DEPARTMENT OF PHYSICS, UNIVERSITY OF CALIFORNIA AT BERKELEY

Instrumentation lab VIII: Op Amps III

Oliver Gorton
Lab Partner: Oliver Wang

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Introduction

For most circuits that we have dealt with in the past, the Op Amp Golden Rules have been sufficient for accurate calculations. However, there are certain circuits where the Op Amp Golden Rules do not hold. This Lab is primarily concerned with those cases. It is of vital importance to understand the limitations of the idealizations that we use to simplify our analysis of circuits in order to know how and under what circumstances our circuit elements will behave, so that we can build circuits that actually work. This lab will explore the imperfections of op amps and how to compensate for those imperfections.

Exercises

Op Amp Input Imperfections

8.1 An Op Amps output is not exactly zero when V+=V-; imperfections lead to a small offset voltage that is added on to the signal (before the amplification in the case of an amplifier circuit). The offset voltage of several Op Amps was measured using circuit 8.1.

Circuit 8.1

Op Amp Number	1	2	3	4	5
Vout (V)	1.53	0.9	0.2	2.52	2.29
Vos (mV)	1.53	0.9	0.2	2.52	2.29

Where Vos is Vout/1000 since circuit 8.1 is a x1000 inverting amplifier.

8.2 This offset can be removed by trimming the op amp with a potentiometer, as shown in circuit 8.2. Using this method, the output (with no input) was reduced to 10mV, meaning that Vos was reduced to 10 microvolts. The output immediately began to drift after several seconds. This drifting is caused by thermal fluctuations of the transistors which affects the flow of current.

Circuit 8.2

8.3 The Op Amp Golden Rules state that the inputs draw no current. This is not precisely the case, however, and indeed a small amount of current does leak through. The input bias current was measured using circuit 8.3:

Circuit 8.3

1. The 10M resistor was shorted and Vos trimmed to zero
2. The short was then removed and the change in the output voltage quickly measured

Change in output voltage: 2.0V.

Change in offset voltage: 2E-3V

Input bias current = Change in offset voltage / Change in Resistance = 2E-3V/10E6Ω = 2E-10A.

Fortunately, this is quite small and therefore has negligible effect on nominal behavior.

8.4 Because op amps are supplied by a power source with limited output current, the op amps have a finite output current and voltage. This effect was demonstrated by driving an op amp follower with a 10Vp-p, 1kHz triangular wave. The result is a signal whose crests have been cut off. See fig.1.

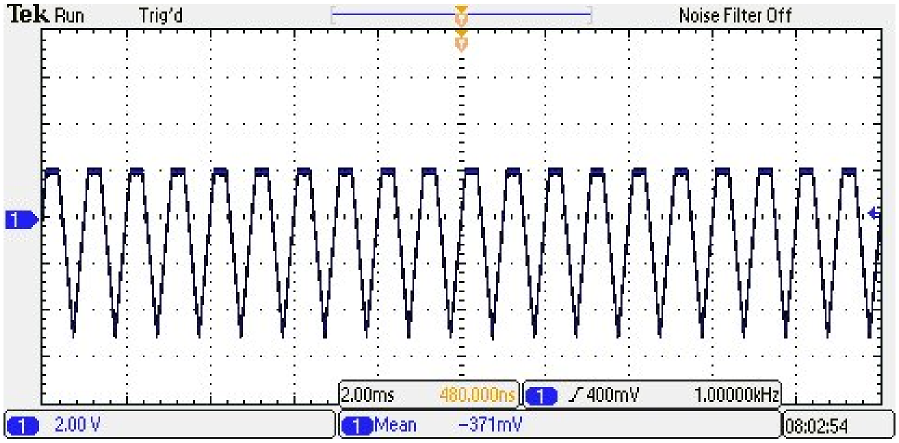


Fig.1. Finite Op Amp Output in Follower Circuit

Circuit 8.4

8.5 A speaker was driven with various input signals through a x10 amplifier (shown in circuit 8.5). Sine waves, triangular waves, and square wave at a given frequency each have slightly different pitch and loudness. This speaker setup has a maximum driving amplitude with which the circuit can be driven before distortions occur: 350mVp-p. The distortion occurs because the output current of the op amp is limited, so the speaker does not get very loud. The sound quality of this speaker is poor.

Circuit 8.5

8.6 Using an op amp to drive a bipolar follower, the output current limit seen in circuit 8.5 was increased (circuit 8.6). Varying the input amplitude of a sine wave from 0.01V to 1V yielded distortions above 50mV, with the distortion remaining unchanged above 100mV. See Fig.2 and Fig.3. The speaker emits a distorted sine note for inputs with distorted outputs. Music fed through the circuit sounds grainy, poor quality.

Circuit 8.6

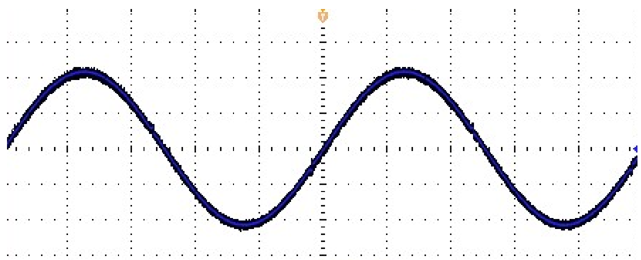


Fig.2. Undistorted Waveform

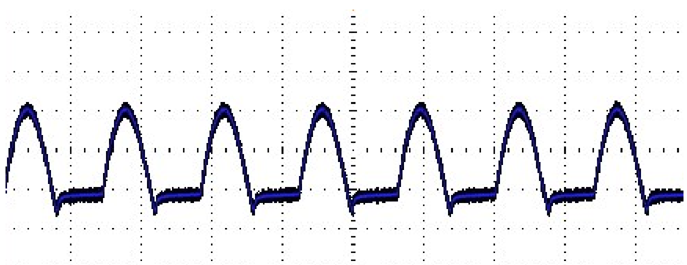


Fig.3. Distorted Waveform

8.7 The follower's performance is improved somewhat by including the follower in the feedback loop, as in circuit 8.7. As the input amplitude of the sine wave is varied from 0.01V to 1Vp-p, a similar distortion as in 8.6 appeared for amplitudes above 150mVp-p. A slight improvement. This circuit would amplify without half-wave distortion signals which remain negative in potential.

Circuit 8.7

8.8 A circuit simulator was used to compare circuits 8.6 and 8.7. This was done for inputs of 0.01p-p, 0.05p-p, and 0.25Vp-p sine waves. There were four differences between the output waveforms of the circuits;

1. A large offset at 0.01V for 8.6, caused by the base-emitter offset voltage of the transistor.
2. A much smaller offset at 0.01V for 8.7, due to the fact that the signal after the transistor is included in the feedback look of the op amp, thus attenuating the offset.
3. A half-wave distortion for both circuits at 0.25V (see Fig. 4). This is caused by the transistor shutting off for positive input voltages, since the base-emitter voltage must be greater than 0.6V in order for current to flow through the transistor, which is controlled by the inverted input signal.
4. Circuit 8.7 performed better than circuit 8.6 at 0.05V because circuit 8.7 includes the follower in the feedback loop, which means the signal is not offset, and therefore not cutoff. See fig.5.

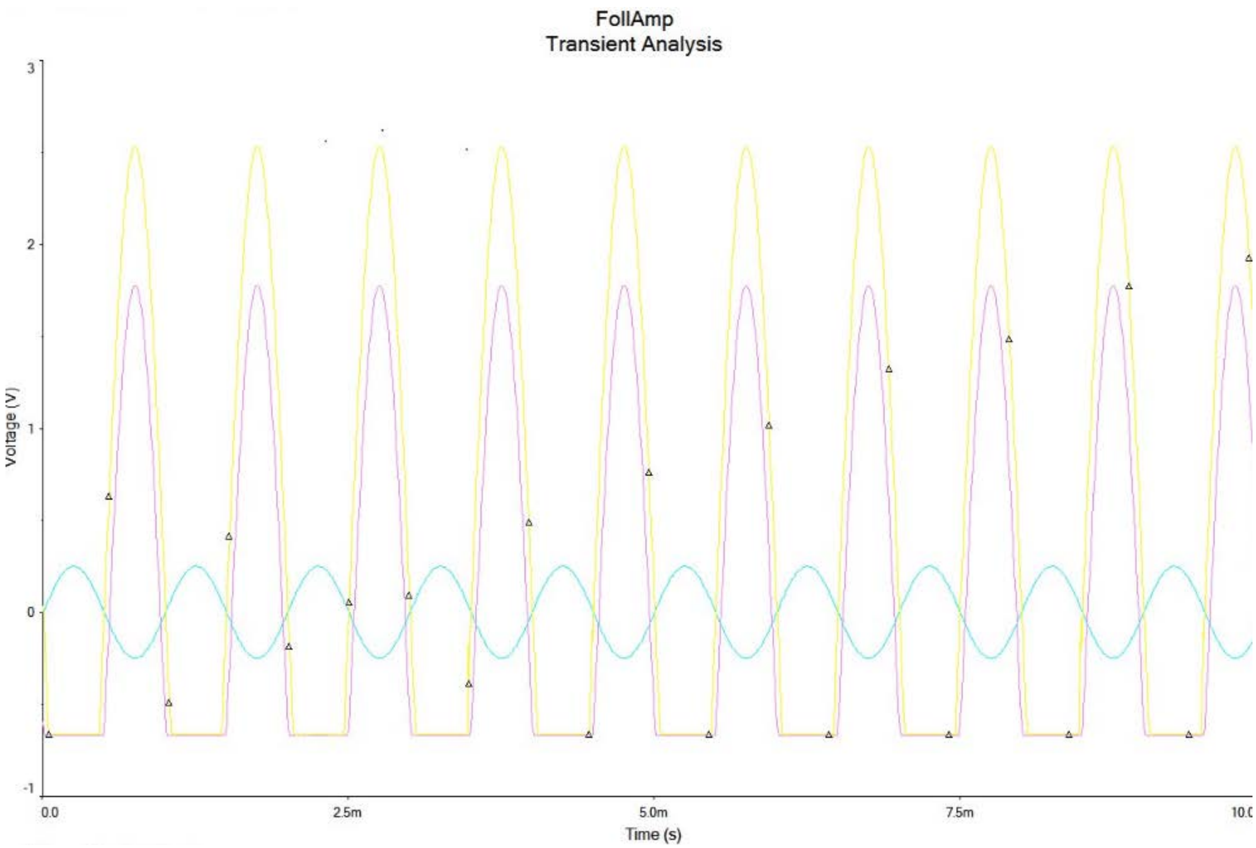


Fig. 4. Half-wave Distortion at 0.25V.

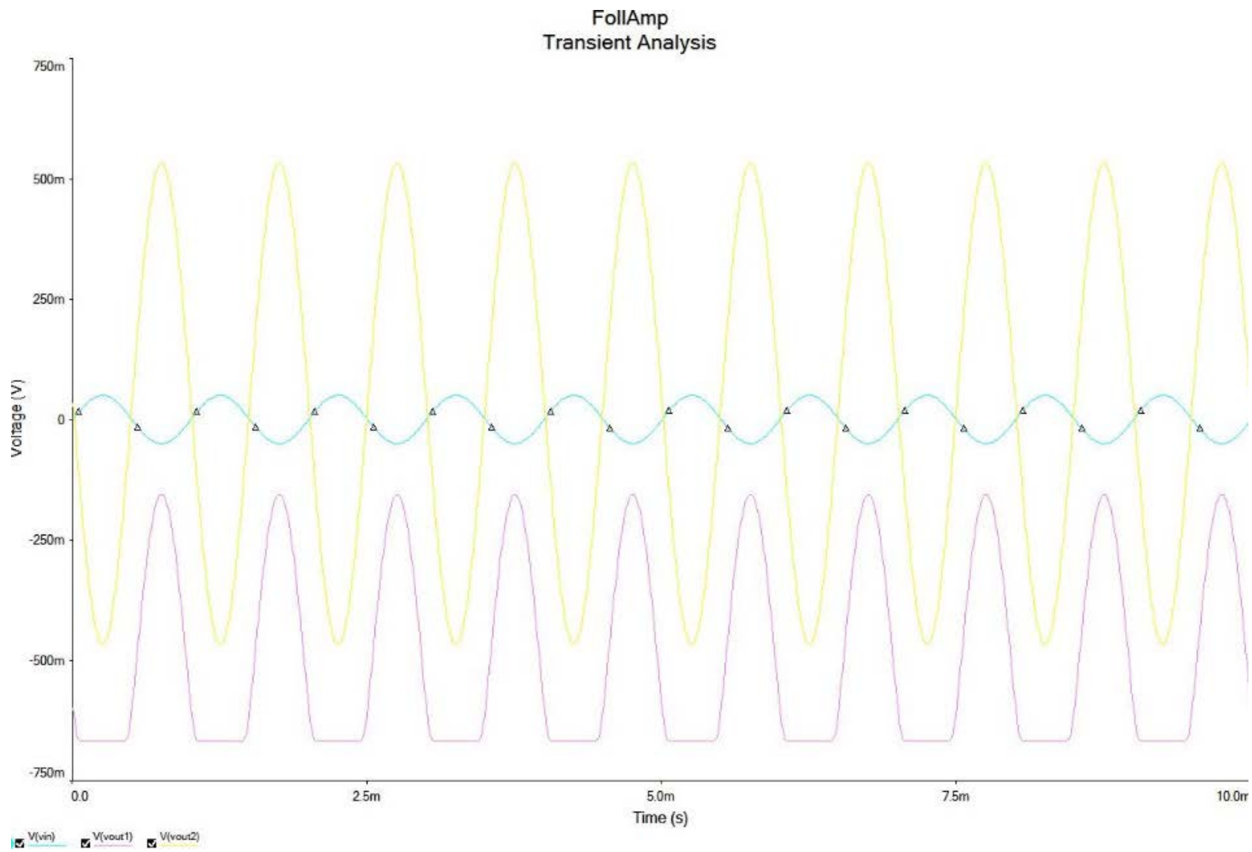


Fig.5. Superior Performance of Circuit 8.7 Over 8.6 at 0.05V.

8.9 A push-pull output stage works (circuit 8.9.1) much better than a follower circuit stage (8.6) for the obvious reason that the signal will not be half cut off; current can be supplied for both voltage polarizations. This circuit still suffers from crossover distortion, however, which were observed whenever the signal crosses zero. Crossover distortions are created by the lag time in between switching transistors for current sources, when the voltage has not exceeded a magnitude of 0.6V from base to emitter. By including the push-pull output stage in the feedback loop the crossover distortion was greatly diminished. See circuit 8.9.2. This improvement could be heard in the quality of the audio output when the circuit was hooked up to a music player.

Circuit 8.9.1

Circuit 8.9.2

Electrical Noise

8.10 The voltage noise of the op amps was measured using the setup shown in circuit 8.10. The preamp was set to gain 100, low pass filter 100kHz, and high pass filter 1kHz. With R set to 0, the scope and DMM was used to measure the noise RMS value.

Circuit 8.10

Scope 53mV RMS

DMM 49mV RMS

Then, with R = 1M:

Scope 14Vp-p noise =

2.4V RMS noise

DMM 5.9V RMS noise

The discrepancy between these two values is due to the fact that the scope maxes out on measurements of 14Vp-p, and therefore cannot accurately measure noise at this level.

8.11 Using a LabVIEW program labeled “Noise Generator” the qualitative properties of several electrical noises was analyzed.

First “Gaussian White Noise” was played and listened to with “Generate Real Time Data”. Then the settings were changed to “Generate Spectrum” which generates a Gaussian distribution and then takes the inverse Fourier transform to find real time data.

> The amplitude histogram for this setting was still Gaussian; for the obvious reason that the inverse Fourier transform of a Gaussian function is again a Gaussian function.

“Uniform White Noise” was also played and listened to. Although this noise distribution is mathematically distinct from a Gaussian distribution, listeners were mostly unable to distinguish between the two for the reason that the human is bad at discerning such structure.

Next the settings were changed to “1/f Noise”.

> This noise sounded like ocean waves crashing on the shore.

In 1/f noise, the amplitude of the components is inversely proportional to the frequency of the components. 1/f noise is mathematically and qualitatively distinct from Gaussian white noise which has been stripped through a low pass filter.

> Gaussian white noise with a low pass frequency of 500Hz sounded more like the noise of a furnace than the noise of the ocean.

This is because the low-passed Gaussian noise is mostly low frequency noise without any of the higher frequency noises that were present in the 1/f noise, which are fundamental to its qualitative properties.

The noise generator was set to “Shot Noise” with the “Average Number of Shots per Sample (ANSS)” set to 0.001.

> Shot noise sounded like the noise speakers make when a wireless communication device is placed too close, or like the noise of a Geiger counter.
>
> (With ANSS = 1) Short noise sounded more like static white noise.
>
> (With ANSS = 100) The white noise sounded smoother: more homogeneous. And quieter.
>
> (With ANSS = 10,000) White noise was very smooth, even more homogeneous. And quieter.

As the ANSS setting was increased, the amplitude histogram became more Gaussian. This is consistent with the qualitative observations recorded in the previous paragraphs; as the ANSS was increased the white noise became more regular and less distinct from itself from moment to moment. The loudness also decreased – this is because from one instant to the next, the variation in the magnitude became smaller, and therefore the change in displacement of the speaker membrane was smaller, leading to reduced loudness.

“Line (60Hz) Noise” was played at various “Harmonic Content” settings.

The sound was deeper at lower harmonic content, and higher, more jagged. Low harmonic content sounded like the noise of a speaker which has been unplugged and is humming. Modulating the speaker volume resulted in a sound that resembled the hum of a lightsaber from Star Wars. High harmonic content sounded like the various pitches in the archaic “dial-up connection tone”.

Frequency Errors

8.12 The Multisim program “DirectGn” was used to record the gain and phase of the LF356 op amp. The resulting plot is shown in fig.6.

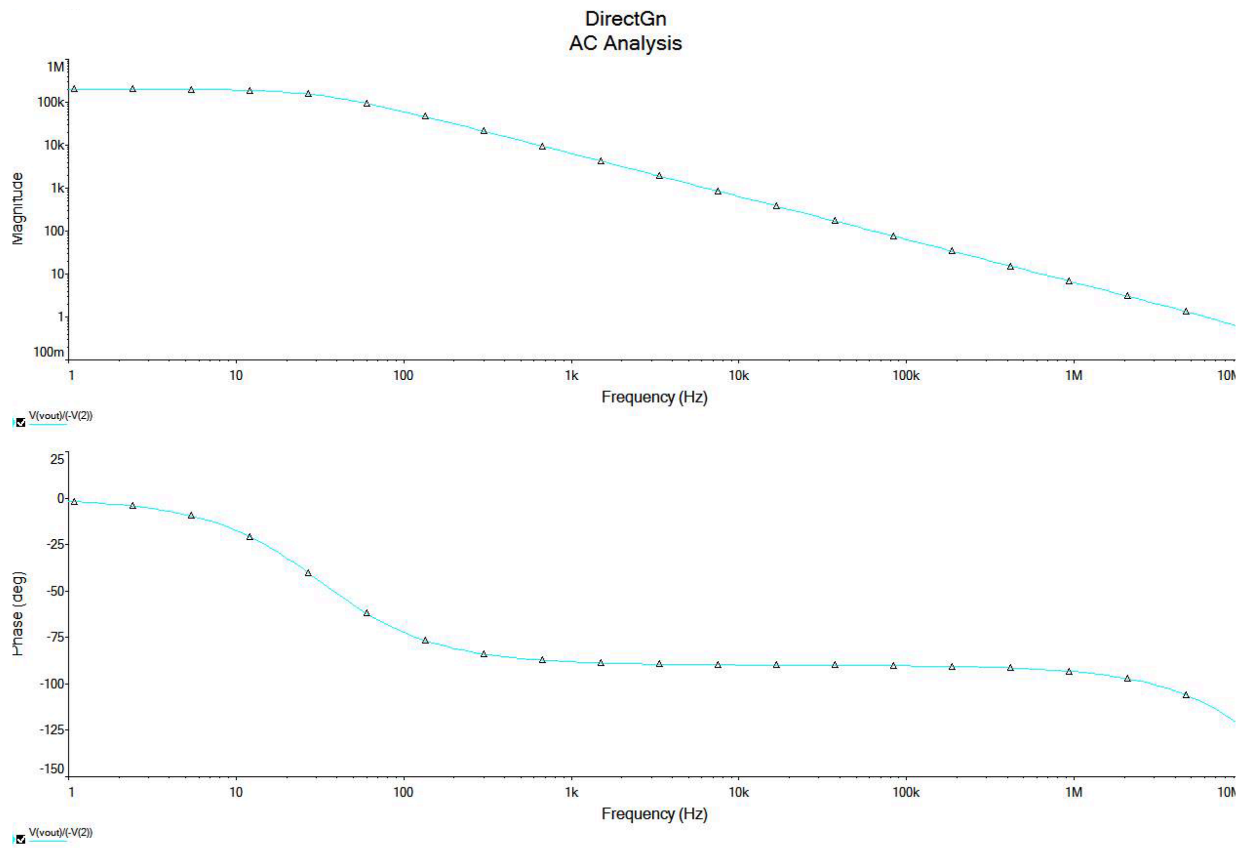


Fig. 6. Phase and Gain of the LF356 Op Amp

8.13

A primitive differentiator was constructed (shown in circuit 8.13).

Circuit 8.13

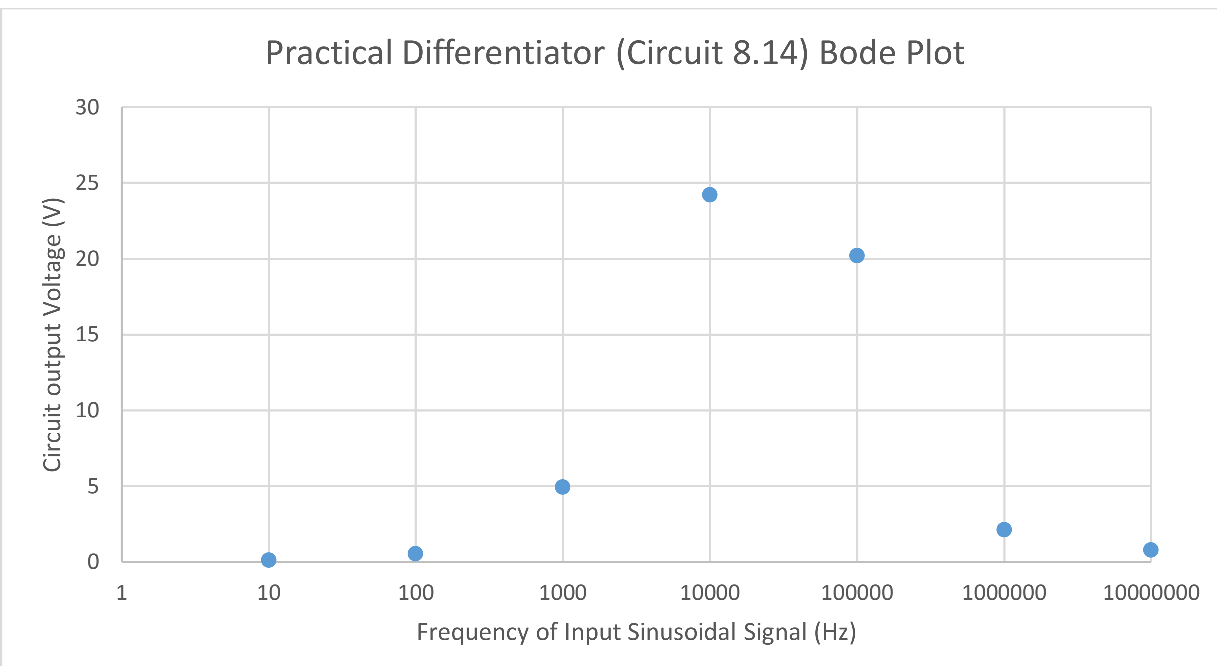
This circuit differentiates its input because the capacitor introduces a 90-degree phase shift, which for all sinusoidal and therefore all combinations of sinusoidal functions is equivalent to differentiation:

$$\frac{d}{dx}f(x) = \frac{d}{dx}\sum_i a_i \sin(\mathrm{b_i}x + \delta) = \sum_i a_i \cos(b_i x + \delta) = \sum_i a_i \sin\left(a_i x + \delta + \frac{\pi}{2}\right) = f(x + \frac{\pi}{2})$$

8.14 A practical differentiator was constructed (shown in circuit 8.14). In this circuit, low frequency signals are phase shifted by the first capacitor and unaffected by the second capacitor and high frequency signals are phase shifted by the second capacitor, but not the first capacitor. Bode plot data was measured and recorded, and is represented below.

Circuit 8.14

Frequency input signal (Hz)	10^1	10^2	10^3	10^4	10^5	10^6	10^7
Amplitude of output signal (V)	0.09	0.52	4.92	24.2	20.2	2.12	0.76



This differentiator circuit has also acts as a bandpass filter with a resonant frequency around 10kHz, so it will not properly differentiate all signals.

8.15 Another imperfection of Op Amps is that they have finite slew rate: the maximum rate with which their output voltage can change. The slew rate of an op amp was measured with an op amp follower circuit (see circuit 8.15). The input was a 200kHz 10Vp-p square wave.

Circuit 8.15

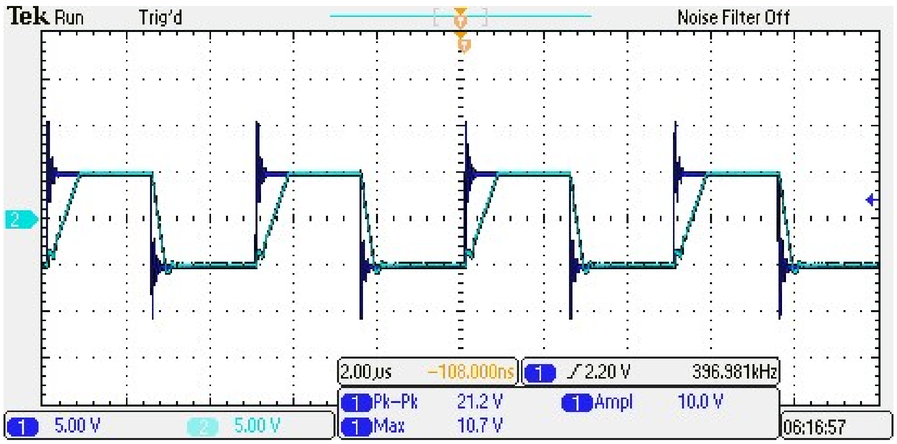


Fig. 7. Finite Slew Rate of an Op Amp.

From fig.7 one can clearly see the finite slew rate of the output signal (‘rhombus’ shaped wave) compared to the input signal (square wave).

Slew Rate (increasing voltage) = 10 volts / 0.8 microseconds = 12.5 V/μs

Slew Rate (decreasing voltage) = 10 volts / 0.4 microseconds = 25 V/μs.

Analysis

8.16 The follower circuits 8.6 and 8.7 cannot produce very negative outputs. Theoretically this problem could be addressed by reducing the emitter resistor from 1k to a much lower resistance like 51Ω, thus bringing the output voltage closer to -12V. However, in practice this is not a viable solution since it would cut down the all-important flow of current to the speaker. Circuit 8.9 gets around this problem all together by adding a second output stage follower which can supply current to away from the load without a resistor, towards the -12V supply.

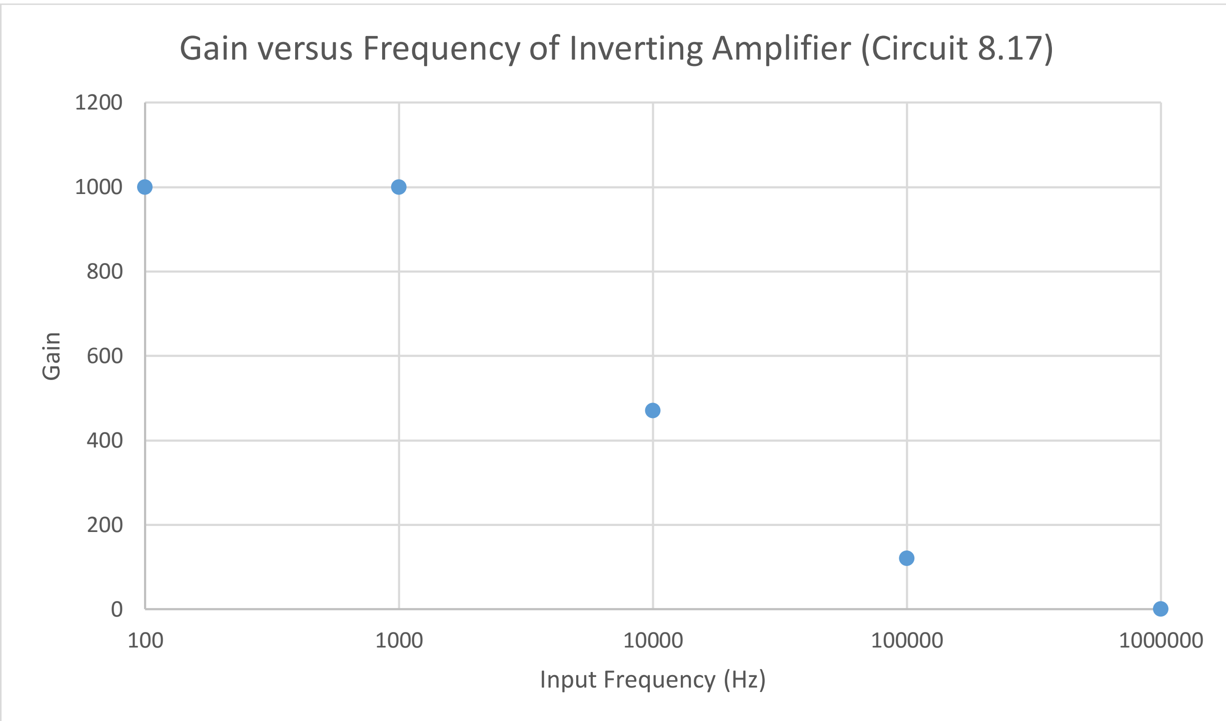
Finite Op Amp Gain

8.17 The frequency response characteristic of a x1000 inverting amplifier was determined with circuit 8.17.

Circuit 8.17

Input Frequency (Hz)	10^2	10^3	10^4	10^5	10^6
Gain	1000	1000	470	120	0
Phase (degrees)	180	180	120	120	*

*Undefined.



8.18 Because of the high DC gain of the LF356 op amp, a low input signal was used in conjunction with secondary and tertiary inverting amplifiers (to measure the input value) in order to measure the gain of the LF 356 op amp. See circuit 8.18. The purpose of the secondary op amp is to match the imperfections of the op amp without any amplification (namely Vos). U2 shift the signal from V- by 90 degrees. The output of U3 cannot be used at high frequencies because the finite slew rate of the op amp will distort the signal.

Circuit 8.18

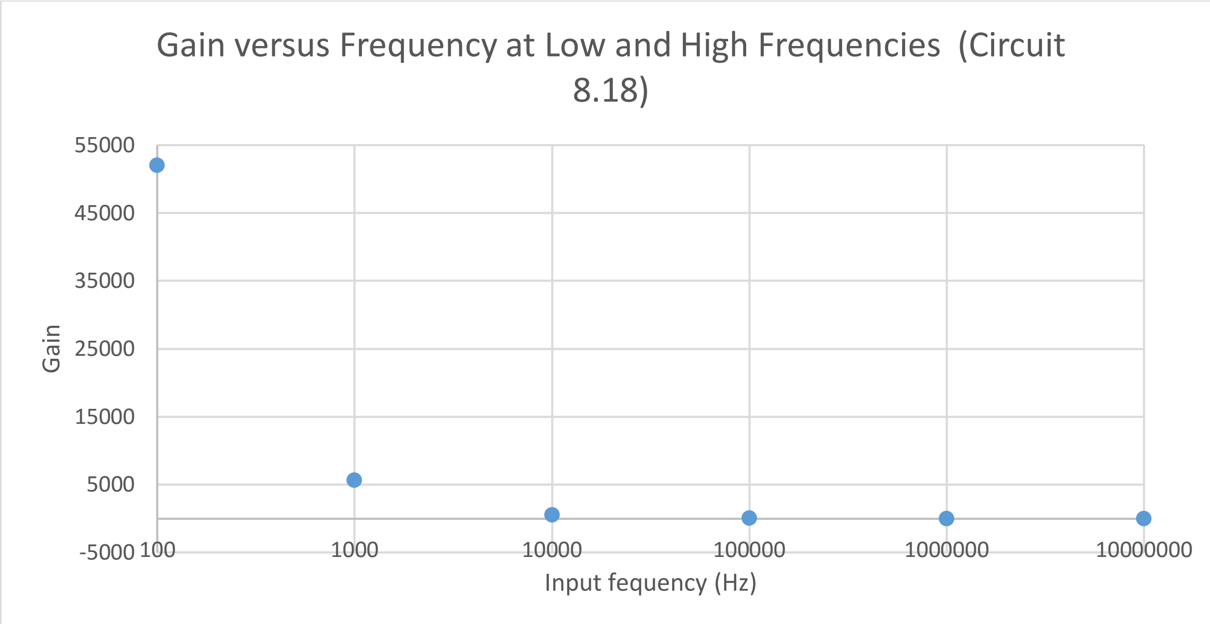
Open-loop gain and phase shift of U1 (open loop gain = |Vout/V-|):

Frequency (Hz)	10^2	10^3	10^4	10^5	10^6
Gain	*	*	480	48	4.8
Phase shift (degrees)	*	*	45	90	90

*Undefined/no signal

Gain and phase shift at low frequencies using U2 and at high frequencies using U3:

Frequency (Hz)	10^2	10^3	10^4	10^5	10^6	10^7
Measure made at:	U3	U3	U3	U2	U2	U2
Gain	52k	5.6k	500	50	4.6	2.8
Phase shift (degrees)	150	90	90	90	70	80



8.19 The gain of an inverting amplifier assuming finite gain is given by:

$$Gain = \frac{V_{out}}{V_{in}} = -\frac{R_f/R_1}{1+(1+R_f/R_1)/A(s)},$$

where

$$A(s) = \frac{A_o}{1+\frac{s}{w_o}},$$

and where A_o is the dc gain constant (the usual notion of gain), s is frequency, and w_o is the pole frequency [1].

Based on data from 8.12 and 8.18, the gain of this inverting amplifier is modeled by:

$$G = \frac{5E6}{f}$$

Where f is the input signal frequency. This works for high frequencies in 8.17.

8.20 Using the simple rectifying circuit 8.20.1 driven with a triangle wave, the output distortion shown in fig.8 was observed at frequencies much higher than 1kHz.

Circuit 8.20.1

Circuit 8.20.2

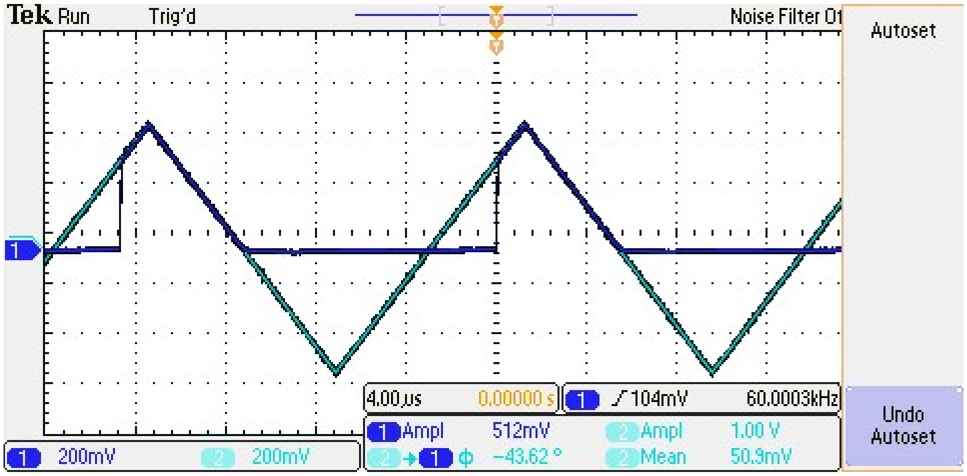


Fig.8. Circuit 8.20.1 output pattern at high frequencies

This distortion is characteristic of the minimum forward voltage across a diode required to initiate the flow of current, which becomes quite noticeable at high frequencies. (Around 300mV.) The op amps' finite slew rate degrades the performance because the voltage does output of the op amp does not change as fast as the input signal, and therefore the circuit does not produce the proper output, which the result of which is amplified by the diodes behavior.

Circuit 8.20.2 works better than circuit 8.20.1 because the potential changes from the input reach the output without first passing through the diodes or op amp. See fig. 9.

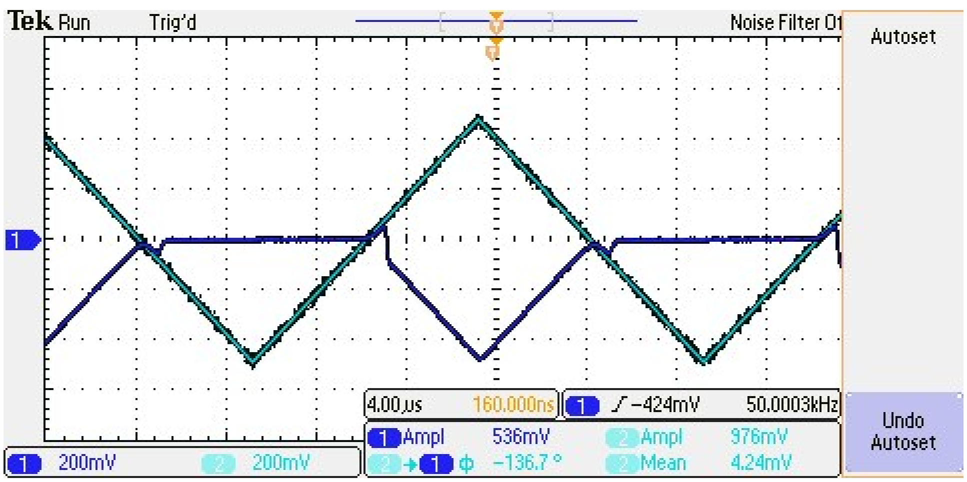


Fig.9. Circuit 8.20.2 output pattern at high frequency

The distortion shown in fig.9 is significantly smaller than the distortion shown in fig.8.

Conclusion

While for most calculations involving op amps the golden rules reign supreme, there are many situations in which they do not hold true. There are four main categories into which the imperfections of op amps can be placed:

Input imperfections, e.g. small offset voltages and nonzero input lead currents;

Output imperfections, e.g. limited power supply resources;

Electrical Noise, e.g. voltage noise, Johnson noise; and

Finite gain of op amps, e.g. finite gain, phase shifts, and finite slew rates.

While all of these imperfections are problematic, many of them have a simple fix, or at least can be avoided by staying within a range of normal operation, which is the case for any real circuit element.

References

[1] Georgia Tech. “Effects of Op-Amp Finite Gain and Bandwidth”. http://users.ece.gatech.edu/mleach/ece3050/notes/OpAmps/opampbw.pdf. Nov. 2, 2015.