# FLASHE PROJECT 2019

## Successive Approximation ADC

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## Introduction

The project outlined in this report involves the construction of a Successive Approximation Analogue to Digital Converter. The circuit takes in an analogue voltage value from an on-board accelerometer and outputs a digital PWM signal, via an embedded Arduino board. The report will describe the functions of the different sections of the converter, the process of building each section and its implementation, and details of how the circuit how tested. Finally, there will be a discussion of the project and what was learned.


## Acknowledgements

With thanks to Fergal Brennan and Martin Fogarty.


## Project planning

| Week | Description | Date |
|---|---|---|
| 1 | Introduction to the Project, Project Plan, Create BOM, Start Power supply | 29-Jan-19 |
| 2 | Complete and test Power Supply. Build and test relaxation oscillator | 04-Feb-19 |
| 3 | Start 8 bit counter | 11-Feb-19 |
| 4 | Complete and test 8 bit counter and start R2R ladder / Ramp generator | 18-Feb-19 |
| 5 | Complete build of R2R ladder, test and verify its operation | 25-Feb-19 |
| 6 | Build comparator circuits and test x, y and z PWM outputs are working | 04-Mar-19 |
| 7 | Build connection to embedded board, pinout and cable. Test connection | 11-Mar-19 |
| 8 | Develop program structure | 18-Mar-19 |
| 9 | Complete outstanding Hardware and establish software control of LED’s | 25-Mar-19 |
| 10 | Detect and measure the PWM signal parameters in code. | 01-Apr-19 |
| 11 | Refining the code; User control of system from command line | 08-Apr-19 |
| 12 | Refining the project; Evaluate SA-ADC performance and write specifications | 15-Apr-19 |

# Overview of the Circuits

## Voltage Regulator

The first section of the ADC consists of a voltage regulator circuit. A voltage regulator is necessary as it important to have a steady, regular power supply to power the rest of the board. This may not be possible from a bench PSU as they may be prone to excessive AC ripple. AC Ripple is the slight variation in a DC signal caused by inadequate conversion of the AC source voltage to DC [1]

The primary component in this section is an **LM7805CT**, a linear voltage regulator with fixed voltage output of 5V [2]. The **LM7805CT** is particularly efficient for this purpose as it can dissipate a lot of heat [3]. The regulator functions by essentially comparing the output voltage to a reference voltage and adjusting based on error until the required output voltage is met [4].

Decoupling capacitors are used to filter the input signal from the PSU to the regulator, and are also used on the IC's output to filter and smooth the output signal. In the context of the full circuit, AC Ripple may potentially become a problem, as it may interfere with the very small reference voltage values output by the ramp generator and the values output by the accelerometer. Therefore it is important to filter the signals in order to reduce AC Ripple as much as possible.

A load resistor is connected to the output of the **LM7805CT** as is an LED, for testing purposes. A rectifier diode is placed on the IC input, to further reduce AC Ripple.

## Relaxation Oscillator

The next section of the ADC consists of a relaxation oscillator. The function of this relaxation oscillator is to act as a clock. The frequency of this clock will determine the eventual Pulse Width Modulation frequency of the output of the comparator..

The primary component at this stage is an **LM74AC**, a Hex Inverter with Schmitt Trigger Input. The **LM74AC** chip contains six inverter gates with Schmitt Trigger inputs [5], two of which are used in this circuit.

The first gate functions essentially as a comparator, comparing the input to the gate with negative and positive threshold voltages. According to the datasheet, the negative threshold for a 5V input is 1V, and the positive 3.55V. A capacitor is placed on the inverting input of the gate, and it is the rate of discharge/discharge of this oscillator that determines the frequency of the output of the oscillator. When the gate is powered, there will be 5V on its output which will then be fed back to the inverting input, causing the capacitor to begin charging. When the capacitor reaches 3.55V, it will then be greater than the positive threshold voltage, and so the output will switch to 0V. At that point the capacitor will begin discharging. When it discharges to the point where it is less than the negative threshold voltage, then the output will switch to 5V. In this way, a 5V square wave is generated. Schmitt Trigger inputs implement hysteresis in the form of the thresholded range of voltages described above (1V – 3.55V). This is used in order to avoid rapid fluctuations between 0V and 5V.

## Counter

In this stage of the ADC, a counter is used to create an 8-bit count from 0 to 255, which will be used to generate a ramp output from the next stage of the circuit. The main component in this section is an **SN74HC590**, an 8-bit digital counter. The clock input to this binary counter comes from the relaxation oscillator built in the previous section. The output of the oscillator was found to be 188.7kHZ, and so this will be twice the frequency of the Least Significant Bit (LSB) of the counter output. If we count the LSB as the "1st" bit and the MSB as the "8th", then the nth bit will be have a frequency that is $2^n$ divisions of the LSB frequency, i.e.:

$$nth\ bit\ frequency = \frac{188{,}700}{2^n}$$

According to the **SN74HC590** datasheet [6], the IC contains both a counter and a storage register, with a separate clock input for each of these. The counter clock is positive-edge triggered, meaning that when the oscillator transitions from low to high, the counter will increment. The clock may be reset through the !CCLR clock clear pin, or enabled through the !CCKEN clock enable pin. An RCO (Ripple Carry Output) pin may be used if multiple counters were to be chained together.

## Ramp Generator

The next section of the circuit consisted of an R2R Resistor Ladder. An R2R Ladder is essentially a series of voltage dividers that output a ramp voltage. This ramp voltage will function as a reference voltage to which the eventual output of the accelerometer will be compared.

The input to the R2R ladder is the 8-bit output of the counter. This consists of 8 separate square wave signals, each half the frequency of the next. Given that these are binary signals, the R2R ladder can be thought of as functioning as a local digital-to-analogue converter [7], within the global analogue-to-digital circuit.

Each bit contributes a proportional amount of voltage to the total summed voltage at the output of the R2R ladder, resulting in a 5V sawtooth wave.

## Comparator

At the next stage of the circuit, an **ADXL335** 3-axis accelerometer will be added to the board. The accelerometer will output voltage values relative to its rate of acceleration in the x-, y-, and z-axes. These voltage values will be compared to the ramp output of the R2R ladder, using an **LM339** chip, which contains four comparators [8]. For each axis signal comparison, a Pulse Width Modulated square wave will be output, whose duty cycle ratio corresponds to the acceleration in that axis.

In this way, the analogue voltage output of the accelerometer is converted to digital values that may be interpreted by an Embedded System.

## Embedded Interface

At this stage of the circuit, pin headers are soldered to the board so that an **ADXL335** 3-axis accelerometer and an **Arduino Uno SMD** may be added. The accelerometer outputs analogue voltage values relative to its rate of acceleration in the x-, y-, and z-axes. The values are then routed to the comparator, which compares them to the analogue reference ramp voltage and outputs three digital Pulse-Width Modulated signals. The PWM signals can be interpreted as the positions of the accelerometer in the X, Y, and Z planes, or as g-force values between -3g and 3g. The values are routed to the Arduino. A programme is embedded onto the Arduino which can interpret the incoming PWM signals and display these in the serial monitor.

## Coding

There are three values from the accelerometer that will need to be read and interpreted by the embedded Arduino programme. Therefore, there are three main functions within the code, each containing a switch statement for the individual axis readings. For example, when the 'x' key is pressed by the user, the variable pwm_x_measurement is set to 'THI', and a boolean flag named ok_to_measure_pwmx is asserted. This allows the function to measure the x-axis value from the accelerometer, MeasurePWMX, to be called, with pwm_x_measurement, set to 'THI', as an initial argument. The first case of the switch statement is implemented, which contains a call to the inbuilt Arduino function pulseIn() [9]. PulseIn() reads the PWM input from the given pin and returns its HIGH duration in microseconds, which is assigned to pwm_x_thi. The switch breaks and the flag, still asserted, is rechecked. MeasurePWMX is again called, and the next case of the switch statement implemented, with pwm_x_measurement set to 'TLO', and the LOW duration of the PWM signal is returned. In the next case, the low and high values are summed to give the period of the PWM signal. In the next case, the function CalculateVin is called, which divides the HIGH duration by the clock period. This gives the number of steps that the ramp has incremented while the comparator output is high. Multiplying this value by resolution of the ramp $\left(\frac{V_{cc}}{2^8}\right)$, gives the voltage value coming from the accelerometer. This value is them displayed on the serial monitor, as is the HIGH duration, LOW duration and the total PWM period.

Functions to calibrate the board and to convert voltage values to G forces, using points taken during calibration and determining the line equation for each axis, are added.

# Implementation of the Circuits

## Voltage Regulator

In this section of the circuit, a DC voltage is taken from a bench PSU (or battery). A ground rail is also established at this point. The input voltage is sent through first through a rectification diode, in order to alleviate AC Ripple. It is further smoothed using an input filter consisting of decoupling capacitors and finally routed through the input pin of the **LM7805CT** voltage regulator. According to the datasheet for the **LM7805CT**, the dropout voltage is 2.0V. This means that for an output of 5V, we can calculate the expected minimum required voltage from the PSU as:

$$V_{OUT} + V_{DROPOUT} = V_{IN(MIN)}$$

$$\therefore 5V + 2V = 7V$$

According to the datasheet, the maximum input voltage should be 35V. A voltage of 12V is used, giving ample headroom on either side. The datasheet states that the output voltage tolerance is +/- 4%, and therefore we can calculate the expected output voltage range as:

$$V_{OUT(RANGE)} = 5V \pm 4\%$$

$$\therefore V_{OUT(RANGE)} = 5V \pm 0.2V$$

$$\therefore 4.8V \leq V_{OUT} \geq 5.2V$$

The resulting 5V (+/- 4%) is routed through an output filter for smoothing and then sent through a diode and load resistor.

It is important to ensure that there are no short circuits in this section, as this may cause the **LM7805CT** to overheat due to too much current flowing through it. If the regulator overheats and enters thermal shutdown, its output voltage may drop below the required value [3].

## Relaxation Oscillator

In this second stage of the circuit, the voltage regulator output is routed to the input of a relaxation oscillator, built from an **LM74AC** IC described above. The output of this oscillator is a square wave, which has been generated via one of the inverter gates of the IC. A second inverter gate functions as a clock buffer to smooth the square wave and reduce noise.

The expected frequency output of the oscillator is a function of the time constant of the circuit and the various input and threshold voltage values [10]. Therefore, when calculating this value, the RC constant must first be determined. The resistance and capacitance of R and C were measured:

$$R_{measured} = 214.8\Omega$$

$$C_{measured} = 21.218nF$$

$$\therefore RC_{measured} = 214.8 \times (21.819 \times 10^{-9})$$

$$\therefore RC_{measured} = 4.6867 \times 10^{-6}$$

This may be compared to the labelled values of the components in order to illustrate the range of tolerance in component labelling:

$$R_{labelled} = 220\Omega$$

$$C_{labelled} = 22nF$$

$$\therefore RC_{expected} = 220 \times (22 \times 10^{-9})$$

$$\therefore RC_{expected} = 4.84 \times 10^{-6}$$

The deviation between the expected and the measured may then be calculated as a percentage:

$$Percentage\ error = \frac{|RC_{measured} - RC_{expected}|}{RC_{expected}} \times \frac{100}{1}$$

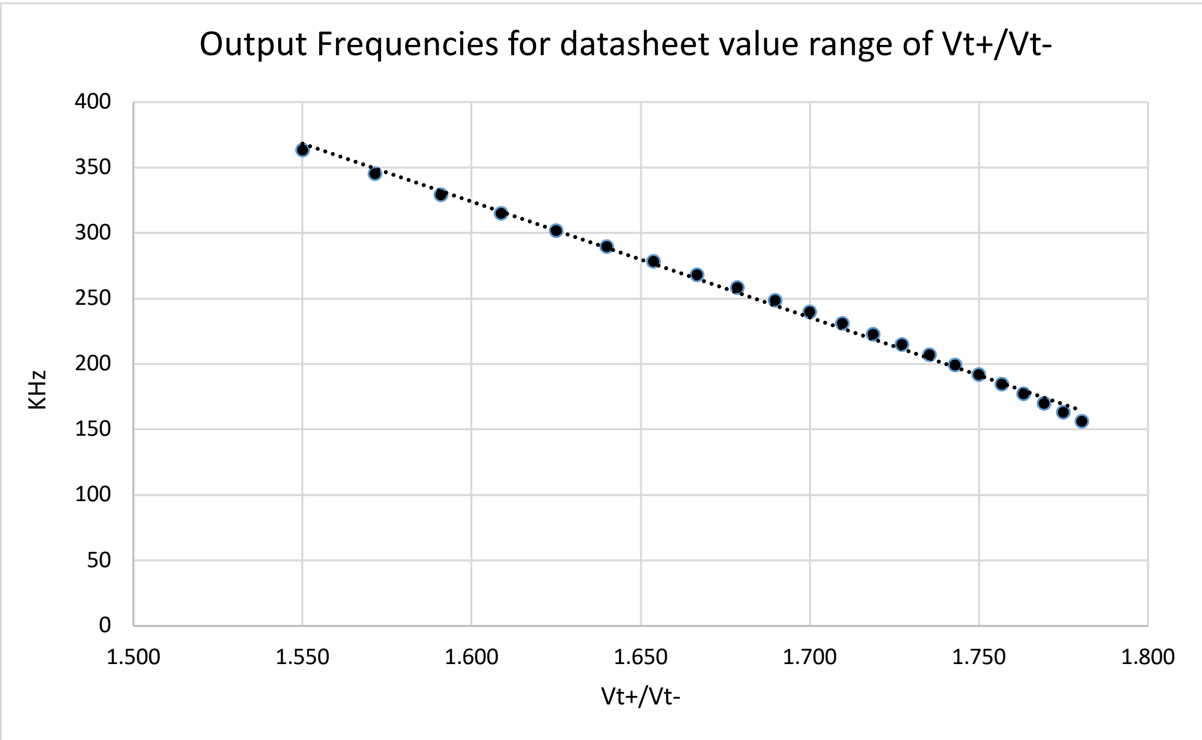
$$= \frac{1.522 \times 10^{-7}}{4.84 \times 10^{-7}} \times \frac{100}{1}$$

$$= 3.17\%$$

The overall output square wave frequency is determined by the following calculation:

$$f = \frac{1}{RC \ln\left(\frac{V_{CC} - V_{T-}}{V_{CC} - V_{T+}} \times \frac{V_{T+}}{V_{T-}}\right)}$$

RC was determined above to be $4.84 \times 10^{-6}$ and $V_{CC}$ determined to be 5.06V (see Testing and Results – Voltage Regulator). However, the $V_{T-}$ and $V_{T+}$ values were not so easily determined as they were found to be values within a given tolerance range, according to the datasheet. Therefore, the potential output frequency had to be calculated within that range, with RC and $V_{cc}$ as constants, and $V_{T-}$ and $V_{T+}$ as variables. The calculated values are listed below (the excel table for these values may be found in the appendix):




## Counter

At this stage of the circuit, the output of the relaxation oscillator is routed to the clock input pins (CCLK/Counter and RCLK/Registry) of the **SN74HC590**. The active low CCLR/Counter Clear pin is routed to the 5V line in order to prevent the counter being cleared to 0, and the active low OE/Output Enable and CCKEN/Count Enable pins are routed to ground to ensure that the count will continue.

The **SN74HC590** will output, from 8 separate pins, parallel binary values that will constitute an 8-bit count from 0 to 255:

| Decimal | Bit 7 (MSB) | Bit 6 | Bit 5 | Bit 4 | Bit 3 | Bit 2 | Bit 1 | Bit 0 (LSB) |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . | . |
| 254 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 255 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

*Table 1: 2^8 binary output values*

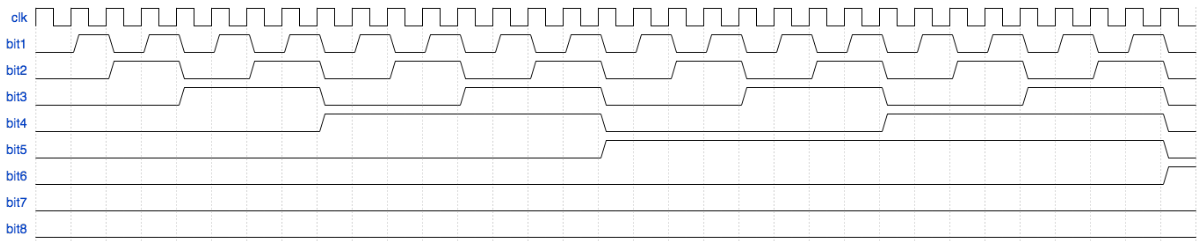



*Figure 1: Section of 8-bit counter timing diagram*

Each of these binary outputs will constitute an on/off voltage of 0V and 5V which will be fed into an R2R resistor ladder in the next stage of the circuit. The resistor ladder will take this square wave input and convert it into a ramp voltage.

## Ramp Generator

Each square wave signal from the counter, detailed in the previous section, is routed separately to the R2R ladder. The ladder is set up in such a way that each individual square wave meets a different level of impedance, which is inversely proportional to the associated bit's significance in the overall 8-bit byte [11]. For example, the Most Significant Bit meets the minimum level of resistance and the Least Significant Bit meets the maximum level. This means that each bit allows for a voltage output proportional to its significance, i.e. MSB allows for the maximum voltage, LSB allows for the minimum.

This proportional voltage output is achieved through the ladder sequence of voltage dividers, with values of 2R for R1 and 2R (through Thevenin equivalence [12]) for R2. Each bit is connected to a voltage divider and must travel through its connected voltage divider, plus all subsequent voltage dividers. Hence, each bit voltage is successively divided, relative to its significance. For example, the LSB must travel through eight voltage dividers, which reduces its voltage by $2^8$. The MSB must only travel through one voltage divider, reducing its voltage by $2^1$. If we count the LSB as the "$8^{th}$" bit and the MSB as the "$1^{st}$", then the nth bit will contribute voltage according to the following equation:

$$nth\ bit\ voltage\ output = \frac{V_{in}}{2^n}$$

| **Bit number** | **Expected voltage output (when high)** |
|---|---|
| 1 (MSB) | $\frac{5.06V}{2^1}$ = 2.53V |
| 2 | $\frac{5.06V}{2^2}$ = 1.265V |
| 3 | $\frac{5.06V}{2^3}$ = 0.633V |
| 4 | $\frac{5.06V}{2^4}$ = 0.316V |
| 5 | $\frac{5.06V}{2^5}$ = 0.158V |
| 6 | $\frac{5.06V}{2^6}$ = 0.079V |
| 7 | $\frac{5.06V}{2^7}$ = 0.040V |
| 8 (LSB) | $\frac{5.06V}{2^8}$ = 0.020V |
| *Total (max - 255)* | 5.04V |

*Table 2: Calculated voltage output values for individual bits*

The resulting voltages are summed, with the maximum value of the sum being the initial square wave peak voltage of 5V. As the binary counter increments, the summing voltages increase proportionally to the bits, resulting in a ramp voltage. Given that the minimum contribution to the ramp is the input voltage having travelled through eight successive voltage dividers, the resolution of the ramp is:

$$Resolution = \frac{V_{in}}{2^8}$$

$$Resolution = \frac{5.06V}{256}$$

$$Resolution = 19.77mV$$

The resolution of the ramp is extremely important, as this will be the minimum voltage that can be compared with the output of the accelerometer.

The construction of the circuit involved placing the resistors according to the network structure. The R resistor value in this case was 5k$\Omega$. Two 10k$\Omega$ resistors were used for the R value instead of a single 5k$\Omega$ resistor, as this increases tolerance from $\pm 5\%$ for a single resistor to $\pm 2.5\%$.

## Comparator

At this point, the ramp voltage is routed to three inverting inputs of the inverting **LM339** comparator. When the **ADXL335** 3-axis accelerometer is added to the board, then its 3-axis outputs will be routed to the non-inverting inputs of the **LM339**. However, during the implementation phase of this circuit, test voltages are taken from the bench PSU, in order that the functioning of the comparator may be easily tested using known values.

The comparator functions by comparing two input signals and outputting a binary "high" signal when the non-inverting input is greater than the inverting input. When the reverse is true, a binary "low" value is output. As the accelerometer voltage will be compared to a sawtooth wave, the output will be constantly low if the accelerometer output is low, constantly high if the accelerometer output is high, and a 50% duty cycle square wave if the accelerometer output is at its mid-point. Given a constant DC test voltage input from the PSU during testing, the output will be high for all points where the test voltage is higher than the ramp voltage, as seen below (adapted from [13]):

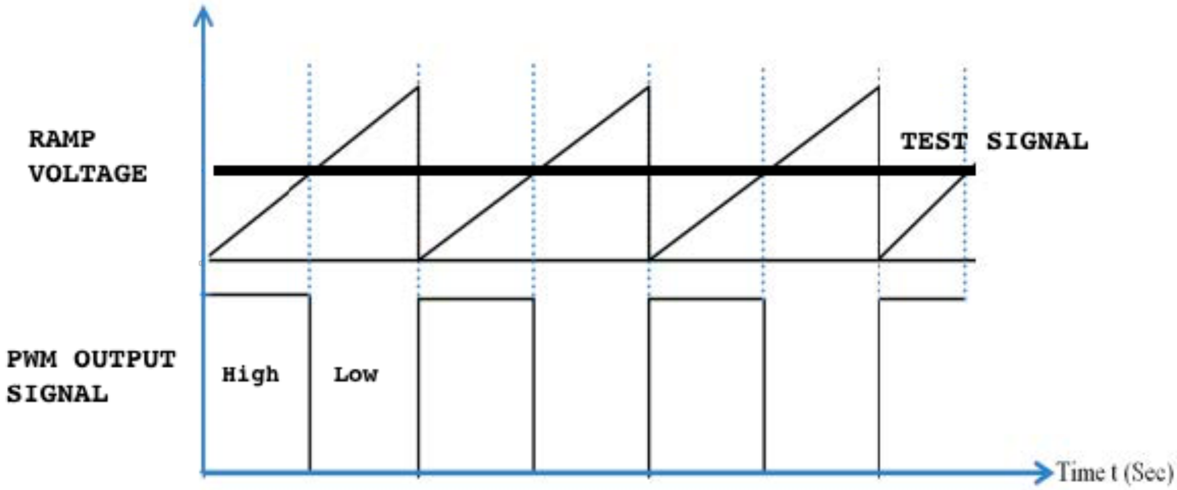



*Figure 2: PWM Output from Comparator*

One of the issues involved with Pulse Width Modulated signals is that of “cross-over”. This refers to the problem of measuring the maximum and minimum values of a PWM signal. If the test signal is at a maximum or minimum, then it will be fully higher or fully lower than the reference signal. If this occurs then there will be no differentiation between high and low in the output, and the output will cease to have a frequency component. This means that it will become a DC signal with a constant voltage of max or 0. Therefore it is important to find the minimum and maximum voltages at which a frequency exists. These will determine the specifications within which the device may operate.

The system transfer function must be determined at this point, in order to be able to understand exactly how the PWM output of the comparator relates to the actual voltages produced by the accelerometer. The values that will determine this transfer function are the ramp voltage (F_RAMP), frequency of the oscillator (F_CLK) and the supply voltage (VCC). Some of these values were measured/calculated at various other points:

$$F_{CLK} \;= \text{188.7kHz}$$

$$VCC \;= \text{5.06V}$$

The frequency of the square wave ramp may be calculated by dividing the clock frequency by the number of steps in the ramp, as each step in the square wave occurs at the pulsing of the clock:

$$F_{RAMP} = \frac{188.7kHz}{2^8}$$

$$F_{RAMP} = 737.1Hz$$

The period of the ramp (and thus the period of the PWM output) is the reciprocal of the frequency:

$$T_{RAMP} = \frac{1}{737.1Hz}$$

$$T_{RAMP} = 1.36ms$$

The resolution of the ramp has previously been calculated as 19.77mV. In order to calculate the duration that the PWM will be high or low given a test input signal, the number of steps required by the ramp to reach that test value must be calculate:

$$NUM\_STEPS = \frac{V_{TEST}}{Resolution}$$

As we cannot have a non-integer amount of steps, this number must be rounded, which introduces a rounding error. The rounding error may be found by subtracting the calculated value (step voltage * step number) from the actual test value.

The time taken for the ramp to reach the test voltage is equal to the ramp step time (clock period) multiplied by the amount of steps required. This time value represents the duration that the output PWM signal will be high:

$$T_{HIGH} = T_{CLK} \times NUM\_STEPS$$

The duration that the PWM signal will be low may be found by subtracting T_HIGH from the overall period of the ramp, T_RAMP:

$$T_{LOW} = T_{RAMP} - T_{HIGH}$$

Therefore, if T_CLK for this circuit is 5.3μs, and the resolution is 19.77mV, then the high PWM value for any test input may be found using:

$$T_{HIGH} = V_{TEST} \times \frac{T_{CLK}}{Resolution}$$

$$T_{HIGH} = V_{TEST} \times \ (2.68 \times 10^{-4})$$

## Embedded Interface

During the implementation of the embedded interface stage, some rerouting was required. At this point, the 5V signal from the voltage regulator was no longer required to pull up the outputs of the comparator, as 5V would now be taken from the Arduino. This required the removal of the link between the comparator output signals and the voltage regulator 5V line, since there would be no common reference if two different 5V supplies were used. Additionally, a link needed to be made to the 5V $V_{cc}$ input from the Arduino.

Two pin headers were required in order to allow for both a 3-axis accelerometer, the **ADXL335**, and an **Arduino Uno SMD** to be connected.

According to the datasheet for the **ADXL335** [14], the device operates by measuring the differential capacitance between a fixed plate and a plate attached to a mass, which moves when the device is moved. This differential represents the acceleration within a given axis, which may also be converted to a g-force value. The **ADXL335** contains an on-board regulator, which allows it to operate within a 3.3V range while taking in a 5V input [15]. It outputs ratiometric/proportional values, meaning that the range of output voltages is scaled along with the possible range of g-force values available.

On the circuit, the X, Y and Z acceleration outputs were routed from the pin header to which the **ADXL335** will be connected to the test voltage inputs of the comparator.

# Bill of Materials

| | Item | Manufacturer Part Number | Description | Package Type | Designator | Supplier | Product Code | Qty | Cost / Unit | Cost | Link |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BOARD | 1 | 1725698 | Wire-To-Board Terminal Block | 6-pin single row Through-hole | n/a | Farnell.com | 3041426 | 1 | €2.80 | €2.80 | https://bit.ly/31z4zGx |
| | 2 | 174889 | Stripboard - single-sided | n/a | n/a | Farnell.com | 174889 | 1 | €12.65 | €12.65 | https://bit.ly/2MRxHpj |
| POWER SUPPLY | 3 | MCGPR35V476M6.3X11 | Electrolytic Capacitor, 47 µF, 35 V, MCGPR Series, ± 20%, Radial Leaded, | Through-hole Radial | C4 | Farnell.com | 9451277 | 1 | €0.07 | €0.07 | https://bit.ly/2LiziUz |
| | 4 | MCF 0.25W 220R | Series, 250 mW, ± 5%, Axial Leaded, 250 V | Through-hole Axial | R1 + R2(x2) + R29-R31 | Farnell.com | 9339299 | 6 | €0.02 | €0.14 | https://bit.ly/2MLV838 |
| | 5 | MC7805CTG | Positive, 10V To 35V In, 5V And 1A Out, TO-220-3 | TO-220 | U1 | Farnell.com | 9666095 | 1 | €0.48 | €0.48 | https://bit.ly/2LIT1zt |
| | 6 | MCGPR16V227M6.3X11 | Electrolytic Capacitor, 220 µF, 16 V, MCGPR Series, ± 20%, Radial Leaded, | Through-hole Axial | C2 | Farnell.com | 9451099 | 1 | €0.09 | €0.09 | https://bit.ly/2XRRAxq |
| | 7 | MC0805B224K500A5.08MM | Multilayer Ceramic Capacitor, 0.22 µF, 50 V, MC Series, ± 10%, Radial Leaded, X7R | Through-hole Radial | C1 + C3 | Farnell.com | 2395774 | 2 | €0.15 | €0.30 | https://bit.ly/2ZxDUrX |
| | 8 | 1N4001G | Standard Recovery Diode, 50 V, 1 A, Single, 1.1 V, 30 A | Through-hole Axial | D1 | Farnell.com | 1458986 | 1 | €0.19 | €0.19 | https://bit.ly/2Xi0abG |
| | 9 | HLMP-1301 | LED, Red, Through Hole, T-1 (3mm), 10 mA, 1.9 V, 626 nm | Through-hole Radial | LED1 + LED2 | Farnell.com | 1003196 | 2 | €0.24 | €0.48 | https://bit.ly/2Ri3jis |
| OSCILLATOR | 10 | K223K15X7RF53L2 | Multilayer Ceramic Capacitor, 22000 pF, 50 V, Mono-Kap Series, ± 10%, Radial Leaded, X7R | Through-hole Radial | C5 | Farnell.com | 1141773 | 1 | €0.01 | €0.01 | https://bit.ly/2XiKEOP |
| | 11 | MKS2C021001A00JSSD | DC Film Capacitor, 10000 pF, 63 V, PET (Polyester), ± 5%, MKS2 Series | Through-hole Radial | C9 + C7 | Farnell.com | 1890129 | 3 | €0.05 | €0.15 | https://bit.ly/2XdpDmJ |
| | 12 | SN74AC14N | Inverter, Schmitt Trigger, 74AC14, 1 Input, 24 mA, 2 V to 6 V, DIP-14 | DIP-14 | U2 | Farnell.com | 1470853 | 1 | €0.52 | €0.52 | https://bit.ly/2XotTiv |
| R2R COUNTE | 13 | SN74HC590AN | Binary Counter, HC Family, 40 MHz, 2 V to 6 V, DIP-16 | DIP-16 | U3 | Farnell.com | 1470786 | 1 | €0.53 | €0.53 | https://bit.ly/31KplxL |
| | 14 | MCCFR0S2J0103A20 | 500mW, 5% | Through-hole Axial | R3 -> R28 | Farnell.com | 1127905 | 26 | €0.06 | €1.56 | https://bit.ly/2L0nrLT |
| COMPAR-ATOR | 15 | LM339AN | Analogue Comparator, Voltage, 4 Comparators, 1.3 µs, 2V to 36V, ± 1V to ± 18V, DIP, 14 Pins | DIP-14 | U5 | Farnell.com | 1564966 | 1 | €0.32 | €0.32 | https://bit.ly/31zSEMz |
| INTERFACE | 16 | L-483GDT | LED, Cylindrical, Green, Through Hole, T-1 3/4 (5mm), 20 mA, 2.2 V, 568 nm | Through-hole Radial | LED3 + LED4 | Farnell.com | 1142545 | 2 | €0.18 | €0.36 | https://bit.ly/2wAw1iL |
| | 17 | ADXL335Z | ADXL335 - 5V ready triple-axis accelerometer (+-3g analog out | 4 x 4 x 1.45 mm LFCSP | ADXL335 | adafruit.com | 163 | 1 | €13.30 | €13.30 | https://www.adafruit.com/product/163 |
| | 18 | A000073 | Development Board, Arduino Uno SMD, ATmega328 MCU, 54 5V I/O, 16 Analogue Inputs, UART | N/A | N/A | Farnell.com | 2285200 | 1 | €18.10 | €18.10 | https://bit.ly/2wAwaUj |
| | 19 | CTB1302/PS24 | Connector Accessory, Pin Strip Header, Camdenboss CTB1302 Series PCB | N/A | N/A | Farnell.com | 2493629 | 1 | €2.11 | €2.11 | https://bit.ly/2RlN4Vt |
| | 20 | RS1-08-G-.413 | 1 X 8 Position Female Socket with 10.5mm Pins and 2.54MM Pitch | N/A | N/A | Farnell.com | 2802333 | 1 | €0.34 | €0.34 | https://bit.ly/2MPBOSw |
| | 21 | 111-2803-008 | Ribbon Cable, Spectra Bond® Flat, Per M, Unscreened, 8 Core, 28 AWG | N/A | N/A | Farnell.com | 1301013 | 1 | €4.18 | €4.18 | https://bit.ly/2WMds0Q |

# Errors

Some errors occurred at various stages during the implementation of the circuit. These were dealt with as follows:

## Voltage Regulator

During the voltage regulator stage, the terminal block component was found to have been soldered incorrectly to the board, as it had been positioned backwards. The component was removed using solder removal braid and a new component sourced and resoldered.

## Relaxation Oscillator

Initial tests of the relaxation oscillator showed that it was not outputting at the expected frequency. After inspection of the board, it was found that some cuts in the board had not been made properly, and some unintentional connections in the tracks remained. After recutting the appropriate sections, the oscillator began clocking at the expected frequency.

## R2R Ladder

It was initially found that the ramp voltage from the R2R was not incrementing smoothly, but rather was jagged and uneven. On inspection of the board, it was found that a track cut had not been made. The appearance of the ramp improved significantly one the cut was made.

## Embedded Interface

On testing the PWM output of the comparator, it was found that a signal was not being obtained for the Z-axis of the accelerometer. After inspecting the circuit visually, a burned section of the board was found between the PWM_Y output of the 5V line, through the pull-up resistor. This was subsequently rerouted, but the problem persisted. Continuity measurements were then taken, and it was found that the connection between the Y-axis output of the accelerometer header and the comparator input was broken. This also was then rerouted, but again the problem persisted. Resistance values were then taken using the multimeter, and a short to ground at the U-output of the comparator was discovered. A visual inspection of the board revealed an accidental connection to the ground line through excess solder on a joint. The joint was de-soldered and cleaned up, and this appeared to solve the problem.

## Coding

An issue was found with the `PulseIn()` function of the embedded code. On occasion, the function returned erroneously low values for the HIGH PWM duration, in the area of 10 – 20 μs. On inspection of the PWM signal using the oscilloscope, it was discovered that there were slight glitches in the X and Z signals, where the value went from HIGH to LOW to HIGH again, or vice versa, over the course of approximately 20μs. According to the Arduino documentation for `PulseIn()`, the function waits for the pin value to change and then begins timing. It then waits for the value to change again and stops timing [9]. Therefore it is likely that the function was reading the PWM glitches as valid signals. Since the function waits for the value to change, it was decided that a debounce-type solution may be effective, and an if-statement included in the `ReadPulse()` function that implemented a new call to `PulseIn()` if the initial value was less than 20μs. This appeared to solve the problem.

# Testing and Results

## Voltage Regulator

Given that the main function of the voltage regulator is to output a specified voltage, the first test performed was on the output voltage of this section of the circuit. As calculated above (see Implementation – Voltage Regulator), the expected output was between 4.8V and 5.2V. The output voltage, when tested, was found to be 5.06V, within the expected margin of error. AC Ripple was also measured at this stage and found to be approx. 50mV. The minimum input voltage was calculated above to be approx. 7V. When measured, this value was found to be 7.23V, which was reasonably close to the expected value. The current from the bench PSU was also measured, and found to be 17.9mA

| **Minimum** | **Typical** | **Maximum** |
|---|---|---|
| 7V | 12V | 35V |

*Table 3: Input Voltage Values*

| **Value** | **Description** | **Expected** | **Measured** |
|---|---|---|---|
| *$V_{in}$ Min* | *Minimum input voltage* | *7V* | *7.23V* |
| *VDD* | *Output voltage* | *4.8V -> 5.2V* | *5.06V* |
| *PIN* | *Input current* | ---------- | *17.9mA* |
| *$V_{AC\ RIPPLE}$* | *AC Ripple on input voltage* | ---------- | *50mV* |

*Table 4: Test Results for Voltage Regulator*

## Relaxation Oscillator

Values related to the input and output of the oscillator were tested at this stage, in order to ensure that this section of the circuit was functioning correctly. The estimated value for the output frequency was $159.35kHZ \leq f \geq 365.23kHz$ (see Implementation – Relaxation Oscillator). When measured on the oscilloscope, the output period was found to be $5.3\ \mu s$, which meant that the frequency was 188.7kHz, which is within the expected range. The ratio of positive to negative pulse width was measured, with the positive width found to be $2.9\ \mu s$ and the negative $2.4\ \mu s$. Ideally, these would have the same value, but the unequal ratio was not found to be overly problematic. The rise time and fall time were also measured, and found to be 30ns and 20ns, respectively.

As before, the voltage and current into the circuit and the AC ripple were measured to see if they had changed given the expansion of the circuit. They were found not to have deviated significantly.

| **Value** | **Expected** | **Measured** |
|---|---|---|
| Circuit voltage | 12V | 12.8V |
| Circuit current | ----- | 29mA |
| Positive pulse width | ----- | 2.9µs |
| Negative pulse width | ----- | 2.4µs |
| Output frequency | 159 -> 365 kHz | 188.7kHz |
| Output Period | 1/159k -> 1/365k seconds | 5.3µs |
| Rise time | ---- | 30ns |
| Fall time | ---- | 20ns |

*Table 5: Test Results for relaxation oscillator*

## Counter

Testing at this stage of the circuit involved determining the output frequencies of each of the 8 output pins of the counter and comparing these frequencies to expected values.

Frequencies were calculated using the equation:

$$nth\ bit\ frequency = \frac{188{,}700}{2^n}$$

| Output | Calculated Frequency (Hz) | Measured Frequency (Hz) | Difference (Hz) | Difference (%) |
|---|---|---|---|---|
| Bit 1 (O/p A0) | 188,700 / 2 = 94,350 | 95,700 | + 1350 | 1.4 |
| Bit 2 (O/p A1) | 188,700 / 4 = 47,175 | 47,000 | -175 | 0.3 |
| Bit 3 (O/p A2) | 188,700 / 8 = 23,587 | 23,900 | +313 | 1.3 |
| Bit 4 (O/p A3) | 188,700 / 16 = 11,794 | 11,900 | +196 | 0.9 |
| Bit 5 (O/p A4) | 188,700 / 32 = 5,897 | 5,980 | +83 | 1.4 |
| Bit 6 (O/p A5) | 188,700 / 64 = 2,984 | 3,000 | +16 | 0.5 |
| Bit 7 (O/p A6) | 188,700 / 128 = 1,474 | 1,490 | +16 | 1.1 |
| Bit 8 (O/p A7) | 188,700 / 256 = 737 | 747 | +10 | 1.3 |

*Table 6: Test Results for 8-bit Counter*

AC Noise was again measured at this point and found to be approx. 25mV, and power consumption was calculated from the input voltage and current and found to be 0.36 Watts.

## Ramp Generator

The ramp generator was tested by measuring the resistance values throughout and across the circuit and comparing them to expected calculated values. If the resistance values were found to be correct, then it is assumed that the voltage values contributing to the ramp will be correct.

| **Test Point 1** | **Calculated Value** | **Measured Value** | **Difference (%)** |
|---|---|---|---|
| GND to A0 | 20kΩ | 19.68kΩ | 1.61 |
| GND to A1 | 25kΩ | 24.50kΩ | 2.02 |
| GND to A2 | 30kΩ | 29.42kΩ | 1.95 |
| GND to A3 | 35kΩ | 34.28kΩ | 2.08 |
| GND to A4 | 40kΩ | 39.20kΩ | 2.02 |
| GND to A5 | 45kΩ | 44.10kΩ | 2.02 |
| GND to A6 | 50kΩ | 49.01kΩ | 1.99 |
| GND to A7 | 55kΩ | 53.98kΩ | 1.87 |

*Table 7: Measured and calculated resistances across R2R ladder*

| **Test Point 2** | **Calculated Value** | **Measured Value** | **Difference (%)** |
|---|---|---|---|
| A0 to A1 | 25kΩ | 24.49kΩ | 2.06 |
| A1 to A2 | 25kΩ | 24.42kΩ | 2.34 |
| A2 to A3 | 25kΩ | 24.41kΩ | 2.38 |

| | | | |
|---|---|---|---|
| A3 to A4 | 25kΩ | 24.41kΩ | 2.38 |
| A4 to A5 | 25kΩ | 24.43kΩ | 2.31 |
| A5 to A6 | 25kΩ | 24.42kΩ | 2.23 |
| A6 to A7 | 25kΩ | 24.50kΩ | 2.02 |
| A7 to A0 | 55kΩ | 53.80kΩ | 2.21 |

*Table 8: Measured and calculated resistances within R2R ladder*

In addition, the output ramp voltage was checked on the oscilloscope to ensure that it was outputting the correct shape and magnitude sawtooth wave. As seen below, the output voltage was found to be a 5V sawtooth wave as expected, and the step size was found to be approximately 20mV:

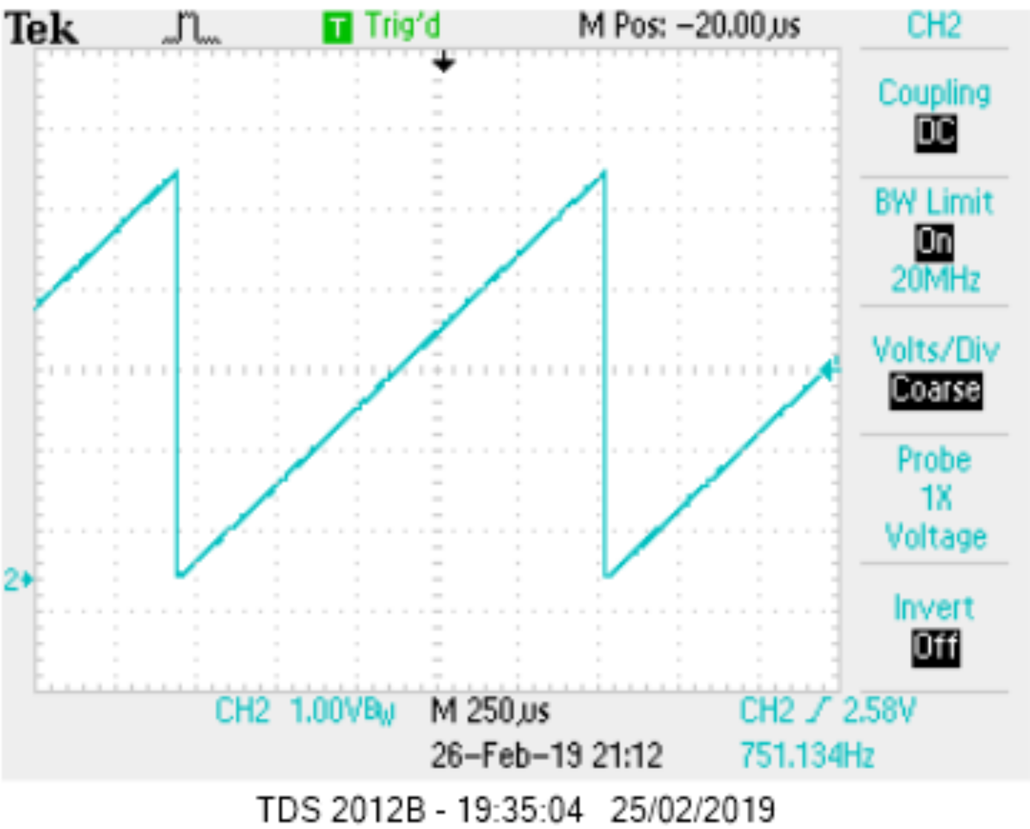



*Figure 3: Ramp output of R2R ladder*

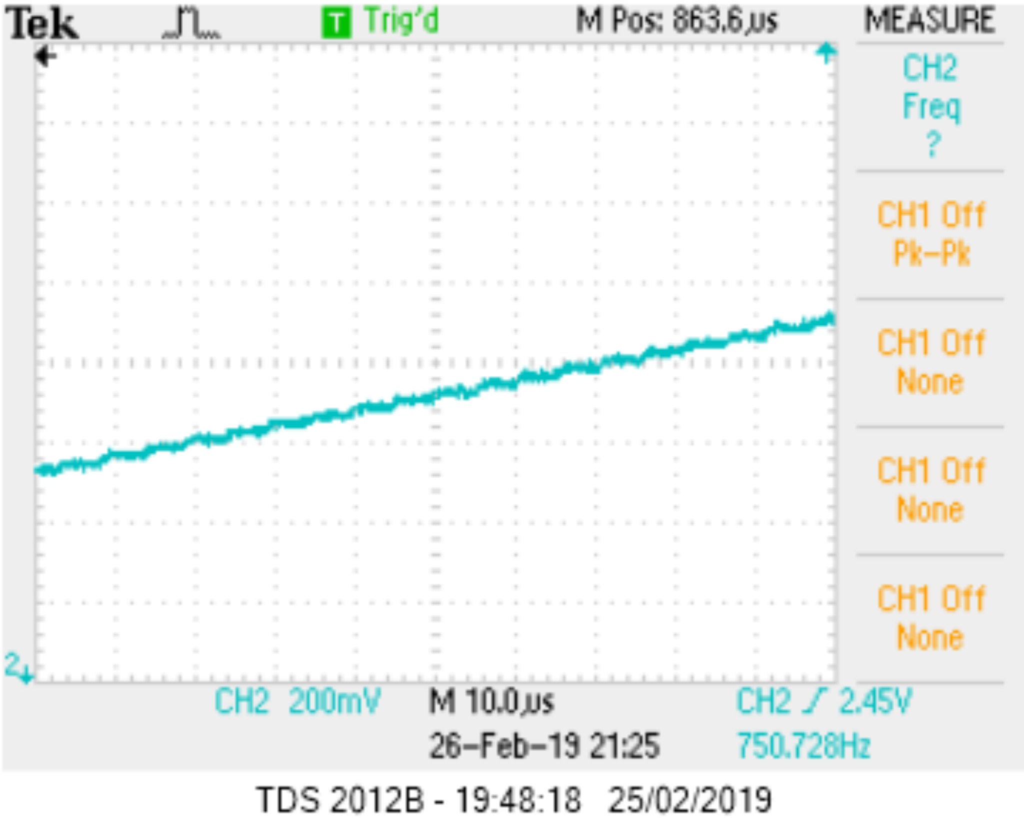



*Figure 4: Individual step size in ramp output*

AC Noise was again measured at this point and found to have increased significantly from 25mV to approx. 60mV with the addition of the R2R ladder to the circuit.

## Comparator

Testing for the comparator involved using the oscilloscope to find the minimum test input voltage value for which the output PWM signal had both a high and low portion. Beyond this point, the PWM will be a DC signal with only a continuous low value, which is of no use. The maximum voltage value was also measured. The useful range of voltages was thus calculated.

In addition, the frequency, period, and voltage of the PWM signal was measured and compared to calculated values, and a range of high/low PWM durations were measured for the test input.

Finally, the power consumption of the circuit at this point was found to be 0.41W, an increase on the previous value of 0.36W

| Value | Expected | Measured | | |
|---|---|---|---|---|
| | | **X** | **Y** | **Z** |
| $V_{sig\_min}$ | ------- | 9mV | 9mV | 8mV |
| $V_{sig\_max}$ | ------- | 5.062V | 5.06V | 5.1V |
| $V_{sig\_range}$ | ------- | 5.053V | 5.051V | 5.092V |
| $V_{PWM}$ | 5.06V | 5.12V | 5.12V | 5.12V |
| F_PWM | 737.1Hz | 752.7Hz | 751.8Hz | 746Hz |
| T_PWM | 1.36ms | 1.33ms | 1.33ms | 1.34ms |

*Table 9: Measured and calculated values for comparator*

| $V_{sig}$ | X | | | Y | | | Z | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Pos PWM** | **Neg PWM** | **Period** | **Pos PWM** | **Neg PWM** | **Period** | **Pos PWM** | **Neg PWM** | **Period** |
| 1V | 263.9μs | 1.065ms | 1.33ms | 270μs | 1.06ms | 1.33ms | 269.1μs | 1.071ms | 1.34ms |
| 2V | 523.2μs | 806.1μs | 1.33ms | 521.9μs | 808.1μs | 1.33ms | 527.8μs | 812.2μs | 1.34ms |
| 3V | 807.9μs | 520.8μs | 1.33ms | 810μs | 520μs | 1.33ms | 814.6μs | 525.4μs | 1.34ms |
| 4V | 1.053ms | 276μs | 1.33ms | 1.072ms | 258μs | 1.33ms | 1.063ms | 276μs | 1.34ms |

*Table 10: Measured PWM values*

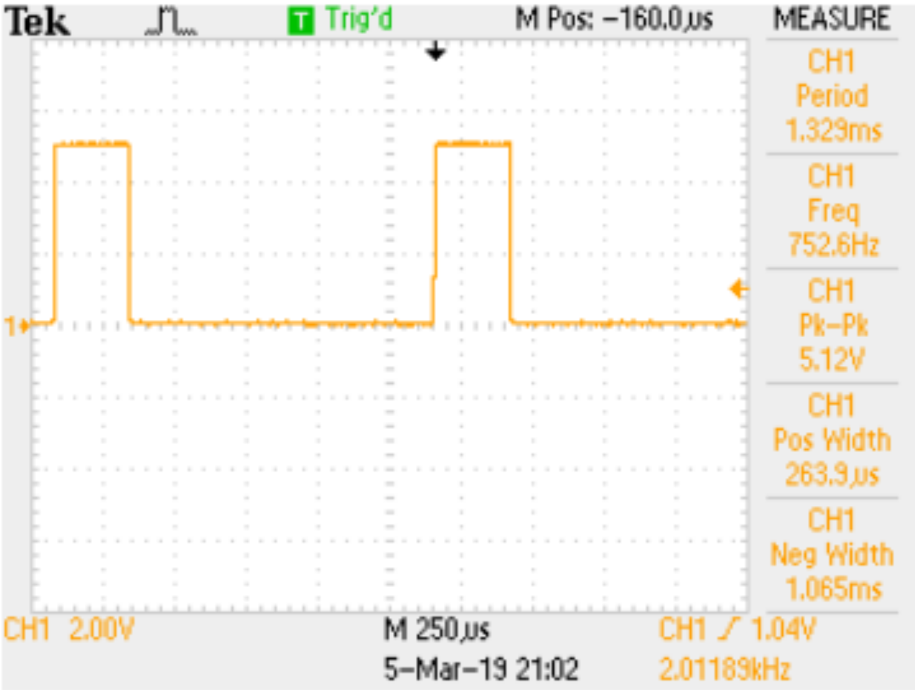



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*Figure 5: PWM output for 1V test input*

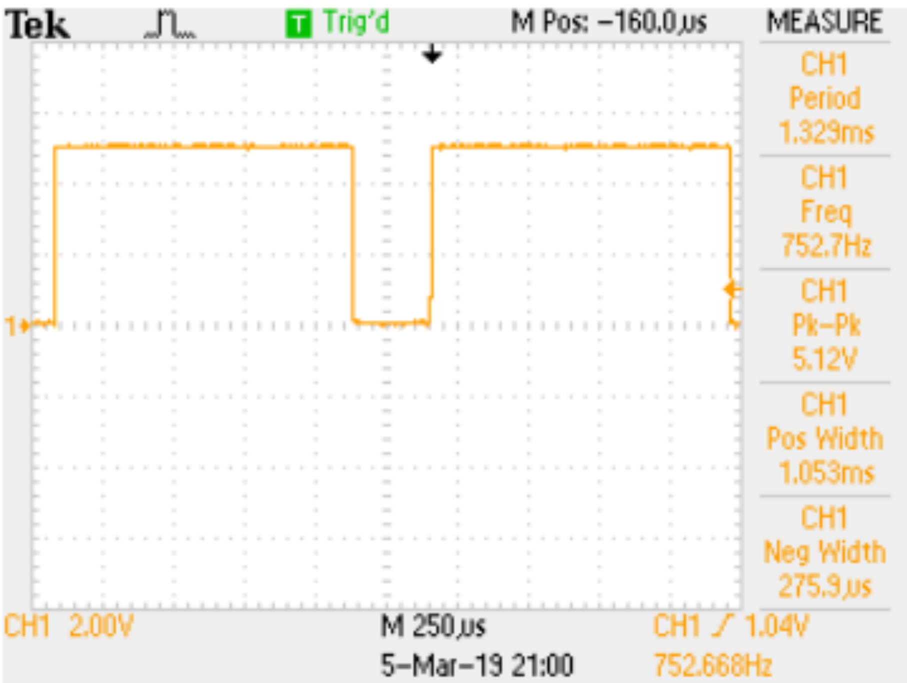


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*Figure 6: PWM output for 4V test input*

## Embedded Interface

Testing of the embedded interface involved taking many of the same measurements as in the previous stage. The difference in this case however, was that the test voltages were routed from the bench PSU through the accelerometer header pins, in order to ensure that the wiring and rerouting necessary for this stage had been correctly completed. Only the varying voltages for the X-axis were tested in this case.

| **Value** | **Expected** | **Measured** | | |
|---|---|---|---|---|
| | | **X** | **Y** | **Z** |
| $V_{sig\_min}$ | ------- | 10mV | 9.5mV | 9.7mV |
| $V_{sig\_max}$ | ------- | 5.15V | 5.12V | 5.2V |
| $V_{sig\_range}$ | ------- | 5.14V | 5.025V | 5.103V |
| $V_{PWM}$ | 5.06V | 5.18V | 5.2V | 5.17V |
| F_PWM | 737.1Hz | 746Hz | 742Hz | 752Hz |
| T_PWM | 1.36ms | 1.34ms | 1.35ms | 1.33ms |

*Table 11: Measured and calculated values for comparator*

| **$V_{sig}$** | **Pos PWM** | **Neg PWM** | **Period** |
|---|---|---|---|
| 1V | 273.5µs | 1.067ms | 1.34ms |
| 2V | 516.4µs | 823.6µs | 1.34ms |
| 3V | 821µs | 519µs | 1.34ms |
| 4V | 1.1ms | 24µs | 1.34ms |

*Table 12: Measured PWM values*

Power consumption was again measured at this stage, and found to be 0.372W, a slight increase on the previous measurement. AC Noise was measured, and found to be approx. 65mV, also a slight increase on the previous measurement.

## Coding

Testing this code for the project involved ensuring that the values output to the serial monitor corresponded with values that would be reasonably expected for particular movements of the board. For example, lying the board flat should result in values of 1g in the z-axis as a result of acceleration due to gravity (*g*), and values of 0g in both other axes.

In addition, the voltages values displayed on the serial monitor were compared with voltages measured at the accelerometer by the multimeter.

| Position | G-force | $V_{SERIAL}$ | $V_{MEASURED}$ | Difference (%) |
|---|---|---|---|---|
| $0^o$ x-axis | -1g | 1.88V | 1.74V | 7.7 |
| $90^o$ x-axis | 0g | 1.56V | 1.63V | 4.3 |
| $180^o$ x-axis | 1g | 1.32V | 1.4V | 5.9 |
| $270^o$ x-axis | 0g | 1.54V | 1.61V | 4.4 |

*Table 13: X-axis Voltage values from serial monitor and multimeter*

| Position | G-force | $V_{SERIAL}$ | $V_{MEASURED}$ | Difference (%) |
|---|---|---|---|---|
| $0^o$ y-axis | -1g | 1.86V | 1.94V | 4.2 |
| $90^o$ y-axis | 0g | 1.72V | 1.84V | 6.7 |
| $180^o$ y-axis | 1g | 1.25V | 1.29V | 3.1 |
| $270^o$ y-axis | 0g | 1.68V | 1.61V | 4.2 |

*Table 14: Y-axis Voltage values from serial monitor and multimeter*

| Position | G-force | $V_{SERIAL}$ | $V_{MEASURED}$ | Difference (%) |
|---|---|---|---|---|
| $0^o$ z-axis | -1g | 1.36V | 1.41V | 3.6 |
| $90^o$ z-axis | 0g | 1.7V | 1.84V | 7.9 |
| $180^o$ z-axis | 1g | 1.96V | 2.02V | 3 |
| $270^o$ z-axis | 0g | 1.68V | 1.72V | 2.3 |

*Table 15: Z-axis Voltage values from serial monitor and multimeter*

From this analysis, it was determined that the maximum voltage values, and thus maximum g-force values due to gravity occurred at $180^0$, and the minimum occurred at $0^0$. Thus the g-force relative to position could be thought of as an inverted cosine wave.

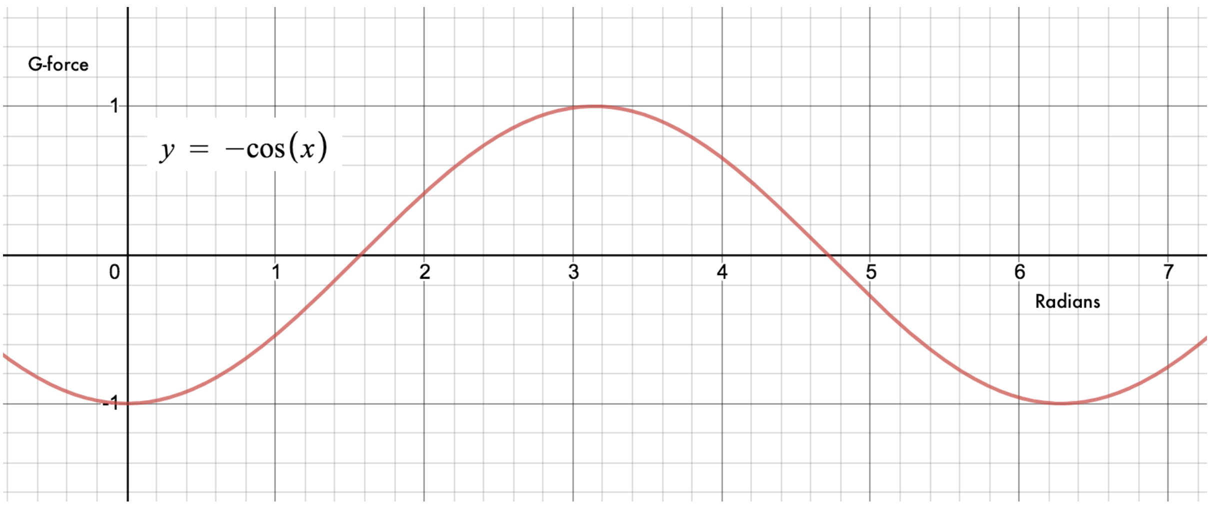


*Figure 7: G-force as a cosine function of position in degrees*

The period of the wave could be calculated by taking the range of voltage values between the max and min (half-wave period) and multiplying by two. Taking $2\pi$ divided by this period would give the coefficient on x for the cosine wave equation:

$$g\ force = -1\cos\left(\frac{2\pi}{2(V_{max} - V_{\min})}x\right)$$

$$g\ force = -1\cos\left(\frac{\pi}{V_{max} - V_{\min}} x\right)$$

This equation was implemented in the embedded code in a function `convert_to_g()`, using the external Arduino library `math.h`.

## Conclusion

The primary learning outcome of this project was a better knowledge of the processes of analogue to digital and digital to analogue conversion. In addition, I learned more about project management, including the importance of keeping detailed records and project planning. I gained more familiarity with test equipment, and learned more about the importance of circuit testing. I learned that circuits of these types are built on tolerances, and to always be conscious of the parameters and limitations of my circuit and aware of the published tolerances and ranges of devices used.

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# Appendix

## Calculations for Relaxation Oscillator frequency

| r | c | rc | vcc | vt- | vt+ | i | vcc-vt+ | vcc-vt- | vt+/vt- | vcc-vt-/vcc-vt+ | ln(vccs) | RC* ln | 1/RC*ln |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1 | 1.55 | 1 | 3.5 | 4.05 | 1.550 | 1.157142857 | 0.584208844 | 2.73802E-06 | 365227 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.05 | 1.65 | 1 | 3.4 | 4 | 1.571 | 1.176470588 | 0.614504053 | 2.88001E-06 | 347221 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.1 | 1.75 | 1 | 3.3 | 3.95 | 1.591 | 1.196969697 | 0.644098719 | 3.01871E-06 | 331267 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.15 | 1.85 | 1 | 3.2 | 3.9 | 1.609 | 1.21875 | 0.67324944 | 3.15533E-06 | 316924 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.2 | 1.95 | 1 | 3.1 | 3.85 | 1.625 | 1.241935484 | 0.702178853 | 3.29092E-06 | 303867 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.25 | 2.05 | 1 | 3 | 3.8 | 1.640 | 1.266666667 | 0.73108502 | 3.42639E-06 | 291852 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.3 | 2.15 | 1 | 2.9 | 3.75 | 1.654 | 1.293103448 | 0.760148681 | 3.5626E-06 | 280693 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.35 | 2.25 | 1 | 2.8 | 3.7 | 1.667 | 1.321428571 | 0.789539026 | 3.70035E-06 | 270245 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.4 | 2.35 | 1 | 2.7 | 3.65 | 1.679 | 1.351851852 | 0.819418486 | 3.84039E-06 | 260390 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.45 | 2.45 | 1 | 2.6 | 3.6 | 1.690 | 1.384615385 | 0.849946869 | 3.98346E-06 | 251038 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.5 | 2.55 | 1 | 2.5 | 3.55 | 1.700 | 1.42 | 0.881285123 | 4.13034E-06 | 242111 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.55 | 2.65 | 1 | 2.4 | 3.5 | 1.710 | 1.458333333 | 0.91359894 | 4.28178E-06 | 233548 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.6 | 2.75 | 1 | 2.3 | 3.45 | 1.719 | 1.5 | 0.947062391 | 4.43862E-06 | 225295 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.65 | 2.85 | 1 | 2.2 | 3.4 | 1.727 | 1.545454545 | 0.981861778 | 4.60171E-06 | 217310 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.7 | 2.95 | 1 | 2.1 | 3.35 | 1.735 | 1.595238095 | 1.01819992 | 4.77202E-06 | 209555 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.75 | 3.05 | 1 | 2 | 3.3 | 1.743 | 1.65 | 1.056301091 | 4.95059E-06 | 201996 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.8 | 3.15 | 1 | 1.9 | 3.25 | 1.750 | 1.710526316 | 1.096416898 | 5.1386E-06 | 194606 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.85 | 3.25 | 1 | 1.8 | 3.2 | 1.757 | 1.777777778 | 1.138833502 | 5.3374E-06 | 187357 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.9 | 3.35 | 1 | 1.7 | 3.15 | 1.763 | 1.852941176 | 1.183880661 | 5.54852E-06 | 180228 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 1.95 | 3.45 | 1 | 1.6 | 3.1 | 1.769 | 1.9375 | 1.231943341 | 5.77377E-06 | 173197 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 2 | 3.55 | 1 | 1.5 | 3.05 | 1.775 | 2.033333333 | 1.283476905 | 6.0153E-06 | 166243 |
| 214.8 | 2.1819E-08 | 4.68672E-06 | 5.05 | 2.05 | 3.65 | 1 | 1.4 | 3 | 1.780 | 2.142857143 | 1.339027426 | 6.27565E-06 | 159346 |