Exploration of the Behavior of Integrator Operational Amplifiers

Ryan Kaufmann

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Abstract

An integrator operational amplifier is a circuit that takes in an input voltage signal and outputs an amplified and integrated form of the voltage signal. The simple circuit consists of only three components, namely a capacitor, operational amplifier, and resistor, and two voltage sources, an input signal and a DC source. In this experiment, the behavior of the integrator operational amplifier circuit was tested against the theory, to see if the output voltage correctly followed the integrating behavior and the amplification was correctly proportional to both the resistance and capacitance. The theory states that the output voltage is a product of the inverse RC time constant and the integral of the input voltage signal. The integrating behavior was tested by analyzing the output voltage curves of both square and sine waves while the amplification was tested through testing various resistor/capacitor combinations and analyzing the output voltage to the input voltage. The integrating behavior seemed to be followed regardless what type of wave was inputted. The frequency and voltage also followed the integration unless the operational amplifier began to become saturated. Furthermore, it was found that at certain values the time constant, the theory was followed nearly perfectly. However, it quickly fell once the time constant got above or below a certain value.

1 Introduction

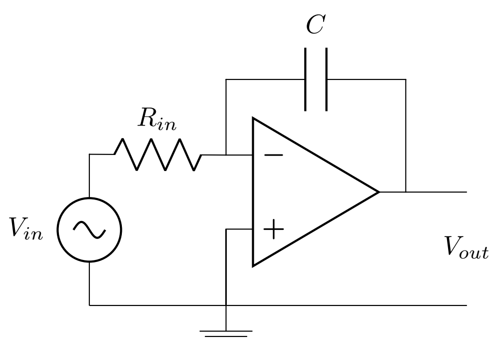
If you haven't already noticed from your daily lives, electronics are a key part to today's society, dictating the way we received information to the way we spend our free time. To many people, the inner workings of our phones, televisions, and computers are hidden. Inside our devices are complicated circuits that are meant for very specific behaviors. In order to convert from alternating current to direct current, many devices like a laptop charger have rectifiers, which consist of diodes, resistors, and capacitors [1]. There are also frequency-selective limiters. Frequency-selective limiters, or FSLs for short, are able to suppress certain types of interference [2]. While it cannot affect white noise interference, it can attempt to cancel out some continuous wave interference. Continuous wave interference can cause adverse affects on the quality of global positioning systems, or GPS [3]. FSLs in the receiver prevent CW interference from highly affecting GPS and other systems.

The circuit we will be testing is called an operational amplifier integrator, or op amp integrator. Op amp integrators are useful especially in analog computers. Op amp integrators provide a way to rudimentarily integrate a function. It can also be used in function generators to create certain signals such as triangle waves, where as differentiator op amps can create square waves from triangle waves. Therefore, they can also have unique applications when it comes to music technology such as wave-shaping.

In this experiment, we will be exploring the properties of an op amp integrator. Specifically, we want to judge how accurately the op amp integrator integrates a given signal using signals of square waves and sine waves at various frequencies and voltages. Then we want to observe the effects that the resistor and capacitor have on the circuit. We will measure the output voltage of the op amp with a sine input and compare it to the input voltage of the op amp and observe how it changes with difference capacitances and resistances.

2 Theory

The op amp integrator circuit is shown as below:



The operational amplifier is an integrated circuit. It has the main function of amplifying a voltage. The operational amplifier, or op amp, is in several circuits that amplifies the voltage and performs an operation on the source. This particular circuit amplifies the source voltage and integrates its signal.

To begin with, let us recall the capacitor theory. The charge on the capacitor can be written like so:

$$Q = CV$$

If the voltage source is assumed to change over time, the then by deriving each side of the equation by time, we get the following:

$$\frac{dQ}{dt} = i = C\frac{dV}{dt}$$

For the purpose of this derivation, assume that the op amp is ideal. An ideal op amp has a couple of unique characteristics that can be summed up in two parts:

I. In a closed loop, the output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

II. The inputs draw no current [4].

We will focus on the second of the two parts.

We can set up a Kirchoff junction rule to determine the value of V_{out}. At the junction connecting the capacitor, resistor, and op amp, the output current must be equal to the input current, according to Kirchoff's law. Recall that the op amp has no input current. Thus, it doesn't contribute to junction. So, the current across the resistor is equal to the current across the capacitor. Using Ohm's law, the relationship becomes:

$$i_R = \frac{V}{R} = C\frac{dV}{dt} = i_C$$

It is important to note that the Vs in the equation are not the same. Since the op amp branch has an input voltage of 0, the voltage across the resistor is V_{in} and the voltage across the capacitor is V_{out}. Thus the equation becomes:

$$i_R = \frac{V_{in}}{R} = C\frac{dV_{out}}{dt} = i_C$$

which can be rearranged to find V_{out} in terms of V_{in}:

$$\frac{dV_{out}}{dt} = \frac{V_{in}}{RC}$$

$$dV_{out} = \frac{V_{in}}{RC}dt$$

$$\int dV_{out} = \int \frac{V_{in}}{RC}dt$$

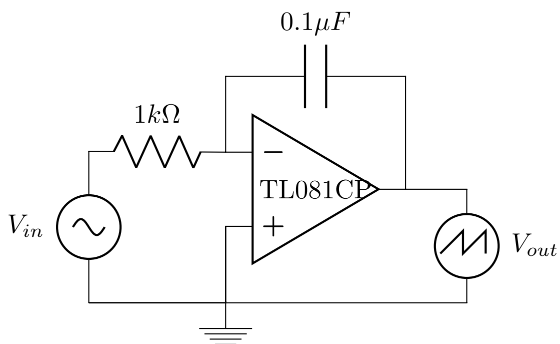
$$V_{out} = \frac{1}{RC}\int V_{in}dt$$

According to this theory, the output voltage is the integral of the input voltage multiplied by the inverse of the resistance times the capacitance. Thus, a square wave input voltage would produce a triangle wave output voltage and a sine wave input voltage would produce a cosine wave output voltage. Furthermore, a change in either the resistance or capacitance should not change the general function of the output voltage but simply the amplitude. A higher product of RC results in a lower amplitude of the output voltage, and vice versa.

3 Experiment

3.1 Integrating Behavior

We begin our experiment by setting up our circuit. The circuit we set up is similar to the one we labeled in the theory section. However, where V_{out} is located, we attached a Rigol DS1000E0 oscilloscope. Furthermore, we used a $1k\Omega$ capacitor and a $0.1\mu F$ capacitor. Thus our circuit appeared as so:



We hooked up a Rigol DG10x2 function generator to our circuit. To test the integrating behavior of the circuit, we applied a square wave then a sine wave input voltage. For each type of wave, we took a reasonable voltage and frequency to begin. Then, we changed the voltage and frequency independently to see how it affected the integral. We expect to see voltage and frequency affecting the integral of the sine wave, while on the voltage should affect the integral of the square wave.

First we observed the behavior of the square wave. We set our function generator to output a square wave with a peak to peak amplitude of 100 millivolts and a frequency of 2 kilohertz. We then took the data of about half of a oscillation off the oscilloscope. To make sure the data was god, we plotted the data for the following result:

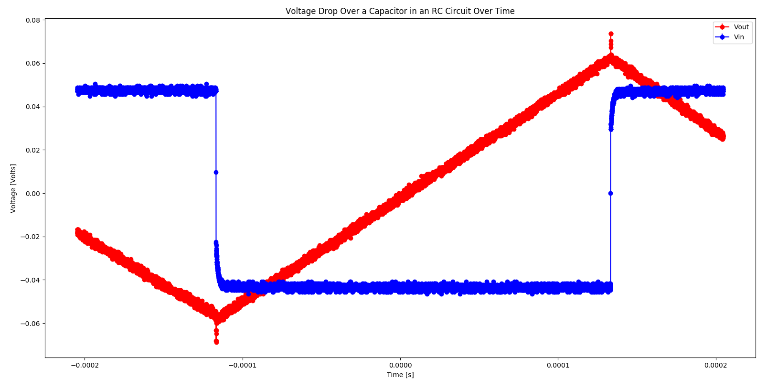


Figure 1: 100mVpp 2kHz Square wave input and op amp integrator output

We repeated this procedure with a square wave at 100 millivolts peak-to-peak and 100 hertz follwed by a square wave at 500 millivolts peak-to-peak and 2 kilohertz. The oscilloscope gave us the following data:

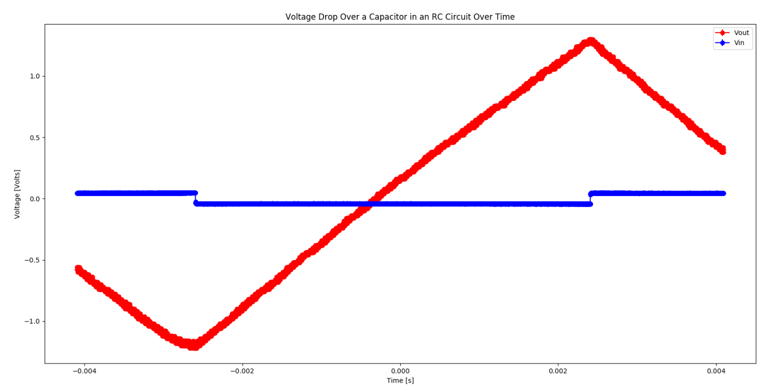


Figure 2: 100mVpp 100Hz Square wave input and op amp integrator output

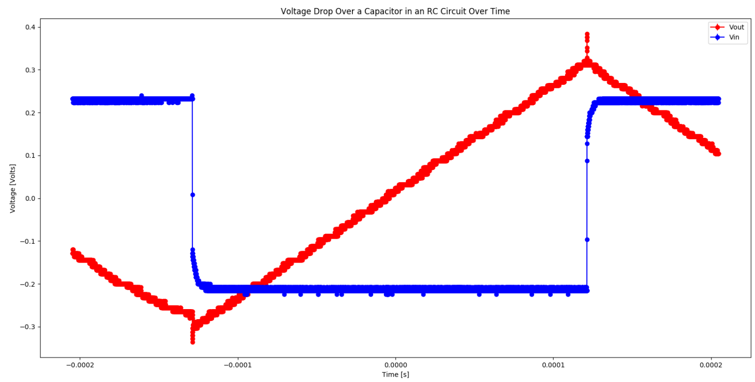


Figure 3: 500mVpp 2kHz Square wave input and op amp integrator output

We repeated this measurement of the same three voltage-frequency combinations for the sine wave as well. However, with the sine waves we didn't restrict to a single half oscillation. While with the square wave we have to limit the oscillations so that we can analyze the one linear piece of the graph, with a sine wave we prefer a series of two or more oscillations so we can see the relationship between the two curves and get good fits as well. Therefore we get the following graphs:

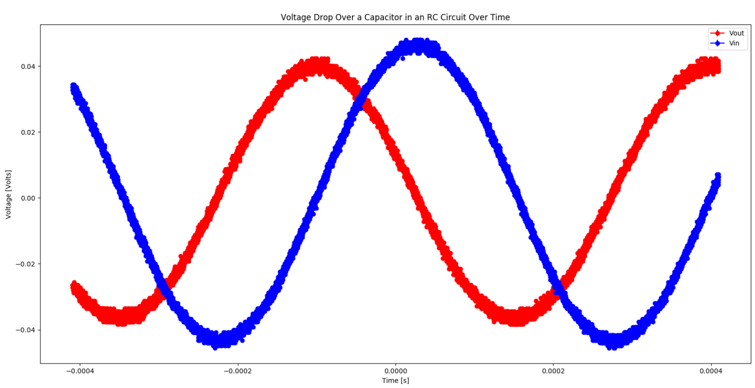


Figure 4: 100mVpp 2000Hz Sine wave input and op amp integrator output

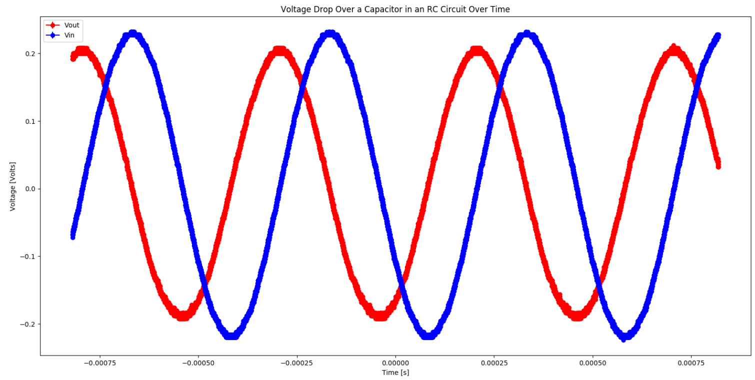


Figure 5: 500mVpp 2000Hz Sine wave input and op amp integrator output

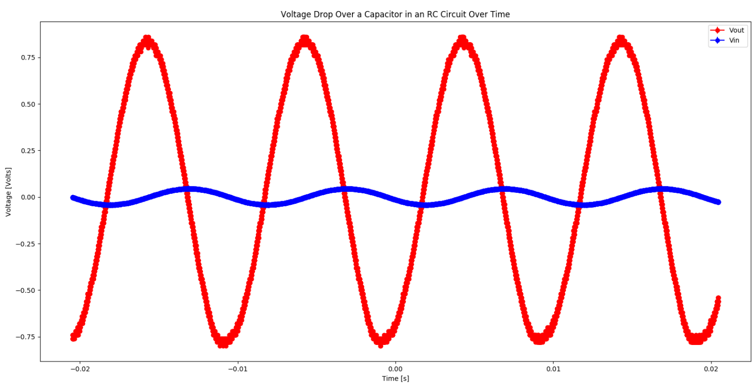
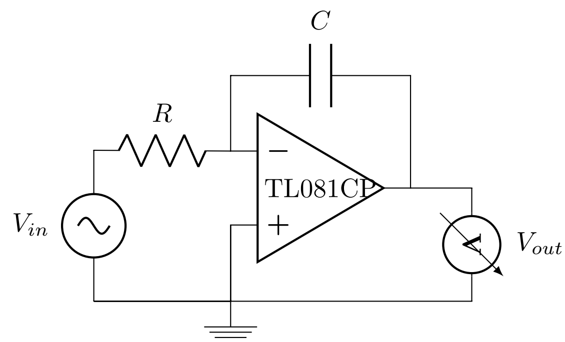


Figure 6: 100mVpp 100Hz Sine wave input and op amp integrator output

We only took uncertainties based on the manufacturer uncertainty labeled in the oscilloscope handbook, since we simply took the data straight from the oscilloscope and did not affect it in any way. In the analysis we will looking at how well our predictions based on the theory compares with the actual results we received.

3.2 Dependency on Resistance

Once we gathered the data on integrating behavior, we further tested the theory by looking at the effects of resistance on the output voltage of the system. We switched out our oscilloscope for a voltmeter, resulting in the following circuit:



In order to do test the effects of resistance, we kept the input voltage source constant at 2 kilohertz and 50 mVrms sine wave. In this section, we changed to rms voltage rather than peak to peak since our digital multimeter, the HP 34401A, measures AC signals by calculating the rms values and displays that. Therefore if we set up our input voltage as also being rms voltage, we can compare the two during the analysis. After setting the input voltage, we kept our $0.1\mu F$ capacitor and varied our resistor starting from 10Ω to $1M\Omega$.

In total, we tested 12 different resistors, as follows:

- 10Ω
- 50Ω
- 100Ω
- $1000\Omega = 1.0k\Omega$
- $2000\Omega = 2.0k\Omega$
- $3900\Omega = 3.9k\Omega$
- $4700\Omega = 4.7k\Omega$
- $5000\Omega = 5.0k\Omega$
- $10000\Omega = 10k\Omega$
- $100000\Omega = 100k\Omega$
- $1000000\Omega = 1M\Omega$

Once we set up our circuit with the resistance we were testing, we recorded the output voltage of the circuit using the digital multimeter. Then, in the analysis, we will compare the ratio of the gain and the inverse time constant to the inverse time constant.

3.3 Dependency on Capacitance

Lastly, we tested the effects of capacitance on the output voltage of the system. Using the same circuit, we reversed the technique we used in the last section. That is, once again using the 2 kilohertz and 50mVrms sine wave, we kept a $1k\Omega$ resistor in our circuit and switched out our capacitor from $220\mu F$ to $1nF$. In total, we tested 7 different capacitors, as follows:

- $220\mu F$
- $100\mu F$
- $10\mu F$
- $1\mu F$
- $100nF$
- $10nF$
- $1nF$

After the circuit was set up with the capacitance we were testing, we again recorded the output rms voltage of the circuit using the same digital multimeter. Then, when we analyze out data our data, we will once again compare the ratio of the gain and the inverse time constant to the inverse time constant itself.

4 Results and Analysis

4.1 Square Wave Integrating Behavior

We start by looking at the integrating behavior of the op amp circuit. With the data that we received from the square wave (Figures 1-3), we limit the data down to half an oscillation, or a single linear line for each the output and input. Then, using a linear curve fit script, we fit the data. From the theory, we expect a relationship of:

$$V_{out} = \frac{V_{in}}{RC} t$$

Starting with the 100mVpp and 2kHz sqaure wave data, we plugged our data into our script. We received a reduced χ^2 of 1.105, showing that our fit is fair. The residuals further enforce this decision with a random scatter around zero. From the fitted function, we get the following parameter and graph:

$$\frac{V_{in}}{RC} = 481.23195 \pm 0.10222$$

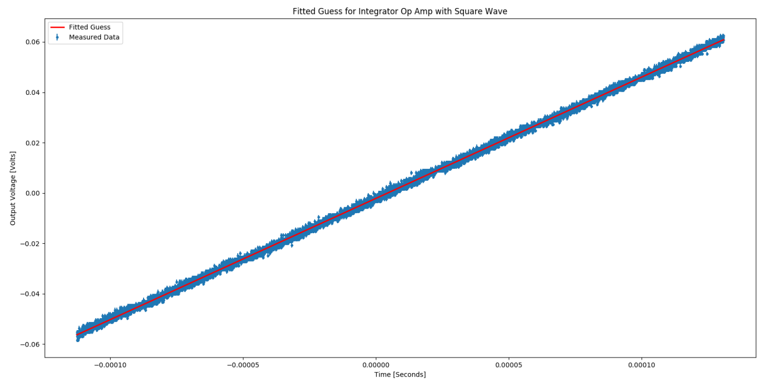


Figure 7: Fit for 100mVpp 2kHz square wave integrator op amp output using linear fit

From the data, it appears as though the data is incredibly linear. Furthermore, if we assume that Vin is equal to the given set voltage with the manufacturer uncertainty, then we can approximate the value of RC. Given our function generator and above parameter, the value of RC is as follows:

$$V_{in} = 0.05 \pm 0.0015$$

$$RC = \frac{V_{in}}{\frac{V_{in}}{RC}} = 1.039 * 10^{-4} \pm 3.117 * 10^{-6}$$

which from our values of resistance and capacitance, is expected. We can compare this with our true value of RC using a T-score:

$$T = \frac{|RC_{theory} - RC_{measured}|}{\sqrt{\sigma_{theory}^2 + \sigma_{measured}^2}}$$

$$T = \frac{|9.35 * 10^{-5} - 1.039 * 10^{-4}|}{\sqrt{(9.84 * 10^{-7})^2 + (3.117 * 10^{-6})^2}}$$

$$T = 3.1818$$

This T-score is higher than we expected based on the closeness of the value. It is possible that our values for our uncertainties are somewhat low for the experiment. It is possible that our value for uncertainty was within ten percent of the actual value, since our uncertainty for the theory was fairly rudimentary. Thus, if we take the upper limit of this uncertainty, our T-score lowers to the more reasonable value of 1.0076:

$$T = \frac{|9.35 * 10^{-5} - 1.039 * 10^{-4}|}{\sqrt{(9.84 * 10^{-6})^2 + (3.117 * 10^{-6})^2}}$$

$$T = 1.0076$$

This value makes more sense once again based on the closeness of the values, and we conclude that there is no difference between the values of RC.

Now that we have analyzed the first square wave, let us do the same for the other two square waves, one with 100mVpp and 100Hz and another with 500mVpp and 2kHz. For the 100mVpp and 100Hz square wave, we plugged our data into the script again. We received a reduced χ^2 of 0.858, which shows a good fit as before. However, our residuals are not as good:

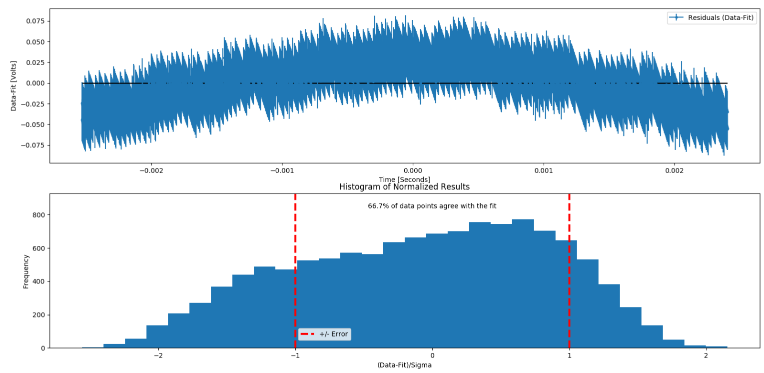


Figure 8: Residual graph of square wave with 100mVpp and 100Hz

As evident from the graph, there is a large bow shaped curve in the graph of the residuals. This suggests that the linear model doesn't work precisely with the data. However, the fit didn't seem bad and the data still seems to fit. The script gave us the following parameter and graph:

$$\frac{V_{in}}{RC} = 500.501 \pm 0.159$$

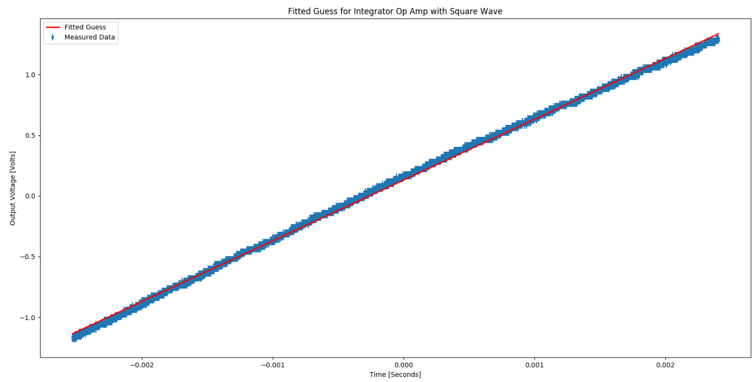


Figure 9: Fit for 100mVpp 100Hz square wave integrator op amp output using linear fit

We can once again repeat this fitting format for the 500mVpp 2kHz square wave. The reduced χ^2 is 1.055 again showing a good fit. However, we once again have a pattern in our residuals:

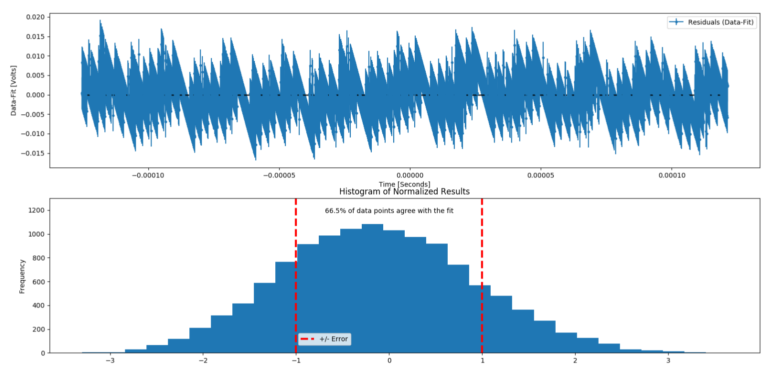


Figure 10: Residual graph of square wave with 500mVpp and 2kHz

The residuals seem to have these bursts of downward motion, but appear randomly at different times, voltages, and slopes. We can still get the measurements that the script outputs:

$$\frac{V_{in}}{RC} = 2.491 \pm 0.000511$$

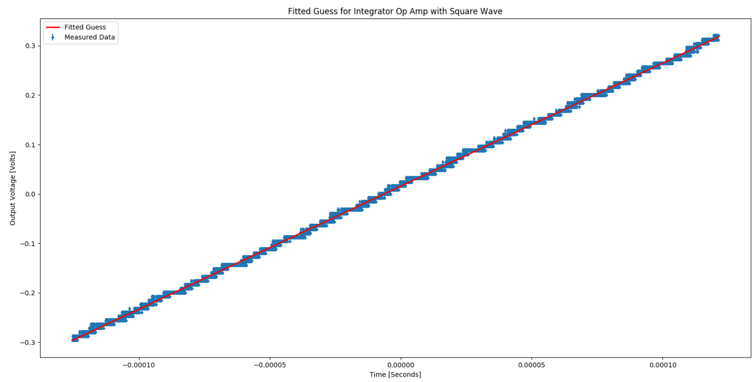


Figure 11: Fit for 500mVpp 2kHz square wave integrator op amp output using linear fit

After seeing the fitted plot, it seems that this pattern we were seeing in the residuals was an affect of the data collection from the oscilloscope. The oscilloscope seemed to have taken a rough form of this data, rather than what we saw in the previous two data collections.

Now with these different values of the slope, we can see how different the RC constants are from each other. We get the following values of the RC constant:

$$RC_{original} = 1.039 * 10^{-4} \pm 3.117 * 10^{-6}$$

$$RC_{freq} = 9.90 * 10^{-5} \pm 2.97 * 10^{-6}$$

$$RC_{volt} = 9.96 * 10^{-5} \pm 1.39 * 10^{-6}$$

And the respective T-scores:

$$T_{original} = 1.0076$$

$$T_{freq} = \frac{|9.35 * 10^{-5} - 9.90 * 10^{-5}|}{\sqrt{(9.84 * 10^{-6})^2 + (2.97 * 10^{-6})^2}} = 0.535$$

$$T_{volt} = \frac{|9.35 * 10^{-5} - 9.96 * 10^{-5}|}{\sqrt{(9.84 * 10^{-6})^2 + (1.39 * 10^{-6})^2}} = 0.614$$

All these values show consistently an agreement with the theory, with agreement from the T-scores that there is no difference between the values. The values agree that the output voltage is mostly linear and has a slope equal to the amplitude of the input voltage divided by the resistance times the capacitance.

4.2 Sine Wave Integrating Behavior

We follow a similar procedure when working with the sine waves. From the data in figures 4-6, it is clear that we are no longer observing a linear fit anymore, which works perfectly in the theory. Instead, we are looking for a sine wave that fits the following form:

$$V_{out} = \frac{V_{in}}{RC\omega} cos(\omega * t)$$

We begin with our data from the 100mVpp 2kHz sine wave. We adapted our script to now fit to sine waves instead of linear fits. When we used it, it returned a χ^2 of 1.095. The residuals further back up the goodness of the fit, being completely random and revolving around zero. With this good fit, we get the following data:

$$\frac{V_{in}}{RC} = 481.696 \pm 0.106$$

$$\omega = 12580 \pm 1.038$$

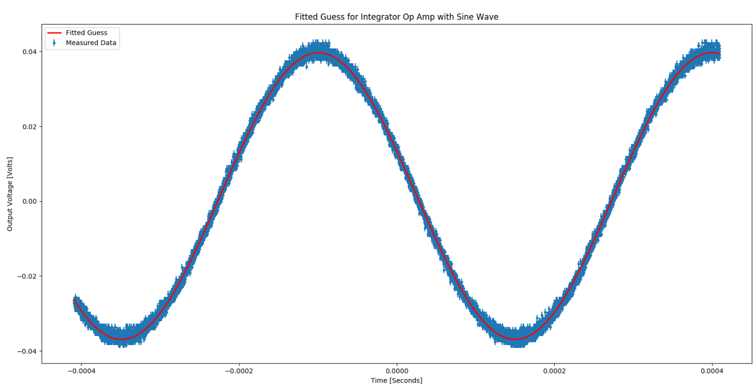


Figure 12: Fit for 100mVpp 2kHz sine wave integrator op amp output using sine wave fit

Just as we did with the square wave, we can if the values for the frequency and RC makes sense with the values we expect. To begin, we must again get the value of RC and the expected value of frequency:

$$V_{in} = 0.05 \pm 0.0015$$

$$RC = 1.038 * 10^{-4} \pm 3.11 * 10^{-6}$$

$$\omega_{gen} = 12566.37 \pm 1.25$$

Then, we can calculate the T-score for each of these parameters:

$$T_{RC} = \frac{|9.35 * 10^{-6} - 1.038 * 10^{-4}|}{\sqrt{(9.84 * 10^{-6})^2 + (3.11 * 10^{-6})^2}}$$

$$T_{RC} = 0.998$$

$$T_\omega = \frac{|12566.37 - 12580|}{\sqrt{(1.038)^2 + (1.25)^2}}$$

$$8.389$$

We can see that our first T-score for the value of RC is great, being below one. Thus, we conclude that there is no difference between the values. However, our values for the frequency don't agree as much. With a T-score of 8, there suggests a difference between the two values. Again this could be another problem with our uncertainties, since the relative uncertainties for both of our values of frequency is around 10^{-4}.

It seems reasonable to suppose that both uncertainties are within five percent of the actual values, since the equipment we are using is rather old and the fitting method may have gotten a bit confused when finding the frequency values. If we suppose this, we can calculate the new T-score for frequency, using the upper limits of the uncertainties:

$$T_\omega = \frac{|12566.37 - 12580|}{\sqrt{(5.19)^2 + (6.25)^2}}$$

$$T_\omega = 1.062$$

which is a better value of the T-score, showing little to no difference between the values of frequency.

We can repeat the same fitting for the other two sine waves we measured. Firstly, with the 100mVpp and 100Hz sine wave, we got a χ^2 of 1.048, and the residuals don't show any clear cut pattern, repeating or otherwise. With this god fit, we can observe our parameters and graph:

$$\frac{V_{in}}{RC} = 510.36 \pm 0.106$$

$$\omega = 628.4 \pm 0.01612$$

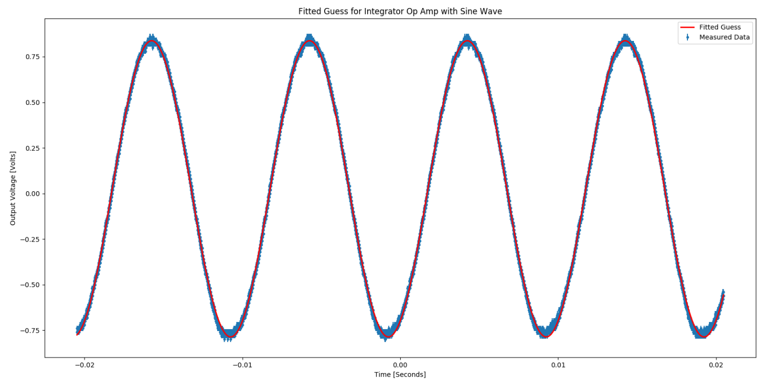


Figure 13: Fit for 100mVpp 100Hz sin wave integrator op amp output using sine fit

Finally, we fitted the 500mVpp and 2kHz sine wave. Our χ^2 was 1.083, similar to our previous fits. However, unlike our other sine fits, there is a pattern in our residuals. Even more interestingly, the pattern is not uniform. We could not determine the significance of the pattern:

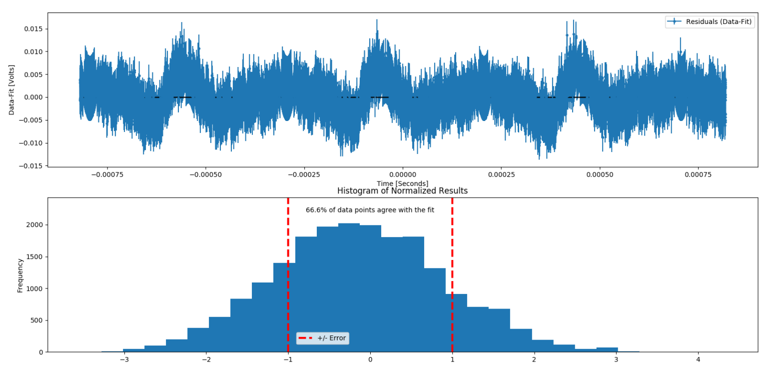


Figure 14: Residual graph of sine wave with 500mVpp and 2kHz

The fit is still good and we can still analyze our data. We get the following measurement and graph:

$$\frac{V_{in}}{RC} = 497.512 \pm 0.089$$

$$\omega = 12560 \pm 0.3423$$

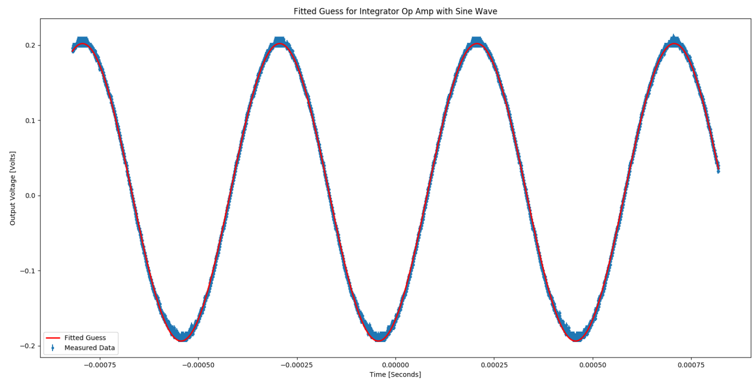


Figure 15: Fit for 500mVpp 2kHz sine wave integrator op amp output using sine fit

Now, we can calculate the T-score for each parameter we measured, to see if it agrees with what we expect from the theory. First, we need all our values for RC and ω:

$$RC_{original} = 1.038 * 10^{-4} \pm 3.11 * 10^{-6}$$
$$RC_{freq} = 9.80 * 10^{-5} \pm 2.94 * 10^{-6}$$
$$RC_{volt} = 1.005 * 10^{-4} \pm 3.02 * 10^{-6}$$
$$\omega_{original} = 12580 \pm 6.25$$
$$\omega_{freq} = 628.4 \pm 0.01612$$
$$\omega_{volt} = 12560 \pm 0.3423$$

And the respective T-scores:

$$T_{RCoriginal} = 0.998$$
$$T_{RCfreq} = \frac{|9.35 * 10^{-5} - 9.80 * 10^{-5}|}{\sqrt{(9.84 * 10^{-6})^2 + (2.94 * 10^{-6})^2}} = 0.438$$
$$T_{RCvolt} = \frac{|9.35 * 10^{-5} - 1.005 * 10^{-4}|}{\sqrt{(9.84 * 10^{-6})^2 + (3.02 * 10^{-6})^2}} = 0.680$$
$$T_{\omega original} = 1.062$$
$$T_{\omega freq} = \frac{|628.3 - 628.4|}{\sqrt{(0.314)^2 + (0.01612)^2}} = 0.318$$
$$T_{\omega volt} = \frac{|12566.37 - 12560|}{\sqrt{(5.19)^2 + (0.3423)^2}} = 1.225$$

From the T-scores, we can see that there is little difference between most of the values. Furthermore, all the values are what we expect and agree with the theory. We can conclude that the integrating part of the equation works with the circuit.

4.3 Changing Resistance

Now that we have analyzed the integrating behavior, we can look more into the effect of resistance and capacitance on the circuit. We notice that in the equation, the resistance and capacitance only affect the amplitude of the output wave. Thus, we can compare the RMS values of the input wave and output wave to see how the RC value effects the amplitude. Recall that we picked RMS since our digital multimeter measures the RMS value of AC waves. When we compute the ratio of the voltages we get the following:

$$\frac{V_{RMSout}}{V_{RMSin}} = \frac{\frac{1}{RC\omega} V_{in} \sqrt{2}}{V_{in}\sqrt{2}} = \frac{1}{RC\omega}$$

We can see that this ratio depends only on the value of RC and the frequency. For this part, we will be keeping the frequency at a constant 2kHz. Thus, if we divide this ratio by $\frac{1}{RC}$, we should get a constant value of the inverse frequency.

After taking the data from the twelve resistances, we can plot the data to see what it looks like. On the x-axis, we plotted the value of 1/RC, while on the y-axis, we plotted the value of $\frac{V_{out}}{V_{in}} RC$. This gave us the following plot and data:

$\frac{1}{RC}$	$Gain * RC$	Uncertainty
Ohms	Hertz	Hertz
9527730	1.14e-5	3.61e-7
1899298	3.63e-5	1.14e-6
984325.6	4.91e-5	1.55e-6
97683.57	7.47e-5	2.36e-6
48791.72	7.68e-5	2.42e-6
32354.33	7.75e-5	2.44e-6
25068.14	7.78e-5	2.45e-6
20614.41	7.78e-5	2.45e-6
19276.65	7.79e-5	2.45e-6
9708.097	7.78e-5	2.45e-6
978.2469	7.77e-5	2.45e-6
94.54076	6.39e-5	2.92e-6

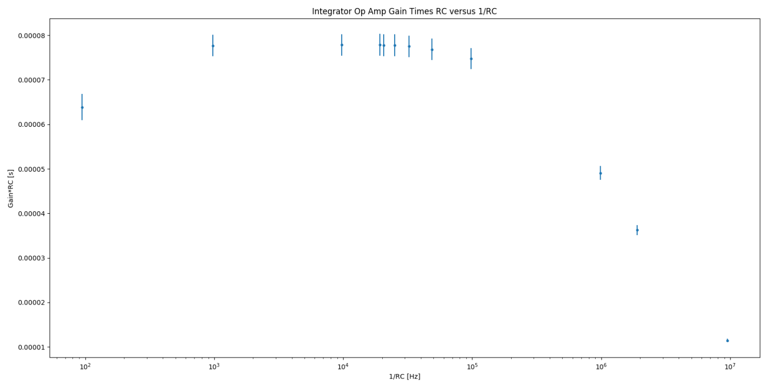


Figure 16: Data for changing resistances

It is obvious from this data that the gain times RC is not constant with respect to 1/RC, which doesn't agree to our predicted behavior. However, this is a property of the non-ideal op amp. There is a certain point where the gain of the circuit drops off. There is also the behavior at the beginning of the plot. It seems that this point of non-ideal behavior stretches to the lower values of 1/RC as well. To curve fit this, we decided to use the function that describes gain as a function of frequency in a non-ideal op amp:

$$\frac{V_{out}}{V_{in}} = \frac{G}{\sqrt{1 + (\frac{G}{RCf_cA_0})^2}}$$

With this new fit function, we began by putting in the changing resistance file. We received a rather abysmal χ^2 of 5.528. The residuals and fit do not help justify the value either. The very first point which seems out of place is too out of place. If we remove that point, our χ^2 drops to 1.437, a much more reasonable number, albeit not perfect. The residuals seem much better as well without the outlier. We get the following fit and parameters:

$$Gain * RC = 7.199 * 10^{-5} \pm 7.833 * 10^{-7}$$

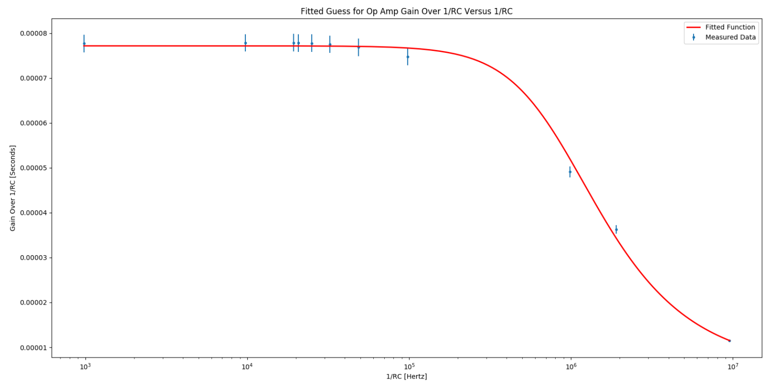


Figure 17: Non-ideal op amp gain fit for changing resistances

Our parameter gain*RC, according to the equation we derived, should be equal to $\frac{1}{\omega}$. We can test this by taking the T-score of the two values:

$$\frac{1}{\omega_{gen}} = 7.958 * 10^{-5} \pm 7.958 * 10^{-7}$$

$$T_{RC} = \frac{|7.958 * 10^{-5} - 7.199 * 10^{-5}|}{\sqrt{(7.958 * 10^{-7})^2 + (7.833 * 10^{-7})^2}}$$

$$T_{RC} = 6.797$$

It seems as though there is a difference between these two values. It could also be that the rudimentary data collection techniques for the uncertainty was not refined enough. More data should be collected to confirm this. However, for now we can conclude that while gain*RC is only dependent on frequency, it is not precisely the inverse of frequency.

4.4 Changing Capacitance

Finally, we can look at the effect of capacitance on the circuit. We took a similar approach as the previous section with changing resistances, however, now with capacitance. The theory from the last section still holds, and just like the last one, we can begin by observing the data and plot:

$\frac{1}{RC}$	$Gain * RC$	Uncertainty
Ohms	Hertz	Hertz
4.814735	1.66e-5	8.32e-6
10.47329	9.55e-6	3.83e-6
86.82984	1.49e-4	5.13e-6
967.5325	7.41e-5	2.33e-6
10693.78	7.44e-5	2.37e-6
97683.57	7.62e-5	2.40e-6
976835.7	7.41e-5	2.34e-6

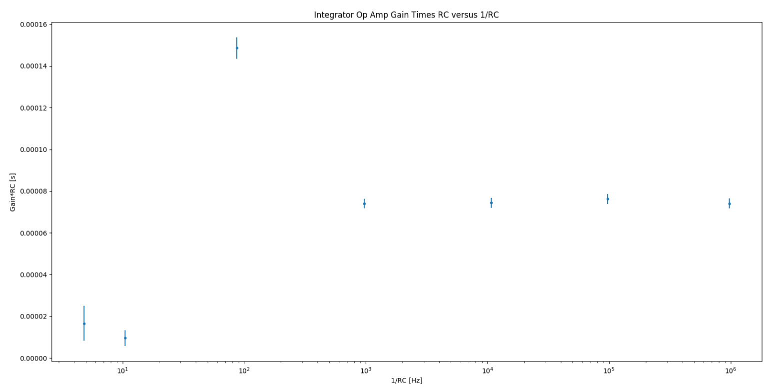


Figure 18: Data for changing capacitances

This data seems to be rather small. So instead of analyzing this, we swill combine with with the data from the resistances. We saw that the behavior we expected was not affected by resistances, so we can use the data to for different capacitances. Thus the full data is as follows:

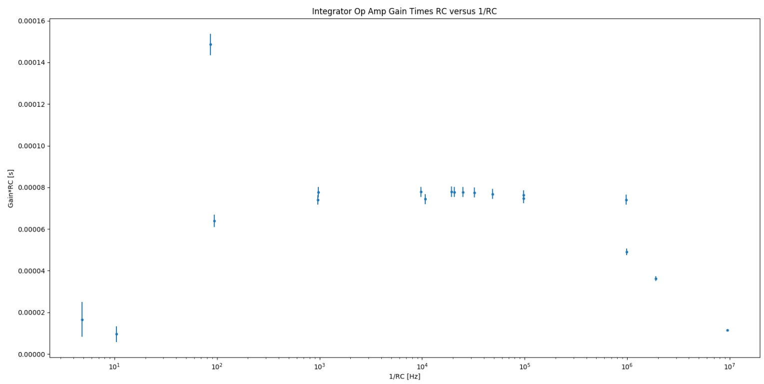


Figure 19: Data for changing capacitances and resistances

Once again using the special curve fit function, we can fit the data from figure 19. If we take all the data, we get a χ^2 of 3.321 which again is a terrible fit that, like the previous section, is not justified by its fit or residuals. So we will limit the data to anything that isn't a large outlier. While our χ^2 does not get any better at 10.92, our residuals and fit look much better now with little pattern and a smooth fit. We also get the following value for gain*RC:

$$Gain * RC = 7.286e - 5 \pm 6.958e - 7$$

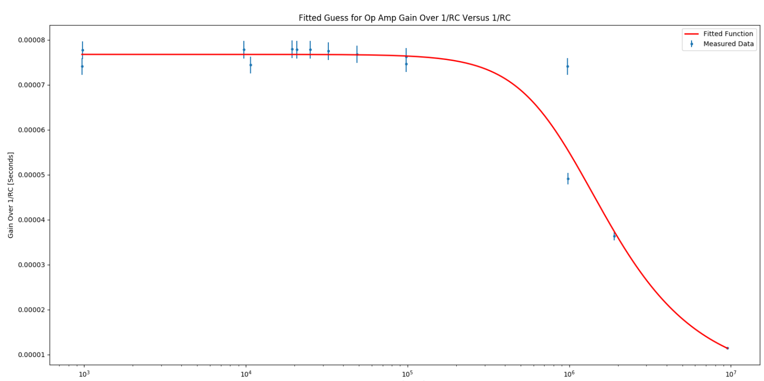


Figure 20: Non-ideal op amp gain fit for changing capacitance

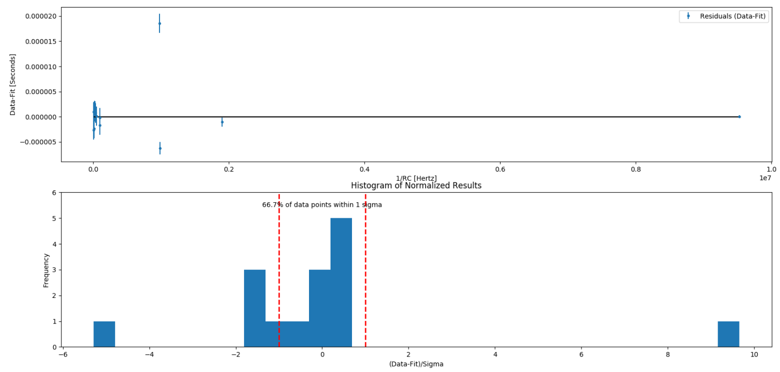


Figure 21: Non-ideal op amp gain fit residuals for changing capacitance

We can end this section and the experiment by calculating the T-score of gain*RC and our value for the inverse frequency. We follow the same procedure and use the same expected value as we did in the resistance section. We get the following values:

$$T_{RC} = \frac{|7.958 * 10^{-5} - 7.286 * 10^{-5}|}{\sqrt{(7.958 * 10^{-7})^2 + (6.958 * 10^{-7})^2}}$$

$$T_{RC} = 6.357$$

From both these sections, it seems as though the behavior we expected showed up and the gain was independent of the value of R or C (and by extension RC), up to a certain point where it broke down. However, while the gain was independent of RC, it wasn't exactly the value we hoped for, being the inverse frequency. There might have been some noise or poor data collection the attributed this behavior and more data should be taken so that it could be categorized.

5 Outlook and Conclusion

This experiment explored the properties of the integrator operational amplifier, specifically how closely it followed its integrating behavior and how the capacitance and resistance of the system affected the system.

For the first part of analyzing the integrating behavior, we took data off of the oscilloscope and fitted them to the correct integrated function, receiving any necessary parameters that were fitted. For this section, we assumed the op amp was ideal and that there was no resistance in the wires. The integrating behavior followed the theory very well. Most of the values agreed with the theoretical counterparts. The square wave produced an accurate linear plot while the sine plot gave a cosine function. The data concluded that the amplitude or slope of the resulting output signal was dependent on Vin, R, and C. The behavior could be further explored by testing other wave forms.

The second part focused on the behavior of the system when the capacitance or resistance was changed. We switched out various combinations of capacitances and resistances and measured the RMS output with a digital multimeter. This was then compared to the RMS input from the function generator. For this section we had to removed the idea that our op amp was ideal. We found that while we half expected a constant value, we knew this wasn't realistic and that the gain would drop off eventually. We found that R and C had an inverse relationship with the gain as we had though but that at high and low values or RC, this was not a feasible model. Instead it seems to follow the equation of the inverting op amp gain function. Furthermore, while we believed the gain to also be dependent on the frequency, there were differences between the values that we got and what we expected, meaning that there may be something affecting the gain that we didn't anticipate, such as resistance in the wire, which we couldn't eliminate. It is possible that the small number of points is also affecting the information given. A larger sample size of both capacitances and resistances would better conclude the role they play in the equation and how well they fit the model.

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