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Two Signal Frequency Meter and Comparator

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TWO SIGNAL FREQUENCY METER AND COMPARATOR

ABSTRACT

The purpose of this circuit is to provide a voltage output linearly proportional to the frequency of the input. The circuit was designed to operate with input frequencies varying between 100 [Hz] and 10 [KHz]. The core of the circuit is the transistor charge pump frequency to voltage converter. The circuit was also designed to be able to measure the frequencies of two signals and compare them by providing an output voltage proportional to the difference in frequencies between the two signals. The approach to designing the entire circuit was to break it down into parts and work from there. The input and output of each subcircuit was known, so the whole team could plan a way to achieve it. When a design was completed, it went through testing to see if any problems were discovered in the design or in the components used. Theoretically with the final design, every 1 [kHz] is 1 [V] in the output. Therefore, 100 [Hz] would output 0.1 [V], 1 [kHz] outputs 1 [V], 10 [kHz] outputs 10 [V] as examples of theoretical outputs.The final design yielded precise results with every taken measurement being under 2% error although the majority of frequencies were measured with under 1% error.

INTRODUCTION

The frequency to voltage converter changes the input signal's frequency into a measurable DC voltage. With the current design, the converter can properly measure signal frequencies from a range of 100 [Hz] to 10 [kHz]. WIth this range of frequencies, the circuit is expected to output 0.1 [V] to 10 [V]. The most significant part of the circuit is the transistor charge pump that converts a square wave into constant voltage proportional to the frequency of the square wave. To provide this square wave the input (which can be of most shapes) is supplied to the high pass filter to center the wave at 0 [V] and it goes to an op-amp schmitt trigger to get the desired square wave. Next the signal is clipped by a zener diode to limit the square wave to a maximum of 5 [V] and provide consistency before the transistor charge pump. Lastly, a pair of these circuits is connected to an op-amp comparator circuit that can output the difference of two input frequencies at the same rate as before 1[V/ kHz] of difference.

TRANSISTOR CHARGE PUMP

The frequency to voltage conversion comes from the principle of a transistor charge pump. The circuit and the concept of using discrete components for frequency to voltage conversion comes from the website *Circuit Diagramz* [1]. Figure 1 demonstrates the full transistor charge pump schematic suggested by *Circuit Diagramz* with modifications such as the specification of the values of C2, C3, and R6; and the addition of a potentiometer to fine tune the output once the circuit was tested.

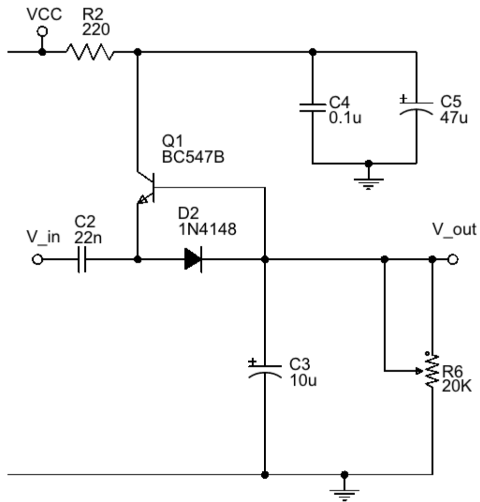

Figure 1. Frequency to voltage converter with selected values for C2, C3, and R7 to accommodate the frequency range and voltage-frequency ratio for our project.

For this circuit to successfully convert frequency to voltage, the input needs to be a square wave of a fixed amplitude [1]. When the input is at the low part of the square wave, C2 charges up quickly and when the square wave quickly changes to high, the charge collected by C2 is transferred to C3 and R6. Diode D2 is a 1N4148 switching diode capable of switching within 4 ns, making it suitable for applications requiring fast switching [2]. This diode prevents any current flowing back to C2. The BJT, Q1, is a power transistor which keeps the voltage on the right hand side of C2 roughly the same as the voltage at the top of C3. According to the post on *Circuit Diagramz*, the overall transfer of charge from C2 and C3 is described by

$$V_{OUT} = (V_{IN} - V_{D2})R_6C_2f_{IN} \quad [1]$$

V_{IN} is simply the amplitude of the square wave input, V_{D2} is the voltage drop provided by D2, and f_{IN} is the frequency of the square wave input. This equation is derived by the following: "the increase of [the output voltage] during a leading edge [of the input square wave] must be equal to the voltage reduction caused by [R6] in each period" [1]. A rough estimation of the diode voltage drop as being 0.7 volts and deciding choosing a 5 volt amplitude for the square wave provides the following equation

$$V_{OUT} = (4.3[V\ ])R_6C_2f_{IN} \ .$$

C2 was chosen to be 22 nF. The relationship between the output voltage and the input frequency was decided to be 1 volt per every 1kHz of frequency ($V_{OUT} / f_{IN} = 1[V/kHz]$). Utilizing these values, R6 could be determined.

$$R_6 = \frac{1[V]}{(4.3[V])(22[nF])(1000[Hz])} = 10.5708[k\Omega]$$

R6 was calculated to be around 10.6 kOhms, so R6 was chosen to be a 20 kOhm potentiometer able to fine tune the resistance as the diode voltage drop or square wave amplitude diverge from our theoretical values. C4 and C5 are there to smooth out the power supply of the transistor. C4 filters out low frequencies and C5 filters out high frequencies. There is a need for two capacitors in parallel for filtering because of limitations in the bandwidth in real capacitors.

INPUT CONDITIONING

For the transistor charge pump frequency to voltage converter to measure the effective frequency of various waveforms (sawtooth, square, triangle, etc), the input signal needs to be converted to a square wave of a fixed amplitude. This is done by constructing an operation amplifier-based Schmitt trigger with adequate hysteresis for noise avoidance. The Schmitt trigger serves as a "zero detector", therefore, our input waveform needs to be centered at zero. A passive high-pass filter was first added at the input stage to remove any DC offset that the input signal might have. Figure 1 illustrates the RC high pass filter input stage of the circuit.

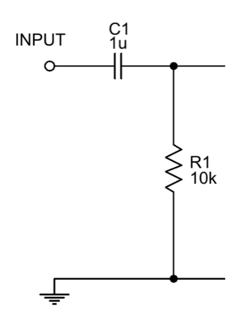

Figure 1. Passive high pass filter at the input.

The actual values of the C1 and R1 were not crucial for the circuit to work properly since the gain and phase changes to the input signal had no effect at the later stages of the circuit as long as frequencies below 100 Hz were not severely attenuated. C1 and R1 were chosen to be 1 uF and 10 kOhm respectively. These values provided a pole at 1/(R1C1) = 100 rad/sec or 15.916 Hz. This provided a consistent 0 dB attenuation for frequencies above 16 Hz, well below the lower bound of our target frequency range.

SCHMITT TRIGGER ZERO DETECTOR

After the high pass filter stage, the next stage in the circuit is an operational amplifier configuration that functions as a zero detector. This configuration allows the op-amp to saturate at VCC and VEE when the input waveform crosses 0V. The op amp Schmitt trigger is illustrated in Figure 2.

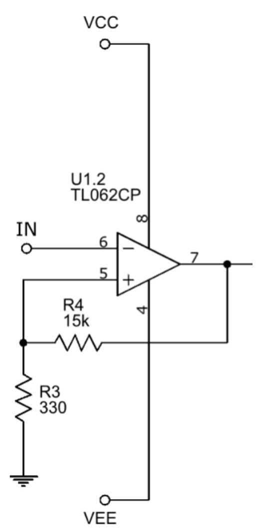

Figure 2. Schmitt trigger utilizing op-amp. VCC and VEE are +/- 15V. TL062CP op-amp chosen after testing UA741.

To avoid false triggering, hysteresis with threshold voltage of about 1/3 V centered at 0V was added. To add this hysteresis, positive feedback via a voltage divider was applied. Applying the voltage divider rule (with the assumption that the op amp saturates at around 14.5), R3 and R4 were calculated using the following equation.

$$V_{th} = 0.333[V] = 14.5[V]\frac{R_3}{R_3 + R_4}$$

Choosing R3 and R4 as 330 Ohms and 15 kOhms respectively, provided at a threshold voltage of +/- 0.312V.

$$14.5[V]\left(\frac{330[\Omega]}{330[\Omega] + 15[k\Omega]}\right) = 0.312[V]$$

When testing this circuit with the Texas Instruments' UA741CP Operational Amplifier with input square wave of amplitude 5V, the output of the Schmitt trigger became distorted at frequencies above around 1kHz. The square wave output was reduced in amplitude and low slew rate caused the square shape of the square wave to look more like a trapezoid than a square. According to the Texas Instrument's datasheet for the UA741 op-amp, it's slew rate is 0.5 V/uS [3 pg. 7]. Because of these issues, we replaced this op amp with a much faster Texas Instrument's TL062CP op-amp. The TL062CP op-amp has a slew rate of 3.5 V/uS [4 pg. 8]. After testing the TL062CP, we successfully reproduced a square wave of the same frequency as the input of the Schmitt trigger for frequencies within our 100 Hz - 10 kHz range. When testing our circuit however, we noticed that our saturation voltages (the amplitude of the square wave generated by Schmitt trigger) varied significantly from 13.5 V to 15 V. This variation in saturation levels most likely came from inconsistencies in VCC and VEE values. Since our transistor charge pump and our frequency to voltage conversion depended heavily on the constancy of the amplitude of the Schmitt trigger, we had to find a solution that fixed the amplitude of the output square wave to a constant value.

ZENER CLIPPING

The solution to the square wave amplitude problem was a resistor-zener diode circuit at the output of the Schmitt trigger. A 10 kOhm resistor was added to the Schmitt trigger output and a zener in reverse bias was attached between the resistor and ground to limit the waveform to around 5V as demonstrated in Figure 3. The zener diode also ratified the waveform. The square wave at the input of the charge pump needed to be positive.

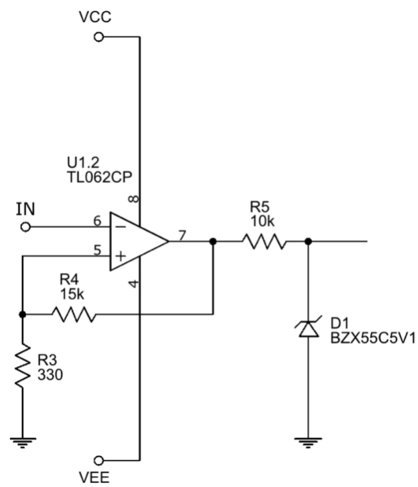

Figure 3. R5 and D1 ractifies and clips waveform at 5V.

Testing this circuit brought light to some issues with the circuit. The additional 10 kOhm resistor and diode reduced the total resistance as seen by the op-amp. This caused the load of the op amp to draw more current than what the op amp could provide. Looking at the TL062CP datasheet we noticed that to allow the op-amp's output to swing to near- saturation levels, the load resistance needed to be near or above 10 kOhm [4 pg. 10].

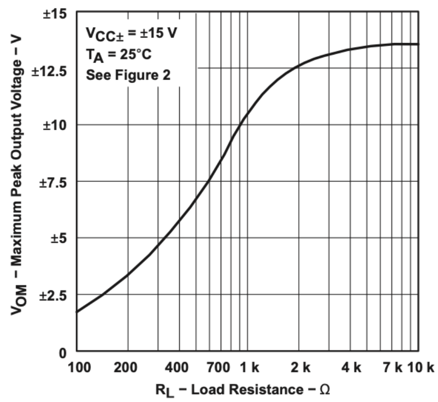

Figure 4. Texas Instruments' datasheet graph illustrating relationship between maximum peak output voltage and load resistance of TL062CP op-amp[4 pg. 10].

Calculating the resistance as seen by the op amp neglecting the diode's internal resistance…

$$R_L = \frac{(15[k\Omega] + 330[\Omega])(10[k\Omega])}{15[k\Omega] + 330[\Omega] + 10[k\Omega]} = 6.052[k\Omega]$$

demonstrates that the load resistance is too low. To solve this issue, R3 and R4 were increased by a factor of 10 (R3 = 3.3 kOhms and R4 = 150 kOhms). This resulted in a load resistance closer to 10 kOhms.

$$R_L = \frac{(150[k\Omega] + 3.3[k\Omega])(10[k\Omega])}{150[k\Omega] + 3.3[k\Omega] + 10[k\Omega]} = 9.388[k\Omega]$$

Figure 5 shows the new schmitt trigger and zener clipping circuit.

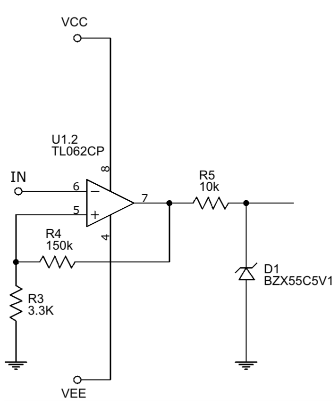

Figure 5. Schmitt trigger and zener clipping circuit with updated R3 and R4 values.

BUFFERS

The input high-pass filter, Schmitt trigger, and zener clipping circuit was terminated by a buffer to ensure isolation with the following stage, the transistor charge pump. The TL062CP is a dual op-amp device, meaning that in one package, the op-amps schmitt trigger and buffer were provided. Figure 6 illustrates the high-pass filter, Schmitt trigger, and zener clipping circuit.

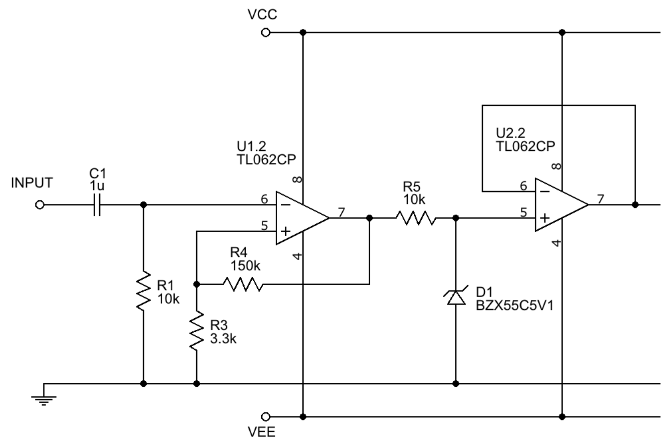

Figure 6. High-pass filter, Schmitt trigger, and zener clipping circuit. Circuit prepares input signal for the transistor charge pump frequency to voltage converter.

An additional buffer was added at the end of the transistor charge pump as well to isolate further circuitry after it. The final schematic for the frequency to voltage converted is illustrated in Figure 7.

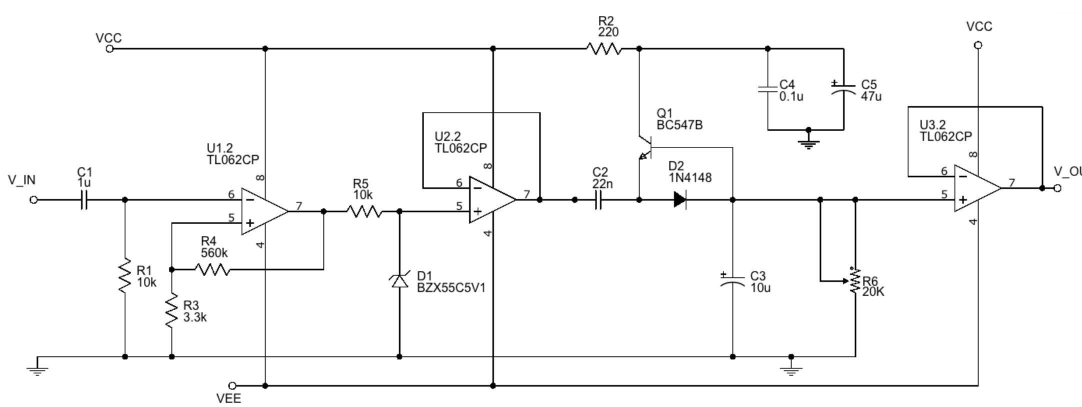

Figure 7. Final frequency to voltage converter.

TWO SIGNAL FREQUENCY COMPARATOR

To allow the comparison of two signal's frequencies a copy of the exact same circuit was constructed and the output of both were connected to an op amp in the subtraction configuration. The output of this comparator circuit is the difference in frequency of both signals with the same proportion (1[V/kHz]). This module of the circuit required a single TL062CP op amp with four resistors in the configuration shown in Figure 8. We selected equivalent values for all of the circuits to maintain the accuracy of our input voltages by giving the op-amp a gain of one. The resistors were chosen to provide a load resistance to the op-amp greater than 10 kOhm as for the reasons discussed earlier and illustrated in figure 4.

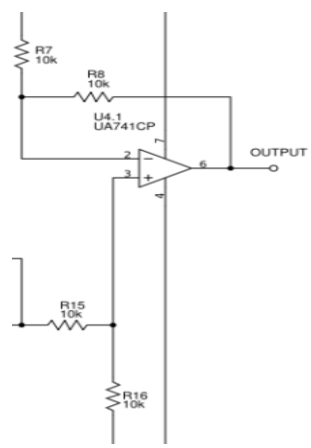

Figure 8. Two Signal Frequency Comparator circuit. Circuit has identical resistor values to maintain a gain of one to give accurate difference between both input voltages.

CIRCUIT SIMULATION

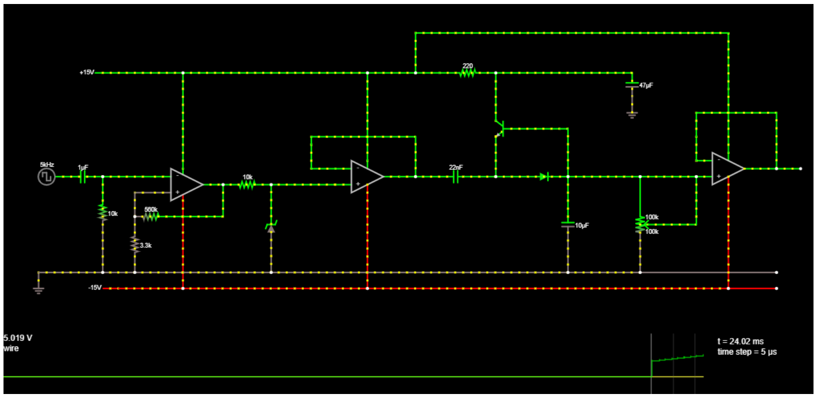

Figure 9. Signal Frequency meter Simulation. Circuit was tested using a falstad circuit simulator applet.

The encompassed circuit design was drawn in the falstad circuit simulator and proved to successfully output a voltage linear to the input signal frequency. Figure 9 depicts a square wave with a frequency of 5 [KHz] and its correlating output of 5.01 [V]. Additionally we simulated the circuit with different Sinusoidal, Triangle, and Sawtooth to validate the design of the schmitt trigger. The individual modules of the circuit design were tested using the simulator throughout the design process to affirm our design approach and thought processes. After verifying our design with the expected simulation results we were able to confidently move on to performing the tests in the lab with the constructed model.

TASKS/DESIGN PROCESS

As a group, we worked on each individual part as a team, spending time researching ideas and sharing them, and then working together to build it. After we found ideas, we proceeded to work on other parts until we completed the project. The parts of the circuit were designed together and developed as time moved on and the project started to develop. At the beginning of design, there were certain parts given to each member, but as time moved on each member ended up helping out where help was needed. Through testing and some analysis, we had to decide how to move forward with our design. According to our original timeline, we planned to have the design with appropriate calculations completed by October 18, building and testing separate parts of our circuits by October 31, combination and more testing by November 7, and finish our set up for the demonstration by November 13. Then the planned demonstration date would be November 25 to prove our design works and accuracy. Starting from the idea of a frequency to voltage converter, the design of the circuit took the longest because it was important to be as accurate as possible while having a design that is not extremely complicated.Through testing, it was discovered that the original designs did not work as well as was expected. Therefore, the design milestone had to stretch longer than planned. The design took longer than intended, but it was important to get a design worth showing. With the design being pushed back, the building and combination were also pushed back a reasonable amount of time. Our complete design and building of the circuit was completed on November 22 which was not a part of the original plan, but the was still completed before the required date. The time spent on the design was weekly from the beginning of the project starting in September and ended on November 22.

EXPERIMENTAL PROCEDURE

To test our circuit, we first started by only testing one individual frequency to voltage converter circuit. We attached our coaxial cable to our AGILENT 33210A signal generator and its leads to the input of the circuit [5]. We then attached the clip cables from a multimeter and the output. We then proceeded to input signals from 100[Hz], then 500[Hz], and from there incremented the signal by 500[Hz] until we reached 10[KHz]. We also made sure to change the signal type- Sinusoidal, Square, Triangle, and Sawtooth- so that we could check if the Schmitt Trigger was working properly. When we got voltages that were reasonably proportional to the input frequencies, we adjusted the potentiometer located in the charge pump to get even more accurate readings. We then proceed to do the same for the second frequency to voltage converter circuit.

Once our individual testings were completed for each frequency to voltage converter circuit, we then connected the two signal frequency comparator to their relative outputs. We attached another signal generator to one of the frequency to voltage converter circuits so that both circuits had a signal generator connected to them. We then attached the multimeter to the compartier’s output, and then we generated various frequencies in each frequency to the voltage converter. We then read the multimeter to see if the difference between the frequencies was proportional to the reading of the multimeter.

RESULTS

For our entire circuit output, these are the values measured at the output of the comparator circuit with one of the signals's input connected to ground to measure the output of an individual frequency to voltage converter and not the difference in frequency between two signals.

Table 1. Measurements relating input frequency and output voltages.

Input Frequency [Hz]	Experimental Output Voltage [V]	Input Frequency [Hz]	Experimental Output Voltage [V]
100	0.10158	5500	5.4897
500	0.50411	6000	5.9931
1000	1.00192	6500	6.4964
1500	1.4959	7000	6.9989
2000	1.9894	7500	7.5017
2500	2.4834	8000	8.0041
3000	2.9793	8500	8.5066
3500	3.4774	9000	9.0093
4000	3.9787	9500	9.5121
4500	4.4822	10000	10.0154
5000	4.9861		

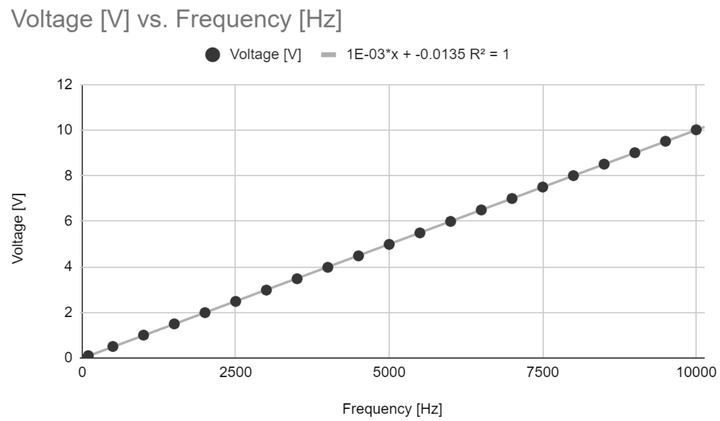

Figure 10. Graph displaying input frequency and output voltage with trendline.

From the results above, the circuit design is highly accurate and follows a linear trend with negligible deviation.

Table 2. Percent error based on measure and expected output voltage

Input Frequency [Hz]	**Expected Values [V]**	**% Error**	**Input Frequency [Hz]**	**Expected Values [V]**	**% Error**
100	0.1	1.580	5500	5.5	0.187
500	0.5	0.822	6000	6	0.115
1000	1	0.192	6500	6.5	0.055
1500	1.5	0.273	7000	7	0.016
2000	2	0.530	7500	7.5	0.023
2500	2.5	0.664	8000	8	0.051
3000	3	0.690	8500	8.5	0.078
3500	3.5	0.646	9000	9	0.103
4000	4	0.533	9500	9.5	0.127
4500	4.5	0.396	10000	10	0.154
5000	5	0.278			

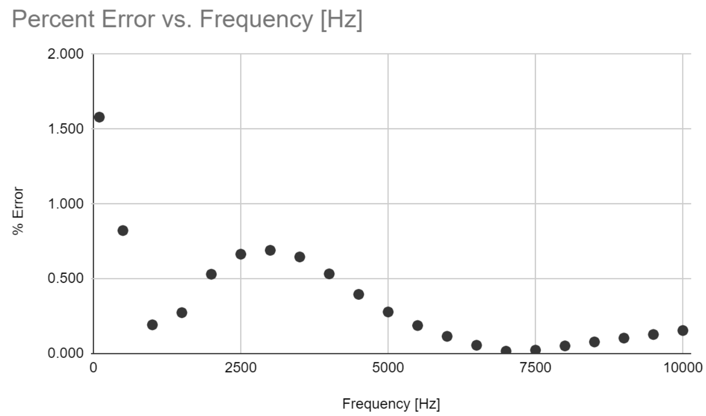

Figure 11. Graph displaying the percent error at different frequencies

Compared to the theoretical values, our results proved to be precise with 1.58% error at 100 [Hz] and less than 1% error for the rest of the values tested.

DISCUSSION

The design of the frequency to voltage converter had numerous issues that needed either a redesign or different component with specifications that meet our requirements. The earliest issue in converter design was the way the voltage was converted to represent the input frequency. The early designs were versions of a peak detector that held max voltages of an AC input. With further inspection, this configuration was not as useful as intended. From there, the transistor charge pump was the solution we needed to get the correct output and ultimately achieve the whole idea of the project. For the charge pump to work, it required a square wave input.

The next step was to design a way to take in any waveform input and somehow turn the signal into a uniform square wave with the same frequency as the original signal. The solution used in our circuit was the schmitt trigger. This subcircuit will always output a square wave from the positive saturation voltage to negative saturation voltage. Although, there were more problems encountered from there. The slew rate of the UA741CP Operational Amplifiers, some hysteresis issues and inconsistent saturation voltages. The slew rate of operation amplifier affected our circuit because the output voltage could not jump from negative saturation to positive saturation as fast as it needed to. This created a trapezoidal waveform which made the rest of the circuit unpredictable because the rising and falling edges were not infinitesimal. The operational amplifier supplied was not able to handle this jump in voltage, therefore a new operational amplifier was found that had a better slew rate. The hysteresis in the schmitt trigger is significant due to the idea that it controls when the trigger reaches its maximums and minimums. The design required a way to detect when the input signal gets to zero. The design went through a few iterations to get an accurate detection to help create the most accurate output.

The last issue encountered was the inconsistency of the operational amplifiers with their saturation voltages. The testing of these circuits found that the saturation voltage changed enough to affect the transistor charge pump. The solution found for this was including a zener diode at the output of the schmitt trigger, so that circuit is clipped at 5 [V] before the charge pump with a minimum voltage of a small negative voltage due to the forward bias of the zener diode. With the zener clipping, the schmitt trigger stayed consistent through any other change in the rest of the circuit and provided a steady output that was required. Lastly, an issue was discovered with the amount of current being drawn from the operational amplifiers. Testing showed small resistances as seen by the output of the operational amplifiers did not limit the current flowing in and as a result limited the output voltage to a fraction of the ideal voltage. Adding higher resistances fixed this problem and allowed for the circuit to work as intended.

SUMMARY AND CONCLUSION

The final objective of our device was to assemble a circuit design that would output a voltage linearly proportional to the frequency of an input signal. We encountered several obstacles in our design approach, leading to the re-evaluation of our methods and the direction of our developing design. We finally were able to converge the core of the design around the strategy of using a transistor charge pump to transition the frequency of the signal to the desired voltage correspondence. We were able to consolidate our circuit around the transistor charge pump's required specifications, resulting in a design that showed enough promise for us to pursue. We proceeded with our design approach by calculating theoretical results, performing simulations, and conducting experimental procedures on constructed models; honing our device's performance through adjustments to individual modules within the schematic. Finally, we attained a finished product consisting of the transistor charge pump module, along with input conditioning modules and output buffer and comparator modules. Our final results project accuracy more than sufficient to validate our design process and device development. We conclude, therefore, that the compilation of the described modules can successfully implement a signal frequency meter and comparator with a percent error less than 2%, given the range of 100 [Hz] to 10 [KHz].

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APPENDIX

Final schematic: