Discussion on Error Correction Teaching of the Open-Circuit Time Constant Method

Qiang Zhou*, Zexuan Chen[a]

School of Electronics and Information Engineering, Beihang University, Beijing, China

*zhouqiang_ee@buaa.edu.cn, [a]sy2302304@buaa.edu.cn

Abstract. Open-circuit time constant method (OCTCM) is an important knowledge point in the course of Analog Electronic Circuit, and it is an important part of the knowledge system of "from Device to single-stage amplification, to multi-stage amplification, to integrated amplification, to feedback, to frequency response analysis". Since OCTCM is universal in analyzing amplifier circuits, most textbooks and teaching materials mainly introduce the analysis procedure of OCTCM based on the two-port model, and give the conclusion that "when the existence of the main pole cannot be determined, the obtained high frequency cutoff frequency needs to be corrected by 1.14". However, it doesn't provide an analysis of the applicability of this conclusion. In order to solve the above problems, this paper first presents the definition, analysis principles, and methods for evaluating the error of OCTCM. Subsequently, it analyzes the frequency response of the double-pole amplifier circuit. On this basis, the analysis of the error of OCTCM is given, including the applicability analysis of the correction coefficient 1.14, the judgment of the dominant pole, and the discussion of other correction coefficients. By introducing the applicability analysis of this problem in the practical teaching, the paper aims to enhance students' understanding of OCTCM and improve educational outcomes.

Keywords: open-circuit time constant method, frequency response analysis, error correction, analog electronic circuits

1 Introduction

Open-circuit time constant method (OCTCM) is an important knowledge point in the course of Analog Electronic Circuit [1-4], and it is an important part of the knowledge system of "from Device to single-stage amplification, to multi-stage amplification, to integrated amplification, to feedback, to frequency response analysis". Since OCTCM is universal in analyzing amplifier circuits, most textbooks and teaching materials mainly introduce the analysis procedure of OCTCM based on the two-port model [1-7], and give the conclusion that "when the existence of the dominant pole cannot be determined, the obtained high frequency cutoff frequency needs to be corrected by 1.14" [2]. However, it doesn't provide an analysis of the applicability of this conclu-

D. Hu et al. (eds.), *Proceedings of the 2024 5th International Conference on Modern Education and Information Management (ICMEIM 2024)*, Atlantis Highlights in Social Sciences, Education and Humanities 29,
https://doi.org/10.2991/978-94-6463-568-3_27

sion, which may lead to an incomplete understanding of the knowledge point among students.

In order to solve the above problems, this paper first presents the definition, analysis principles, and methods for evaluating the error of OCTCM. Subsequently, it analyzes the frequency response of the double-pole amplifier circuit. On this basis, the analysis of the error of OCTCM is given, including the applicability analysis of the correction coefficient 1.14, the judgment of the dominant pole, and the discussion of other correction coefficients. By introducing the applicability analysis of this problem in the practical teaching, the paper aims to enhance students' understanding of OCTCM and improve educational outcomes.

2 Error Problem of Open-circuit Time Constant Method

2.1 Problem Definition

The problem comes from the actual teaching. The course of Fundamentals of Electronic Circuits aims at solving the problem of the high frequency cutoff frequency of the bipolar amplifier circuit. When the existence of the dominant pole is unknown, the obtained high cutoff frequency needs to be corrected by 1.14 [2].

In the course of Fundamentals of Electronic Circuits, the textbook adopts the bipolar point system to carry out error analysis on the actual value of the high cutoff frequency of the amplifier circuit and the theoretical value calculated by the OCTCM. In this analysis, whether w_{p_1} and w_{p_2} meet the dominant pole is not considered. The view of the textbook is: In order to exploit the advantages of OCTCM (fast and convenient) in solving the high cutoff frequency, and make the calculation results closer to the reality at the same time, two extreme cases $k \ll 0.1$ and $k = 1$ are taken to obtain $D_1 = \frac{w_H}{w'_H}(k \ll 0.1)$ and $D_2 = \frac{w_H}{w'_H}(k = 1)$. Then the arithmetic mean $D = \frac{D_1+D_2}{2} \approx 1.14$ is obtained as the final correction coefficient.

So, there is:

$$w_H \approx \frac{1.14}{\sum_{i=1}^{n}\left(-\frac{1}{P_i}\right)} = \frac{1.14}{\sum_{i=1}^{n}(R_{io} \times C_i)} \quad (n \geq 2) \tag{1}$$

In the extreme case calculation listed in the textbook, the actual situation is 1 to 1.287 times that obtained by the OCTCM. Therefore, the maximum error rate caused by the 1.14 correction is 14%, which is similar to the error tolerance of 10%, so the textbook considers it acceptable.

The limitation in the textbook is that one should not simply use the two errors corresponding to $k \ll 0.1$ and $k = 1$ for simple arithmetic averaging. Instead, it is suggested to use the weighted average error $\overline{D}$, calculated from the uniform distribution of k over the entire domain $0 < k < 1$, as the final correction coefficient when dealing with two poles. Therefore, it is necessary to conduct a quantitative error assessment between the theoretical high cutoff frequency value $1.14w_{Hi}$ proposed in the textbook and the true high cutoff frequency value w_{Hr} in the circuit. Then, it is necessary to consider how to determine whether there is a dominant pole and in what circumstances to adopt a correction coefficient. Finally, it is not difficult to raise the question of whether there is a correction coefficient closer to the true value than 1.14 for a bipolar system, which can be summarized as three basic questions:

- Question 1: Compared to not using a correction coefficient, does taking 1.14 as the correction coefficient improve the approximation of the data?
- Question 2: Under what circumstances should correction coefficients be used (i.e. how to determine whether there is a dominant pole).
- Question 3: Is there any other better correction coefficient compared to 1.14?

After discussing the analysis principles and methods, the frequency response of the amplification circuit and the error analysis of OCTCM will be provided separately. The analysis method in this article can be extended to the case of multiple poles ($n \geq 3$).

2.2 Analysis Principles and Methods

Starting from the physical structure of the transistor and considering the influence of the emission junction and collector junction capacitance, a physical model under the action of high frequency signals can be obtained, which is called the mixed π model [2, 6]. On the basis of calculating the static current of the amplifier circuit, a simplified equivalent circuit of high frequency small signal is obtained. The source voltage gain, amplitude-frequency characteristic curve and cutoff frequency are obtained under AC analysis, and the results are consistent with MATLAB [7-9].

The Multisim simulation tool can be used to perform transient analysis and Fourier analysis on a typical high-frequency amplifier circuit. The actual high-frequency response can be obtained by dividing the effective value of the response obtained by the obtained sinusoidal signal source as the excitation by the effective value voltage of the excitation. The 3dB bandwidth, the cutoff frequency f_{Hr} and the characteristic frequency can be obtained by Fourier analysis. The high cutoff frequency f_{Hi} derived from the theory and the high cutoff frequency f_{Hr} derived from the actual simulation are analyzed, and the relative error is calculated:

$$D = \frac{|f_{Hi} - f_{Hr}|}{f_{Hr}} \times 100\% \qquad (2)$$

Then, the relative error analysis of the ratio k of various correction coefficients and different poles is carried out by program C, and different error curves and their trends can be obtained. The boundary of the dominant poles of the system can be determined by carefully comparing the corrected error curves and the uncorrected error curves, and the response conclusions of basic questions 2 and 3 can be obtained.

3 Frequency Response Analysis of Amplifier Circuits

For question 1, it is necessary to know the error of $1.14w_{Hi}$ compared with the true value w_{Hr} when k changes uniformly over the domain (0,1) after using 1.14 as the correction coefficient.

According to (3):

$$\frac{1}{w_{Hi}} = \frac{1}{w_{P1}} + \frac{1}{w_{P2}} = \frac{1+k}{w_{P1}} \tag{3}$$

We can know:

$$w_{Hi} = \frac{w_{P1}}{1+k} \tag{4}$$

By solving the original gain equation [1-2, 10], there is:

$$w_{Hr} = \frac{w_{P1}}{\sqrt{(1+k^2+\sqrt{k^4+6k^2+1})/2}} \tag{5}$$

Thus, the expressions of w_{Hi} and w_{Hr} regarding k are obtained. By bringing in the value of k, the error corrected by the correction coefficient 1.14 can be obtained from the error formula, as shown in (6):

$$D = \frac{|1.14w_{Hi} - w_{Hr}|}{w_{Hr}} \times 100\% \tag{6}$$

The source code for this study is written in C, and the generated relative error data is stored in Microsoft Excel. Our analysis focuses on "the values of k", "uncorrected error", and "corrected error". This paper examines the relative error and the trend of the fitted curve.

For Question 2, the criterion for determining the presence of a dominant pole is based on the principle that a correction coefficient should not be applied when a dominant pole is present, and should be applied when it is absent. The problem then centers on identifying the conditions under which using a correction coefficient results in a lower error compared to not using it.

For Question 3, a corresponding C program has been developed, and the data is stored in categories labeled "correction coefficients," "average error," and "maximum error." This program investigates whether an optimal correction coefficient exists by evaluating various values as correction coefficients (ranging from 1 to 1.28) and comparing the error distribution as k varies from 0 to 1. To assess the performance of each correction coefficient, we focus on both the average value and the extreme value, where the average value indicates the overall stability of the system, and the extreme value indicates the local stability of the system.

4 Error Analysis of Open-Circuit Time Constant Method

4.1 Correction Coefficient 1.14 Applicability Analysis

As can be seen in Fig. 1, the error caused by not using the correction coefficient 1.14 is between 0% and 24%, and the average error reaches 17.68%. After applying the correction coefficient of 1.14, the error range is reduced to 0% - 14%, and the average error is reduced to 8.40%.

Therefore, using 1.14 as the correction coefficient can obviously improve the approximation degree of the data, so that the approximate solution obtained from the two poles can widely meet the engineering requirements of error less than 20%. Based on this, it can be concluded that using 1.14 as the modified parameter can improve the degree of data simulation well, and its error limit is less than 15%.

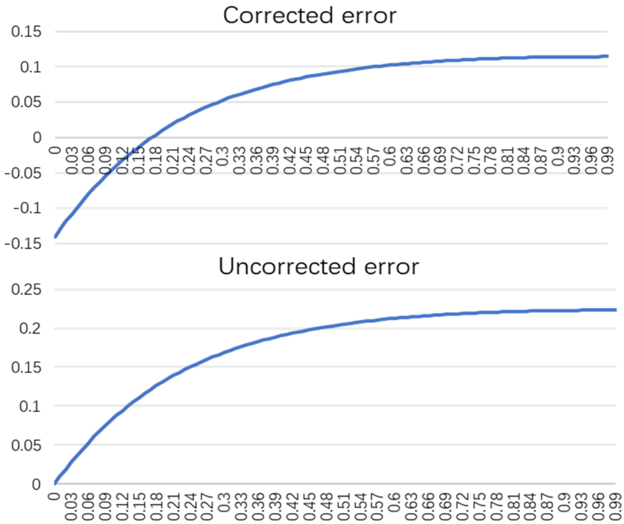

Fig. 1. Comparison of corrected error and uncorrected error using 1.14 as correction coefficient.

4.2 The Judgment of the Dominant Pole

Here, the three columns of data, "k", "uncorrected error", and "corrected error" in Microsoft Excel, are still used for comparison and analysis, as shown in Fig. 2.

According to Fig. 2, when $k < 0.08$, the correction coefficient should not be applied. Conversely, when $k > 0.08$, using 1.14 as the correction coefficient yields better simulation performance. Therefore, $k = 0.08$ can be identified as a critical threshold for determining the presence of a dominant pole. The corresponding error distribution is illustrated in Fig. 3, with an error range of 0% to 11.4% and an average error of 7.82%.

Based on the above data and analysis, it can be concluded that the dominant pole should be 0.08 as the distinction limit for the double-pole high-frequency amplifier circuit.

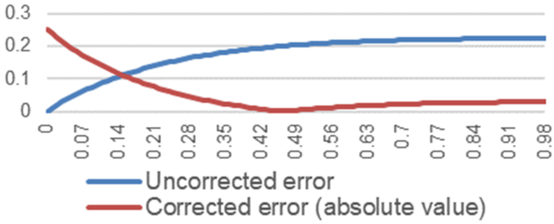

Fig. 2. Correction error and uncorrected error with 1.14 as correction coefficient.

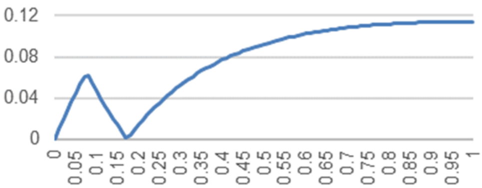

Fig. 3. Error distribution with a correction coefficient of 1.14 when k>0.08 and not corrected when k<0.08.

4.3 Discussion of Other Correction Coefficients

In order to compare the advantages and disadvantages of each correction coefficient, the two indexes of average value and extreme value are focused on.

The mean relative error (MRE) is recorded in Table 1. The correction coefficient ranges from 1.00 to 1.27, and the value step of the correction coefficient is 0.01. Assuming that k follows a uniform distribution from 0 to 1, according to Table 1, it can be seen from the change trend of the average value that when the correction coefficient is 1.25, the average error is the smallest, around 5.1449%.

As can be seen in Fig.4, when the correction coefficient is 1.25, the minimum average error is about 5.1449%, and the error range is from 0% to 25%. The dominant pole at this time should be distinguished at around 0.15. After judging the dominant poles, the error distribution is shown in Fig. 5. At this point, the average error is 3.37%, and the error range is form 0% to 11%.

Next, we will discuss whether there is a better correction coefficient than 1.14. As shown in Fig. 6, with a correction coefficient of 1.12, the error ranges from 0% to 13%. The dominant pole is approximately 0.6. After identifying the dominant poles, the error distribution is presented in Fig. 7, with an average error of 9.01% and a range of 0% to 13%.

Based on the above analysis, it can be concluded that if the ratio k of the two poles follows a uniform distribution over (0,1), there is a better degree of emulation when 1.25 is used as the correction coefficient. In this case, the boundary of the dominant pole is 0.15. In addition, when the correction coefficient is widely used without judging whether dominant pole exists, 1.12 is used as the correction coefficient to have better fidelity.

Table 1. The Distribution of the Mean Relative Error (MRE) with Correction Coefficient.

Serial Number	Correction Coefficient	MRE	Serial Number	Correction Coefficient	MRE
1	1.00	0.177	15	1.14	0.084
2	1.01	0.169	16	1.15	0.079
3	1.02	0.161	17	1.16	0.075
4	1.03	0.153	18	1.17	0.070
5	1.04	0.146	19	1.18	0.067
6	1.05	0.139	20	1.19	0.063
7	1.06	0.132	21	1.20	0.060
8	1.07	0.125	22	1.21	0.057
9	1.08	0.118	23	1.22	0.055
10	1.09	0.112	24	1.23	0.053
11	1.10	0.106	25	1.24	0.052
12	1.11	0.100	26	1.25	0.051
13	1.12	0.094	27	1.26	0.052
14	1.13	0.089	28	1.27	0.053

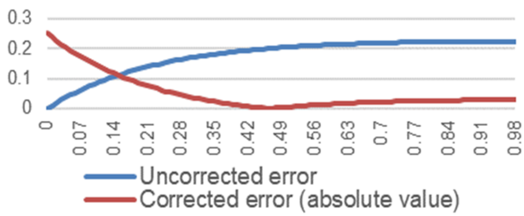

Fig. 4. Corrected error using 1.25 as correction coefficient and uncorrected trend.

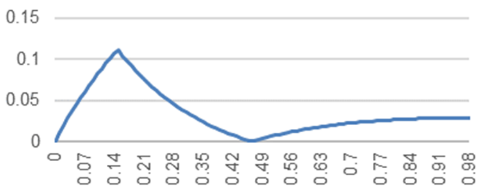

Fig. 5. Error distribution with a correction coefficient of 1.25 when k>0.15 and not corrected when k<0.15.

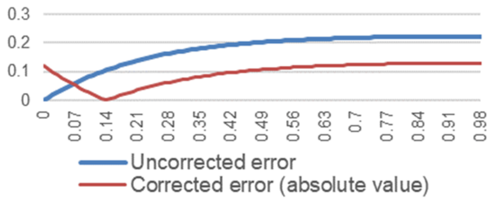

Fig. 6. Corrected error using 1.12 as correction coefficient and uncorrected trend.

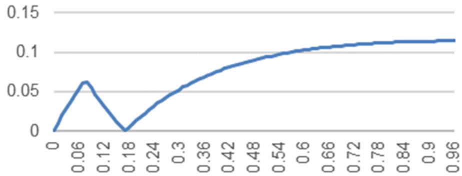

Fig. 7. Error distribution with a correction coefficient of 1.12 when k>0.06 and not corrected when k<0.06.

5 Conclusions

This paper first discusses the definition, analysis principle and method of the error of OCTCM, and then analyzes the frequency response of the double-pole amplifier circuit. Then, frequency response analysis is conducted for bipolar amplification circuits. Based on this, an analysis of the error of the open circuit time constant method is given, including applicability analysis of the correction coefficient 1.14, determination of the main pole, and exploration of other correction coefficients. By introducing the applicability analysis of this problem in practical teaching, it can help students understand the OCTCM and play a good role in teaching.

References

1. S. Tong and C. Hua, Fundamentals of Analog Electronic Technology, 6th ed. Beijing: Higher Education Press, 2023.
2. X. Zhang and F. Zhang, Fundamentals of Electronic Circuits. Beijing: Higher Education Press, 2011.
3. B. Liu, Fundamentals of Electronic Circuits, 2nd ed. Beijing: Higher Education Press, 2013.
4. H. Kang, Fundamentals of Electronic Technology (Analog Part), 7th ed. Beijing: Higher Education Press, 2021.
5. X. Li, Fundamentals of Analog Electronic Technology. Beijing: Tsinghua University Press, 2005.

6. P. R. Gray, P. J. Hurst, S. H. Lewis, and R. G. Meyer, Analysis and Design of Analog Integrated Circuits, 6th ed. New York: John Wiley & Sons, 2024.
7. F. Asadi, Analog Electronic Circuits Laboratory Manual. New York: Springer, 2023.
8. R. J. Baker, H. W. Li, and D. E. Boyce, CMOS Circuit Design, Layout, and Simulation. Beijing: Mechanical Industry Press, 2003.
9. J. Williams, Analog Circuit Design: Art, Science, and Personalities. Boston: Elsevier, 2015.
10. R. Prasad, Analog and Digital Electronic Circuits: Fundamentals, Analysis, and Applications. Cham: Springer Nature, 2021.