EEEE2059
Practical Engineering Design Solutions and Project Development

Electronic Project: Session Week I
Analogue Signal Conditioning Circuits Design

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Introduction

A radar speed gun (as shown in Figure 1) is a device used to measure the speed of moving objects. It is used in law-enforcement to measure the speed of moving vehicles and is often used in professional spectator sport, for things such as the measurement of bowling speeds in cricket, speed of pitched baseballs, and speed of tennis serves. A radar speed gun is a Doppler radar unit that may be handheld, vehicle-mounted, or static. It measures the speed of the objects at which it is pointed by detecting a change in frequency of the returned radar signal caused by the Doppler effect, whereby the frequency of the returned signal is increased in proportion to the object's speed of approach if the object is approaching, and lowered if the object is receding. Such devices are frequently used for speed limit enforcement. At the end of this project, a complete working Doppler radar based speed gun is to be developed.

Figure 1. Handheld radar speed gun

The general aim for session week I was to produce two analogue signal conditioning circuits for interfacing the Doppler radar module to the STM32L476 microcontroller. To achieve this aim, several approaches were listed below:

- Surface Mount Soldering Test
- Radar Module Characterization
- Design, simulate, prototype on breadboard, and test an amplifier circuit that provides sufficient gain to amplify the output of the Doppler radar module to a range suitable for use with the ADC on the STM32L476 microcontroller.
- Design, simulate, prototype on breadboard, and test an amplifier circuit that provides sufficient gain to amplify the output of the Doppler radar module so that it can be used as an input to a comparator. This means higher gain than in the other case.
- Design, simulate, prototype on breadboard, and test a bandpass filter circuit.
- Combine ADC amplifier and filter onto one PCB, retest.
- Combine comparator amplifier and filter onto one PCB, retest.

A key aspect of engineering work is that there is rarely one way in which to approach a problem. Engineers are expected to be able to evaluate different ways of accomplishing a problem and to choose the best method of developing a solution – and that decision will not just be based on the technical specification but also commercial, regulatory, and other similar considerations. Thus, as shown in the Figure 2 below, two approaches were to be attempted and the performance for both cases was to be evaluated and a case for which was the best circuit was to be presented.

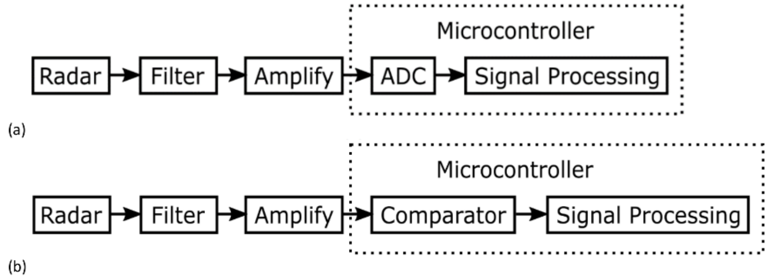

Figure 2. Block diagrams: (a) ADC approach (b) Comparator approach

Surface-mount technology (SMT) is a method in which the electrical components are mounted directly onto the surface of a printed circuit board (PCB) as shown in Figure 3 below. In industry, this approach has largely replaced the through-hole technology construction method of fitting components, in large part because SMT allows for increased manufacturing automation which reduces cost and improves quality – It also allows for more components to fit on a given area of substrate. Therefore, the surface-mount approach and test were to be performed.

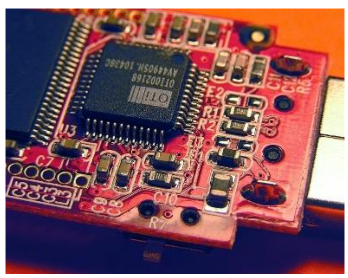

Figure 3. Surface-mount components on a USB flash drive's circuit board

The core hardware component used in this project for analogue signal acquisition was the X-Band Radar Motion Sensor (HB100) as shown in the Figure 4 below. According to the technical specification of the module, a person with 70 kg and 170 cm walking towards the sensor at 1 m generates a 5 mV 72 Hz signal. The Received Signal Strength and Noise parameter values were to be characterized to obtain the DC offset voltage and AC response of the radar module.

Figure 4. X-Band Radar Motion Sensor (HB100)

The core theory of the Doppler radar based speed gun was the Doppler principle. As shown in Figure 5, the Doppler effect (i.e. Doppler shift) is the change in frequency of a wave in relation to an observer who is moving relative to the wave source. A common example of Doppler shift is the change of pitch heard when a vehicle sounding a horn approaches and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by, and lower during the recession. Therefore, the speed of a moving object can be obtained using the formulas in Figure 6.

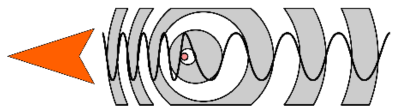

Figure 5. Change of wavelength caused by motion of the source

$$S_{TX} = A\sin 2\pi f_t t$$
$$S_{RX} = A\sin(2\pi f_r t + \emptyset)$$
$$f_r = f_t - f_d$$

Stationary Target: f_d = 0 => Only phase shift (delay)

Moving Target: $f_d = \frac{\Delta v}{c} f_t$ => phase shift (delay) and frequency shift (Doppler shift)

Figure 6. Doppler principle

The digital signal processor used in this project was the STM32L476 Discovery board as shown in the Figure 7 below. Although in this session week, the programming was not to be performed, but since the signal output of the analogue signal conditioning circuit was going to be connected to one of the STM32L476 Discovery board GPIOs, certain properties of the board (e.g. the GPIO pins could only take 3.3 V) were to be considered when designing the signal conditioning circuit.

Figure 7. STM32L476 Discovery board

All the designed circuits were to be prototyped and verified on breadboard before soldering and integration to make sure that there was no major design mistake, otherwise, it was difficult to modify design choices after soldering the components onto a highly integrated circuit board.

The last but the most important, the reasons why an analogue signal conditioning circuit consisting of a filter and an amplifier was required instead of using the raw signal from the radar module were listed below:

1. The output of the Doppler radar module was quite noisy and in particular contained frequencies that were of no interest. Therefore, a filter was required to filter out the noise and unimportant frequencies so that the frequencies of interest were obtained.
2. The ultimate output of the analogue signal conditioning circuit was to go to the STM32L476 microcontroller, however, the output of the radar module after filtering had to have a sufficient gain to allow the microcontroller to make a good measurement. Because when using an ADC, ideally the entire range of the ADC was to be covered by the input to get the best resolution. With too much gain the ADC would overflow, and the signal would be distorted. With too little gain the "bits" were effectively wasted and the result would be not as good. Therefore, a nicely designed amplifier was required.

Methods

In this session week, an analogue signal conditioning circuit consisting of a filter and an amplifier was to be designed. Apart from the filter and the amplifier, a comparator had to be designed. The STM32L476 Discovery board had an on-board comparator to be used, but in this week, a comparator was to be designed anyway to obtain the processed signal output from the comparator. The comparator was also able to be used in comparator control and acquisition in signal processing instead of using the embedded comparator on STM32 board to save time for programming as long as the comparator was designed correctly.

Radar module characterization

But before any useful decision was able to be made about how to design the amplifier, the output of the Doppler radar module had to be obtained and studied. The module was carefully connected to a 5 V power supply and the output pin (IF) was connected to the oscilloscope. The DC voltage level that was present was noted down which was the DC offset of the radar module which was important for design. The tuning fork was supposed to be used in front of the radar to obtain a small oscillating signal at the frequency of the tuning fork (use this frequency to set the oscilloscope time base). However, in practice, the vibration of a tuning fork was too small to be captured by the radar module in which case the moving iPad was used in characterization of the radar module by moving it towards the radar module. Then a bigger but much less repeatable response was obtained, and the voltage levels were noted down. (Assuming the furthest range needed to measure at is 1 m.) Hence, the radar module was characterized by obtaining its DC offset voltage and AC response (i.e. the maximum and minimum output voltage levels).

Note that the radar module was quite fragile so that when connecting it to the power supply, the current limit had to be set to 0.2 A. And when radar module was powered on, the current through it was to be lower than 0.04 A otherwise the module was likely broken.

Filter design

A band pass filter as shown in the Figure 8 below was designed to remove the frequencies lower than 5.13 Hz and higher than 1.092 kHz which was combined with a simple single order RC based high pass filter and a simple single order RC based low pass filter.

Passive filters can be small and cheap but restricted in their output response. Using an active filter design gives better control over the output and gives some buffering which can be important to ensure the filter response does not change depending on what circuit it is driving. Also, the active filter was used to pre-amplifier the output before the signal went into another stage at amplifier, because single-stage large-gain amplification would result in bandwidth loss.

The filter circuit in Figure 8 introduced an integrated arranged inverting amplifier between the high and low pass elements which, comparing to passive RC bandpass filters, had a much better response and a narrower range of frequencies to be isolated, since the cut off of the high and low pass elements must be kept sufficiently far apart avoiding interacting with one another.

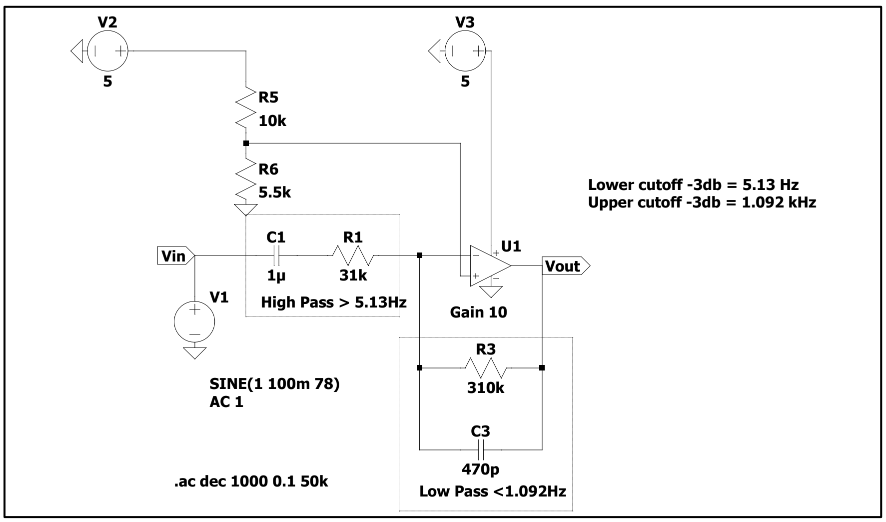

Figure 8. Filter schematic

Filter design equations for the circuit shown in the Figure 8 above were:

$$G = -\frac{R_3}{R_1} = -\frac{310\ k\Omega}{31\ k\Omega} = -10 \quad \text{Eq. 1}$$

$$f_{Cl} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi \times 31\ k\Omega \times 1\ \mu F} = 5.13\ Hz \quad \text{Eq. 2}$$

$$f_{Ch} = \frac{1}{2\pi R_3 C_3} = \frac{1}{2\pi \times 310\ k\Omega \times 470\ pF} = 1.092\ kHz \quad \text{Eq. 3}$$

The verification of the filter design was following the procedure: Firstly, a simulation of the circuit was created, and its operation and performance were verified. Secondly, a prototype version was built and tested on breadboard. Lastly, the filter was characterized in terms of its amplitude and phase response with respect to frequency using an appropriate frequency range.

Amplifier design

Two different amplifiers were designed: one for ADC amplification and another for comparator amplification. For ADC approach, an op-amp amplifier circuit as shown in the Figure 9 below was designed for interfacing the Doppler output to the microcontroller ADC input. From Doppler radar characterization (the results of which were discussed in detail in the following section), it was obtained that the DC offset was 110 mV by approximation and the amplitude was 110 mV by approximation in which case the range of the output voltage level was from 0 to 220 mV. Since the voltage range of the ADC on microcontroller was from 0 to 3.3 V and the output of the radar module was to be designed to cover as much the ADC range as possible without overflowing to have better ADC sampling results, therefore, an op-amp of gain -1.5 was applied after the inverting bandpass filter with a gain of -10 designed above so that the overall gain of the whole filter and amplifier circuit was 15 in which case all the ADC range was covered in theory.

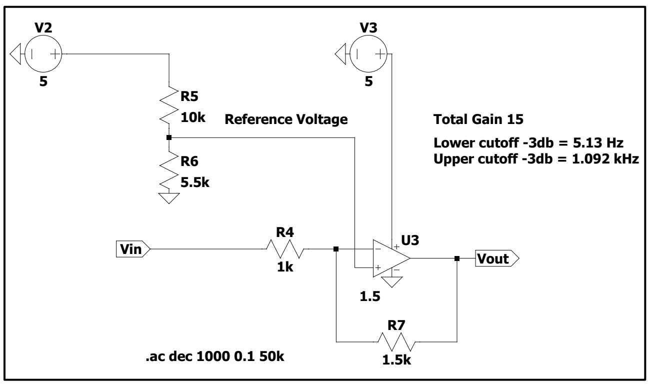

Figure 9. ADC amplifier schematic

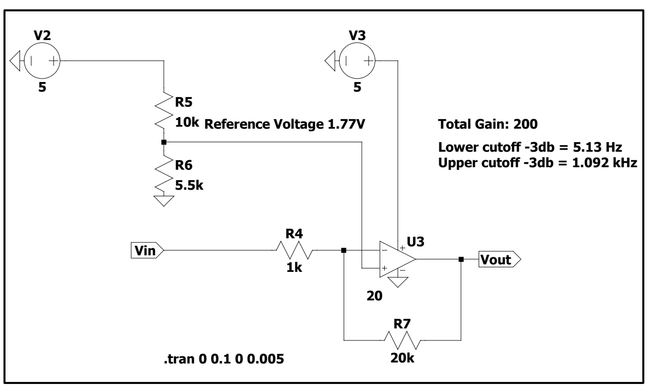

Figure 10. Comparator amplifier schematic

As shown in the Figure 10 above, an op-amp for comparator approach was designed aiming to have an distorted output without caring the shape of the signal, but the edges that would go past the comparator reference level were considered along with the bandwidth loss due to high gain. Therefore, the op-amp was designed to have gain of -20 which was added to the filter circuit shown in Figure 8 after the filter to have an overall gain of 200 to realize comparator approach.

Similar to the verification for filter design, to verify the amplifier design for both approaches, simulations of both circuits were to be run appropriately with the results recorded, then prototypes of both circuits were to be built and tested on breadboard to characterize the amplifiers in terms of their gain and phase response with respect to frequency.

Advanced design: Radar Feed Horn

When characterizing the radar module, it was noticed that the signal the module obtained was quite noisy and also the module had a short limited detection range in which case it was not sensible enough detecting the moving objects relatively far away (i.e. the frequency change was unsignificant). Therefore, a feed horn was designed and added on top of the radar module to optimize the sensitivity of the radar module and reduce irrelevant noise physically.

A Horn or Feed Horn (as shown in Figure 11 on LHS) is a special antenna design for higher frequency ranges. The design more of less resembles the sound outlet of a brass-wind instrument, for example, a hunting horn. This funnel-shaped construction then ends into a waveguide. Horns are used both as a separate antenna or as a primary radiator to feed a reflector antenna. If it is used to feed a reflector antenna, it is called a feed horn.

As shown in the Figure 11 on RHS, the cardboard lined with tin foil was used to make a radar feed horn which in theory was able to reduce noise and focus on signal of interest.

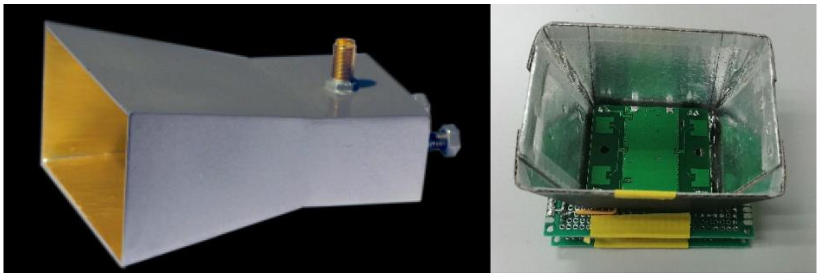

Figure 11. Radar Feed Horn (LHS: a soft-soldered feed horn, RHS: our design)

Results & Discussions

Advanced design: Radar Feed Horn

In practice, after the radar feed horn was applied onto the Doppler radar module, the obtained raw signal had slight amplification and significant noise reduction. Comparing to the original raw signal obtained by the Doppler radar module, the obtained signal after applying the feed horn was purer and the analogue signal conditioning was able to be done more effectively.

Radar module characterization

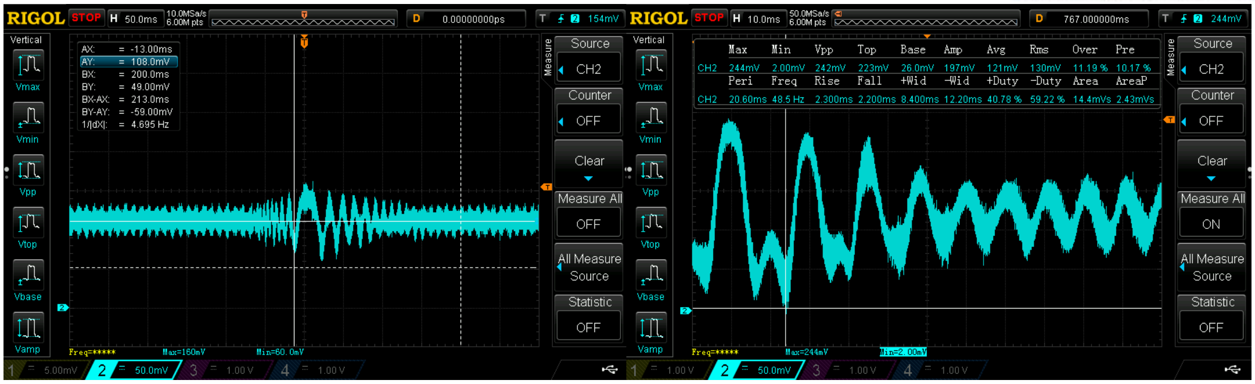

Figure 12. Radar module characterization (LHS: DC offset, RHS: Max & Min voltage level)

As shown in the Figure 12 above, the waveform on LHS was static noise of the Doppler radar module which was used to obtain the DC offset of the radar module. Read from the oscilloscope, the average output voltage level of the radar module when no moving object in front of the radar was 108.0 mV. Therefore, the DC offset of the radar module was obtained as 110 mV by approximation. The waveform on the RHS was obtained by moving an iPad towards the radar module rapidly which was the AC response of the module. From the AC response obtained, the maximum and minimum voltage levels of the module were obtained as 136 mV and 106 mV correspondingly. Therefore, the amplitude of the AC response was obtained as 110 mV by approximation in which case the output voltage range of the module was from 0 to 220 mV.

Filter design

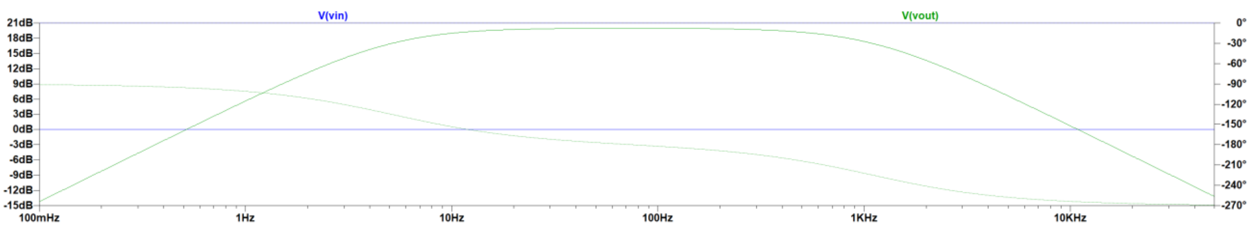

Figure 13. Simulation results of filter circuit

As shown in the Figure 13 above, the output was greatly dropped when the frequency was lower than 5 Hz or higher than 1 kHz and the output at frequencies in between maintained at relative high level which matched the calculation indicating a good filter design.

However, the simulation results sometimes might not be reliable in practice, therefore, for both ADC and comparator approaches, the simulation results as well as the practical results of filter and amplifier circuits obtained from oscilloscope were covered below.

Filter and Amplifier

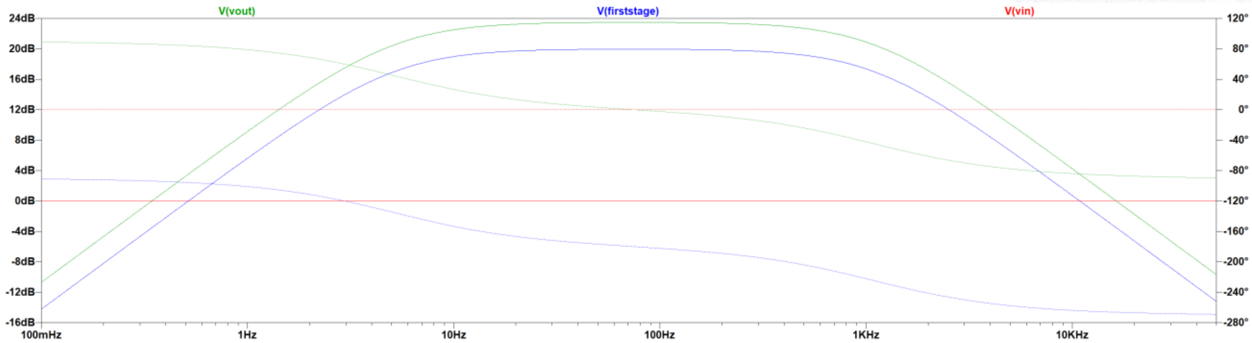

Figure 14. Simulation results of filter and ADC amplifier circuit

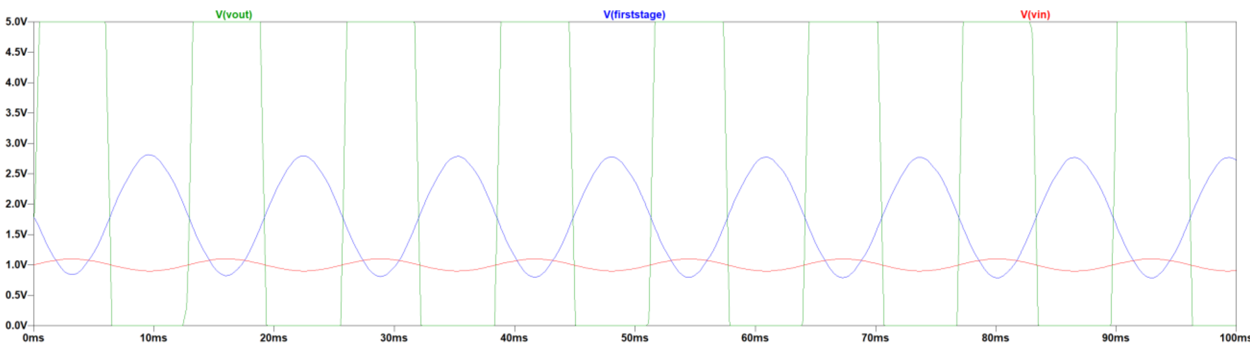

Figure 15. Simulation results of filter and Comparator amplifier circuit

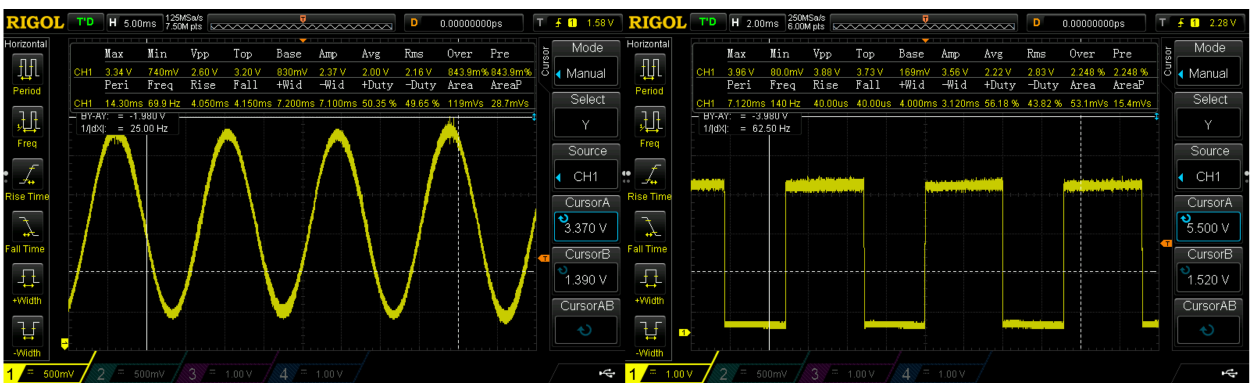

Figure 16. Practical results of filter and ADC amplifier (LHS) and comparator amplifier (RHS)

The simulation results were shown in the Figure 14 and 15 above which matched the calculation indicating a good design for both ADC amplifier and comparator amplifier. Then prototypes of both circuits were built on breadboard and tested using a signal generator, and the output response of both approaches were as shown in the Figure 16 above. For ADC approach (LHS), the output voltage level varied from 740 mV to 3.34 V which was able to cover the 3.3 V voltage range of the ADC on microcontroller approximately without much “bits” loss. In that case, the ADC approach of analogue signal conditioning circuit was designed successfully to be interfacing with the microcontroller. For comparator approach (RHS), the edges were sharp indicating a successful design of comparator approach of analogue signal conditioning circuit which was to be used to interface with the microcontroller without the embedded comparator.

Combined circuits

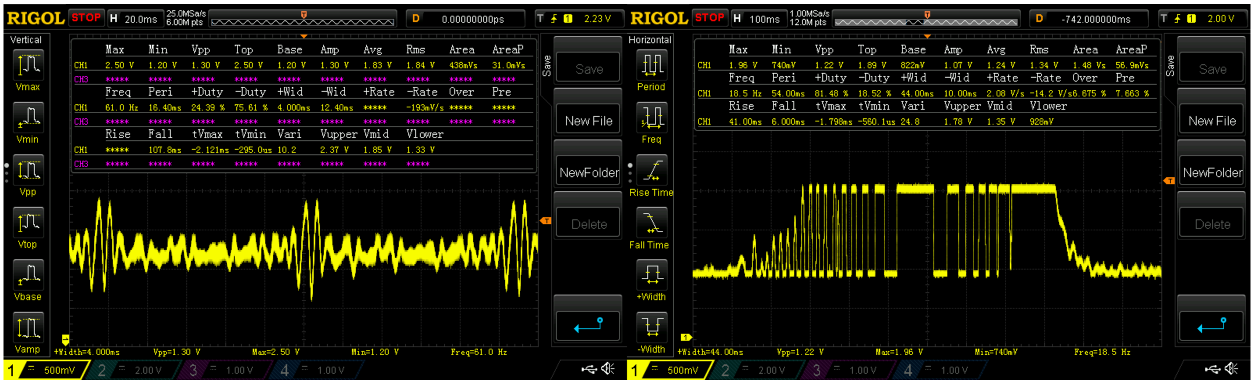

Figure 17. Combined circuits output response (LHS: ADC, RHS: Comparator)

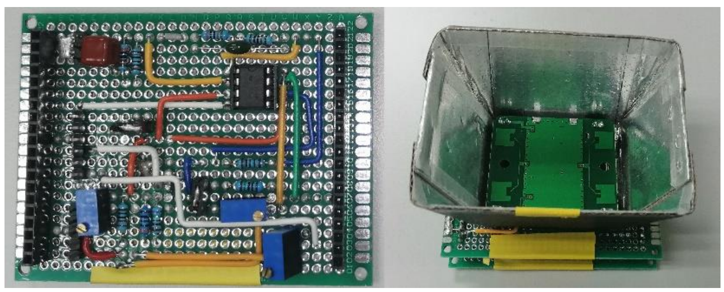

Figure 18. Final integrated two-mode circuit (soldering work)

As shown in the Figure 17 above, both combined circuits were functional, however, it was obvious that the output voltage level was not as wide as 3.3 V, because in practice the raw output of the radar hardly reached the maximum or minimum levels characterized earlier so that the actual output range was quite narrower than the calculated 3.3 V. Also, the waveform on RHS had unsharp failing edges which was the distortion caused by significantly high amplification. As shown in the Figure 18 above, the final integrated circuit had two modes which was able to be switched between ADC amplifier and comparator amplifier by placing a jumper.

Conclusion

In this session week, two approaches of analogue signal conditioning circuits were designed, verified, and integrated with the characterized Doppler radar module. A radar feed horn was added as an advanced design to enhance the signal acquisition, a filter was designed to filter out the significantly low and high frequencies so that only the frequencies of interest were preserved, and also two amplifiers were designed for ADC and comparator approaches so that the performance of either approach was to be evaluated and the better approach was to be applied. Both approaches were tested functional to interface with microcontroller but with a narrower output range than microcontroller's GPIO's. From experiments, I have learnt that the simulation can be so different than in practice that adjustments are always needed based on practical results.

References

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