpAmp parameters.

A systematic treatment of sources of errors in important applications of the above four basic types of operational amplifiers is presented in Chapter 3.

Input stages are evaluated in Chapter 4. Important aspects such as bias, offset, noise, and common-mode rejection are considered. Low-voltage input stages with a rail-to-rail input voltage range are extensively discussed.

A classification of push-pull output stages is presented in Chapter 5. Three possible topologies are explored: voltage follower stages, compound stages, and rail-to-rail general amplifier stages. Designs are presented with feedforward and feedback biasing class-AB techniques.

Emphasis is on voltage and current efficiency.

A classification of operational amplifiers into nine main overall configurations is presented in Chapter 6. The classification consists of two two-stage OpAmps, six three-stage OpAmps, and one four- or multi-stage OpAmp. High-frequency compensation techniques are developed for all configurations ranging from one gain stage up to four or more gain stages. Methods are presented for obtaining a maximum bandwidth over power ratio for certain capacitive load conditions. Slew-rate and distortion are also considered.

Chapter 7 presents design examples of each of the nine main configurations. Many well-known OpAmps are fully elaborated. Among them are simple CMOS OpAmps, high-frequency bipolar OpAmps, Precision bipolar and BiCMOS OpAmps, low-voltage CMOS and bipolar OpAmps, and OpAmps with a high output drive capability in CMOS as well as in BiCMOS technology.

The design of fully differential operational amplifiers with common-mode feedback is developed in Chapter 8. Special focus is on low-voltage architectures.

When the output port as well as input port are designed such that they are both isolated from ground, the most universal linear active network element is created: the operational floating amplifier. The concept of this OpAmp gives the designer the freedom to work with current signals as well as voltage signals. Realizations of operational floating amplifiers are developed in Chapter 9 also in relation to instrumentation amplifiers.

Problems and simulation exercises have been supplied for most of the chapters to facilitate self-evaluation of the understanding and design skills of the user of this book.

NOTATION

OpAmp	operational amplifier
OA	operational amplifier
OIA	operational inverting amplifier
OVA	operational voltage amplifier
OCA	operational current amplifier
OFA	operational floating amplifier
GA	general amplifier stage
VF	voltage follower stage
CF	current follower stage
CM	current mirror stage
IA	instrumentation amplifier

a	temperature coefficient
A_v	voltage gain
A_{vo}	DC voltage gain
β	current gain of bipolar transistor
B_v	voltage attenuation of feedback network
C	capacitor value
C_{ox}	specific capacitance of gate oxide
C_M	Miller capacitor value
C_P	parallel capacitor value
D	distortion
f	frequency
f_T	transit frequency of a transistor
f_o	zero-dB frequency
g_m	transconductance of a transistor
i	small-signal current
I	current
I_B	bias current
I_C	collector current
I_D	drain current
I_E	emitter current
I_S	supply current
I_Q	quiescent current

k	Boltzman's Constant
K	$= \mu C_{ox} W/L$
L	length of gate in MOS transistors
M	CMOS transistor
R	resistor value
S	signal
S_r	slew rate
T	generalized transistor
Q	bipolar transistor
v	small-signal voltage
V	voltage
V_B	bias voltage
V_{CC}	positive supply voltage with bipolar transistors
V_{DD}	positive supply voltage with MOS transistors
V_{EE}	negative supply voltage with bipolar transistors
V_G	generator voltage
V_{GS}	gate-source voltage
V_{GT}	active gate-source voltage $(V_{GS}-V_{TH})$
V_S	total-supply voltage
V_{SN}	negative supply voltage
V_{SP}	positive supply voltage
V_{SS}	negative supply voltage with MOS transistors
V_T	thermal voltage kT/q
V_{TH}	threshold voltage of MOS device
W	width of gate in MOS transistors
μ	mobility of change carriers

Extrinsic device parameters

R_L
C_L
C_M
R_D R_C
R_G R_B
R_S R_E

Intrinsic Small-signal transistor parameters

r_{ds} r_{ce} r_o
r_{gs} r_{be}
r_s r_e
c_{ds} c_{ce}
c_{gs} c_{be}
g_m g_m
μ_n μ_p
β_n β_p

1. DEFINITION OF OPERATIONAL AMPLIFIERS

Nullor Concept

In 1954 Tellegen introduced the concept of a universal active network element under the name of "ideal amplifier" [1.1]. The name "nullor", generally accepted now, was given to it by Carlin in 1964 [1.2]. The symbol of a nullor is shown in Fig. 1.1.

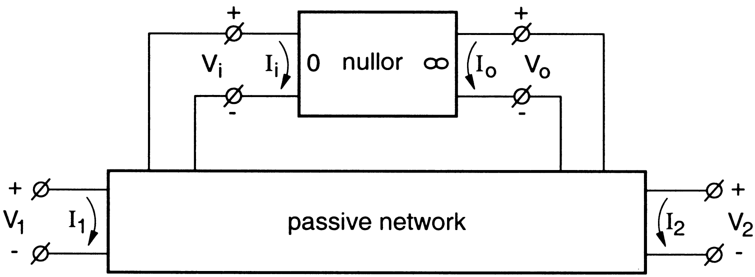

Fig. 1.1: A two-port network composed of a passive network and a nullor

The nullor is defined as a two-port network element whose ports are called input and output ports and whose input voltage V_i and input current I_i are both zero, so:

$$V_i=0, \qquad I_i=0 \tag{1.1}$$

The nullor concept only has significance if a passive network external to the nullor provides for a feedback from the output port into the input port [1.3]. The output voltage V_o and the output current I_o will be determined by the passive network elements in such a way that the input requirements $V_i=0$, $I_i=0$ are satisfied.

An accurate signal transfer requires, firstly, accurate passive components and secondly, a practical nullor realization which approximates $V_i=0$, $I_i=0$.

This implies that the nullor realization should have a high gain, a low input noise, and low offset voltage and current (see Chap. 2.1). All linear and non-linear analog transfer functions can be implemented with nullor realizations and passive components.

Classification based on number of floating ports

We will now classify four nullor types on the basis of the number of ports which are floating, beginning with both ports grounded and ending with both ports floating. There are two main reasons for this kind of classification. Firstly, the larger the number of ports which are grounded the simpler the construction of the active device will be. Secondly, the larger the number of grounded ports the lower the number of possible feedback topologies will be allowed.

We will give each of the four nullor types a name which will be explained later. The first one with two grounded ports will be called operational inverting amplifier (OIA). The second one with the input port floating and output port grounded will be called operational voltage amplifier (OVA). The third one with the input port grounded and output port floating will be called operational current amplifier (OCA). Finally, the fourth one with both ports floating will be called operational floating amplifier (OFA). The adjective "operational" was coined by John R. Ragazzini and his colleagues in a paper [1.4] published in 1947. That paper described the basic properties of an OIA used with linear and nonlinear feedback. The adjectives "inverting" (I), "voltage" (V), "current" (C), or "floating" (F), are given by the present author to distinguish the four types of Operational Amplifiers according to their most striking attribute, as we will see in the next sections of this chapter. The most popular one, the OVA will be shortened to OpAmp in most parts of this book, where the distinction between the different types is not needed.

1.1 Operational Inverting Amplifier (OIA)

A practical approximation of a nullor having both ports grounded will be called an "operational inverting amplifier" (OIA). The grounded input port makes the construction of the input stage relatively easy, because it only needs to function at one voltage level [1.4] [1.5]. Similarly, the grounded output port makes it relatively easy to construct an output stage having a high power efficiency, because the current return path can be directly connected to the grounded supply voltages. The negative sign (inverting) of the amplification factor makes it possible to obtain stable negative feedback with passive components connected directly from the output to the input port. The parallel connection of the feedback circuit at the input and output of the amplifier results in a low virtual entrance impedance (see Chap. 3.1), suitable for accurate current sensing at virtual zero input power, and a low exit impedance, suitable for obtaining an accurate output voltage.

Current-to-Voltage Converter

The most simple application of an OIA is the transimpedance amplifier or current-to-voltage transactor. This circuit is shown in Fig. 1.1.1.a with a symbol of a nullor and in Fig. 1.1.1.b with a practical symbol of an OIA.

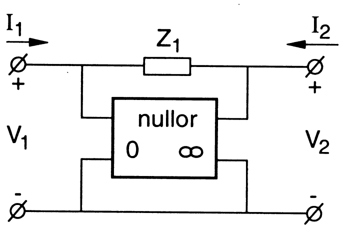

Fig. 1.1.1.a: Transimpedance amplifier with a nullor symbol

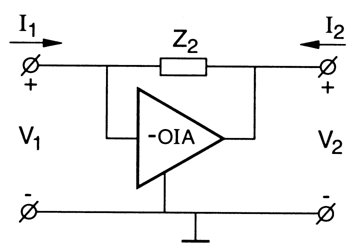

Fig. 1.1.1.b: Transimpedance amplifier with an OIA symbol

The current-to-voltage transfer factor

$$Z_t = V_2/I_1 = -Z_1, \text{ at } V_1 = 0 \tag{1.1.1}$$

can be accurately determined by $-Z_1$ if the OIA satisfies two requirements: firstly, a high gain, and secondly, a low input offset voltage and offset current. A high gain also assures low entrance and exit impedances.

1.2 Operational Voltage Amplifier (OVA)

A practical nullor approach having only the output port grounded and the input port floating [1.6, 1.7] will be called "operational voltage amplifier" (OVA) or OpAmp. Currently, it is the most widely applied universal active device. The floating character of the input port imposes special demands on the construction of the input circuit, as will be discussed in Chapter 4.3 and 4.4. The floating input port allows series coupling of negative feedback.
This results in a high entrance impedance suitable for accurate voltage sensing at virtual zero input power. The parallel coupling of the feedback network with the grounded output port assures a low exit impedance.

Non-inverting Voltage Amplifier

The most essential application of the OVA is the non-inverting voltage amplifier or voltage-to-voltage transactor. The circuit is drawn in Fig. 1.2.1.a with a nullor symbol and in Fig. 1.2.1.b with a practical amplifier symbol for an OVA.

The voltage amplification factor

$$A_u = V_2/V_1 = (Z_1 + Z_2)/Z_2, \text{ at } I_1 = 0 \tag{1.2.1}$$

can be accurately determined by the impedance ratio $(Z_1+Z_2)/Z_2$ if the OVA satisfies the requirements: a high gain, a low input offset voltage and current, independent of the common-mode voltage of the input port, and a low input bias current. A high gain assures a high entrance impedance and a low exit impedance.

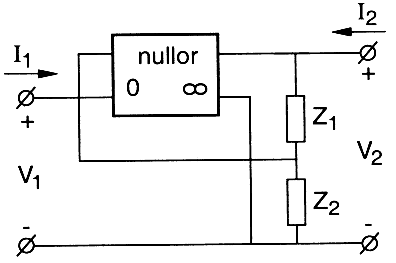

Fig. 1.2.1.a: Voltage amplifier with a nullor symbol

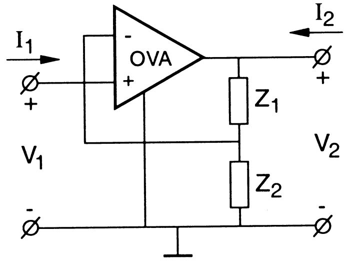

Fig. 1.2.1.b: Voltage amplifier with an OVA symbol

Voltage Follower (VF)

A special situation occurs if the OVA has its negative input terminal connected with the output terminal. We will call such a device a "voltage follower" (VF), because the exit voltage follows the entrance voltage. The construction of a universal active device with this connection may be simpler than without this connection, because no voltage shifting is required between the input and output. The VF circuit is given in Fig. 1.2.2.b with an OVA symbol.

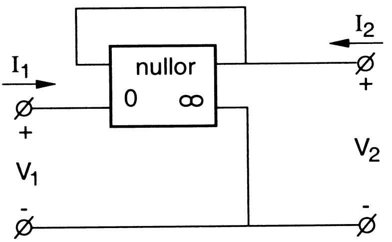

Fig. 1.2.2.a: Voltage follower with a nullor symbol

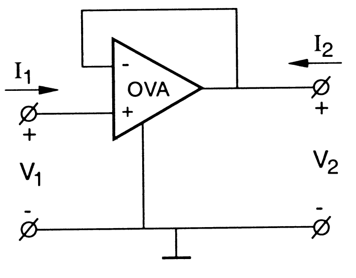

Fig. 1.2.2.b: Voltage follower with an OVA symbol

The voltage follower has the unique property that the voltage amplification factor

$$A_u = V_2/V_1 = 1 \text{ at } I_1 = 0 \qquad (1.2.2)$$

precisely equals plus unity, independently of any passive components, if the amplifier satisfies the three requirements: high gain, low input offset voltage and current, and a low input bias current. The accuracy of the plus-unity voltage transfer is not limited by the tolerances of any passive components. Note that the accuracy of the minus-unity voltage transfer of a voltage inverter does depend on the tolerance of a ratio of two impedances, as shown in Chapter 3.1, Fig. 3.1.2.

The voltage follower uses the most important attribute of a floating input port, viz. that the potential at one input terminal precisely follows the potential at the other input terminal.

1.3 Operational Current Amplifier (OCA)

A nullor approximation which has only the input port grounded and the output port floating [1.8] will be called an "operational current amplifier" (OCA). An output port with a floating character is difficult to construct, as we will see in Chapter 9. However, this labour is rewarded for applications requiring a high output impedance by using feedback in series coupling with the output port. This series feedback results in an exit with a current-source character, while the grounded input port with parallel feedback assures a low entrance impedance.

Current Amplifier

The most elementary application of the OCA is a current amplifier, whose circuit is shown in Fig. 1.3.1.b with an OCA symbol. The amplifier is the current dualogon of the voltage amplifier of Fig. 1.3.1.b. The amplification factor

$$A_I = -I_2/I_1 = -(Y_1+Y_2)/Y_1, \text{ at } V_1=0, \qquad (1.3.1)$$

is accurately determined by the admittance ratio $(Y_1+Y_2)/Y_1$ if the amplifier satisfies: a high gain, a low input offset voltage and current, and an output port with a low output bias current, because this current is directly added to the output. Note, that the minus sign merely results from the choice of the opposite current notations of I_1 and I_2. The low entrance impedance allows current sensing at a low entrance voltage V_1. The current source character at the exit yields an accurate current transfer independently of the load impedance.

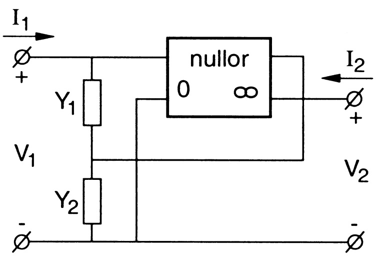

Fig. 1.3.1.a: Current amplifier with a nullor symbol

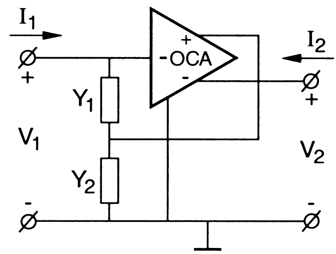

Fig. 1.3.1.b: Current amplifier with an OCA symbol

Current Followers (CF)

A special situation occurs if the negative input terminal of the OCA is connected with the output terminal. We will call such a configuration a "current follower" (CF), because the exit current follows the entrance current. This circuit is the current dualogon of the voltage follower. The circuit is drawn in Fig. 1.3.2.a with a nullor symbol and in Fig. 1.3.2.b with an OCA symbol.

The current follower has the unique attribute that the current amplification factor

$$A_i = -I_2/I_1 = 1, \text{ at } V_1=0, \qquad (1.3.2)$$

precisely equals plus unity, independently of any passive component values, if the gain is high, the input offset voltage and current is low, and if the output port has a low bias current. In contrast, the current-amplification factor of a current mirror, which nominally is minus unity, does depend on the matching of two passive elements (see Chap. 3.4).

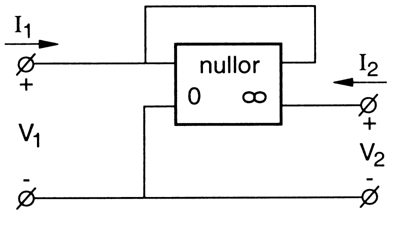

Fig. 1.3.2.a: Current follower with a nullor symbol

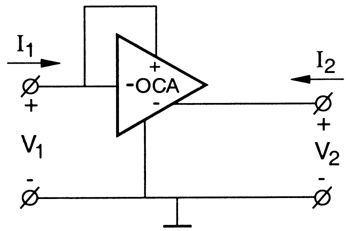

Fig. 1.3.2.b: Current follower with an OCA symbol

Note that the minus sign in Eq. (1.3.2) is needed because the output current I_2 is defined in the opposite direction regarding I_2, when the current is being transferred through the CF.

The current-follower action reveals the most important attribute of a floating output port, namely that the current which flows into one output terminal is precisely followed by the current which flows out of the other output terminal. This attribute is the very dualogon of the voltage-follower action of a floating input port.

1.4 Operational Floating Amplifier (OFA)

A nullor approximation which has both the input and the output ports floating [1.9] will be called an "operational floating amplifier" (OFA) [1.8, 1.9]. Earlier it was called a "monolithic nullor" [1.10], or second generation current conveyer [1.11]. The construction of such a universal active device combines the demands of both floating input and output ports.

The OFA provides the maximum freedom for composing feedback configurations. With simple passive components it is possible to apply negative feedback in series with input and output ports, which results in both a high entrance and exit impedance.

Voltage-to-Current Converter

A specific application of the OFA is the voltage-to-current converter or transadmittance amplifier. Such a circuit is shown in Fig. 1.4.1.a with a nullor symbol and in Fig. 1.4.1.b with a practical OFA symbol. The voltage-to-current transfer factor

$$Y_t = I_2/V_1 = Y_1,\ at\ I_1 = 0, \tag{1.4.1}$$

will be accurately determined by one admittance $-Y_1$ if the amplifier satisfies four requirements: high gain, low input offset voltage and current, low input bias current, and low output bias current. The negative feedback in series with both ports ensures a high entrance impedance and a high exit impedance, which gives the transactor a voltage-sensing entrance and a current-source exit character.

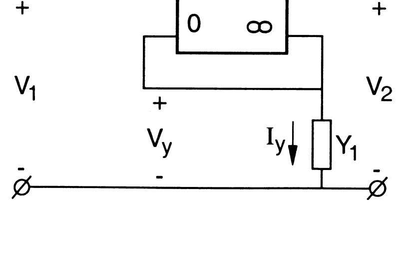

Fig. 1.4.1.a: Transadmittance amplifier with a nullor symbol

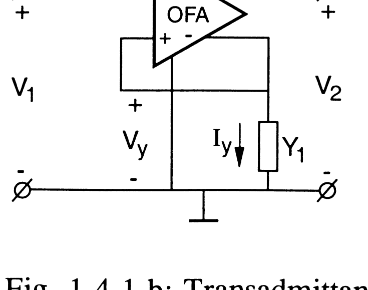

Fig. 1.4.1.b: Transadmittance amplifier with an OFA symbol

Voltage and Current Follower (VCF)

In fact, the transadmittance amplifier of Fig. 1.4.1.a/b does not apply all potentialities of the OFA. It is applied in the special case in which the lower terminal of the input port is connected with the lower terminal of the output port. This connection may simplify the construction of the OFA, because no voltage level shifter is needed between the input circuit and one output terminal, as we will see in Chapter 9.2. An OFA with this connection can be called a "voltage and current follower" (VCF).
A nullor which has this connection is also called a "three-terminal nullor" or a "unitor" [1.12]. In Fig. 1.4.1.b the VCF firstly acts like a voltage follower, accurately transferring the entrance voltage V_1 towards the voltage V_y on the upper side of the admittance Y_1, and secondly like a current follower, accurately transforming the current I through the

admittance Y_1 towards the current I_2 at the upper exit terminal.

1.5 Conclusion

A classification of universal active devices has been given on the basis of the number of ports which are connected to ground or to each other. The more ports not internally connected, the more freedom there is in the choice of the feedback configuration although this creates more complications with the construction of the device. Fig. 1.5.1 presents an