# ECSE331 Lab 3

# Op-Amp Imperfections


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ECSE331

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# ECSE331 Lab-3 Report

***Abstract* — In the real world, op-amps suffer from non-ideal DC and AC impacts. In this report, students will analyze the effects of DC and AC imperfections of the 741 op-amp on corresponding circuits and investigate various circuit techniques to minimize the impacts.**

## I. INTRODUCTION

In this lab, students will investigate the 741 op-amp imperfections. By studying op-amp imperfections, students will better understand real-world op-amps. In this report, students will analyze three major impacts of the 741 op-amp: non-ideal DC effects, effects of finite gain and bandwidth on the performance of closed-loop op-amp circuits, and effects of nonlinear behavior. To do so, students will build different circuits, measure corresponding values, and compare these measured values with theoretical values.

## II. EXPERIMENT RESULTS

### *A. (a) Offset Voltage*

In this part, we built the circuit as shown in Fig. 1. To set $V_{off}$ to zero, we replaced it with a short circuit.

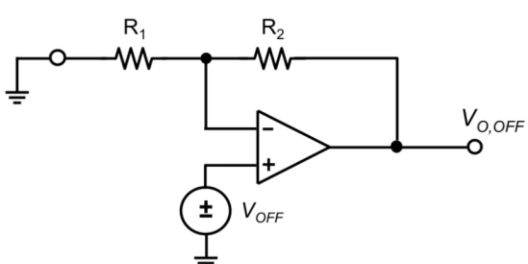


**Fig. 1. Inverting amplifier with an input-referred offset voltage**

Modeling $V_{off}$ as a *DC* voltage source, we could derive an expression for the output voltage $V_{o,\, off}$ in terms of $R_1$, $R_2$, and $V_{off}$ :

$$V_{O,off} = V_{off} \times (1 + \frac{R_2}{R_1}) \quad (1)$$

With no input to the op-amp circuit, ideally the output voltage should be zero. However, we measured the output voltage using the digital multi-meter, and a 1.0428$V$ voltage appeared (Fig. 2). This is due to the non-ideal behavior of the op-amp in the real world.

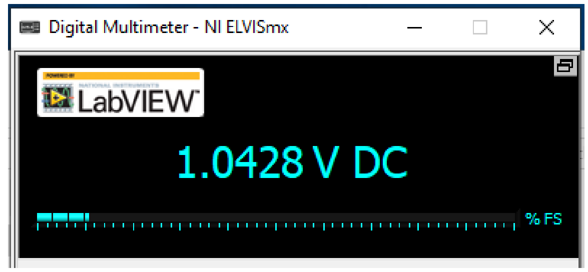


**Fig. 2. Measured $V_{off}$ with no input to the op-amp circuit**

Using the formula *(1)*, we got the $V_{off}$ equal to 1.042$mV$. From the 741-datasheet, the maximum input offset voltage is 5$mV$. Comparing our result to the one from the datasheet, the input offset voltage of the op-amp we used fell within the predefined range and worked properly.

### *(b) Input Bias and Offset Currents*

In this part, we built two test circuits, as shown in Fig. 3 and Fig. 4, to measure the effects of two different currents drawn by the op-amp through its two inputs.

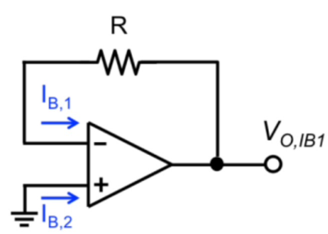


**Fig. 3. Test circuits for measuring the effect of $I_{B,\,1}$**

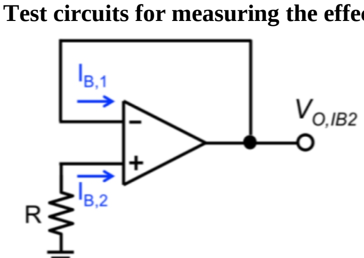


**Fig. 3. Test circuits for measuring the effect of $I_{B,\,2}$**

We measured output voltages $V_{O,\, IB1}$ and $V_{O,\, IB2}$. However, the value was too small to measure with the DMM. To have a better measurement of $V_{O,\, IB1}$ and $V_{O,\, IB2}$, we cascaded an inverting amplifier, with a gain of 100V/V, at its output (Fig. 4).

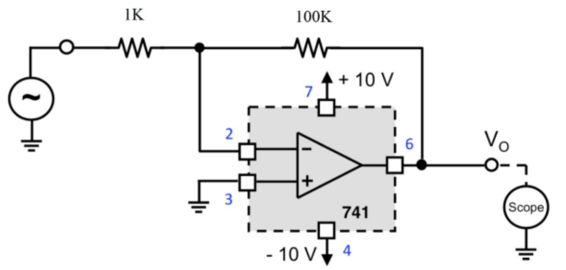


**Fig. 4. Cascaded inverting amplifier with a gain of 100V/V**

Then we derived expressions for these two in terms of two input currents, $I_{B,\ 1}$ and $I_{B,\ 2}$, respectively:

$$V_{O,IB1} = I_{B,1} \times R \ (2)$$

$$V_{O,IB2} = -I_{B,2} \times R \ (3)$$

With our measured results of $V_{O,\ IB1}$ (Fig. 5), $V_{O,\ IB2}$ (Fig. 6), and the two expressions shown above, we could get the value of $I_{B,\ 1}$ and $I_{B,\ 2}$ by working backward.

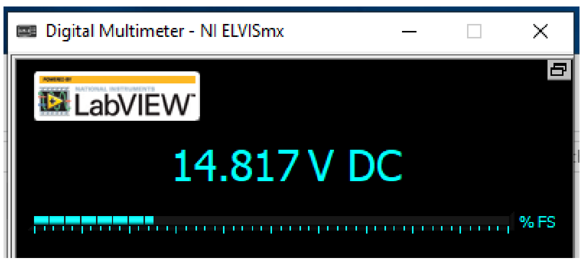


**Fig. 5. Measured result of 100V$_{O,\ IB1}$**

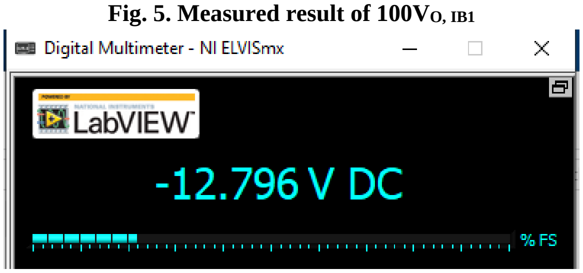


**Fig. 6. Measured result of 100V$_{O,\ IB2}$**

Hence, $\cdot\ I_{B,1} = \frac{V_{O,IB1}}{R} = \frac{14.817V \div 100V/V}{1M\Omega} = 0.14817\mu A$

$$\cdot\ I_{B,2} = \frac{V_{O,IB2}}{R} = \frac{-12.796V \div 100V/V}{1M\Omega} = -0.12796\mu A$$

$$\cdot\ |I_{B,2}| = 0.12796\mu A$$

From $I_{B,\ 1}$ and $I_{B,\ 2}$, we calculated the bias current $I_B$ using the formula *(4)*, which is $0.138065\mu A$.

$$I_B = \frac{I_{B,1} + I_{B,2}}{2} \ (4)$$

We also calculated the offset current $I_{OS}$ using the formula *(5)*, which is $20.21nA$.

$$I_{OS} = |I_{B,1} - I_{B,2}| \ (5)$$

From the 741op-amp datasheet, we found out the maximum input bias current is 1.5μA, and the maximum input offset current is 500nA. Hence, our results fell within the accepted range.

### *(c) Offset Compensation*

To reduce the effect of op-amp DC imperfections, we added a single resistor $R_C$, whose resistance equals the resistance of $R_1$ in parallel with $R_2$, in series with the non-inverting input terminal of the op-amp (Fig. 7).

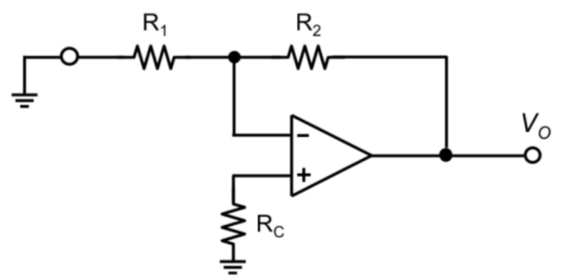


**Fig. 7. DC-compensated-amplifier**

To calculate its offset voltage, we then measured its output voltage, $V_o$. As the supply voltage can be negative, it is possible for us to get a negative output voltage, as shown in Fig. 8, even with a non-inverting amplifier. The magnitude of the measured result of $V_o$ is 20.780$mV$.

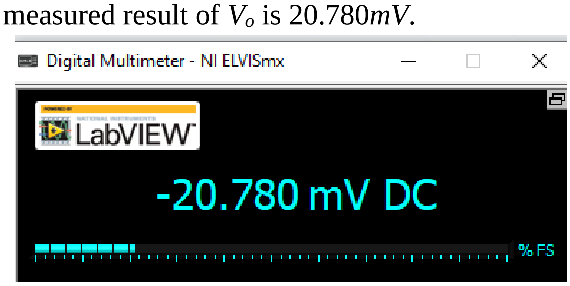


**Fig. 8. Measured result of 100V$_O$ of DC-compensated amplifier**

Using the formula (1), we calculated the offset voltage, and the result was 0.0208$mV$. Comparing the op-amp offset voltage (1.042$mV$) without resistance compensation in part A. (a), we noticed this DC-compensated amplifier helped provide a 98% decrease of the $V_{off}$ in part A. (a).

### *B. Effects of Finite Gain and Bandwidth on Closed-Loop Operation*

In this part, we investigated the open-loop DC gain and 3 dB frequency of the circuit shown in figure 9 using bode analyzer. In theory, the Gain-bandwidth product = $G_{DC} \times \omega_{3dB} = \omega_{t.}$

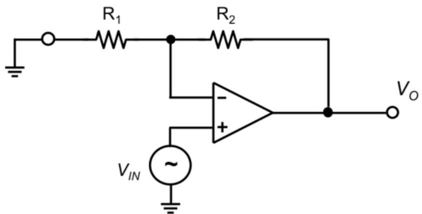


**Fig.9. Noninverting amplifier configuration for investigating the effects of finite gain and bandwidth on its closed-loop operation.**

As we can see from figure 10, when $R1 = 10k\Omega, R2 = 50k\Omega$, and input voltage is 100 Hz sine-wave with a peak-to-peak amplitude of 100 mV, the measured DC gain is 15.613 dB and 3-dB bandwidth is around 158489 Hz since we assume that there will be approximately no change of gain from 0Hz to 100Hz. The measured gain-bandwidth product is thus $10^{12.622/20} \times 158489 = 677796.2$. The expected GBP is $\omega_t \approx 794328$. Note that $\omega_t$ should be the frequency where Gain = 1dB. However, our bode plot doesn't contain this point. The difference is approximately $\frac{794328-677796.2}{794328} = 14.7\%$.

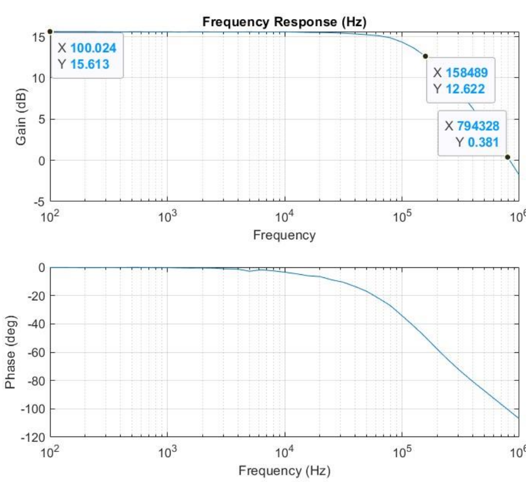


**Fig.10 Bode plot of the frequency response of the given circuit with $R_2$=50k Ohms.**

We then changed R2 to 100 $k\Omega$ and held R1 and input voltage constant. After repeating the same procedures, we got the bode plot shown in figure 11. It's shown that DC gain becomes 20.837 dB and 3-dB bandwidth becomes to 79432.9 Hz. In this case, the measured GBP is $10^{18.087/20} \times 79432.9 = 637309.5$. The expected GBP is approximately 794328. The relative difference is thus $\frac{794328-637309.5}{794328} = 19.8\%$.

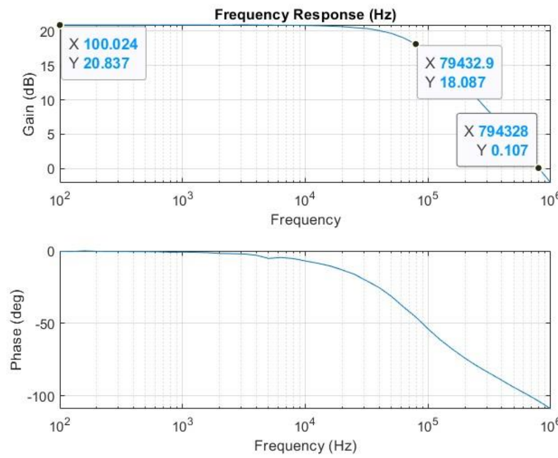


**Fig.11 Bode plot of the frequency response of the given circuit with R2=100k Ohms.**

Finally we changed R2 to 220 k$\Omega$ with other conditions held constant. The result bode plot is shown in figure 12. We can observe from the cursors that the DC gain is 27.279 dB and 3-dB bandwidth becomes 39810.7 Hz. In this case, the measured GBP is $10^{24.236/20} \times 39810.7 = 648335$. The expected GBP is approximately 794328. The relative difference is thus $\frac{794328-648335}{794328} = 18.4\%$.

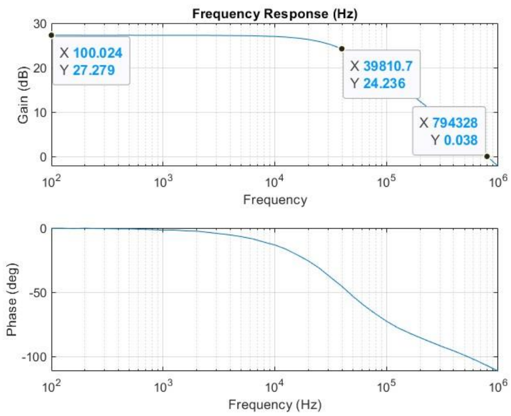


**Fig.12 Bode plot of the frequency response of the given circuit with R2=220k Ohms.**

### *C. (a)Output saturation effects*

A sine wave passing through the linear system retains its shape at output. However, when input signal is too large, the output will get saturate. We swept the amplitude starting from very small voltage until it's get saturated. In this part, we'll use the same circuit shown in figure 9.

As we can see from figure 13, the output signal is saturated to 9.29V. Hence Vmax = 9.29V. We can also find that when Vout less than the 0.028V, the output signal is alway around 0.028V. Vmin is thus 0.028V.

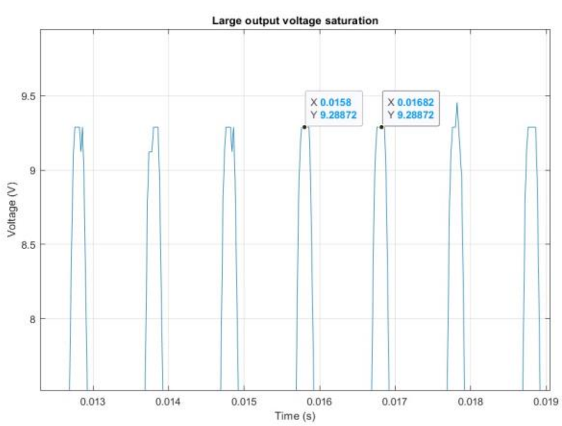


**Fig.13 Vmax measured when output is saturated.**

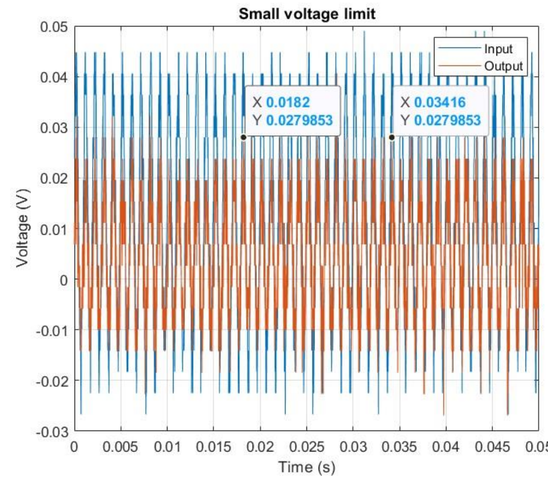


**Fig.14 Vmin measured when output doesn't respond to the input signal.**

### *(b)Slew-Rate Limiting*

If the rate of change of the output signal exceeds the slew rate, the output signal will not resemble the input. In this part, we'll explore the effect and measure the slew rate.

We will use the same non-inverting circuit shown in figure 9 with R1=R2=10K$\Omega$. Firstly, we begin with the square wave input signal with 100mv amplitude and 100 Hz frequency. As we can see from figure 16, it's operating in a linear manner, and gain is $G = \frac{0.222V}{0.113V} = 1.96$.

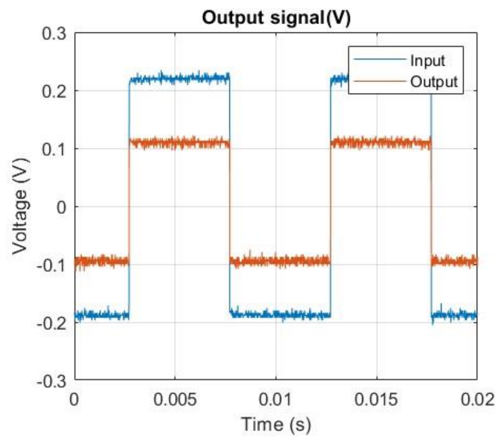


**Fig.15 Output voltage measured when input is 100Hz square wave with 0.1V amplitude.**

We then increased the amplitude until the output shape no longer resembles a square wave as shown in figure 16. $SR = \frac{\Delta V}{\Delta t} = \frac{1.43+0.02325}{2.64*10^{-6}} = 5.5 \times 10^{5} V/s$.

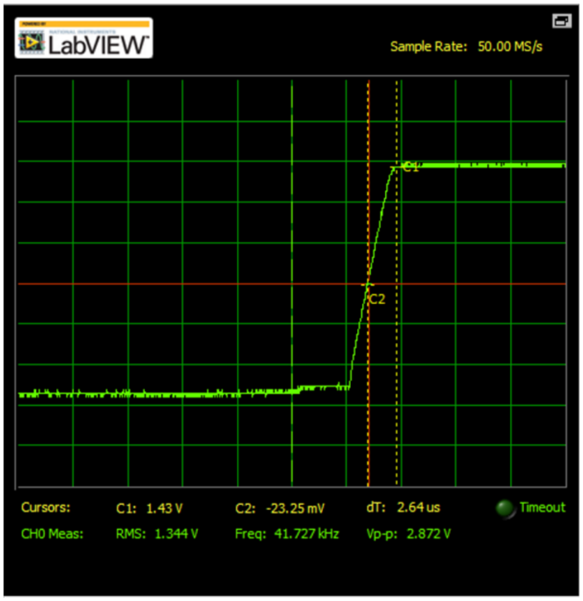


**Fig.16 Output voltage measured when output saturates with square input signal.**

Then, we changed the input signal to a sine-wave with an amplitude of 1V and 100Hz frequency,we slowly increase the frequency until distortion occurs as shown in figure 17. The frequency that we observe is around 70.3KHz.

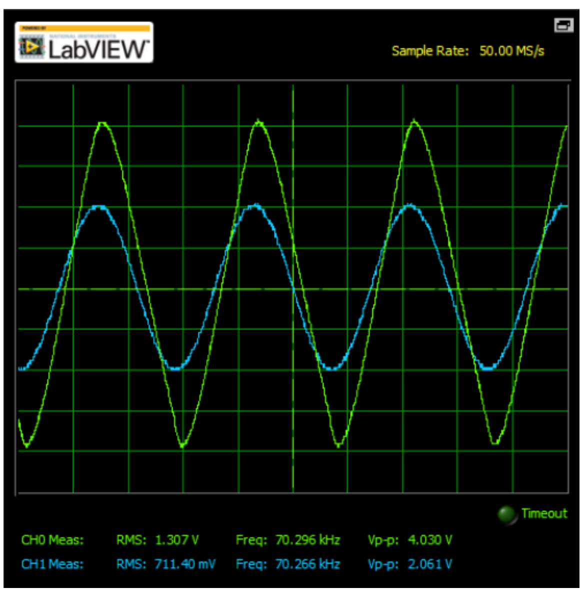


**Fig.16 Output voltage measured when output distorts with 1V amplitude sine wave.**

We then changed the amplitude to 1.5V and swept the frequency to get the frequency that output starts to distort. This frequency is 44.1KHz in this case.

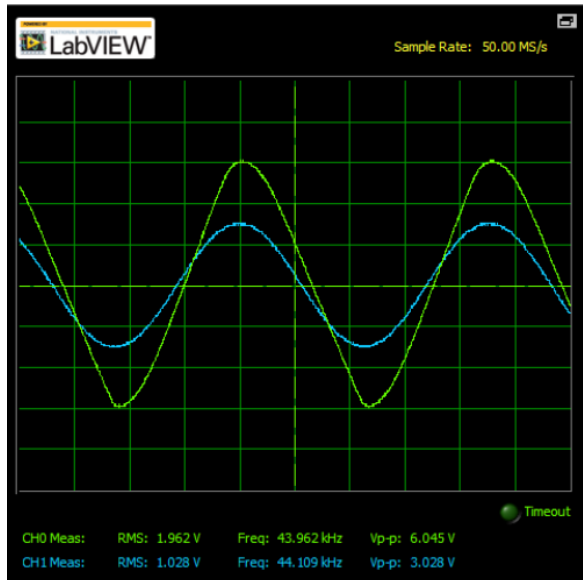


**Fig.17 Output voltage measured when output distorts with 1.5V amplitude sine wave.**

Repeating the same procedures, we changed the amplitude to 2V,3V,4V. The corresponding frequencies are 33.6Khz, 22.1Khz, and 17.1Khz respectively.

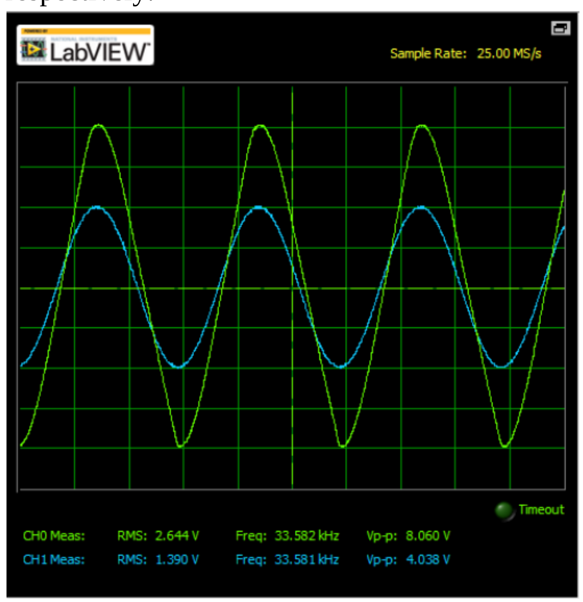


**Fig.18 Output voltage measured when output distorts with 2V amplitude sine wave.**

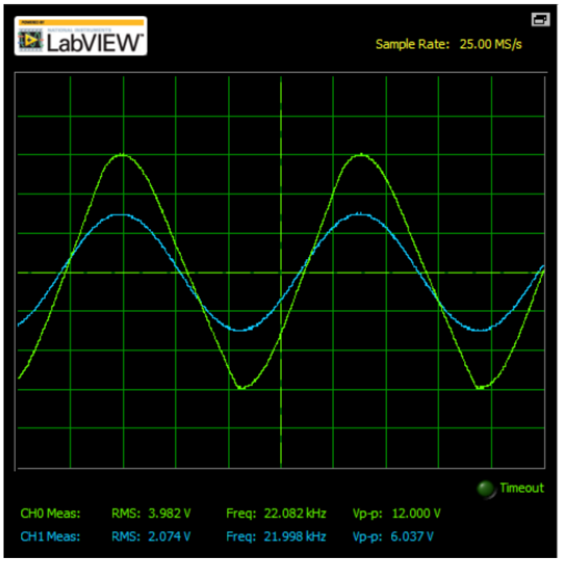


**Fig.19 Output voltage measured when output distorts with 3V amplitude sine wave.**

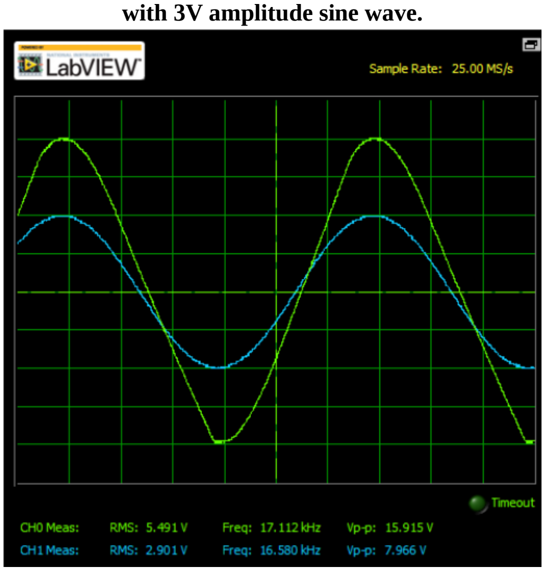


**Fig.20 Output voltage measured when output distorts with 4V amplitude sine wave.**

Figure 21 shows the plot $f_M$ versus amplitude. As the amplitude increase the distortion frequency starts to decrease.

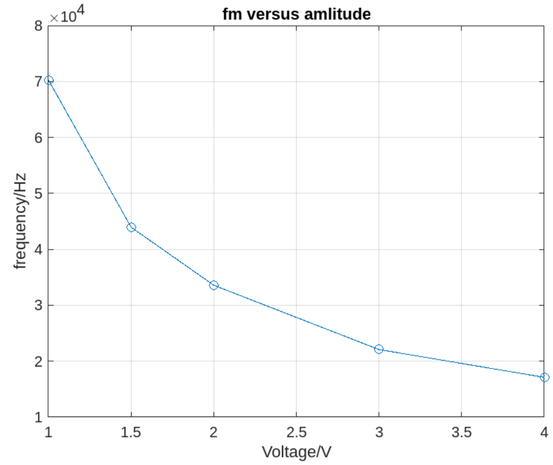


**Fig.21 The plot $f_m$ versus amplitude.**

**TABLE I**
**Amplitude-frequency Product**

| Amplitude(V) | $f_M$ (Khz) | $f_M$ × Amplitude |
|---|---|---|
| 1 | 70.296 | 70.396K |
| 1.5 | 43.962 | 65.943K |
| 2 | 33.582 | 67.164K |
| 3 | 22.082 | 66.246K |
| 4 | 17.112 | 68.448K |

As we can see from the table, the amplitude frequency product seems to be a constant between 65k and 70k. However, we can only make a rough estimation since we only measured 5 data points. If we use a smaller interval and have more measurements, more accurate conclusion will be derived.

## III. CONCLUSION

By doing this lab, students learned imperfections of the op-amp in the real world and grabbed skills of analyzing the major impacts of the 741 op-amp. We consolidated our knowledge by putting them in practice. By building circuits, doing circuits analysis, and comparing these measured values with theoretical values, student understood behaviors of op-amp in the real world better.