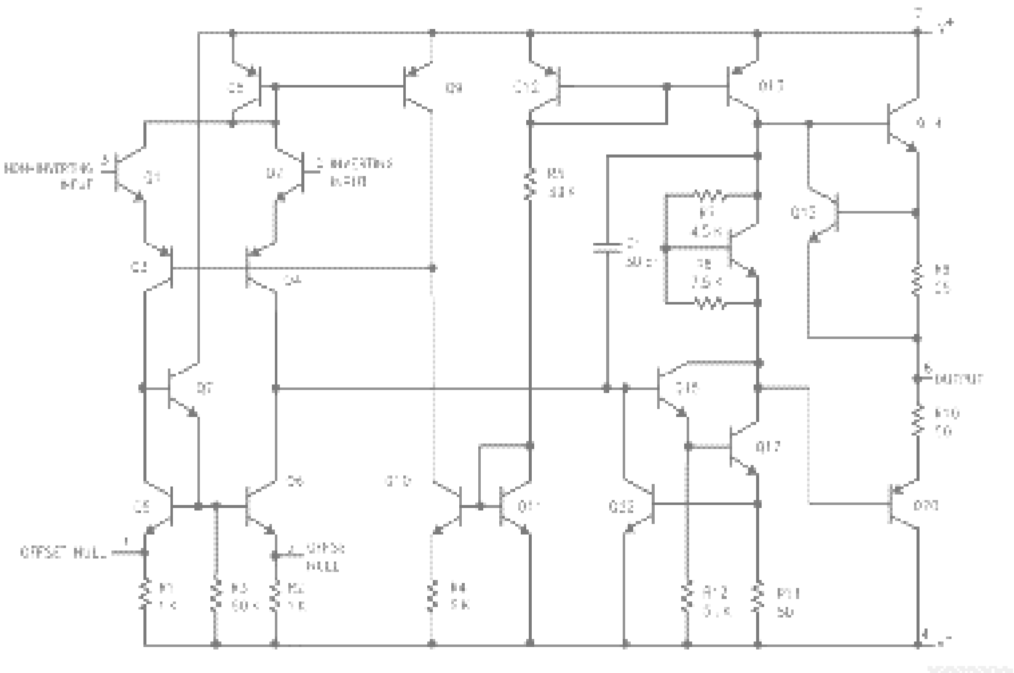
Lab-Report
Analogue Electronics

Operational Amplifiers



Name: Dirk Becker
Course: BEng 2
Group: A
Student No.: 9801351
Date: 25/02/1999

UNIVERSITY of EAST LONDON

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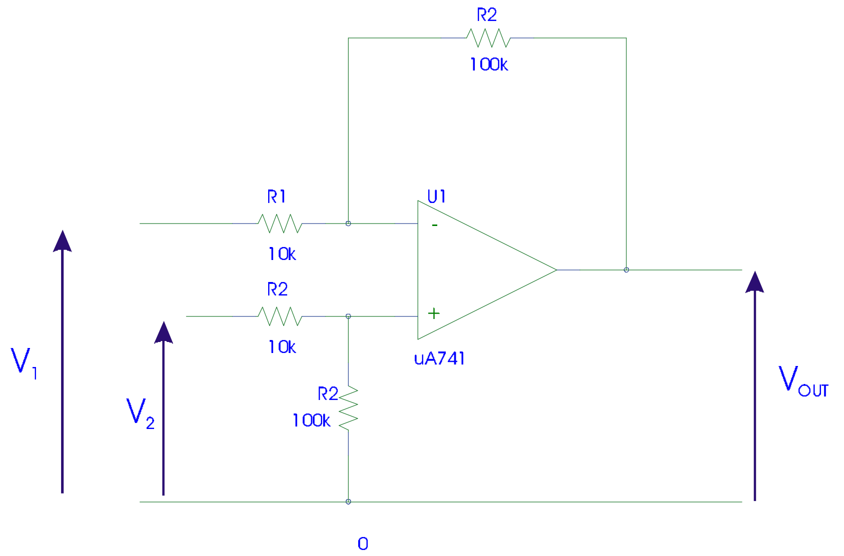
2. Introduction

Operational amplifiers were first used in the late 1940s for performing mathematical calculations, or so called operations like adding, subtracting, multiplication, etc.. Operational amplifiers are very common used since their availability on Integrated Circuits (ICs) in the 1960s. For instance the LM341 was introduced in 1967.
An operational amplifier is a very high gain differential amplifier with high input impedance and low output impedance. Today they are used in nearly all electronic circuits and replace numbers of discrete transistors.

3. Common mode gain

a) Without nulling potentiometer

First part of the Lab was to determine the common mode gain at different input voltages. The common mode gain is the amplification of the opamp with no different input voltages. It should be usually 0, but practically a small voltage will occur at the output.



Measured values:

$V_1=V_2$	V_{Out}	A_C
0V	**-2.3mV**	**0**
5V	**6.0mV**	**$1.2*10^{-3}$**
10V	**14.3mV**	**$1.43*10^{-3}$**

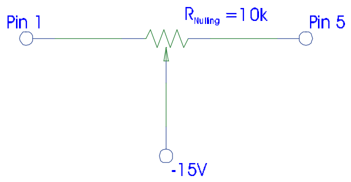
where A_C is defined as the common mode gain:

$$A_C = \frac{V_O}{\frac{1}{2}(V_1 + V_2)}$$

The higher the common input voltage, the higher the common mode gain (which is not wanted).

b) Nulling potentiometer

For a better suppression of the common mode gain a nulling potentiometer can be connected to the most opamps. It is used to set the output voltage to 0V, when no differential input voltage is applied (common mode).



The above figure shows the connection of a nulling potentiometer to a opam LM741, which was used in the Lab.

The adjustable range of the nulling potentiometer with no different input voltage (V_1=V_2=0V) was: $V_{max}|_{V1=V2=0V}$=109.9mV (left end of potentiometer)
$V_{min}|_{V1=V2=0V}$=-114.9mV (right end of potentiometer)

When the potentiometer is adjusted so that V_{Out}=0V at V_1=V_2=0V, the following output voltages and common mode gains can be obtained:

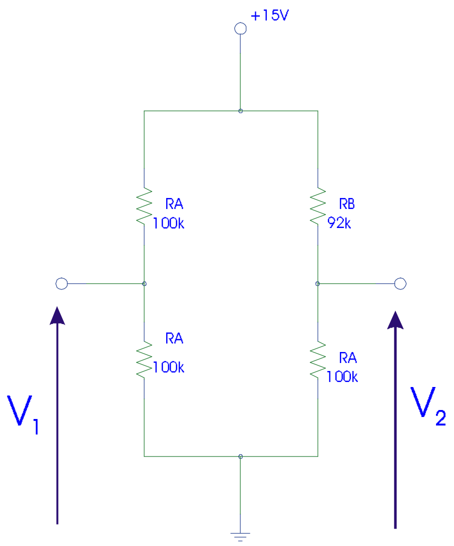
V_1=V_2	V_{Out}	A_C
5V	**8.2mV**	**$1.64*10^{-3}$**
10V	**16.5mV**	**$1.65*10^{-3}$**

The nulling potentiometer improves only the common mode gain for small input voltages. For higher input voltages the common mode gain is equal or greater than without nulling potentiometer. This results from the internal structure of the opamp LM341.

4. Voltage Amplification

a) Bridge circuit

To generate two different voltages a bridge circuit should be connected together. The circuit diagram is shown below:



The bridge outputs were V_1=7.5V and V_2=7.67V.
The calculated bridge voltages are:

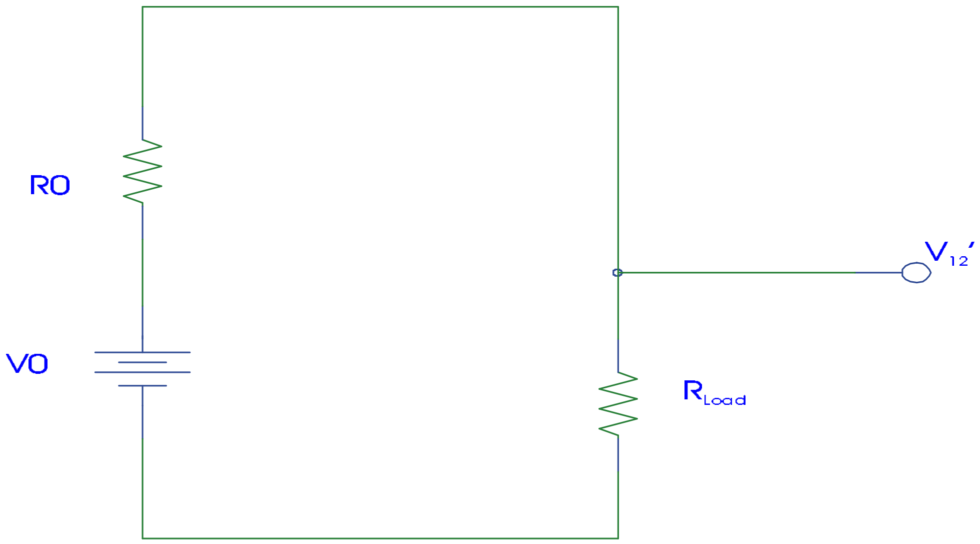
$$V_{1Calc} = \frac{R_A}{2R_A} 15V \qquad V_{2Calc} = \frac{R_A}{R_A + R_B} 15V$$

$$V_{1Calc} = \frac{100k\Omega}{200k\Omega} 15V = 7.5V \qquad V_{2Calc} = \frac{100k\Omega}{192k\Omega} 15V = 7.81V$$

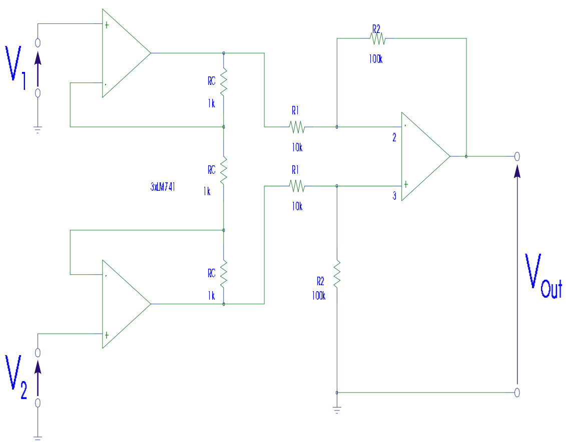
The difference between the calculated and the measured voltages result on the inaccurate values of the used resistors (+-5%). Although the measuring instruments have a small uncertainty.

b) Differential gain

The outputs of the bridge should then be connected to the corresponding inputs of the operational amplifier from part 3) Common mode gain. The resulting circuit diagram is shown in the following figure:



The output voltages of the bridge change when the bridge is connected to the opamp stage because the amplifier inputs are a load to the bridge. The new bridge output voltages can be calculated using Thevenin's theorem, where V_0 is the disconnected bridge voltage.



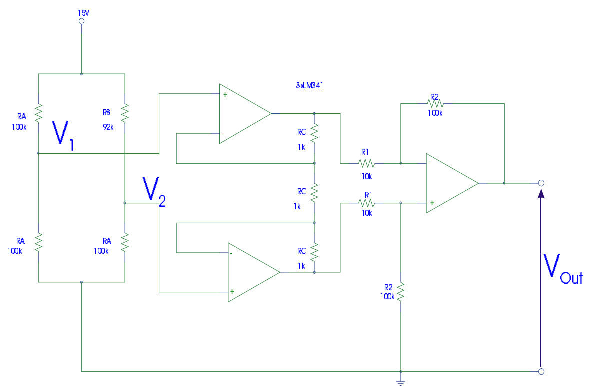
$$V_{01} = \frac{1}{2} R_A 15V = 7.5V \quad (\text{for } V_1')$$

$$R_{01} = \frac{1}{2} R_A = 50k\Omega$$

$$R_L = R_1 + R_2 = 110k\Omega$$

$$\Rightarrow V_1' = \frac{R_L}{R_L + R_{01}} V_{01} = \frac{110k\Omega}{160k\Omega} 7.5V$$

$$V_1' = 5.16V$$



The output voltages of the bridge decrease when connecting to the opamp-circuit because of it's load function.

The measured output values of the connected bridge were:
V_1'=5.35V
V_2'=5.32V   at an output voltage V_{Out}=513mV

The difference between the calculated and the measured values of the bridge outputs (=the opamp input voltage) results from the inaccuracy values of the used resistors.
Every resistor can have a tolerance of +-5% which can change the parameters of the circuit very much (worst case = all the devices have their maximum tolerance).

From the above results the differential gain of the amplifier stage was to determine:

$$A_D = \frac{V_{Out}}{V_1 - V_2}$$
$$A_D = \frac{0.513V}{5.35V - 5.32V}$$
$$\underline{\underline{A_D = 17.1}}$$

Calculated value of A_D:

$$A_D = \frac{R_2}{R_1} = \frac{100k\Omega}{10k\Omega} = 10$$

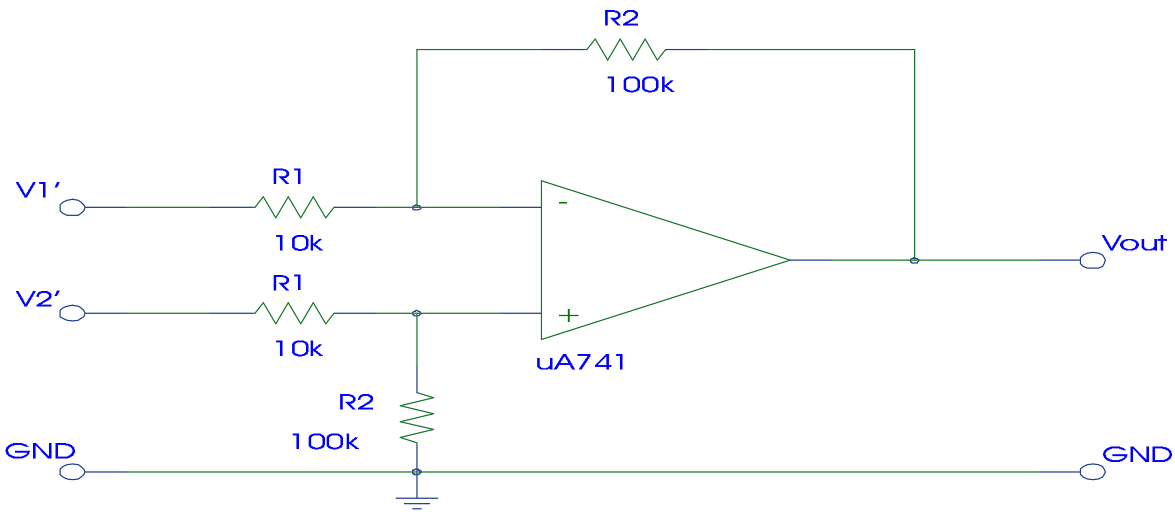
c) Common mode rejection ratio

A significant feature of a differential amplifier is that the signals which are opposite at the inputs are highly amplified, while those which are common to the two inputs are only slightly amplified. The ratio of the differential gain and the common mode gain is called the common mode rejection gain (CMRR).

$$CMRR = \frac{A_D}{A_C} \approx \frac{17}{0.0015} = 8500$$
$$CMRR\big|_{dB} = 20\log\left(\frac{A_D}{A_C}\right) \approx 20\log\left(\frac{17}{0.0015}\right) = 79dB$$

5. Instrumentation Amplifier

a) Common mode gain



After connection of the instrumentation amplifier circuit shown in the figure above the common mode gain was to determine and to compare with the differential amplifier from Part 3) Common mode gain.

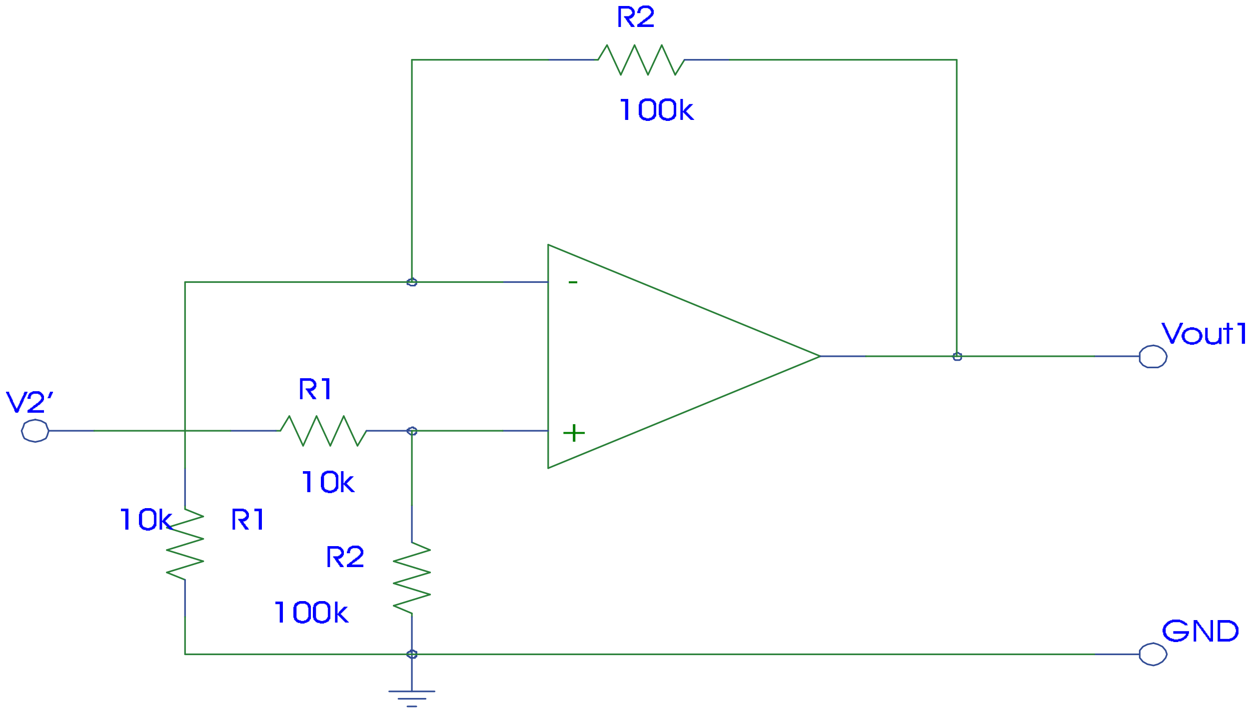
$$A_C = \frac{V_O}{\frac{1}{2}(V_1 + V_2)}$$

V_1=V_2	V_{Out}	A_C
0V	**0V**	**0**
5V	**197mV**	**0.0394**
10V	**197mV**	**0.0197**

The nulling potentiometer had to be aligned again, because the two additional connected amplifiers have each their own output voltage offset, which has to be compensated by the nulling potentiometer of the differential amplifier (the last opamp).
The common mode gain is now larger than at the first part of the lab report, because the common mode gains of the 3 different opamps are resulting in a new common mode gain for the whole instrumentation amplifier.

b) Differential gain

The differential gain was again determined by connecting the bridge to the corresponding inputs of the amplifier.
The circuit diagram of the connected bridge is shown below:



The output voltages of the connected bridge are now nearly the same than the output voltages of the unconnected bridge, because they are only connected to the opamp inputs which have an input resistance of more than several hundreds kΩ(for the LM741 typically 2MΩ) .

V_1=7.5V (unconnected) → V_1=7.48V (connected)
V_2=7.67V (unconnected) → V_2=7.7V (connected)

V_{Out}=6.44V

hence the differential gain A_C can be determined:

$$A_D = \frac{V_{Out}}{V_1 - V_2} = \frac{6.44\text{V}}{7.7\text{V} - 7.48\text{V}}$$

$$\underline{\underline{A_D = 29.3}}$$

The theoretically calculated of A_D is calculated by

$$A_C = \left(1 + \frac{2R_C}{R_C}\right)\frac{R_2}{R_1}$$

$$\underline{\underline{A_C}} = 2 \times \frac{100\text{k}\Omega}{10\text{k}\Omega} \underline{\underline{= 30}}$$

So the measured value is very close to the theoretically calculated value. The deviation of both values results from the inaccuracy of the used resistors and of the not ideal opamp.

c) Common mode rejection ratio (CMRR)

The common mode rejection ratio is calculated using the equations from part c) Common mode rejection ratio.

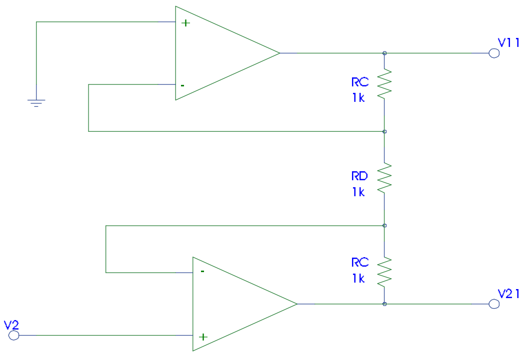
$$\mathrm{CMRR} = \frac{A_D}{A_C} \approx \frac{29.3}{0.04} = 732.5$$

$$\mathrm{CMRR}\big|_{dB} = 20\log\left(\frac{A_D}{A_C}\right) \approx 20\log\left(\frac{29.3}{0.04}\right) = 57\mathrm{dB}$$

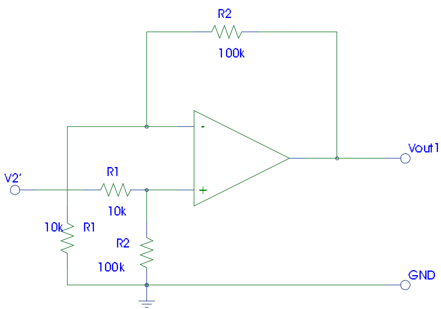
The CMRR is about ten times less than the CMRR of the single differential amplifier.

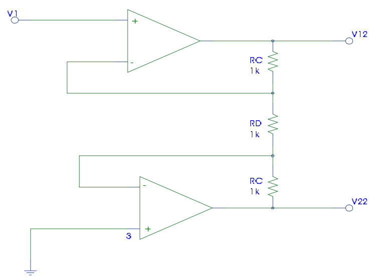
d) Derivation of differential amplification

i. Output differential amplifier



Superposition





$$\frac{V_{Out1}}{V_+} = \frac{R_2 + R_1}{R_1} \quad \rightarrow (V_1' = 0V)$$

$$V_+ = \frac{R_2}{R_1 + R_2} V_2'$$

$$\frac{V_{Out1}}{V_2'} = \frac{R_2 + R_1}{R_1} \frac{R_2}{R_1 + R_2} = \frac{R_2}{R_1}$$

$$V_{Out1} = \frac{R_2}{R_1} V_2'$$

$$\frac{V_{out2}}{V_1'} = -\frac{R_2}{R_1} \quad \rightarrow (V_2' = 0V)$$

$$V_{out2} = -\frac{R_2}{R_1} V_1'$$

Now the two separate calculated voltages are added:

$$V_{Out} = V_{Out1} + V_{Out2}$$

$$V_{Out} = \frac{R_2}{R_1} V_2' - \frac{R_2}{R_1} V_1$$

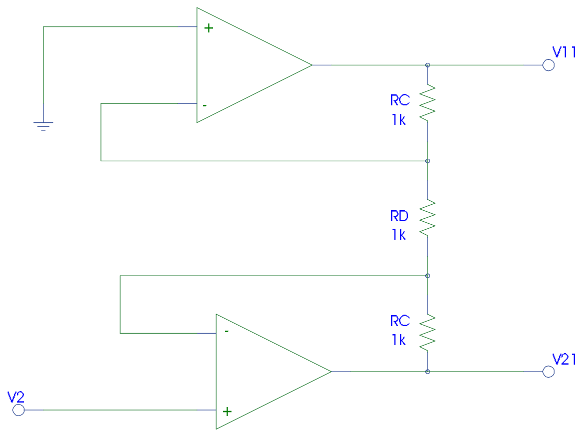
$$V_{Out} = \frac{R_2}{R_2} (V_2' - V_1')$$

$$\underline{\underline{\frac{V_{Out}}{V_2' - V_1'} = \frac{R_2}{R_1} = A_D}}$$

ii. Input amplifier

(via Superposition and virtual earth)

V_1=0V

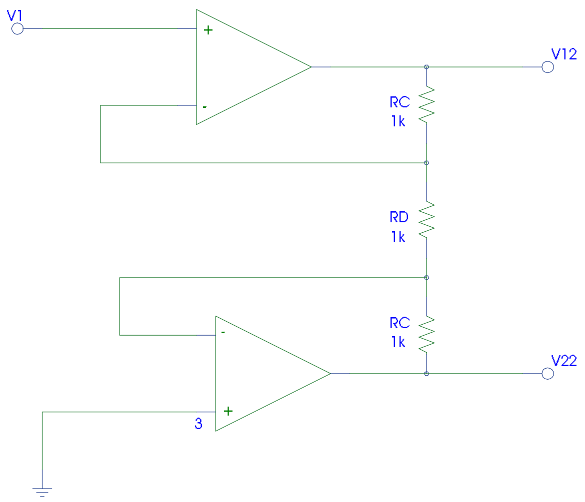


$$\frac{V_{21}}{V_2} = \frac{R_C + R_D}{R_D}$$

$$\underline{V_{21} = \left(1 + \frac{R_C}{R_D}\right) V_2}$$

$$\underline{V_{11} = -\frac{R_C}{R_D} V_2}$$

V_2=0V



$$\frac{V_{21}}{V_1} = \frac{R_C + R_D}{R_D}$$

$$V_{12} = \left(1 + \frac{R_C}{R_D}\right) V_1$$

$$V_{22} = -\frac{R_C}{R_D} V_1$$

Superposition of V_{11}, V_{12} and V_{21}, V_{22}

$$V_1' = V_{11} + V_{12} = -\frac{R_C}{R_D} V_2 + \left(1 + \frac{R_C}{R_D}\right) V_1$$

$$V_2' = V_{21} + V_{22} = \left(1 + \frac{R_C}{R_D}\right) V_2 - \frac{R_C}{R_D} V_1$$

Now regarding to i) Input amplifier

$$V_2' - V_1' = V_2\left(1 + \frac{2R_C}{R_D}\right) - V_1\left(1 + \frac{2R_C}{R_D}\right)$$

$$V_2' - V_1' = (V_2 - V_1)\left(1 + \frac{2R_C}{R_D}\right)$$

This equation now into $\frac{V_{Out}}{V_2' - V_1'} = \frac{R_2}{R_1} = A_D$

$$V_{Out} = \frac{R_2}{R_1}(V_2' - V_1')$$

$$V_{Out} = \frac{R_2}{R_1}(V_2 - V_1)\left(1 + \frac{2R_C}{R_D}\right)$$

$\underline{\underline{A_D = \frac{V_{Out}}{V_2 - V_1} = \frac{R_2}{R_1}\left(1 + \frac{2R_C}{R_D}\right)}}$ or with the resistors from the Lab $\underline{\underline{A_D = \frac{V_{Out}}{V_2 - V_1} = \frac{R_2}{R_1}\left(1 + \frac{2R_A}{R_B}\right)}}$

QED

6. Comparison 741 vs. instrumentation/strain gauge amplifier

Item	741(C)	RS strain gauge Amplifier
V_{in}	**+-15V**	**+-12V**
I/P offset voltage	**4mV**	**200µV**
I/P impedance	**>0.3 MΩ**	**>5MΩ**
Bandwidth (unity gain)	**>437kHz**	**450kHz**
O/P voltage span	**+-12V**	**V_S-+2V**
O/P current	**+-25mA**	**5mA**
closed loop gain	**30dB**	**3..60dB**
open loop gain	**--**	**>120dB**
CMRR	**57dB**	**>120dB**
Power dissipation	**3x0.5W**	**0.5W**
max. bridge supply current	**--**	**12mA**
Price	**3x£0.50**	**£44.43**

7. Conclusuion

Opamps are very unique electronic devices. Because of their in some cases nearly perfect characteristics it’s very easy to built up cheap and well working amplifiers.
The opamp circuits have to be designed carefully and especially for instrumentation amplifiers the other used devices, like resistors must be selected very carefully in order to obtain correct results. For an instrumentation amplifier used for measuring it is very important to deliver exact results.