Journal of Electrical and Electronic Engineering
2022; 10(4): 149-157
http://www.sciencepublishinggroup.com/j/jeee
doi: 10.11648/j.jeee.20221004.13
ISSN: 2329-1613 (Print); ISSN: 2329-1605 (Online)

Feedback Modelling in Amplifier Circuits Using Open-Loop Transfer Functions

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To cite this article:
Spyros Loutridis. Feedback Modelling in Amplifier Circuits Using Open-Loop Transfer Functions. *Journal of Electrical and Electronic Engineering*. Vol. 10, No. 4, 2022, pp. 149-157. doi: 10.11648/j.jeee.20221004.13

Received: July 10, 2022; **Accepted**: July 25, 2022; **Published**: July 29, 2022

Abstract: Negative feedback is an established technique used to improve the quality of an amplifier. The modelling of the closed-loop circuit is a complex procedure that, if not done properly, may give erroneous results. A new method for modelling amplifiers that use negative feedback over a broad frequency range is presented. The method overcomes the main difficulties of the two-port analysis, namely the identification of the feedback type and the determination of the feedback network loading to the open-loop amplifier. Compared to other methods, it is more suitable for handling frequency-dependent quantities. All topologies are treated as voltage amplifiers. The open-loop amplifier is described by three open-loop transfer functions. The theoretical context of the non-ideal op amp is used to derive the closed-loop quantities, discriminating between the non-inverting and the inverting case. The proposed method provides accurate results over a broad range of frequencies. The poles and the zeros can be readily calculated as well as the loop gain, to examine the stability of the amplifier. It can account for complex loads and frequency-dependent gain-setting resistors. Another advantage is that once the open-loop transfer functions are known, other closed-loop configurations can be computed with no additional effort. Circuit complexity has not been found to be a problem. The proposed modelling technique has been used in the class for a number of years with undergraduate students responding positively to it.

Keywords: Feedback Circuits, Loop-Gain, Two-Port Analysis, Return Ratio

1. Introduction

The concept of feedback is fundamental in electronics and control systems. Negative feedback has certain benefits, the most important being the desensitization of the closed-loop gain. Other benefits include the extension of bandwidth, the reduction of noise and harmonic distortion. Negative feedback also modifies the input and output impedances, providing a means for tailoring the driving impedance at a specific port to our needs. The downside is a potential for instability that has to be taken care of at the design stage.

Most textbooks present feedback theory in terms of two-port analysis, [1-3], assuming unidirectional amplifier and feedback path. A simplified analysis of feedback amplifiers based on the two-port methodology was given by Marrero, [4]. Similarly, Yeung's approach [5] is essentially based on the two-port analysis. The problem with the two-port technique is that its ability to correctly describe the amplifier is based on the loaded open-loop gain, a vague quantity that occasionally accepts different definitions. Another difficulty is that the type of feedback, voltage or current, needs to be determined and then the feedback factor calculated. In addition, input and feedback signal mixing has to be characterized as series or shunt. This categorization creates four types of amplifiers: series-shunt, series-series, shunt-shunt, shunt-series, leading to an unnecessary complication.

A general method to analyze feedback amplifiers was proposed by Bode [6]. Bode introduced the concept of the return ratio (RR). The RR for a controlled source can be found by setting all independent sources to zero, breaking the connection between the controlled source and the circuit, then driving the circuit at the break point with an independent source of equal strength and calculating the resulting output through the feedback loop. The return ratio technique was further refined by Rosenstark, [7]. Using Blackman's formula, we are able to find the impedance at any port, [8]. Finding a dependent source that produces the simplest way to the result is a matter of experience. Otherwise, the procedure may be cumbersome and the result not particularly insightful.

Another technique for feedback circuit analysis is the one based on signal flow graphs, [9]. The method can in principle be used to handle any feedback architecture, however the choice of the parameters that represent each flow line is more or less an arbitrary process. Other methods for feedback circuit analysis can be found in references [10-13].

Regarding the subject of feedback amplifier modeling, little work has been done especially on models that predict the amplifier behavior over a broad frequency range. Cunha et al. [14], presented a low-pass equivalent feedback topology for feedback amplifier modelling where the open-loop gain is approximated by a polynomial, the coefficients of which are found with a recursive procedure. To complete the model, input- and output- matching filters are used. Yang [15], presented a simple model for the operational amplifier where the open-loop gain is represented with a transfer function with two poles. The model was found to be adequate for educational purposes. Gu et al. [16], proposed a new method based on dual-port network to solve an amplifier circuit using negative feedback. All parameters were assumed to be frequency independent.

In practical circuits, the open-loop gain as well as the port impedances are a function of frequency. The gain of an amplifier can exceed 100,000 at very low frequencies and reduce to less than unity at frequencies above 10 MHz. The same variability exists in the port impedances. For this reason, it is inadequate to characterize the performance of an amplifier with a single number. From the literature review it occurs that no existing technique is particularly suited for handling frequency dependent quantities. In this paper, a method for modelling amplifiers with feedback is presented that is based on the measurement and subsequent modelling of three main quantities: the unloaded open-loop gain, the open-loop input impedance, the open-loop output impedance. From these three transfer functions, all closed-loop quantities can be derived from a simple theory that is based on the concept of the non-ideal operational amplifier.

The structure of the paper is as follows: In Section II the theoretical background for the analysis of both inverting and non-inverting amplifiers is presented. Section III presents the analysis of amplifier circuits containing one or two poles in their transfer function. In Section IV, the proposed modelling method is applied on a practical amplifier circuit. In Section V the case of frequency-dependent gain-setting resistors is examined. The paper closes by highlighting all significant contributions made to the field.

2. Expressions for the Gain and Port Impedances of Feedback Amplifiers

2.1. Non-inverting Amplifier

Figure 1 depicts a simple model for a non-inverting amplifier. Here $Z_i(j\omega)$ is the open-loop input impedance, $Z_o(j\omega)$ the open-loop output impedance and $A(j\omega)$ the unloaded open-loop gain. The voltage dependent voltage source amplifies the error signal between the (+) and (-) nodes providing the output $V_o(j\omega)$. It is important to clarify how the quantity $A(j\omega)$ is calculated because it differs from the usual definition of the open-loop gain in two-port theory. The unloaded open-loop gain is calculated by removing any load connected at the output and taking the limit values $R_2 \to \infty$ and $R_1 \to 0$. The gain $A(j\omega)$ is higher than the traditional loaded open-loop gain and also extends higher in frequency. The open-loop input impedance must be calculated under the same conditions. The open-loop output impedance is calculated in the usual way by grounding the input, removing the load and connecting a current source I_S at the output. If V_o is the voltage measured at the output then $Z_o = V_o/I_s$. This procedure has to be followed for each single frequency within the frequency range of interest.

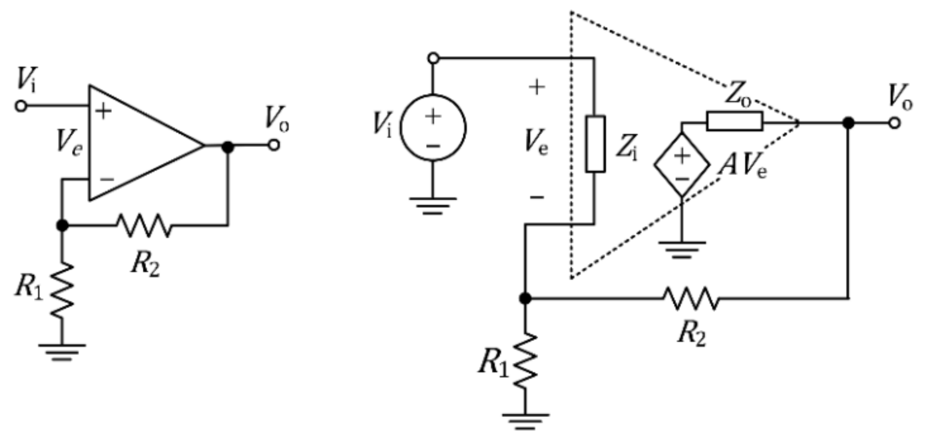

Figure 1. *Left: Non-inverting amplifier configuration, Right: amplifier model with voltage dependent voltage source.*

By writing the node equations of the circuit it is trivial to show that the closed-loop gain is given by the expression

$$A_{Vf} = \frac{V_o}{V_i} = \frac{(R_1+R_2)AZ_i+R_1Z_o}{D} \tag{1}$$

where the denominator is

$$D = (A+1)R_1Z_i + (R_1+Z_i)(R_2+Z_o) \tag{2}$$

The expressions for the closed-loop input and output impedances are as follows:

$$Z_{if} = \frac{D}{R_1+R_2+Z_o} \tag{3}$$

$$Z_{of} = \frac{[(R_1+R_2)Z_i+R_1R_2]Z_o}{D} \tag{4}$$

where D is given by (2) and subscript "f" denotes a quantity with feedback applied to the circuit.

While the input and output impedances are a property of the amplifier itself, the gain is altered by the presence of any source impedance and load connected to the output. Referring to the general circuit of figure 2, after having computed the quantities A_{vf}, Z_{if} and Z_{of} from Eqs. 1-4 the total gain from input to output can be found as

$$\frac{V_o}{V_i} = A_{vf} \cdot \frac{Z_{if}}{Z_s+Z_{if}} \cdot \frac{Z_L}{Z_{of}+Z_L} \tag{5}$$

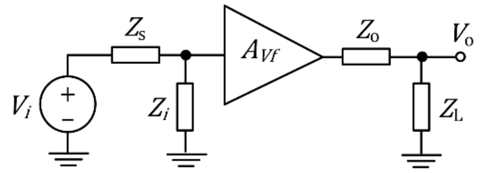

Figure 2. *The general case where the source has internal impedance Z_s and a load Z_L is connected to the output.*

2.2. Inverting Amplifier

Figure 3 shows an amplifier that inverts its input. In principle, every amplifier can be connected as inverting or non-inverting, however there are topologies that better serve for one case or the other. The quantities A, Z_i, Z_o are the same to that of Figure 1 and need not be measured again. The main difference between the circuits of Figure 1 and Figure 3 is that in the circuit of Figure 3 the input signal is applied through resistor R_1.

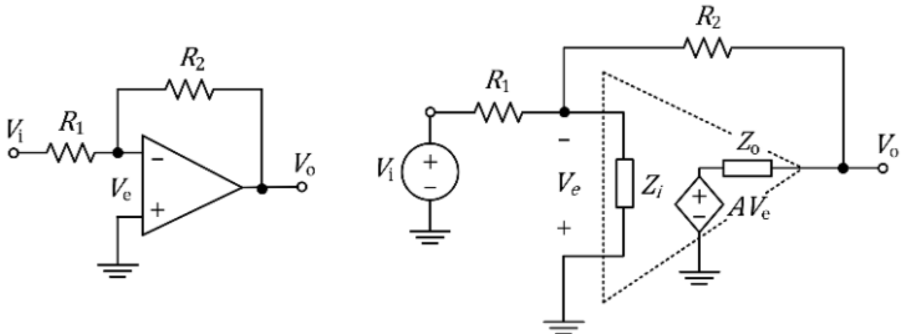

Figure 3. *Right: Inverting amplifier configuration, Left: amplifier model with voltage dependent voltage source.*

The closed-loop gain is given by the expression

$$A_{Vf} = \frac{V_o}{V_i} = -\frac{(AR_2-Z_o)Z_i}{D} \tag{6}$$

where D is taken from Eq. (2). The closed-loop input impedance is

$$Z_{if} = \frac{D}{R_2+Z_o+(A+1)Z_i} \tag{7}$$

The output impedance for the inverting configuration is given by Eq. (4).

3. Amplifier with Frequency-Dependent Gain

3.1. Amplifier with One Pole

For simplicity, we will assume that the open-loop amplifier has DC gain A_o and only one pole p. Then the open-loop gain transfer function can be written in the form

$$A(s) = \frac{A_o}{1+s/p} \tag{8}$$

Substituting Eq. (8) in Eq. (1), assuming that every other parameter is independent of frequency, we get the expression for the closed-loop gain

$$A_{Vf}(s) = \frac{N(s)}{D(s)} \tag{9}$$

$$N(s) = R_1R_os + [R_1R_o + A_oR_i(R_1+R_2)]p$$

$$D(s) = [R_1R_i + (R_1+R_i)(R_2+R_o)]s + [A_oR_1R_i + (R_1+R_i)(R_2+R_o)]p$$

From Eq. (9) the DC closed-loop gain is

$$A_{DC} = \frac{R_1R_o+A_oR_i(R_1+R_2)}{A_oR_1R_i+(R_1+R_i)(R_2+R_o)} \tag{10}$$

If A_o is large, then Eq. (10) simplifies to the ideal gain expression

$$A_{ideal} = \frac{R_1+R_2}{R_1} \tag{11}$$

From the numerator of Eq. (9) we find that a new zero appears at frequency

$$z_{new} = -\frac{A_oR_i(R_1+R_2)}{R_1R_o}p \tag{12}$$

From the denominator of Eq. (9) we find the pole of the closed-loop system to be

$$p_{new} = -\frac{A_oR_1R_i+(R_1+R_i)(R_2+R_o)}{R_1R_i+(R_1+R_i)(R_2+R_o)}p \tag{13}$$

Both z_{new} and p_{new} lie on the left half-plane. Because $A_o >> 1$, the pole p_{new} appears at a much higher frequency than the original pole p. It is a well-known fact that in feedback we trade gain for bandwidth.

To conclude, the application of negative feedback to the one-pole open-loop amplifier had three main effects: a) decreased the voltage gain, b) increased the frequency of the pole, c) created a zero in the transfer function.

3.2. Amplifier with Two Poles

If the open-loop amplifier has DC gain A_o and two poles p_1, p_2 its transfer function can be written as

$$A(s) = \frac{A_o}{(1+s/p_1)(1+s/p_2)} \quad (14)$$

Then, substituting Eq. (14) in Eq. (1) we get the closed-loop gain of the amplifier in the form

$$A_{Vf}(s) = \frac{a_2 s^2 + a_1 s + a_o}{b_2 s^2 + b_1 s + b_o} \quad (15)$$

where the coefficients are

$$a_2 = R_1 R_o \; a_1 = R_1 R_o (p_1 + p_2) \; a_o = A_o R_1 R_i p_1 p_2 \quad (16)$$

$$b_2 = R_1 R_2 + R_i(R_1 + R_2) + R_o(R_1 + R_i) \; b_1 = b_2(p_1 + p_2) \quad (17)$$

$$b_o = [(R_1 + R_i)(R_2 + R_o) + A_o R_1 R_i] p_1 p_2 \quad (18)$$

Depending on the magnitude of p_1, p_2 and the values of the other parameters, the poles can be real or complex. In practical cases the open-loop gain, input impedance and output impedance are all frequency dependent quantities. Also, in the general case, the gain-setting resistors can be impedances Z_1, Z_2. It is practically almost impossible to derive an analytical expression even for the simplest topology; therefore, another way of dealing with the problem of modelling has to be found. In the next paragraph, we will show a way of representing the open-loop quantities with transfer functions and predicting from them the closed-loop behavior for every case of interest, without having to simulate or build the actual circuit.

4. Implementation of the Proposed Method in a Practical Amplifier Circuit

4.1. Amplifier Connected as Non-inverting

In figure 4 the circuit diagram of a power amplifier is depicted. The structure is typical of many commercial amplifiers. Transistors Q_1, Q_2 form a differential stage. The error signal is created by subtracting the feedback signal from the input. The feedback signal is generated by sampling the output by means of the voltage divider R_1, R_2. Transistor Q_3, in common emitter configuration, provides most of the voltage gain. Miller compensation is implemented at this stage with capacitor C_c = 33 pF. This capacitor provides local feedback, limiting the gain at high frequencies. Transistors Q_4, Q_5, working in common collector mode, act as drivers for the output transistors. Transistors Q_6, Q_7 provide the necessary current gain for the load, which is a resistor of 8 ohms. Transistors Q_8, Q_9 function as constant current sources. The voltage gain is set by resistors R_1, R_2. The ideal voltage gain assuming infinite open-loop gain is 27.83 (28.9 dB).

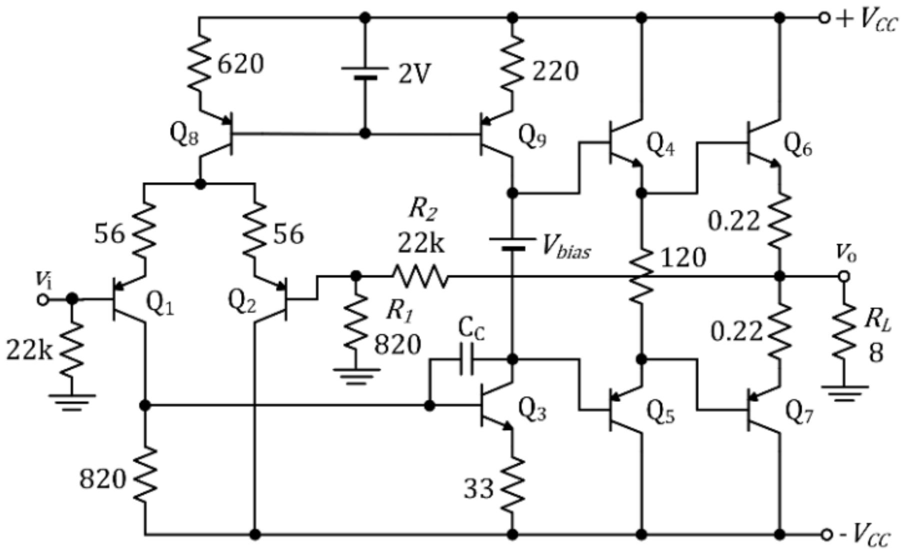

Figure 4. *Circuit diagram of power amplifier.*

The circuit was simulated in Spice using proper models for the transistors. Then, the unloaded open-loop gain, the input impedance and the output impedance were measured and the data saved in files. To measure the open-loop gain, first R_L is removed, then a large inductor (1 GH) is connected between the output and R_2. In addition, resistor R_1 is effectively shorted by connecting a 1 kF capacitor in parallel. This way the DC conditions of the amplifier remain undisturbed.

The Spice data is shown in Figure 5 (circles). The discrete-time data set is read by Matlab and a transfer function is estimated that best fits the data.

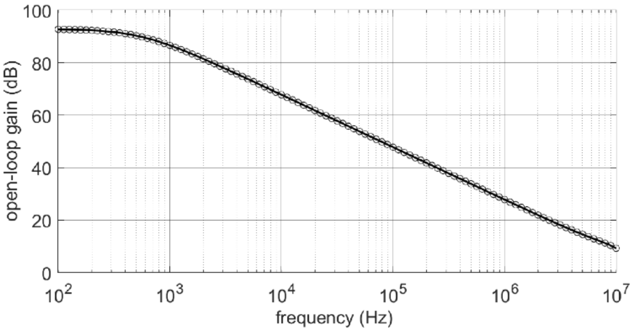

Figure 5. *Unloaded open-loop gain as predicted by the transfer function of Eq. (19) (straight line). The original data are plotted with circles.*

The user can choose the maximum number of poles and zeros so that the mean squared error of the estimation is minimized. Usually, a third order transfer function gives a good enough approximation. The transfer function used to model the open-loop gain is

$$A(s) = \frac{-7.5\cdot 10^{14}s + 9.5\cdot 10^{23}}{s^3 + 7.42\cdot 10^7 s^2 + 6.14\cdot 10^{15}s + 2.16\cdot 10^{19}} \quad (19)$$

$A(s)$ is an approximation of the original $A(j\omega)$ and its magnitude is plotted in Figure 5 using a straight line. As can be noticed the fit between the two data sets is almost perfect.

Analogous expressions are estimated for the open-loop input and output impedances, again using 3rd order transfer functions, Figure 6. The true open-loop input impedance is found by numerically removing the 22 kΩ resistor at the input.

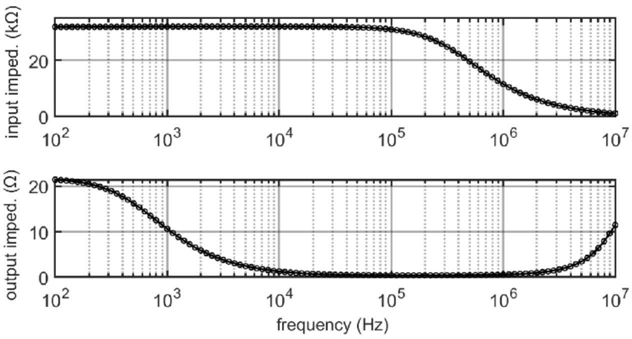

Figure 6. *Input and output open-loop impedances. The original data are plotted with circles.*

Having obtained transfer functions $A(s)$, $Z_i(s)$ $Z_o(s)$ we have a complete description for the amplifier without feedback. The closed-loop quantities are estimated from Eqs. (1-4). The closed-loop voltage gain in dB is plotted in Figure 7 (straight line) along with the results from Spice simulation (circles). The match is almost perfect. It should be noted that for all closed-loop transfer functions phase information is also available, but is omitted for the sake of clarity.

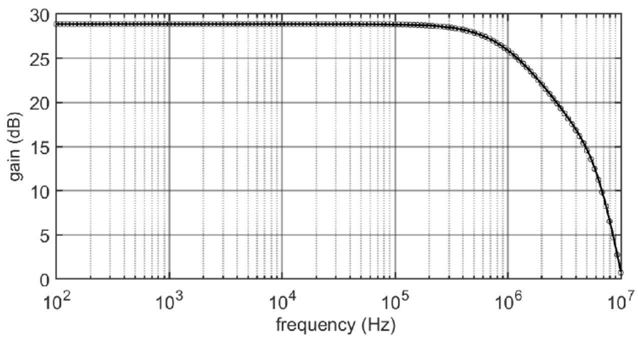

Figure 7. *Calculated closed-loop gain from the model transfer function (straight-line). The simulation results are plotted with circles.*

One advantage of the proposed modelling method is that the transfer function for the closed-loop system is available in analytic form and hence the poles and the zeros can be readily calculated. $A_{Vf}(s)$ is a 9th order transfer function with 9 poles and 8 zeros as given in Table 1. The DC gain is 27.76.

Table 1. *Poles and zeros of the closed-loop transfer function.*

poles (MHz)	zeros (MHz)
-0.991	-5.9 ± j10.54
-3.7 ± j5.28	-6.27 ± j11.32
-6.72 ± j10.3	-20.11
-5.91 ± 10.98	-150.01
-19.37	129.96 ± j129.78
-61.5	-

All poles lie in the left half-plane, therefore the amplifier is stable. The lowest pole at 991 kHz determines the -3 dB point.

Having derived the expression for the closed-loop gain, the loop gain T can be calculated from the equation

$$T(j\omega) = \frac{f\cdot A_{Vf}(j\omega)}{1 - f\cdot A_{Vf}(j\omega)} \quad (20)$$

where f is the feedback factor. For the amplifier of Figure 4 the feedback factor is 820/22820. The loop gain (magnitude and phase) is plotted in Figure 8. The unity gain frequency (0 dB point) occurs close to 1 MHz. At this point the phase is -99° and the phase margin is calculated as 180°-99° = 81°. This result is confirmed by Spice.

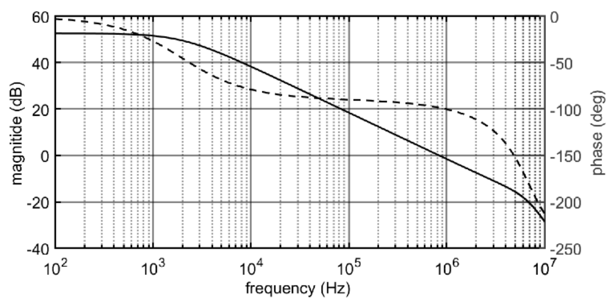

Figure 8. *Loop gain for the amplifier of Figure 4; magnitude plotted with solid line, phase plotted with dashed line.*

Having verified the reliability of our model we can now compute the closed-loop frequency response for various gains. Figure 9 depicts the magnitude response for gains of 5, 10, 20 and 30. In the case of gain 5 we notice a pronounced peak in the frequency range between 5 and 6 MHz. The lowest pair of poles for this case is -0.796 ± j5.634 MHz, giving a damping factor ζ = 0.14. The low damping explains the response peaking. For a gain lower than 9 the lowest poles that occur is a complex pair, whereas for higher gains the lowest pole is real.

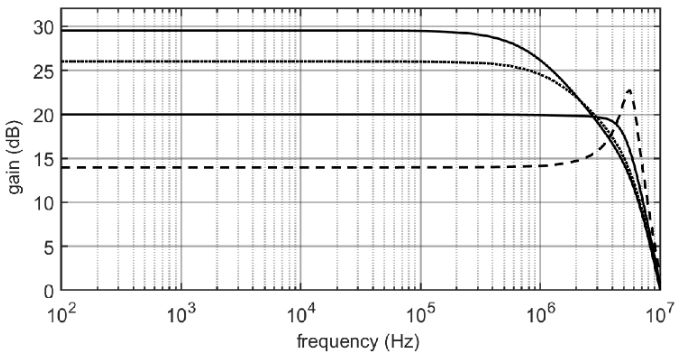

Figure 9. *Closed-loop frequency response; gain from bottom to top: 5, 10, 20, 30.*

4.2. Amplifier Connected as Inverting

As explained in the previous paragraph the three transfer functions *A(s)*, $Z_i(s)$, $Z_o(s)$ constitute a complete model for the amplifier of Figure 4. No additional information is necessary regarding its small signal behavior. Figure 10 shows the same circuit connected as an inverting amplifier. The input signal is fed to the base of transistor Q_2 through resistor R_1 whereas the base of transistor Q_1 is grounded.

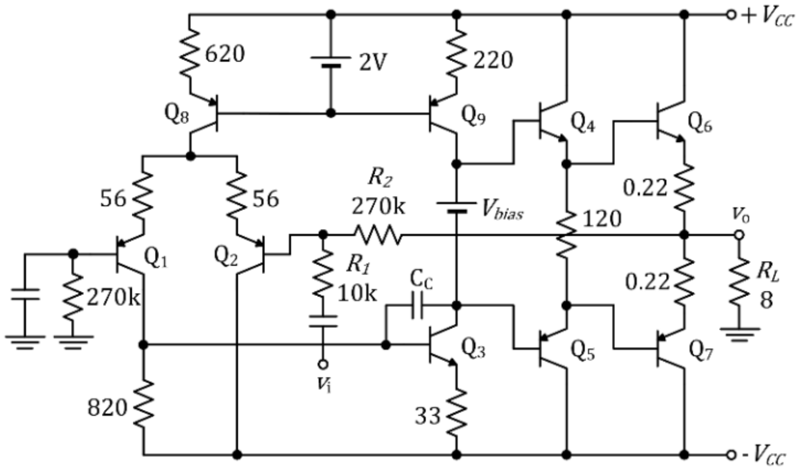

Figure 10. *Inverting amplifier with a nominal gain 28.6 dB.*

Its frequency response can be calculated from Eqs. (6-7) with no additional measurements. The ideal gain with R_1 = 10 kΩ, R_2 = 270 kΩ is -27. The closed-loop frequency response with R_1 = 10 kΩ, R_2 = 270 kΩ is the middle curve in Figure 10. The results are verified by Spice simulation.

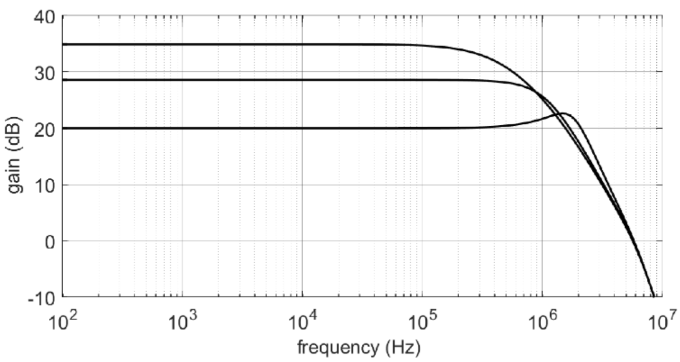

Figure 11. *Closed-loop frequency response of the inverting amplifier of Figure 10. From top to bottom the ratio R_2/R_1 is 560kΩ/10kΩ, 270kΩ/10kΩ, 100kΩ/10kΩ.*

5. Frequency-Dependent Gain-Setting Resistors

Until this point, the gain-setting resistors were taken to be independent of frequency. However, there is no limitation in our method regarding the nature of R_1, R_2 or R_L. Using the circuit of Figure 12 as an example we will study a case where Z_1, Z_2 are complex impedances. This circuit is a special type of filter that applies equalization to vinyl disk playback. Vinyl disks are recorded with standard RIAA curve. The active network of Figure 12 is a response shaping network that implements the inverse transfer function that has the analytical form

$$H(s) = K\frac{1+\tau_2 s}{(1+\tau_1 s)(1+\tau_3 s)} \tag{21}$$

where K is the gain at DC and the time constants are $\tau_1 = 3180$ μs, $\tau_2 = 318$ μs, $\tau_3 = 75$ μs.

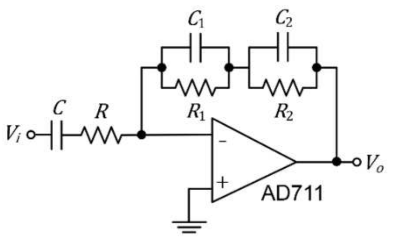

Figure 12. *An active filter that implements the inverse RIAA curve used in vinyl disk playback. Component values: R = 1 kΩ, C = 10 μF, R_1 = 88.33 kΩ, C_1 = 36 nF, R_2 = 7.5 kΩ, C_2 = 10 nF.*

The expressions for the feedback impedances are as follows:

$$Z_1 = R + \frac{1}{Cs}\; Z_2 = \frac{R_1}{R_1C_1s+1} + \frac{R_2}{R_2C_2s+1} \tag{22}$$

As a first step $A(j\omega)$, $Z_i(j\omega)$ and $Z_o(j\omega)$ for the op amp must be measured and converted to transfer functions with the help of Matlab as explained in paragraph 4.1. Impedances Z_1, Z_2 given by Eqs. (22) are also inserted in the model. The frequency response is calculated from Eq. (6). In Figure 13 the circuit frequency response is compared to the ideal response as given by Eq. (21). For the most part of the audio frequency range the circuit response follows closely the ideal response. The deviation observed at low frequencies is due to the zero at $s = 0$ created by the combination of components R and C. The departure from the ideal response at high frequencies is due to the limited open-loop gain of the op amp.

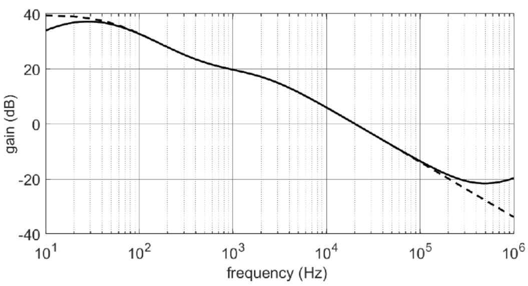

Figure 13. *The frequency response obtained with the active circuit of Figure 12 (solid line). With the dashed line the ideal inverse RIAA curve.*

The procedure described in Sections 4, 5 can be summarized as follows:

i) The unloaded open-loop gain $A(j\omega)$, input impedance $Z_i(j\omega)$ and output impedance $Z_o(j\omega)$ of the amplifier are measured.
ii) Using Matlab System Identification Toolbox transfer functions of arbitrary order are determined that best describe our data.
iii) Resistors R_1, R_2 are identified. If they depend on frequency, an appropriate expression is written for impedances Z_1, Z_2.
iv) Using the theoretical context of the non-ideal op amp laid out in Paragraph 2 the closed-loop gain is calculated as well as the closed-loop impedances.
v) If the source has internal resistance or a load is connected at the output a correction is done using Eq. (5).

6. Discussion

The modelling of amplifiers that employ feedback is an open research field. Previous studies followed a rather simplistic approach, where the parameters are either frequency independent or the gain transfer function contains a maximum of two poles. In the proposed scheme, the order of the open-loop transfer functions is not predefined but determined by the experimental data. For the open-loop transfer functions, poles are used as well as zeros, to correctly describe both magnitude and phase over a broad range of frequencies. The final closed-loop transfer function is usually of a much higher order than the original open-loop transfer functions.

The fundamental assumption in the proposed methodology is that the circuit main attributes, such as gain and impedances, can be described with transfer functions. Amplifiers, especially when working under open-loop conditions, are nonlinear circuits. In addition, the circuit behavior is perplexed by component tolerances and the changes caused by temperature variation. Fortunately, the application of feedback drastically stabilizes circuit performance and improves circuit linearity. Because of this reason, the assumption of linearity is not as limiting as it would be in a circuit with no feedback. The proposed method is expected to provide a reasonable approximation for the circuit's performance under small signal conditions. To account for the nonlinearity when the amplifier is working under large signal conditions a completely different model would be required, perhaps a time-based model.

Having a concise and accurate model for the amplifier is important because we can study how a change of a parameter modifies the open-loop transfer functions and how this is reflected to the amplifier's closed-loop performance. For example, designers make a lot of effort to ascertain that the circuit operation is stable and free of unwanted oscillations under varying conditions. The circuit can be steady with a certain load but unsteady with another. This, as well as other problems, can be studied with the proposed method.

The proposed methodology will provide good results if the data collected are accurate. This is the reason we have chosen to get our data from simulation rather than real measurements. Current network analyzers have a dynamic range that exceeds 100 dB and a resolution better than 10 ppm, therefore the measurement of ports impedances should present no difficulty. However, the measurement of the unloaded open-loop gain in practical circuits can be a real challenge. The main problem is that the biasing of the amplifier should not be disturbed, hence the use of a large inductor in the feedback loop and a large capacitor that shorts the (-) input. The problem of accuracy exists at very low frequencies. Practical limits for the component values are 100 H for the inductor and 20,000 μF for the capacitor. The input signal should be kept as small as possible to avoid non-linearity and circuit overloading.

An indirect way to obtain the unloaded open-loop gain is to measure the loop gain with the set up shown in Figure 14. The signal from the generator is injected in the feedback loop using a transformer. A suitable point for injection is one where the input impedance is high. The loop gain is computed as $T = -V_o/V_i$. For a given feedback factor $f = R_1/(R_1+R_2)$ the unloaded open-loop gain is T/f. The method requires a wide-bandwidth transformer and its validity remains to be confirmed in practice.

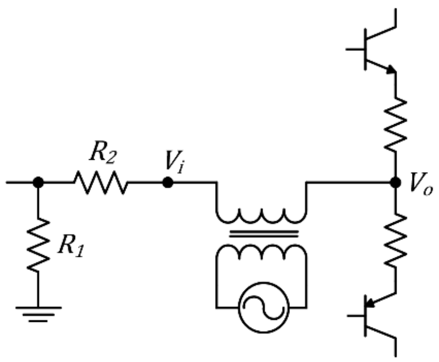

Figure 14. *Set up to measure the loop gain of an amplifier.*

As a final word, let us further clarify what is meant by the term “unloaded open-loop gain”. To measure it, the load is removed and we take the limit values $R_2 \to \infty$, $R_1 \to 0$. Because we use the term “open-loop” we should not jump to the conclusion that the rest of the circuit has no feedback. In fact, the amplifiers of Figures 4 and 10 that we have studied have local feedback in the form of degeneration as well as Miller compensation. In accordance with the simple models of Figures 2 and 3, only the feedback introduced by the addition of resistors R_1, R_2 is examined, everything else is a part of the open-loop amplifier.

7. Conclusion

A new method for modelling amplifiers that use negative feedback over a broad frequency range has been presented. The open-loop amplifier is fully described by three transfer functions. A simple theory based on the non-ideal op amp concept provides the closed-loop quantities, discriminating between the non-inverting and the inverting case.

The proposed methodology treats every amplifier as a voltage amplifier. This way the main difficulties in the application of the two-port methodology (identification of feedback type and loading from the feedback network) are solved. Once the open-loop transfer functions are formed, any possible configuration of the basic amplifier can be computed with no additional work done.

The model is flexible enough to account for frequency-dependent gain-setting resistors as well as complex loads. The poles and the zeros can be easily calculated as well as the loop gain. Work is underway to apply the proposed modelling method to real circuits working under typical conditions met in practice.

Acknowledgements

The author wishes to express his gratitude to the anonymous reviewers. Their thoughtful comments and efforts helped in improving the manuscript.

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