# INVESTIGATION OF THE CHARACTERISTICS OF CLOSED-LOOP NON-INVERTING OPERATIONAL AMPLIFIER AT AN EXTENDED FREQUENCY RANGE

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**Annotation**

*This article encompasses the description along with the theory of non-inverting operational amplifiers and compares theoretical characteristics with those obtained in the laboratory. The goal is to validate the tendency of the input-output voltage relationship at a fixed 1.25 kHz frequency and the tendency of the gain-frequency relationship based on an officially recognized hypothesis using KL-900A Basic Communication Trainer. The literature on non-inverting amplifier characteristics is provided considering the ideal case scenarios which, to some extent, deviate from their practical characteristics. Also, the frequency that could be applied to the non-inverting operational amplifier circuit KL-900A module is limited to 200 kHz. For this reason, the experiment at an extended frequency range varying from 20 Hz to 1.7 MHz was conducted to see either the discrepancy or partial conformity of the operational amplifier characteristics theory and comment on factors that influence the deviation of acquired parameters from ideal parameters and highlight the usefulness of having an extended frequency range for KL-900A Basic Communication Trainer.*

**Key words:** KL-900A Basic Communication Trainer, operational amplifier, non-inverting amplifier, amplitude and frequency characteristics.

**Introduction**

It is out of doubt that the modern technological world is full of innovative ideas related to electronic equipment and its design. Operational amplifier is a key element of the integrated circuit which provides consumers with amplified signals to facilitate the perception of signal's nature and allow utilize it in the spheres of interest. Understanding basic principles of circuitry where operational amplifiers exist and being aware of its characteristics, can contribute to the proper exploitation of electronic instruments and assist in producing much more complex systems.

**Research Object**

Basic Communication Trainer for studying the basic principles of telecommunication equipment – KL900A which includes power supply and audio generator KL-92001, PSK/QPSK modulator KL-94006 modules, digital storage oscilloscope with FFT; PFM3000 - Frequency meter, RF generator KI-2220.

**Problem and Relevance of the Research**

Laboratory research is a crucial part of the activities of both scientific and higher education institutions. Along with the introduction of modern technologies, equipment and systems, it is important to improve the existing equipment with a view to modernize it, in particular, to expand the functional spectrum. KL900A Basic Communication Trainer's built-in generator KL-92001 is limited to 200 kHz, which obstructs its users to conduct more advanced research on operational amplifier circuit characteristics. The research on closed-loop non-inverting operational amplifier circuit at extended frequency range using separate RF generator KI-2220 reveals the necessity of improving the technical capabilities of the existing equipment. This will allow to broaden the picture of circuity characteristics and compare the obtained results concerning operational amplifier LF356 device with manufacturer's proposed specifications.

**Research Objectives**

Consideration of theoretical basics of operation of the operational amplifier and its experimental confirmation. This report focuses on the acquaintance with a closed-loop non-inverting operational amplifier to get an idea of its working principles and to extend the passport characteristics of the KL-900A. Then, the evaluation of the acquired results will be presented and commented on. The experiment itself consists of:

1. Measuring the output voltage at different input voltages at a fixed frequency.
2. Measuring the voltage gain at different frequencies from 20 Hz to 1.7 MHz.

**Research Methodology**

1. Review of scientific literature.
2. Conducting laboratory research.
3. Displaying graphs with the obtained results.
4. Analysis and conclusion.
5. Recommendations derived from the outcome of the experiment.

**Background**

An Operational amplifier is a device which can be found in various electronic equipment. It is a universal building block (Assim & Balashov, 2021) that is used in analogue and digital systems, i.e., filters, rectifiers, converters, comparators, servo valve drivers, etc. Its main function is to increase the input voltage amplitude by a factor determined by the design of the operational amplifier consisting of resistors, capacitors, and transistors. Furthermore, the voltage gain is also dependent on the frequency of the input signal which can dictate the magnitude of amplification (George & Winder, 2003).

There are two distinct ways of creating the feedback to an operational amplifier – inverting and non-inverting configuration. The difference between the two different setups is that the output signal is brought back either to inverting or non-inverting terminals. The non-inverting operational amplifier considered in this report is a specific operational amplifier with the input signal connected to its non-inverting input (+). The feedback signal is accordingly transferred to the inverting terminal (-). It implies that if an AC signal is supplied to the non-inverting terminal, the output signal is in phase with the original signal, and for the DC case, the polarity stays the same. The closed-loop feedback is established with the purpose to control the voltage value at the inverting terminal. Figure 1 (Carter & Brown, 2001) represents the basic circuit of a non-inverting operational amplifier (R1, R2 – fixed resistors, $V_{out}$ – output voltage, $V_{in}$ – input voltage, GND – ground).

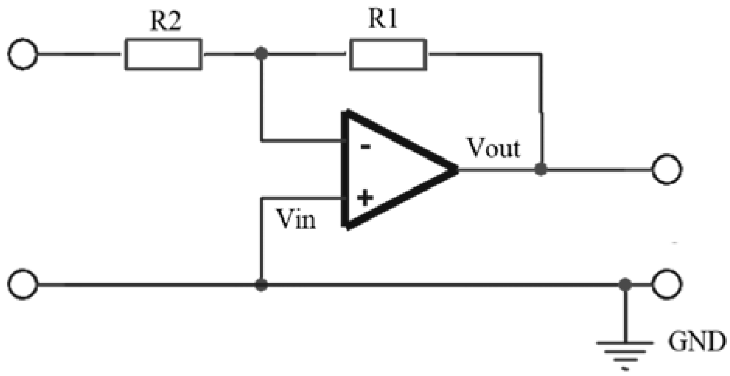


Fig. 1. Basic closed loop non-inverting operational amplifier circuit

The working principle of the closed-loop non-inverting operational amplifier is that it distinguishes the slight voltage difference between the positive and negative input ports and increases the voltage with respect to it. The output cascade drives current into R1 until the negative and positive input voltages are equal $V_{in}$. This happens because of the virtual short between two input terminals. Owing to the voltage divider rule, the voltage coming to the negative terminal can be regulated. After applying the previously mentioned rule and introducing mathematical manipulations, the input and output voltage relationship can be deduced:

$$V_{in} = V_{out} \cdot \frac{R2}{R1+R2} \quad (1)$$

$$\frac{V_{out}}{V_{in}} = \frac{R2+R1}{R2} = 1 + \frac{R1}{R2} \quad (2)$$

At this point, the input-output voltage relationship depends on the ratio of the gain resistors. If R2 value is relatively large compared to R1, the circuit becomes a unity gain buffer, and vice-versa, if R1 value is much bigger than R2, the infinity gain takes place. R1 can be replaced by the potentiometer, resulting in the possibility to vary the voltage gain. As practice shows, the infinity gain is only possible in ideal operational amplifiers based on their characteristics (Mancini, 1999). When it comes to real operational amplifiers, the gain is defined by the voltage source. The saturation concept is prevalent in this type of circuitry, so the output voltage is limited by the power supply voltage as can be seen in Figure 2 (George & Winder, 2003) (Дьяченко, 2013).

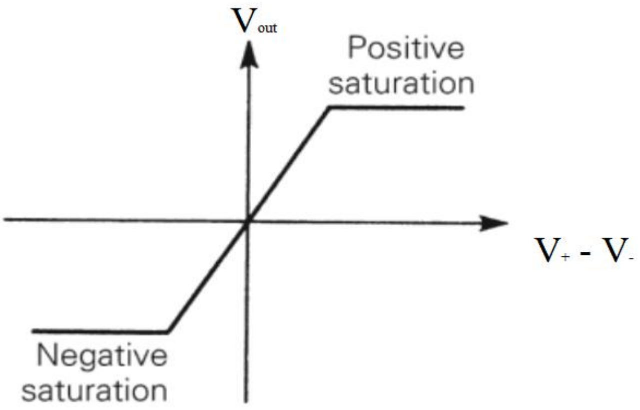


Fig. 2. Operational amplifier output voltage limitation due to saturation

Another important factor that must be taken into account is frequency characteristics (Asharani, Chinnaiah, & Keerthi, 2020). Real operational amplifiers have a frequency-dependent gain which can tremendously influence the performance of the device. The open-loop compared to closed-loop operational amplifiers are providing a greater voltage gain. Nevertheless, closed-loop operational amplifiers are capable of operating in a greater frequency range which can come in hand with specific electric equipment which requires voltage amplification at high frequencies.

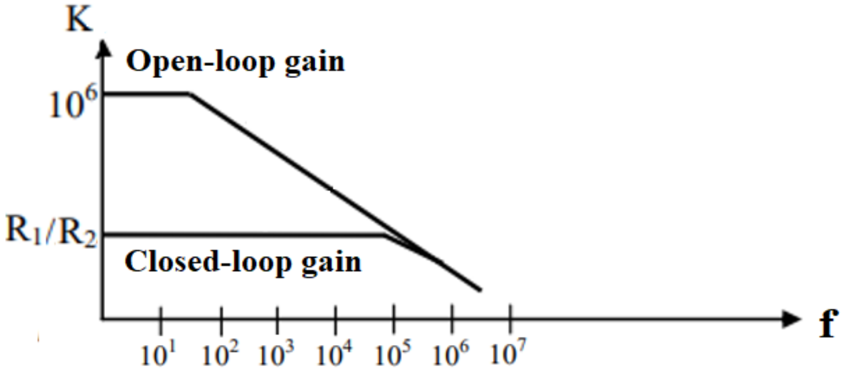


Fig. 3. Open loop and closed-loop frequency response of the operational amplifier circuit

Figure 3 acts as a justification for the proposed statement and it represents the frequency characteristics of both open-loop and closed-loop operational amplifiers. It becomes obvious that K (voltage gain) in open-loop circuits is much greater compared to closed-loop (Oljaca & Surtihadi, 2010) (George & Winder, 2003).

**Characteristics of Closed Loop Non-Inverting Operational Amplifier**

The scope of the experiment lies within the investigation of the closed-loop non-inverting operational amplifier circuitry response at low, medium and high frequencies in order to make emphasis on required extension of frequency range of KL-900A Basic Communication Trainer. The work was carried out on KL-900A Basic Communication Trainer (Figure 4) which essentially includes modules with experimental circuits. To visualize the amplification process an oscilloscope was used.

Fig. 4. KL-900A Basic Communication Trainer

The circuit assembly is presented in Figure 5 (VR1 – variable resistor, R1, R2, R3 – fixed resistors, OA – operational amplifier, C1, C2 – fixed capacitors, SG – signal generator, SR – oscilloscope). The operational amplifier model used in the experiments described below is LF356. LF356 is a junction field effect transistor input operational amplifier IC. The IC features low input bias and offset currents/low offset voltage and offset voltage drift, coupled with offset adjust which does not degrade drift or common mode rejection. The IC is always available in an 8 – pin hermetically sealed dual in line IC package (DIP). LF356 has a wide range of working conditions, a wide array of operating voltages, and is compatible with almost every TTL, CMOS, & PMOS device. The IC also offers many different features such as high input impedance and high noise immunity. The device is also designed (Rendón & Angélica, 2019) for wide bandwidth and extremely fast settling time. In terms of the electrical characteristics, the typical gain bandwidth is 5 MHz and dual supply voltage ±15 V (LF356 Datasheet, 1998). Two different experiments took place to determine the amplitude and frequency characteristics of a closed-loop non-inverting operational amplifier.

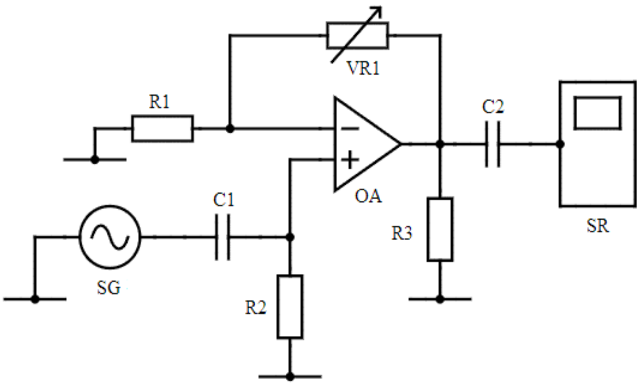


Fig. 5. Experimental closed-loop non-inverting operational amplifier circuit with AC input signal

The first experiment was conducted by applying a fixed frequency – 1,25 kHz and varying the input voltage value to explore the amplitude characteristics. The results are shown in Table 1 and Figure 6. The trend is close to linear until it reaches the plateau at input voltage – 1.6 V. It implies the fact that the system has reached its saturation point and is not capable of increasing the output voltage due to restrictions associated with the voltage supply source. The gain is presented in the form of the gradient of the trendline. It provides information on the voltage amplitude ratio. It is conspicuous that the gain remains the same throughout the input voltage growth prior to saturation. The outcome of this experiment validates that the alteration of input voltage does not impact the voltage gain. The increase of input voltage results in a proportional rise in output voltage.

Table 1

Results of the voltage amplitude experiment

| $V_{in}$ (V) | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{out}$ (V) | 0.0 | 1.3 | 2.4 | 3.6 | 5.0 | 6.2 | 8.3 | 9.3 | 10.0 | 10.0 | 10.0 |

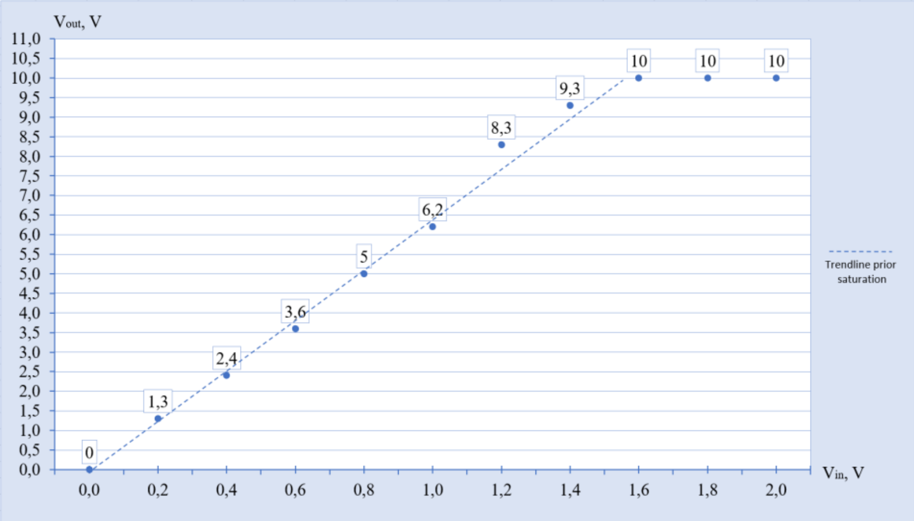


Fig. 6. Closed-loop non-inverting operational amplifier input and output voltage amplitude relationship at 1.25 kHz

The second experiment is focused on an extended frequency range at fixed voltage input – 0.5 V. Initially used built-in function generator KL-92001 could produce 220 kHz sinusoidal signal whereas the frequency limit indicated by the equipment manufacturer was 200 kHz. Although the frequency limit was exceeded by 10%, this was still not enough to depict the complete graph regarding operational amplifier circuit frequency-gain response. From this point forward, the RF generator KI-2220 (max 150 MHz) is introduced to go beyond 220 kHz limit. By varying the frequency of the input signal from a signal generator, starting at 20 Hz and, ultimately, reaching 1.7 MHz, the output voltage amplitude was measured. Subsequently, the voltage gain was calculated based on the input and output voltage ratio. The frequency characteristics shown in Table 2, 3, 4.1, 4.2 and Figure 4 provide an overview of the effectiveness of a closed-loop non-inverting operational amplifier. It can be inferred from the graph that the gain follows the logarithmic trend at the first zone where the frequency ranges from 20 Hz to 300 Hz. The amplitude ratio is prone to increase rapidly at relatively low frequencies. The second zone lies within the 300 Hz and 200 kHz frequency range. After 300 Hz, the plateau is depicted, signifying that the saturation level is reached, and no voltage gain increase is possible. It lasts till the frequency is high enough to impact the efficacy of the operational amplifier circuit and the threshold value at which the gain starts to fall is around 200 kHz. The third zone is the region of high frequency (0.3 – 1.7 MHz). Here, the downward trend is present, indicating that the high frequency has a negative impact on voltage gain.

Table 2

Results of experiment (First zone)

| f (Hz) | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{out}$ (V) | 0.5 | 1.4 | 2.4 | 3.3 | 3.8 | 4.2 | 4.4 | 4.6 | 4.8 | 5.0 | 5.2 |
| K (gain) | 1 | 2.8 | 4.8 | 6.6 | 7.6 | 8.4 | 8.8 | 9.2 | 9.6 | 10.0 | 10.4 |

Table 3

Results of experiment (Second zone)

| f (kHz) | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|
| $V_{out}$ (V) | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 |
| K (gain) | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 | 10.4 |

Table 4.1

Results of extended frequency range experiment (Third zone)

| f (MHz) | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|
| $V_{out}$ (V) | 5.2 | 4.8 | 4.4 | 4.0 | 3.4 | 3.0 | 2.7 | 2.5 |
| K (gain) | 10.4 | 9.6 | 8.8 | 8.0 | 6.8 | 6.0 | 5.4 | 5.0 |

Table 4.2

Results of extended frequency range experiment (Third zone) continuation

| f (MHz) | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 |
|---|---|---|---|---|---|---|---|---|
| $V_{out}$ (V) | 2.3 | 2.0 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 | 1.1 |
| K (gain) | 4.6 | 4.0 | 3.4 | 3.2 | 3.0 | 2.8 | 2.6 | 2.2 |

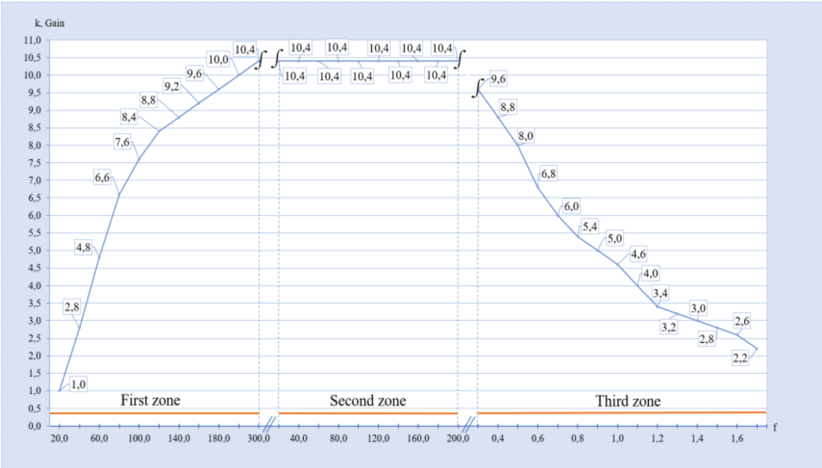


Fig. 7. Closed-loop non-inverting operational amplifier circuit gain and frequency relationship: First zone – frequency range 0-300 Hz; Second zone – frequency range 20-200 kHz; Third zone – frequency range – 0.2-1.7 MHz

The theoretical illustration of frequency response presented in Figure 3 is considered to be an ideal case scenario. Examining the obtained results of voltage gain from 20 kHz to 1.7 MHz that were shown in Figure 7, it becomes clear that the real frequency characteristics generally resemble the proposed one in the theory section of this report. A slight deviation from a linear decrease at high frequencies can be ascribed to the tolerance associated with electric components' parameters and precision of measurement. Overall, the closed-loop non-inverting operational amplifier circuit has shown great results in sustaining maximum allowed voltage gain over a long frequency range from 20 kHz to 200 kHz. The results obtained from the experiment concerning closed-loop operational amplifier circuit show resemblance to the theory provided in Background section in the form of circuit behaviour throughout the chosen frequency range.

The characteristics of the operational amplifier show that there is a decrease in gain at low and high frequencies. Unequal amplification at different frequencies is observed because of the reactive components. The resistance of these components varies with frequency. Moreover, the circuit assembly has some distributed parasitic capacitance. The lower the frequency of the signal gets, the greater capacitance occurs, and, as the result, less voltage is sent to the output. The decrease in gain with increasing frequency can be explained in the following manner. The conductivity of the capacitance rises when the frequency is increasing. As the frequency grows, parasitic capacitance creates a more pronounced short circuit with the ground and some part of the AC signal gets eliminated. Eventually, the entire AC signal goes to the ground through parasitic capacitance. The resistance of the capacitance decreases with increasing frequency, while the depth of negative feedback increases. This leads to a decrease in gain. The report fully confirms the basic working principles of the operational amplifier circuit and indicates that extended frequency range is crucial to fully understand how the circuit is behaving.

## Conclusion

The experiments were conducted on KL-900A Basic Communication Trainer to verify the behaviour of a closed-loop non-inverting amplifier circuit at different voltage input levels and extended frequency range. The results provided in graphs and tables confirm the theory regarding the frequency and amplitude characteristics of the operational amplifier. The input-voltage amplitude relationship is constant throughout every input voltage increment until the operational amplifier circuit reaches the saturation point. The frequency response of the circuit shows how the system reacts when the sinusoidal signal is supplied at different frequencies. It is proved that maximum voltage gain can be maintained over a decent frequency range if this range is known and not exceeded. The frequency extension using separate frequency generator helped to observe the operational amplifier circuit response of KL900A Basic Communication Trainer module at higher frequencies, thus allowing to fully get acquainted with closed-loop non-inverting operational amplifier circuit characteristics.

The assessment of the experimental results acquired during the research of operational amplifier circuit at an extended frequency range is performed referring to the specifications of integrated chip LF356 provided by various manufacturers such as ST Microelectronics, Texas Instruments, Linear Technology, National Semiconductor, Newark Electronics and Maritex. Taking into account the presence of specific non-linear distortions from the frequency response graph in the region of maximum and minimum gain, the operational amplifier bandwidth was considered within the frequency range from 0.5 MHz to 1.5 MHz. The calculated interval was obtained within 4 MHz - 4.6 MHz range which closely corresponds to the manufacturers' bandwidth specifications (5 MHz) mentioned above. Minor deviations may be induced due to the characteristics of the KL-92001 module - supply voltage ± 12 V, as well as the parameters of the operational amplifier circuit of the KL-94006 module - input capacitance 250 pF and the feedback resistor 1 kΩ, do not fully comply with the specifications of the integrated chip LF356 ± 15 V, 100 pF and 2 kΩ respectively. The obtained results can be considered satisfactory given the fact that the experiment was conducted on training equipment. It is recommended to rearrange the operational amplifier circuit of the KL-94006 module by altering the assembly and values of the components with respect to the specifications of one of the LF356 chip's manufacturers. This could potentially result in a higher probability of research results matching theoretical ones.

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