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Composite Amplifier with Extremely High CMRR

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Abstract

The purpose of the research was to analyse details in the application of operational amplifiers in precision analog circuits. Special attention was given to deviations caused by common mode rejection ratio, not thoroughly analysed in the literature. The research is started with theoretical analysis. Composite amplifier circuits are proposed to achieve better performances than with a single operational amplifier could be achieved. Benefits of the proposed circuits are shown by simulations based on the simulation models and measurements on the real model. The theory and practice introduced below could be well included in undergraduate course in analog electronics.

Keywords: operational amplifier; composite amplifier; high common mode rejection ratio (CMRR);

Nomenclature

A	amplifier gain
CM	common mode
CMRR	common mode rejection ratio
IC	integrated circuit
R	resistor
U_I	input voltage
U_O	output voltage

1. Introduction

Building high precision instruments needs almost ideal operational amplifiers. Effects of offset, common mode rejection ratio (CMRR) and other imperfections have to be reduced as much as possible. One way is to apply precision operational amplifiers but their parameters are limited and their price is high. Another approach is to use composite amplifiers proposed in this text. Instead of a single operational amplifier, composite amplifiers are built from two or more operational amplifiers with significant improvements in resulting parameters.

This topic is not covered in the literature and in usual analog electronics courses so finished students could have problems in their professional carrier. This material could be included in undergraduate or graduate lectures and laboratory practice to open new ideas in construction of precision analog circuits.

2. Construction of Composite Amplifiers

The idea is to combine two or more operational amplifiers to achieve the common mode rejection ratio (CMRR) of the composite amplifier higher than for a single operational amplifier (Horowitz & Hill, 2017) (Mancini, 2001). Adjusting the power supplies of the operational amplifier, the common mode (CM) input voltage could be eliminated. This could be done with the composite amplifier (Radetić, 2014) in Fig.1.

The first operational amplifier (IC1 - OP37) is with low offset voltage (<50 μV). Its CMRR is over 120 dB. This will insert, for input CM voltage of 1 V, change of the input offset voltage for 1 μV. We want to reduce this component even more. To achieve that, we introduced power supply voltages with floating ground voltage equal to the input voltage (U_I). The floating ground voltage is achieved by another operational amplifier (IC2 - TL081) adjusted to a unity gain amplifier.

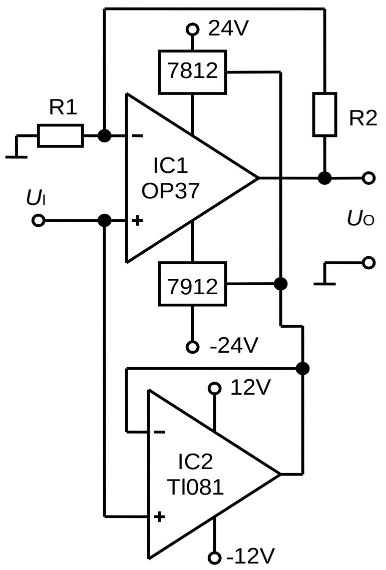

Fig.1. High CMRR composite amplifier with two operational amplifiers.

There are no special requirements for this amplifier, only its speed has to be acceptable and its bias current has to be low to follow well the input voltage and do not impose significant loading on the source of the input signal (its input bias current is about 100pA).

For this composite amplifier, the offset voltage component for IC1, caused by CMRR is:

$$\left|\Delta U_{I,CMRR,IC1}\right| = \frac{U_{I,CMRR,IC2}}{CMRR1} = \frac{U_I}{CMRR1}\left(\frac{1}{CMRR2} + \frac{1}{A_{0,2}}\right) \tag{1}$$

This way the resulting CMRR for this composite amplifier is:

$$CMRR = \frac{U_I}{\left|\Delta U_{I,CMRR,1}\right|} = \frac{CMRR1}{\frac{1}{CMRR2} + \frac{1}{A_{0,2}}} = \frac{CMRR1 \cdot CMRR2 \cdot A_{0,2}}{A_{0,2} + CMRR2} \tag{2}$$

Resulting CMRR for the composite amplifier is now very high, about 200 dB. Besides the error voltage caused by CMRR, there is an error component caused by high but limited gain of IC1.

The output voltage is not referred to real ground (it is referred to the floating ground). It is calculated as:

$$U_O = U_I + \frac{R_2}{R_1}U_I = U_I\left(1 + \frac{R_2}{R_1}\right) \tag{3}$$

Referred to the floating ground of the supply voltages, the output voltage is:

$$\Delta U_O = \frac{R_2}{R_1}U_I \tag{4}$$

This voltage inserts to the input of IC1 the following voltage:

$$\left|\Delta U_{I,A_0}\right| = \frac{\Delta U_O}{A_{0,1}} = \frac{U_I}{A_{0,1}}\frac{R_2}{R_1} \tag{5}$$

This voltage has the same order of magnitude as the error caused by CMRR. Elimination of this voltage is also desirable.

Consider now the amplifier in Fig.2 (Mancini, 2001). By this circuit, the output of IC1 is on the same potential as its input, so there is no unwanted feedback caused by the limited gain A_0 of this operational amplifiers. To achieve stability, it is necessary to add a local feedback on operational amplifier IC3.

For DC voltages the output voltage of IC1 is equal to the input voltage, augmented by offset voltages of IC2 and IC3. The input offset voltage component of IC1, caused by CMRR is:

$$\left|\Delta U_{I,CM}\right| = \frac{U_{I,OP2} + U_{I,OP3}}{CMRR1} = \frac{1}{CMRR1}\left(U_{I,OP2} + U_{I,OP3}\right) =$$
$$= \frac{1}{CMRR1}\left(\frac{U_I}{CMRR2} + \frac{U_I}{A_{0,2}} + \frac{U_I}{CMRR3} + \frac{AU_I}{A_{0,3}}\right) = \tag{6}$$
$$= \frac{U_I}{CMRR1}\left(\frac{1}{CMRR2} + \frac{1}{A_{0,2}} + \frac{1}{CMRR3} + \frac{A}{A_{0,3}}\right) \approx \frac{U_I}{CMRR1}\frac{A}{A_{0,3}}$$

The resulting CMRR is now:

$$CMRR = \frac{\left|\Delta U_{I,CM}\right|}{U_I} = \frac{1}{CMRR1}\left(\frac{1}{CMRR2} + \frac{1}{A_{0,2}} + \frac{1}{CMRR3} + \frac{A}{A_{0,3}}\right) \approx \frac{1}{CMRR1}\frac{A}{A_{0,3}} \tag{7}$$

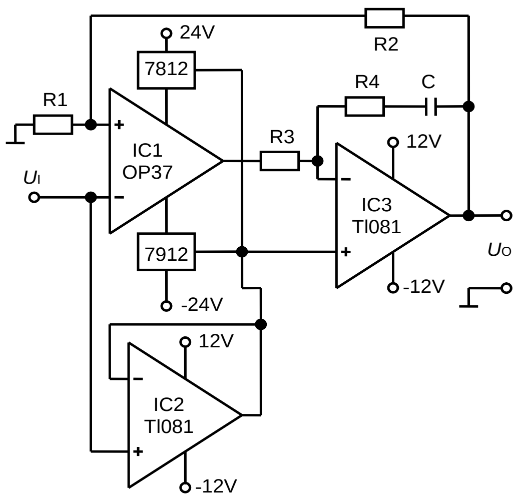

Fig.2. High CMRR composite amplifier with three operational amplifiers.

This way the voltage component of the input offset voltage, caused by input CM voltage of IC1, is eliminated up to such level that the CMRR value for the composite amplifier is over 200 dB.

Open loop voltage gain of the composite amplifier for DC is equal to the product of gains of operational amplifiers IC1 and IC3:

$$A_0 = A_{0,1}A_{0,3} \tag{8}$$

3. Simulations

Simulations of the suggested composite amplifiers are done in software LTSpice (Analog Devices). The simulation model is shown in Fig.3. High open loop voltage gain for DC voltages is achieved, A_0>200dB. The 3 dB bandwidth of the open loop gain is 1 mHz. For a closed loop amplifier with gain A=1000, the 3dB badwidth is over 20 kHz as shown in Fig.4.

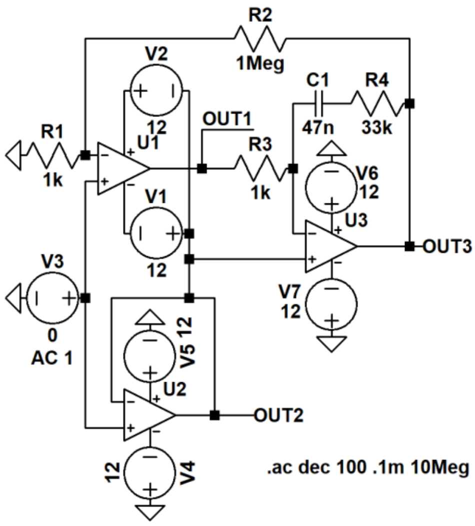

Fig.3. LTSpice simulation model for high CMRR composite amplifier in Fig.2.

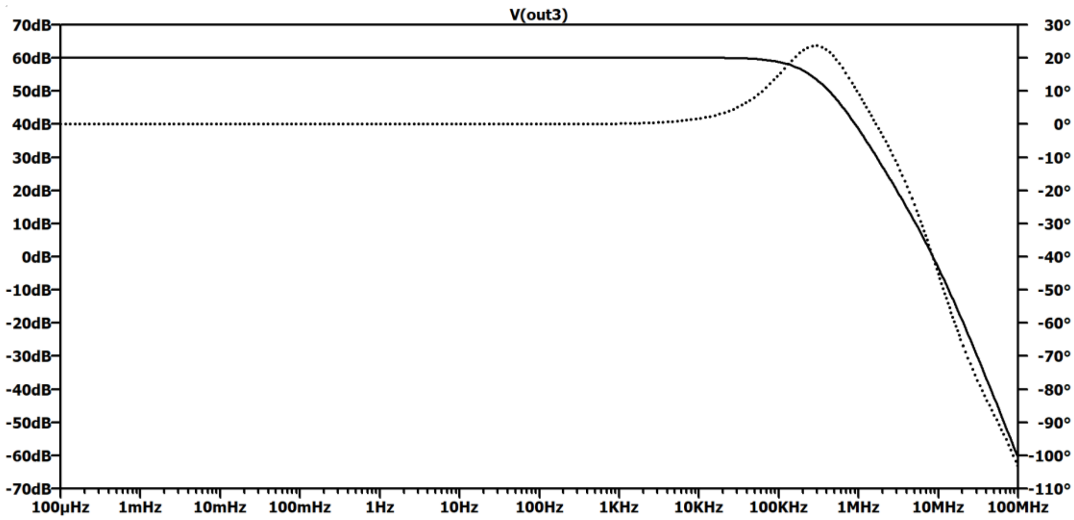

Fig.4. Gain and phase characteristics of the composite amplifier in Fig.2.

4. Measurements

The composite amplifiers are built according to schematics in Fig.1 and in Fig.2. Stability of the local feedback loop in Fig.2 is obtained.

CMRR of the composite amplifier can be measured according to the setup in Fig. 5. OP stands for the composite amplifier under test, OP1 is an auxiliary amplifier closing the feedback loop. Input voltage is changed by a switch from -0.5V to +0.5V. Output voltage of the composite amplifier is forced to 0 V by the auxiliary amplifier. Capacitor 100 pF stabilize the feedback loop. Voltage measurement have to be done between test points in the figure. Change of this voltage, by change of input voltage, represents the amplified input CMRR voltage component:

$$\Delta U_O = A\frac{\Delta U_I}{CMRR} \text{ which gives: } CMRR = A\frac{\Delta U_I}{\Delta U_O} \tag{9}$$

For A=1000 and ΔU_I=1V, CMRR=1000/ΔU_O. For example, operational amplifiers OP07 shows ΔU_O=5mV so its rejection ratio is 200 000 or CMRR(dB)=106 dB.

This measurement can be done with an ordinary millivoltmeter available in school laboratories. Precise measurement of much higher CMRR values, typical for the composite amplifier, is not so straightforward but the significant improvement can be detected.

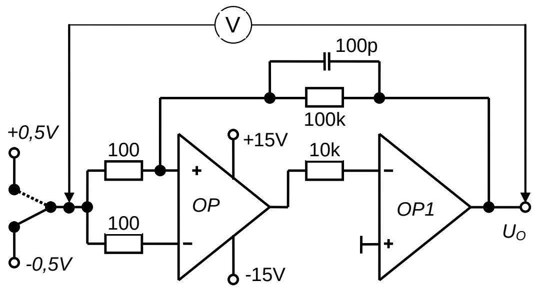

Fig. 5. Test circuit for measuring CMRR of operational amplifier OP.

5. Conclusions

Composite amplifier with extremely increased CMRR (CMRR>200dB) and high open loop gain is obtained (A_0>200 dB). The resulting amplifier is with low noise and with low offset voltage (<50 μV). Even the frequency band is improved. Tests of the ideas introduced here are done with free simulation software and ordinary laboratory equipment available for courses in analog electronics. Based on the acquired knowledge gained with high precision systems like the one presented in this paper, the students will be able to design, simulate, and use the acquired knowledge and skills in practice. They can build more complex electronic circuits with the application of composite operational amplifiers.

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Short professional biography

Radojle Radetić was born in 1957 in Buđevo, Serbia. Graduated at Faculty of Technical Sciences in Novi Sad in 1981, master thesis done at Electrotechnical Faculty in Belgrade in field of power electronics, doctor thesis done at the Faculty of Technical Sciences in Novi Sad in electrical measurement. From 1981 to 1987 was working in the Department of Power Converters at Faculty of Technical Sciences. From 1987 to 1999 was working in Research Centre of the Copper Institute in Bor, was developing power electronic and electrothermal equipment, electrochemistry and measurement devices. From 1999 is with Serbian Distribution Company – Department in Bor. Owner of several awards for his outstanding work. Built numerous instruments and apparates in the given fields. Author of over 60 scientific articles. Author of over 10 text books.

Nándor Burány was born in 1958 in Ada, Serbia. Graduated at Faculty of Technical Sciences in Novi Sad in 1982, master thesis and doctor thesis done at Electrotechnical Faculty in Belgrade in field of power electronics in 1990 and 2008 respectively. From 1982 to 1991 was working in the Department of Electronics at Faculty of Technical Sciences. From 1993 he is with the Technical Engineering College in Subotica giving lectures in electronics courses. Author of over 30 scientific articles. Built numerous instruments and apparates in field of analog electronics and power electronics.