Design, Simulation, and Implementation of a Low-Distortion, Adjustable Sine Wave Oscillator at 10kHz

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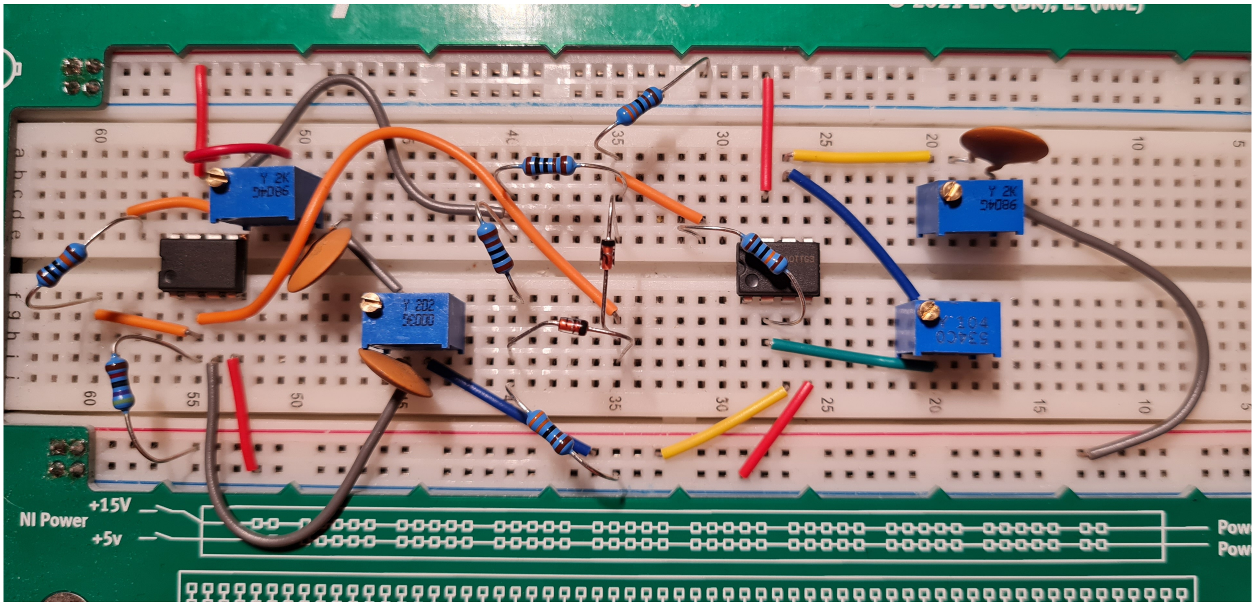


Date: January 26, 2024

Categories of evaluation	Grades
Student specialization (based on Bloom's taxonomy): knowledge → comprehension → application → analysis → synthesis → judgment	
Achieved results: working circuit → full functionality in all modes → good performance → excellent performance with innovations	
Documentation and formalization: Requirements met → Full coverage of the results → Strong argumentation → Easily readable → Pleasant and coherent story → Original style	
Final grade	

*All sub-grades should be above 5, then the final grade can be calculated as an average

Contents

1 Abstract

This report details the comprehensive process in creating a highly accurate and tunable 10kHz sine wave oscillator. The development of the oscillator is the heart of this project that should deliver a sine wave with minimum distortion as possible and adjustable output amplitude from 0 to 5Vpp. The entire process from conceptualization till realization is a complicated balance of contribution between theoretical calculations, advanced digital simulations, physical assembly on actual breadboard. In one of the innovative approaches further incorporated in the report to enhance sine-wave purity, there has been a combination of circuit design techniques with precision component selection. This ensures that robust performance from the oscillator unfolds closely along the line shown by theoretical models. The project is one example of integration of basic principles of electronics with modern, simulation tools for garnering a design of oscillator distinguished through accuracy, adjustability and clarity of signal.

2 Introduction

This report shall explain the engineering process behind developing a 10kHz sine wave oscillator with its amplitude adjustable from 0-5Vpp using simple components available, producing minimum harmonic distortion. The philosophy of this project is to design an oscillator while balancing some between performance, simplicity, and precision, keeping in mind frequency and amplitude parameters specified independently.

Just like a theoretical analysis, the approach goes beyond to its practical implementation. The first thing to do is evaluate oscillator architectures based on frequency stability, waveform purity, and design complexity. Then the selected architecture is subjected to analytical calculations to acquire component values as well as the expected performance. In this regard, simulations' distortion analysis was conducted in a bid to validate the design with respect to frequency accuracy. Finally, a breadboard prototype of the oscillator was implemented in order to ensure that it emulated the designed specifications. Iterative testing and adjustments were done with comparisons of real-world performance to the theoretical predictions. The report explains each development phase doing so by taking consideration of the design.

3 Literature Review

3.1 Lecture Notes and Slides

The design approach for this project is mainly based on the knowledge found in lecture notes and slides. Specifically pertaining to RC oscillators. This presented a theoretical background necessary for mastering the design principles for oscillators and encompassed all the necessary calculation to come up with standard oscillator configurations.

3.2 Online Resources

So much more information invaluable as compliments to the readings on the text book were gathered from the page on electronic oscillators in Wikipedia (`https://en.wikipedia.org/wiki/Electronic_oscillator`). This resource acted as a manual for several types of oscillators with further detailed walk-throughs, namely the Wien-bridge, phase-shift, and crystal oscillators. Individual specifications were in greater detail for each type of oscillator in identifying suitability to meet requirements of this project. This was important towards understanding stability trade-offs of oscillators, precision of frequency, and purity of waveform. Information obtained from this online resource was relevant in the designing of the oscillator especially with the choosing of the most appropriate type that will give an output of 10kHz with little distortion and that has adjustable amplitude.

4 Comparison of Alternatives

Throughout this project, there were several alternatives in choosing the type of oscillator, thus the need for evaluating based on complexity of operation, frequency control accuracy, and amplitude control accuracy. The major three types include:

4.1 RC Phase Shift Oscillator

The RC phase shift oscillator was considered for the simple fact that its design is simple and the frequency can be easily adjusted. However, determination of the frequency is made by several RC stages thus increasing solely component count but complexity of the design as well. In addition, the amplitude control in such an oscillator is not direct and for this reason may be inappropriate for applications that require precise adjustment of amplitude.

4.2 LC Oscillator

Further evaluation also focused on LC oscillators whose frequency stability characteristics and high Q-factor are well known. However, the dependence of the frequency tuning in LC oscillators on, both inductance and capacitance values can be a limiting factor if one specifically aims at 10kHz. Additionally, it has not been precise either to a greater extent with amplitude control in the LC oscillators hence cannot meet the requirement for amplitude adjustability of the project.

4.3 Wien Bridge Oscillator

From the evaluation of all the above options, what would stand out is Wien bridge oscillator. Such an oscillator serves as a compromise between simplicity and performance, especially to produce stable and clean sine wave with the required frequency of 10kHz. The Wien bridge oscillator has a good amplitude control mechanism and these make it suitable in meeting the objectives of the project effectively with minimal distortion and adjustable amplitude.

Referring to these considerations, a decision on going forth with the Wien bridge oscillator was called for considering that its main requirements of the project included a precise frequency, pure waveform, and adjustable amplitude feature among others.

5 Proposed Architecture

The sine wave oscillator in this project would be designed using a precision Wien bridge configuration. This architecture has been adopted given its tested efficiency in generating stable and pure sine wave at the required 10kHz. In the wien bridge configuration, an operational amplifier Op-Amp is combined with a pair of resistors and capacitors playing as a frequency-selective network. The latter one gives high accuracy to the working frequency of the oscillator.

In order to maintain a relatively steady amplitude without overloading the amplifier on signal peaks, the design consists of a non-linear feedback technique. This is done by having two diodes that are connected before the voltage dividers. These diodes limit the output voltage to 5Vpp and as such provide amplitude stabilization, which will keep the voltage signal within the mentioned range of 0 to 5Vpp.

Further in the chain, a low-pass filter is attached to this architecture, requiring the cutting of frequencies above 10kHz. This filter reduces harmonic distortion. An extra variable resistor is included in the feedback loop of the second Op-Amp for fine-tuning of the required output amplitude which is needed because of the adjustability required.

A possible limitation in this design is available in the harmonic suppression capability. The current filter configuration delivers a harmonic attenuation level at about 50dB (HD2 - 2nd order harmonic distortion). That height is sufficient for many applications but stages of additional filtering might need for more stringent requirements. In addition, the current design lacks a dedicated buffer stage that would interface with the oscillator's output. Lack of an output buffer stage could expose the performance of the oscillator to variation due to fluctuations of the external load, which can be considered in the subsequent design review.

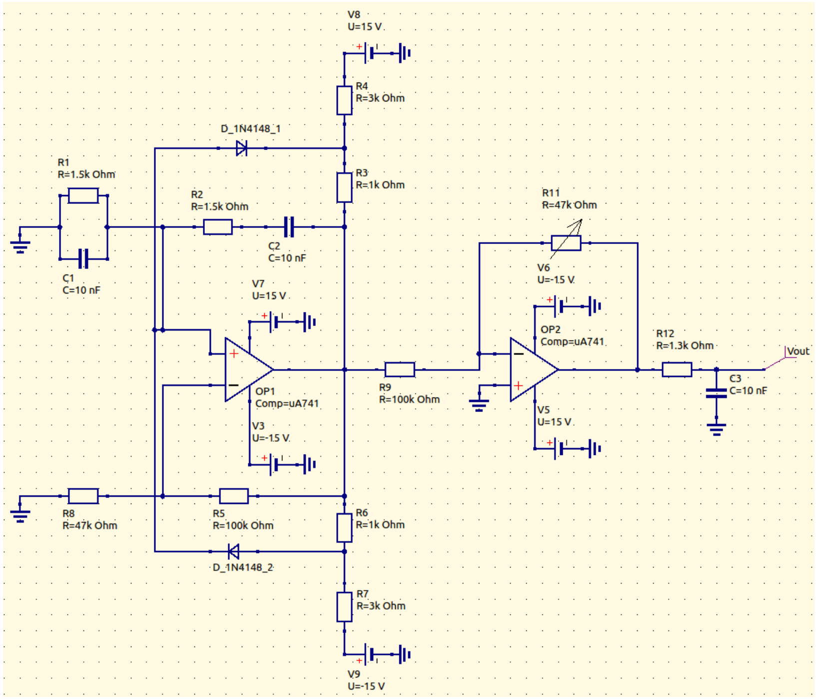


Figure 1: Wien Bridge Oscillator Schematic

5.1 Background Theory

The conceptual foundation of this oscillator project is anchored in oscillator dynamics and operational amplifier (Op-Amp) functionality. The Wien bridge oscillator structure is employed, utilizing a resistor-capacitor (RC) network for frequency determination. This network, combined with an Op-Amp, forms a feedback loop essential for sustained oscillations. The frequency of oscillation is predominantly defined by the RC components. Given the target of 10kHz for the oscillator, component values are calculated to meet this frequency precisely.

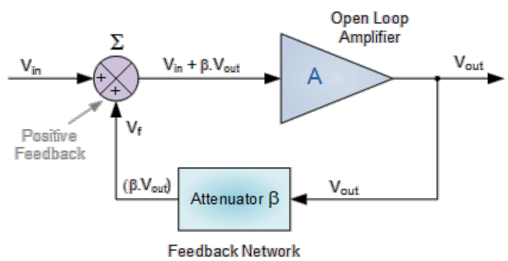


Figure 2: Oscillator Feedback Loop

From the first principles the harmonic oscillator is like the Figure 2 feedback loop where part of the circuit is an amplifier and the other is the attenuator. That is why the primary considerations when building the schematic was to build part of the circuit to handle amplification through an op-amp and the other to be frequency dependent and therefor be an attenuator.

5.2 Analysis

In-depth analysis involves examining the interplay between the frequency-selective network, the amplifier, and the harmonic suppression mechanisms.

5.2.1 Frequency-Selective Network

The network comprises two resistors and two capacitors, forming the crux of the oscillator's frequency determination. Given capacitors of 10nF, the resistors are calculated to be approximately 1.5 kΩ to achieve the 10kHz target frequency. The resonant frequency being:

$$f = \frac{1}{2\pi RC} \tag{1}$$

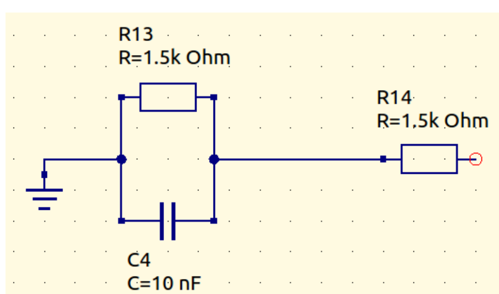


Figure 3: Frequency Affected Component

5.2.2 Amplifier with Gain Control

The uA741 op-amp forms the core of the amplifier module, with a gain setting slightly above 3 to ensure stable oscillations. Resistor values are set with R13 at 100kΩ and R15 at 47kΩ to achieve this gain.

The voltage gain A_v of the Wien bridge amplifier is given by:

$$A_v = 1 + \frac{R13}{R15} \tag{2}$$

To ensure that the gain is at least three, the following inequality must be satisfied:

$$1 + \frac{R13}{R15} \geq 3 \tag{3}$$

Rewriting the above inequality to express $R15$ in terms of $R13$ yields:

$$R15 \leq \frac{R13}{2} \tag{4}$$

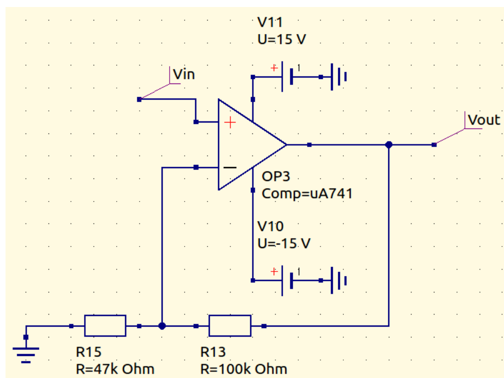


Figure 4: Amplifier Circuit Component

5.2.3 Harmonic Suppression

A low-pass filter, crucial for reducing harmonic distortion, uses a 10nF capacitor and a resistor of approximately 1.3kΩ, set to attenuate frequencies beyond the 10kHz cutoff while maintaining the integrity of the 10kHz sine wave.

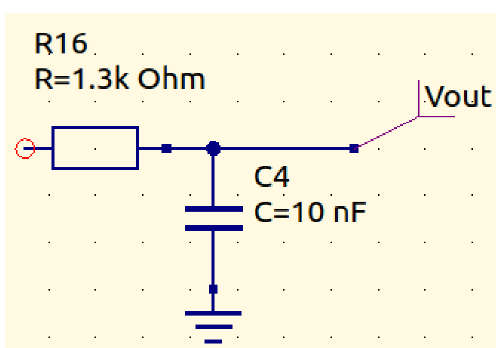


Figure 5: Low Pass Filter Component

5.3 Design

Design decisions focus on achieving precise frequency and amplitude control, with a keen consideration of component tolerances.

5.3.1 Amplitude Stabilization and Control

Diodes are employed in a voltage divider configuration for amplitude stabilization, ensuring the output remains within the 0 to 5Vpp range. Resistors R13 and R17 are set to 3kΩ, while R16 and R14 are set to 1kΩ. This setup also incorporates anti-clipping diodes around the op-amp to maintain smooth signal peaks and prevent distortion at higher amplitudes.

$$V_{\text{positive limit}} = V_{\text{diode}} \times \left(1 + \frac{R1}{R2}\right) \tag{5}$$

For the negative limit:

$$V_{\text{negative limit}} = -V_{\text{diode}} \times \left(1 + \frac{R1}{R2}\right) \tag{6}$$

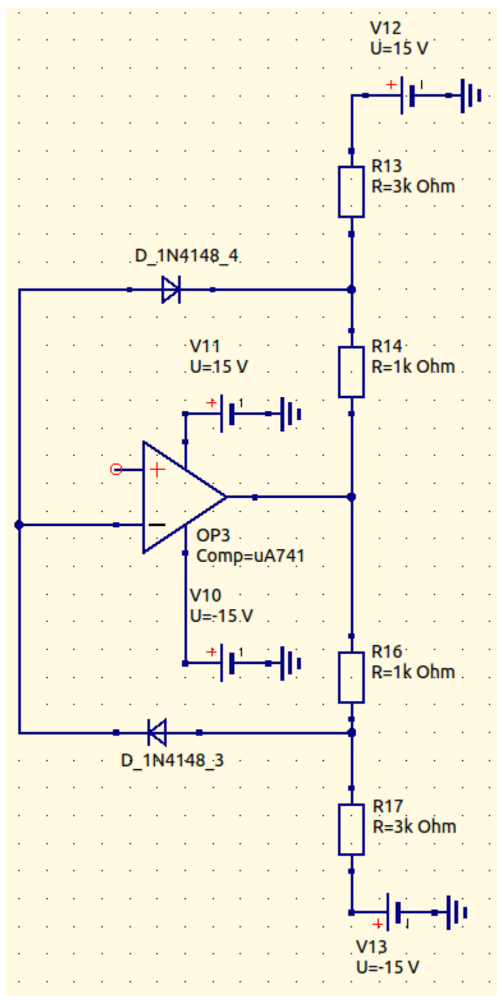


Figure 6: Anti Clipping Diodes Component

5.3.2 Adjustable Amplitude Circuit

An additional inverting op-amp is used for fine-tuning the amplitude, with resistor values R18 and R19 to be determined to be (100kΩ and around 47kΩ (for 5Vpp Amplitude) respectively) based on the initial output, allowing for adjustments from 0 to 5V.

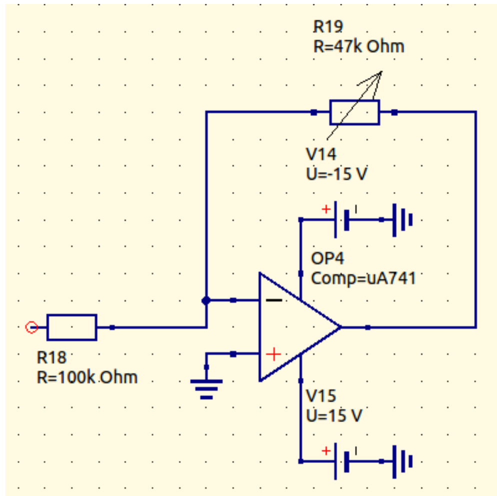


Figure 7: Amplitude Control Component

5.4 Simulations

Finally, the simulation of the oscillator circuit was made using Qucs Spice to check the theoretical analysis and tune the design parameters.

5.4.1 Frequency Determination in Wien Bridge

The first part of this involved making the Wien bridge equivalent segment. With an unexpected deviation in frequency, the use of a different value for the resistors would have to be employed. Check showed that with a resistor's value of 1.5kΩ a 10kHz frequency is achieved by way of deviation from the initial theory.

5.4.2 Adjusting Output Amplitude

Following the frequency calibration, it was time to consider amplitude control. The simulations from the software indicated a gain adjustment because calculations showed that the Wien bridge's output amplitude was about 20V, which needed scaling down to a maximum of 5V. Since there is a voltage drop across the final filter, the gain was adjusted to about 0.36 by using a potentiometer and resistance of 100kΩ.

5.4.3 Signal Shape Optimization

Further simulations reveled the discontinuity of the waveform shape by taking a form of a triangular wave instead of a sine wave. A solution to this problem was by adding in the anti-clipping circuit, which consequently not only improved the waveform to its stable form but also crisp up the sinusoidal characteristics.

5.4.4 Harmonic Analysis

A full simulation across the harmonic content revealed no significant harmonics in a signal. However, that marked for further investigation during physical testing on the breadboard.

6 Implementation

6.1 Realized Circuit

Procedurally, the actual construction of the oscillator circuit was done on a breadboard in a very systematic way that is whereby each sub-circuit built and tested incrementally step by step. This step-by-step incremental approach allowed to detect and remove those faults at an earlier stage before moving to the next ones.

First, a core Wien bridge oscillator was designed, followed by elements of amplitude regulation built into the design. Then a lot of attention to layout and wiring in order to reduce noise and interference. An anti-clipping circuit to remove distortion while still maintaining waveform integrity and stability was also designed.

There were many changes in the layout of circuit during the final assembling stages. Many components were moved, wires shortened or lengthened to better compactness and reliability of the whole circuit. The result was good as compared to the prototype but there are areas for further improvements in future layout.

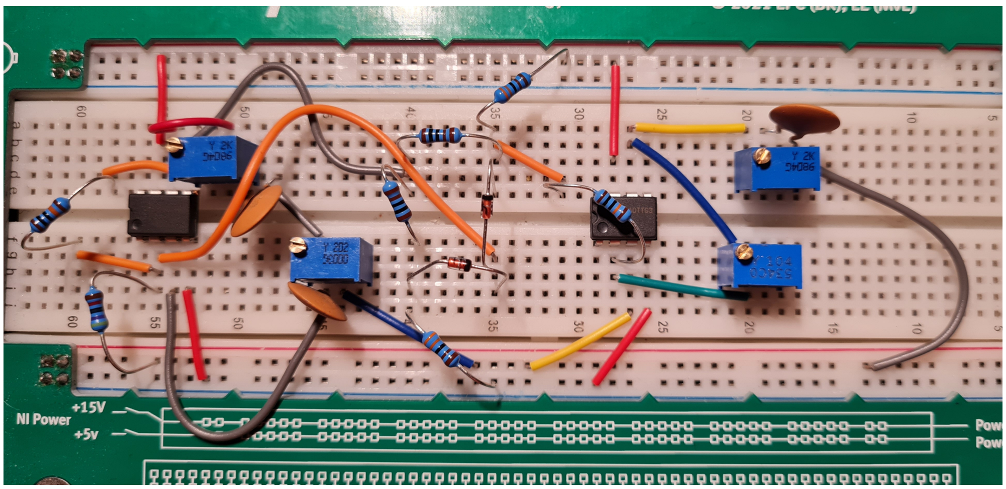


Figure 8: Final Circuit

6.2 Measurement Results

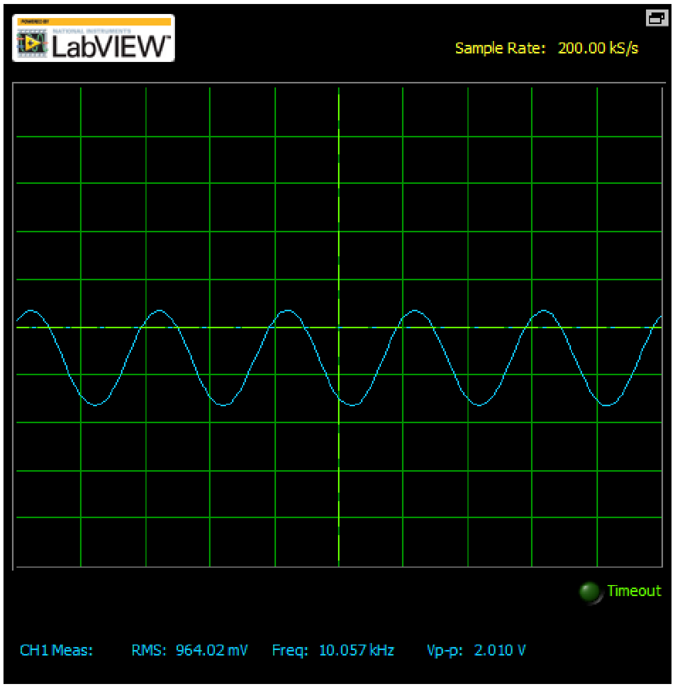
6.2.1 Output Signal Analysis

The oscilloscope was used to analyze the time-manner domain and frequency-domain responses of the oscillator output signal. In checking quality of waveform and accuracy of the frequency, this analysis procedure is important.

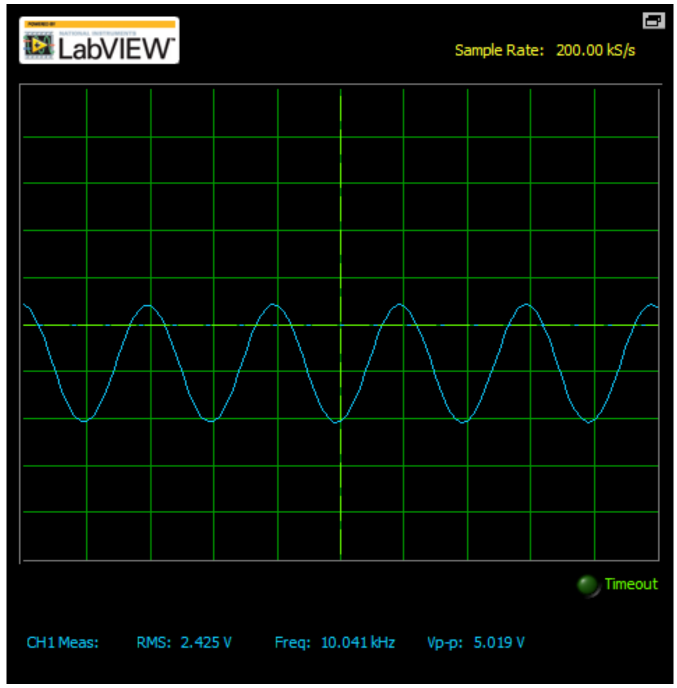
A time-domain observation sparing minimal distortion of the sinusoidal wave. The frequency analysis's main frequency peak was at 10.093kHz, closest to the target of 10kHz. An amplitude reading for the maximum gain was recorded as 5.02Vpp. These readings depicted the intended precision of the oscillator to generate frequencies and control their amplitudes.

6.2.2 Amplitude Variability Impact

Amplitude changes are performed on the amplitude control circuit using the potentiometer. The frequency did not change and remained as 10kHz. Variations in waveform shape when the amplitude was set to different values were noted, but it only amounted to a very small value indicating that such harmonics were almost minimal.



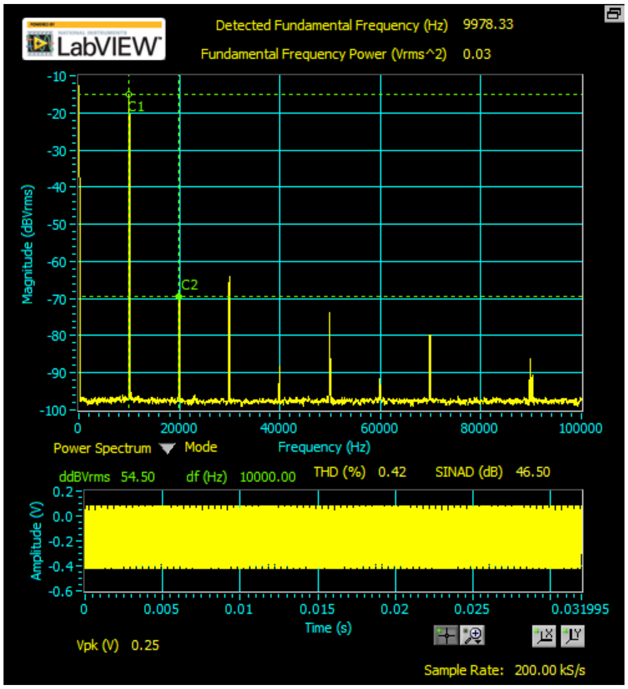
(a) Amplitude Analysis 2Vpp



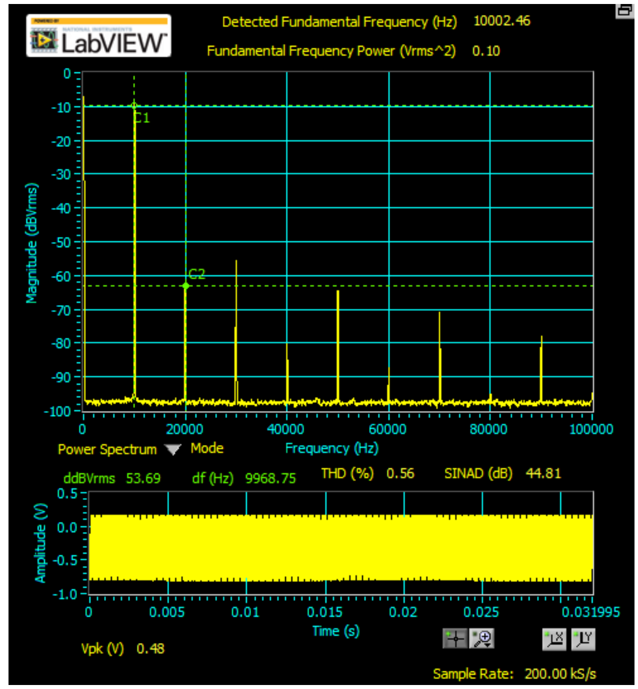
(b) Amplitude Analysis 5Vpp

6.2.3 Harmonic Distortion Analysis

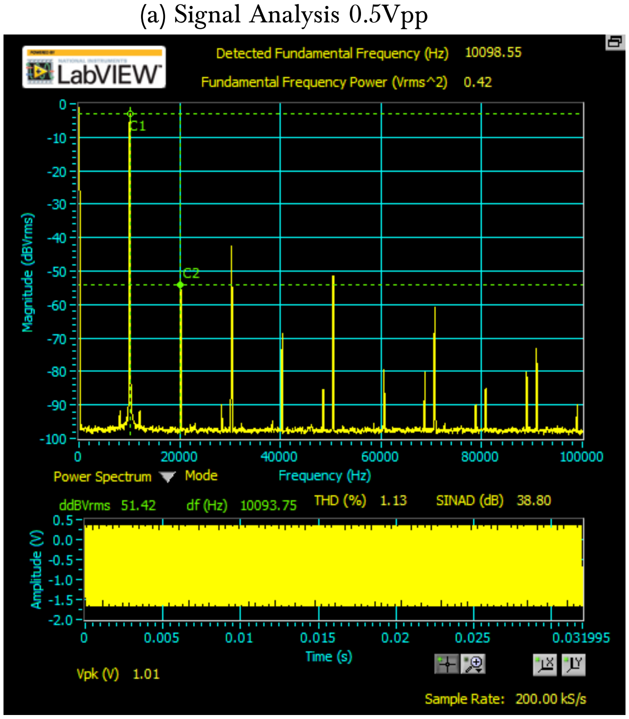
At a 5Vpp output, the frequency spectrum analysis exhibited the next harmonic peak at 51.65dB (HD2 - 2nd ordering harmonic distortion) weaker than the 10kHz primary tone hence showing good harmonics suppressions. Additional minor peaks around 10kHz, however, were ascribed to component inconsistencies in the frequency-selective network.



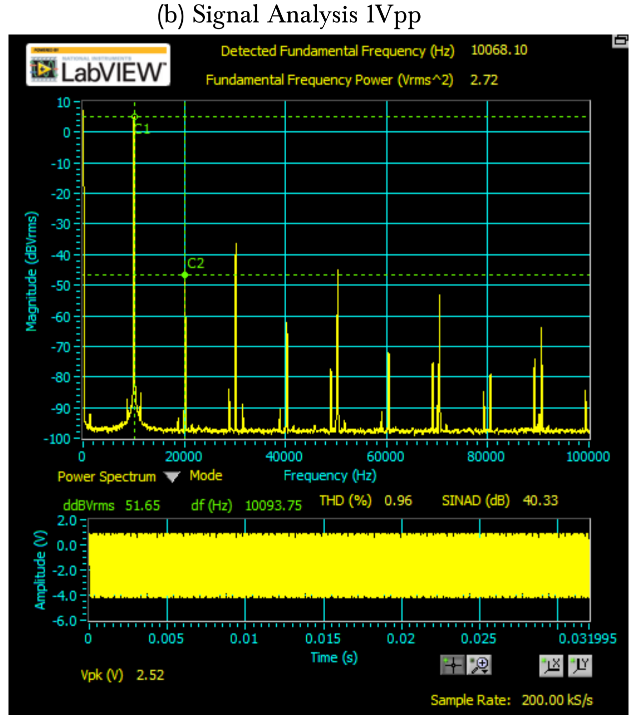
(a) Signal Analysis 0.5Vpp



(b) Signal Analysis 1Vpp



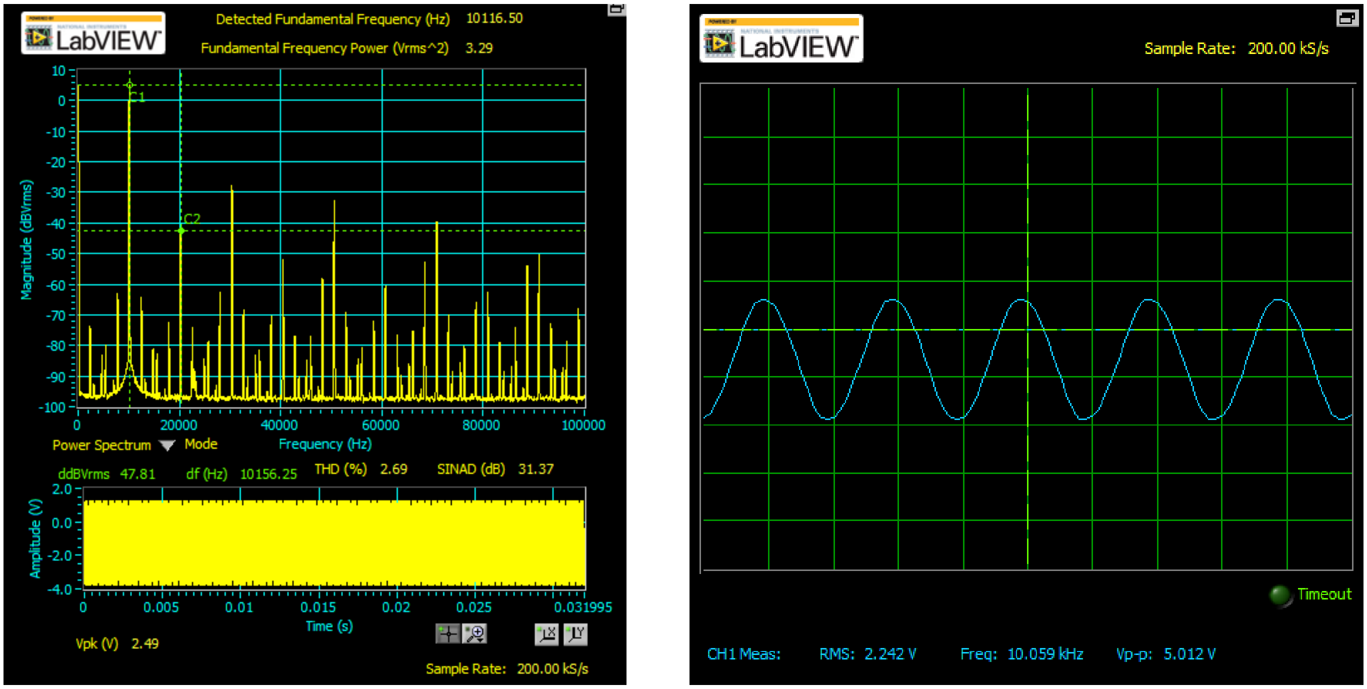
(c) Signal Analysis 2Vpp



(d) Signal Analysis 5Vpp

6.2.4 Efficacy of the Final Filter

This observation, made more obvious by comparing the outputs pre and post-filtering, is further emphasis of the importance of the final low-pass filter. Over-looking it allowed the signal to be displayed with some non-sinusoidal characteristics. A corresponding frequency spectrum analysis showed slightly closer harmonic peaks, meaning that interference would be more pronounced.



(a) Signal Analysis With No Filter

(b) Amplitude Analysis With No Filter

7 Reflections

7.1 Concepts vs Simulations

The major challenge noted is the variance in resistor values from the theoretical design and design through simulation of the circuit. Exact cause still is due to multiple stages of attenuation where resistance plays a major role but is a pointer to a flexible design in view of such variances, and requires a good amount of trial and error.

7.2 Simulations vs Measurements

Such a kind of harmonic distortion did not show in the conducted simulations but was recorded in real-world testing. Here, therefore, a glaring difference is shown where simulations cannot readily capture all that occurs in the real world. On-site changes were thus required to address these harmonics, further justifying the need for thorough trial and error tests to back simulations.

7.3 What is limiting the performance of your oscillator project? Why can you not solve the final bottlenecks?

The tolerance levels of the used components are the main constraint affecting the performance of the oscillator. Unavoidable deviations from the calculated values due to these tolerances introduce a fundamental limitation, which is not easily circumvented with the present component selection.

7.4 Can you improve further your design given more time?

Two main enhancements could be pursued. First and most priority would be to add a buffer before the final output. This buffer will allow protecting the filter's performance from getting compromised by external loads. Secondly, further stages of filtering may be employed to better harmonic suppression from the current 51dB (HD2 - 2nd ordering harmonic distortion) attenuation being achieved, to some target far closer to 100dB and hence very much purify the sine wave output.

8 Conclusions

The design and development of a 10kHz Wien bridge oscillator through this project has been an interesting effort from which several key inputs have been concluded. Foremost among these is the realization that the Wien bridge architecture is highly effective for generating sinusoidal waves at this frequency when adequately controlled and supplemented with the right components. Challenges faced, and overcome in this project underscore critical importance of precision both in design and practical implementation.

Secondly, the project has outlined that differences between theoretical designs, simulations, and reality will always exist. These differences particularly through component tolerances and harmonic distortion re-emphasize test rigor and flexibility in electronic design.

Finally, the computation in the project went advanced my technical skills. This will involve attaining an in-depth understanding of all the mechanics involved in coming up with electronic circuits conceptualization from idea to actualization. This experience sets a basis for future undertakings, especially in the improvement of the designing process and raising practicality when it comes to troubleshooting in electronics.