

Electromagnetic Field Detector Circuit Using A Single Supply Operational Amplifier

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Abstract

Electrical and magnetic fields (EMFs) have become a major health concern. EMFs may be responsible for causing cancer, and negatively affect people using pacemakers and other electromagnetic sensitive devices. Electrical and magnetic fields often co-exist, overlapping each other. From physics we know that a time-varying magnetic field will create an electrical field. An inductor is an excellent probe to pick up such electromagnetic fields. This project shows how an inductor can be used to successfully detect electromagnetic fields. With the help of a multi-meter the induced current can be measured and the magnetic field strength calculated.

Introduction

Detecting electromagnetic fields (EMFs) has become increasingly important. There are several health issues related to strong EMFs, especially involving cell phones. Persons relying on pacemakers must also be aware of strong EMFs, because EMFs can influence pacemakers undesirably. From an engineering standpoint, electromagnetic fields must be considered when circuits sensitive to EMFs are connected to circuits surrounded by strong EMFs. A circuit might yield very different outputs if a strong electromagnetic field influences it.

The first part of this project includes a thorough analysis of the circuit and the underlying physical principles. Once an understanding is gained for the circuitry, I will discuss my results building the actual circuit, and simulating it using *B² Spice* software.

During my analysis I found that relatively strong EMFs surround cell phones and other commonly used household items such as microwaves and televisions. The detection circuit can find the presence of EMFs. Using analytical calculations, I can calculate the strength of the magnetic field surrounding each device. Using these results I can conclude the theoretical and practical operation of the detection circuit and its components.

Theoretical Background

This project intends to successfully detect electromagnetic fields using an inductor as a probe. The circuit used to achieve this uses only one amplifier and one transistor. The remaining components are passive resistors and capacitors. Before we can thoroughly analyze the circuit, the physical principle of self-induction and electromagnetic fields must be explained to gain a basic understanding for the physical reasons why the circuit works.

Induction and Self-Induction

The principle of induction states that an electric potential is created when the magnetic flux, Φ , of an inductor changes with time, t . The induced voltage is equal to the product of the windings, n , of the inductor, and the change in magnetic flux over time (see Equation 1).

$$V_i = -n \frac{d\Phi}{dt} \quad \text{Equation 1 - Law of induction}$$

The potential that induction creates is not the only inductive process though. The windings of the inductor itself experience induction. The induced current within the inductor's windings oppose the current created by the induced potential. This process is called self-induction. Self-induction opposes the flow of induced current, which is the reason why an inductor is an open-circuit during transient state. The induced potential must first overcome the induced current due to self-induction.

Electromagnetic Fields

Electrical and magnetic fields can co-exist without influencing each other. Both fields are inherently connected if we look at them over a change of time t . There are two basic laws governing electromagnetic fields.

1. Electrical currents and electrical fields changing with time are surrounded by magnetic fields.
2. Magnetic fields changing with time are surrounded by electrical fields.

Using these two laws and the understanding of induction, we can explain why electromagnetic fields can be detected with an inductor. If we can show that a voltage potential is created, induction must have occurred if no other source is present. Induction only occurs if a magnetic field changes with time. Last, if a magnetic field changes with time, an electrical field must surround it. In conclusion, an electromagnetic field is present if the inductor passes a signal into the amplifier.

Using this basic understanding, we can determine the energy of a magnetic field in an inductor. The energy of a magnetic field in an inductor is equal to the product of inductance, L , and the current, I , through the inductor (see Equation 2).

$$E = \frac{1}{2} L \cdot I^2 \quad \text{Equation 2 - Energy of magnetic field in an inductor}$$

Analysis of Detection Circuit

The circuit to detect the electromagnetic fields uses two active parts, an operational amplifier and a transistor. The remaining parts of the circuit are capacitors, resistors, and two diodes. Figure 1 shows the electromagnetic field detector circuit.

The 1 mH inductor is the probe. It is connected to the inverting and non-inverting end of the amplifier in series with a capacitor to eliminate dc values. The feedback loop consists of a 2.2 M Ω resistor and a capacitor to eliminate dc voltages. Connected to the non-inverting end is a voltage divider between two 10 k Ω resistors.

The transistor is an npn bipolar junction transistor. It is connected in a common-emitter configuration. The transistor does not provide any amplification and is essentially a voltage follower. Figure 2 shows the output of the transistor using $v_{in} = 9V$. The output is 8.2 V,

accounting for the voltage drop across the diode. The transistor simply separates the output to the meter from the output of the amplifier. The output of the transistor is fed to two diodes to full-wave rectify the signal the inductor picks up. The signal is then displayed on the digital multi-meter (DMM).

Two 220 μF capacitors are used to ensure that dc voltages fail to reach the transistor and that the diodes only conduct when a signal that changes with time flows across them. DC signals will close the path to ground using these capacitors.

The circuit receives power from a 9V battery for the amplifier supply voltage. The amplifier uses an asymmetrical supply voltage, with 9V connected to v^+ and 0V (ground) connected to v^- .

Analysis of the Amplifier

The amplifier in this detection circuit does not assume a traditional role. Taking the amplifier arrangement out of the circuit yields a setup as in Figure 3. The feedback-loop consists of a resistor and capacitor that forms impedance. The actual gain, in a traditional sense, is the feedback impedance Z_f divided by the capacitive impedance X_c . The gain of the amplifier must be dependent on frequency, because X_c and Z_f change with frequency.

Figure 3 shows the amplifier configuration using the virtual ground concept. Starting at the 9V dc supply, we can identify that the dc current can only go to ground through the voltage divider between the two 10 k Ω resistors. There is no current flow through the amplifier terminals, and the capacitor blocks the path into the non-inverting terminal. The current divides equally over the 10 k Ω resistors. This leaves the node between the feedback

path and the inverting terminal at 4.5 V. Let the 1 mH inductor be the input source v_i . We can write a node equation summarizing the currents as follows:

$$\frac{v_i - 4.5V}{X_c} + \frac{v_o - 4.5V}{Z_f} = 0$$

Equation 3 - Node equation for the amplifier using virtual ground analysis

Rearranging the equation for v_o yields:

$$v_o = 4.5V - Z_f \left(\frac{v_i - 4.5V}{X_c} \right)$$

Equation 4 - Theoretical output of the operation amplifier

This theoretical output of the amplifier depends mostly on the frequency of the amplifier. At low frequencies, Z_f is small compared to X_c yielding a small output voltage. At high frequencies, Z_f is much larger than X_c , yielding a large output.

In conclusion, the amplifier is not set up in a traditional configuration that can easily be identified. Since the theoretical output is a constant subtracted by a negative ratio, we can say that the configuration is inverting. The probe is the source of input (v_i) and assumes the role of a floating source. The gain of the amplifier is dependent on frequency, not only due to the inherent amplifiers characteristics, but also due to the impedances X_c and Z_f .

Procedure

To build the circuit, I attached a 10 inch shielded audio cable to the inductor and placed the cable through the plastic body of a pen. I wanted to prevent the probe from picking up electromagnetic fields emitted to the circuit itself. The 10-inch displacement and the shielded cable ensure that only the field surrounding a device is picked up.

Instead of using the LF351 operational amplifier I used a LM324 op-amp. The unity gain frequency of the LF351 is four times higher than that of the LM324, though this will not affect the circuit dramatically. On the other hand, the slew rate of the LF351 is 13 $\mu\text{V/s}$ in contrast to the 0.5 $\mu\text{V/s}$ of the LM324. Rapidly changing magnetic fields, causing a rapidly changing input signal, will fail to register using this amplifier due to the limiting slew rate. The LM324 is a single supply voltage amplifier, just as the LF351.

Instead of using a BC109C transistor, I used a generic 2N2222. Both transistors exhibit very similar characteristics and they are both npn type bipolar junction transistors. Using the 2N2222 does not affect the circuit, especially since the transistor is used primarily as a voltage follower and there is no gain associated with it.

After building the circuit I tested it thoroughly. Using a digital multi-meter (DMM), I probed for the induced voltage potential and the current. Using Equation 2 (p. 4) I calculated the strength of the magnetic field within the inductor.

Data

The following data is used to draw conclusions about the electromagnetic field detection circuit. The electromagnetic field strength is calculated using Equation 3. The unit for the field strength is Joules, the unit of energy. Note that the DMM only picks up frequencies that are changing rapidly. A value of “no reading” is assigned if the DMM could not detect the frequency of the induced current. The measurements can be viewed in Table I.

Simulating the circuit, yields very different results from what I expected. This is because it is very complicate to model a changing electromagnetic field using *SPICE* software. Figure 5 shows the typical response of the amplifier circuit (pictured in Figure 4). The output peaks

initially at 4.5 V and then drops to 1.6 V, where it oscillates slightly between 1.6 V and 1.8 V. This is not the output that I experienced when using the detection circuit itself.

The frequency response of the amplifier is shown in Figure 6. The response is graphed from 1 Hz to 100 kHz.

Analysis

The analysis of the circuit is divided in two parts. The first part discusses the theoretical analysis of the circuit. Using *B² Spice* software, I analyzed several simulations of the amplifier model used in the circuit. I will use these simulation results to discuss the expected output of the circuit. I will focus mostly on the operation amplifier in this part. Part two of the analysis concentrates on the results using the actual detection circuit to probe for electromagnetic fields. This analysis will focus on the overall performance of the circuit.

Theoretical Analysis

Equation 4 shows the theoretical output of the amplifier, derived using the virtual ground concept. From this equation we can see that the output primarily depends on the frequency of the input signal, because it affects how the amplifier will react and the magnitude of the ratio Z_f / X_C .

Figure 6 shows the frequency response of the amplifier when a signal is applied to it. In order to obtain this graph, I replaced the 1 mH inductor with a voltage source. The input signal v_i is a sinusoid that oscillates at a frequency of 10 kHz and has a peak of 2 V. Figure 4 shows that the maximum gain of the amplifier is reached between 500 Hz and 6 kHz. Also, the gain is greater for high frequency values than it is for lower frequencies. There is no

actual dc gain in the circuit. For a dc input of 5 V, the output is a steady 1.5 V (see Figure 7). The magnitude of the input dc signal does not influence the output at all.

The general output for a simulation using a time-varying input source is shown in Figure 5. The output initially peaks at 4.5 V and then drops to 1.6 V, where it oscillates between 1.6 V and 1.8 V. This is not the response that I expected. I tried using several input sources, varying from small signal current sources, to voltage sources that change rapidly or slowly. I also used a 1 mH inductor as the source and put an initial current on it. Figure 8 shows the output for the simulation of a fluxed inductor. The amplifier response is the same as in Figure 5.

The reason why the response of the circuit is generally the same is hard to explain. I tried to verify the output by circuit analysis, but could not find adequate reasons. It is hard, if not impossible, to fully simulate a changing magnetic field, and the induced potential it would cause, in *B² Spice*. The direction, magnitude, and frequency of a magnetic and resulting electrical field can change at any moment and the software cannot sufficiently simulate this phenomenon.

An overall simulation of the circuit yields little to no output. *B² Spice* gives the usual output after the amplifier, but once that signal passes through the transistor it goes to zero. I tried using an ammeter and a voltmeter instead of just a probe but neither yield any kind of output.

In conclusion, *B² Spice* helped me understand discrete parts of the circuit, especially the amplifier configuration. Simulating the entire circuit fails to yield good results. This is due to the fact that I cannot model an electromagnetic field using *B² Spice* software.

Practical Analysis

The circuit I built performs exceptionally well. It detects changing magnetic fields, and with the help of the digital multi-meter (DMM) I can compare the electromagnetic fields (EMFs) relatively to each other. As a reference, I used the induced current measured when no apparent strong EMF was surrounding the circuit. The induced current for air was 20-30 μA . Using Equation 2, I calculated the resulting magnetic field strength to be 0.2 – 0.45 pJ (pico Joules). If I put the probe close to the circuit the induced current changed slightly at times, but to a degree that is negligible. Using this reading as a reference, I investigated common household items where I expected electromagnetic fields to be present.

The first item I analyzed was the cell phone. Cell phones in conjunction with EMFs have been studied in great detail, due to the hypothesis that prolonged cell phone use may cause cancer. This made the cell phone a good item to test the performance of the circuit. In Table I we can see that the induced current was 200 – 300 μA when the cell phone was in use. There was no significant EMF surrounding the cell phone when it was in stand-by. The resulting magnetic field was 20 – 45 pJ, a magnetic field 100 times stronger than the magnetic field of air.

Other devices I investigated were the microwave and television. When both are turned on, they are surrounded by a magnetic field of about 10 – 12 pJ, a field that is 50 times stronger than that of air. An operating laptop computer and cordless phone have magnetic fields surrounding them. The strength of those fields is 10 to 15 times stronger than the relative field surrounding air.

I tried to measure the frequency of the induced current but could only get two useful readings. I thought that there might be a correlation between the field strength and the

frequency, but the data is unfortunately not very useful. The frequency of the current induced by the cell phone was 420 Hz, and the frequency of the current induced by the television was 9 kHz. Using these two readings I cannot draw conclusions about a correlation between the magnetic field strength and the frequency of the induced current.

One last point I would like to make is that I could have also measured the induced voltage potential instead of the induced current. However, I could not find an equation to use the induced voltage potential to calculate the electrical or magnetic field strength. It seemed reasonable in this case to use the induced current. I checked that the induced voltage potential and the induced current change in a similar fashion and that measuring both do not aid the analytical process.

Conclusion

The main conclusion of this project is that I can detect electromagnetic fields using the circuit in Figure 1. I can calibrate the circuit by measuring the EMF surrounding the circuit before I probe for electromagnetic field. The induced voltage or current gives a relative comparison to draw conclusions about the electromagnetic field strength.

There are electromagnetic fields surrounding common household items. The item with the strongest EMF in my dataset was the cell phone. Health organizations have voiced concerns about strong EMFs surrounding cell phones and their possible link to cancer over the past years. A person is certainly immersed in a much stronger EMF when using a cell phone in contrast to other devices. Even though my measurements show that the television and microwave have EMFs that are still half the strength of the EMF surrounding the cell phone, we have to keep in mind that we are holding cell phones close to our heads. It makes the impact that EMFs created

by cell phones can have more eminent than the EMFs of microwaves, televisions, or other devices.

Another conclusion I can draw from the project is that separating the probe from the circuit does not affect the measurements. The circuit has such a small electromagnetic field that it does not influence results. The real advantage in separating the probe from the circuit is the added mobility of the probe. It helps to move the probe to desired places, but the circuit itself does not emit an EMF strong enough to influence the reading.

Using the LM324 operational amplifier did not seem to affect the circuit. I did obtain results, and that was the most important objective. I do believe though, that an amplifier with a slew rate similar to that of the LF351 would have yielded more accurate results. In the future, obtaining the required amplifier can improve this circuit. Finding an electromagnetic field of known strength and using this known field as a reference can also help with the analysis of the acquired data. A field of known strength enables us to do an absolute comparison, instead of the relative comparison I chose.

Last, I would like to conclude that analyzing the entire circuit using *B² Spice* software is impossible. The circuit is designed to measure the induced current or voltage due to electromagnetic fields. It is hard to model a changing electromagnetic field using *B² Spice* software. Finding the frequency response of the amplifier was very helpful, but simulation results of the circuit and the amplifier helped little to evaluate the overall operation of the circuit.

Figures and Tables

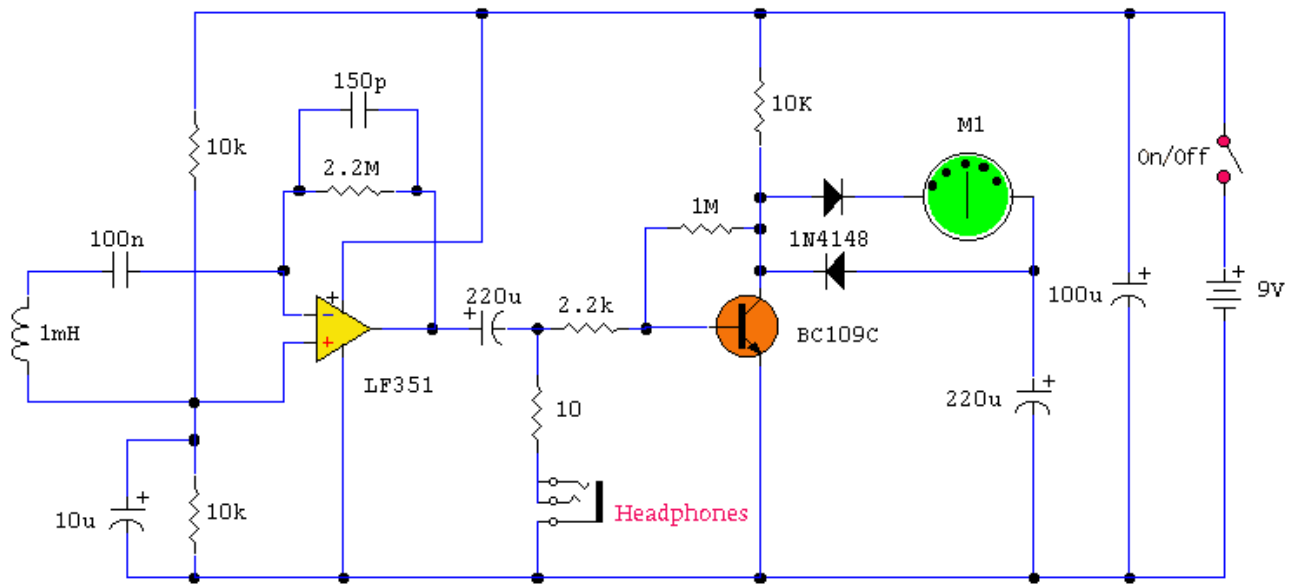


Figure 1 - Electromagnetic field detector circuit

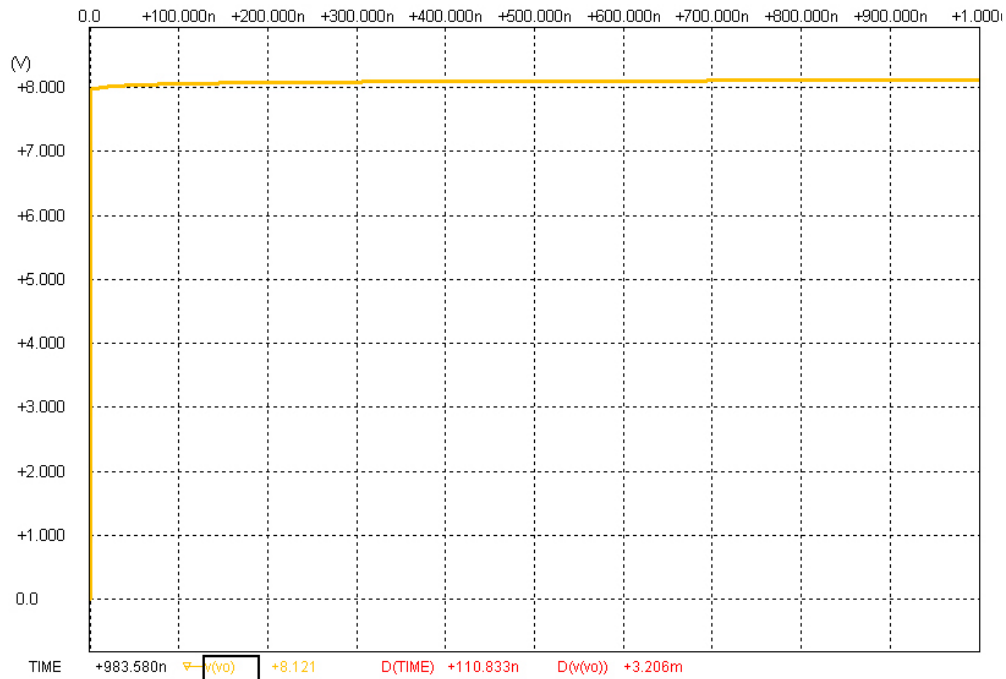


Figure 2 - Transistor output with $v_i = 9V$

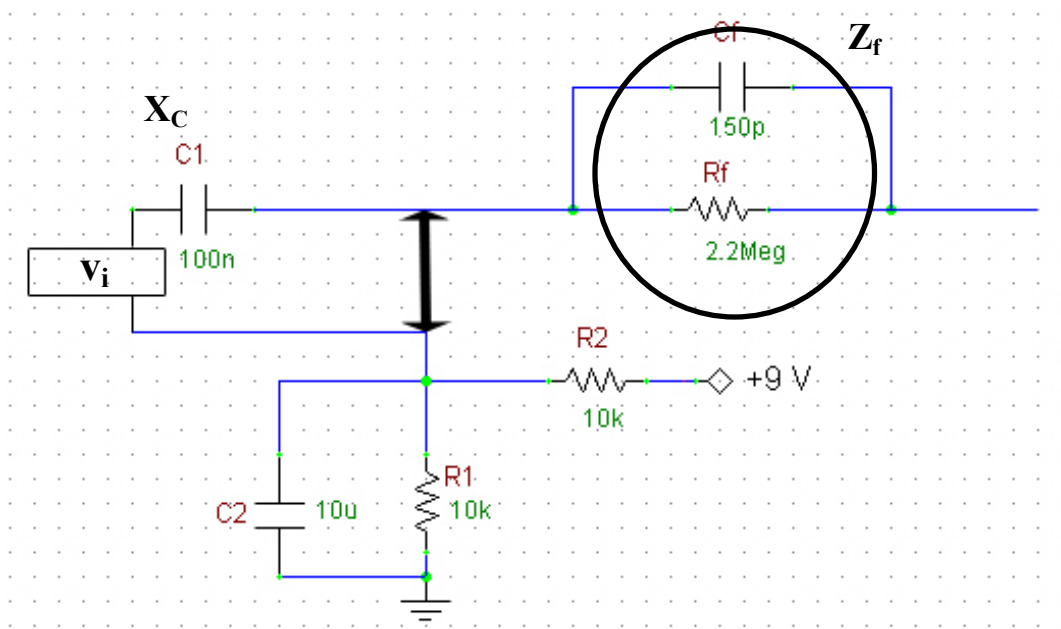


Figure 3 - Op-amp analysis using virtual ground concept

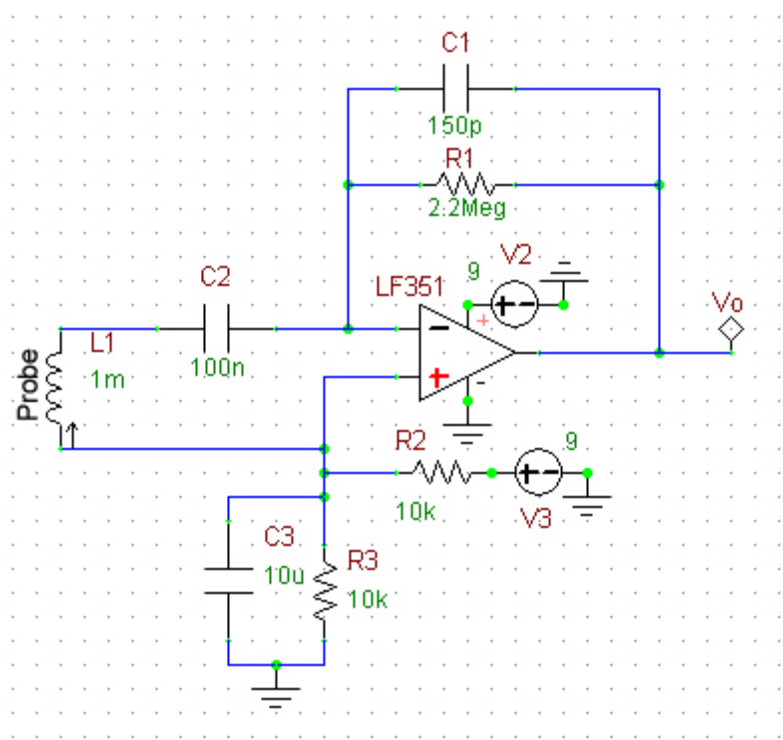


Figure 4 - Op-amp configuration in the detection circuit

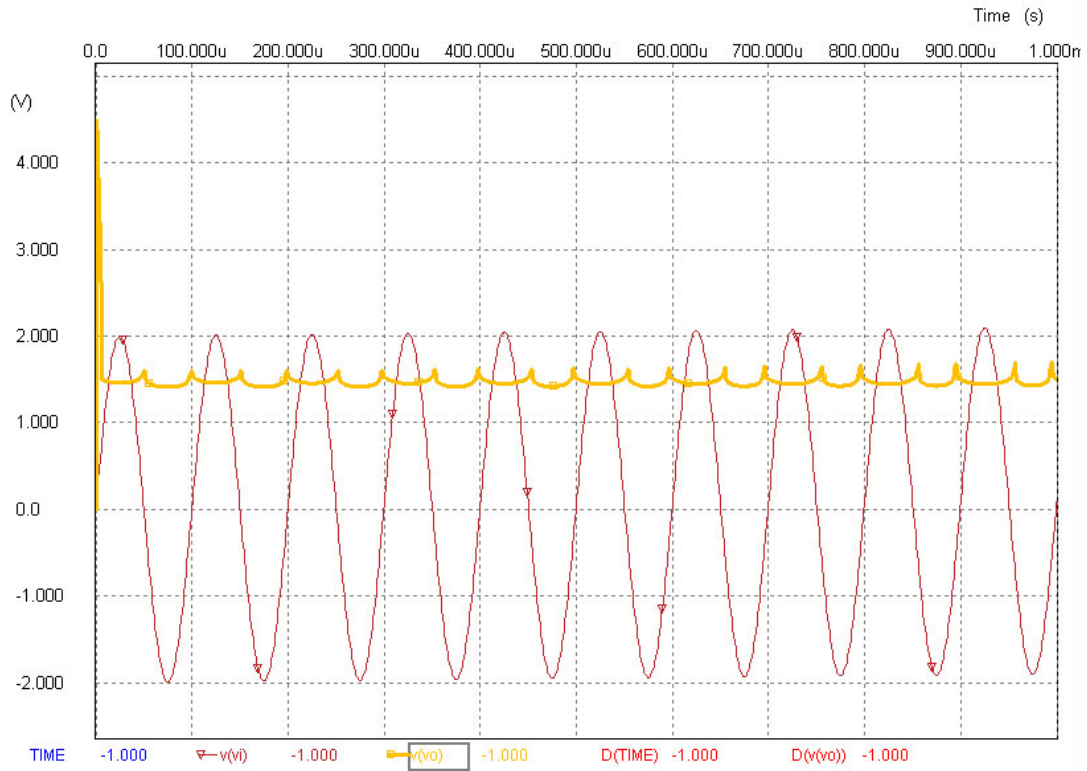


Figure 5 - Typical amplifier output, $v_i = 2 \sin(\omega t)$



Figure 6 - Amplifier frequency response from 1 Hz to 100 kHz

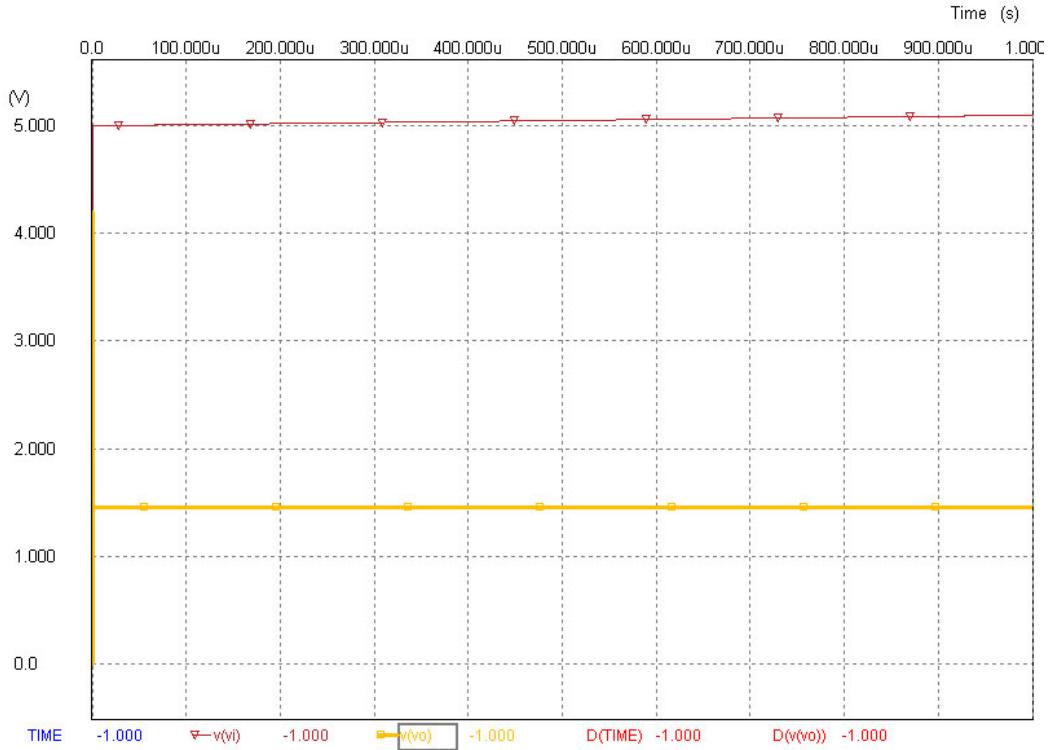


Figure 7 - Op-amp dc response ($v_o = 1.5$ V)

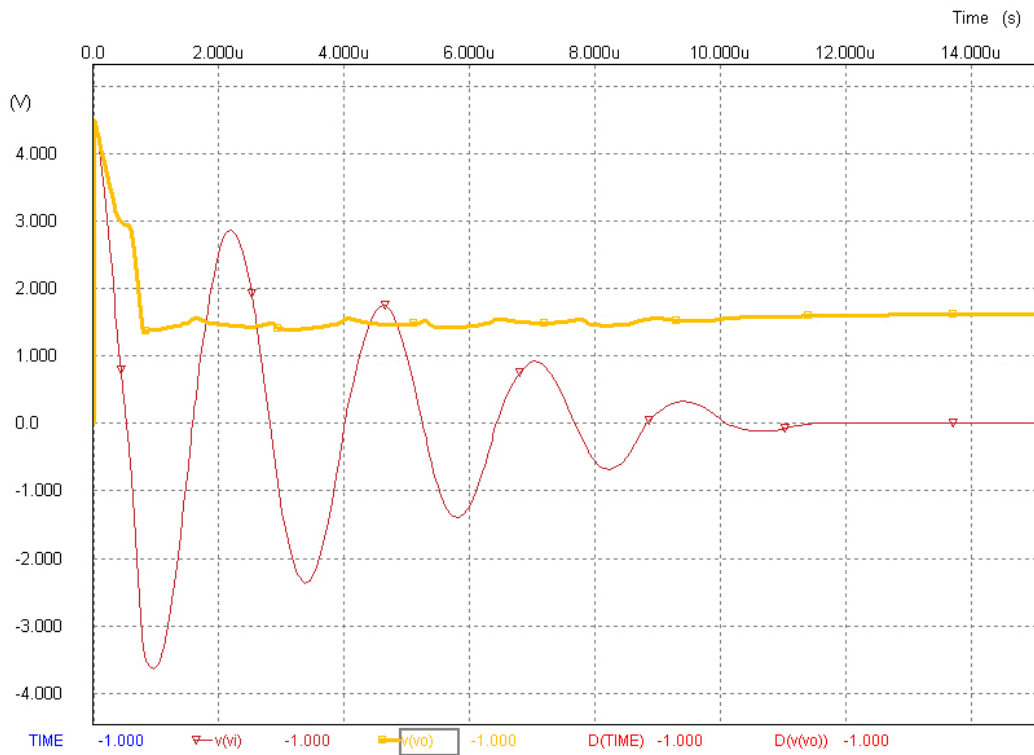


Figure 8 - Op-amp response using 1 mH inductor as source (fluxed at 100 μ A)

Device / Gadget	Induced current (μA)	Electromagnetic Field Strength (μJ)	Frequency (Hz)
Air / circuit surrounding	20 - 30	0.2 – 0.45	No reading
Cell phone (while calling)	200 - 300	20 – 45	420
Operating microwave	145	10.5	No reading
Operating television	160	12.8	9 – 9.1 k
Operating laptop computer	70 - 100	2.45 – 5	No reading
Cordless telephone	80	3.2	No reading

Table I - Induced currents, magnetic field strength, and frequency

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