High-Frequency Phase Detection

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Abstract

Phase detection plays an integral role in radio frequency (RF) systems found in particle accelerators. Since accelerating a beam requires a specific phase in the period, phase detection is necessary to determine if an accelerating cavity is at resonance with the applied RF signal. Superconducting technology has led to smaller accelerating cavities which operate at higher frequencies making phase detection a bit more complex. A phase detector was designed using a double-balanced mixer with the RF input signals passing through an ultra-fast comparator before the mixer. Analog Devices' ADCMP572 ultra-fast comparator was selected for testing of a high-frequency phase detector due to its very short propagation delay (150 picoseconds) [1].

Introduction

Phase detection plays an integral role in the radio frequency (RF) systems found in particle accelerators and, due to superconducting cavities that operate at higher frequencies, there is a need for phase detectors that can be accurate and reliable at high frequencies. Our unique challenge for this was selecting a comparator that was capable of performing ultra-fast signal changes. The technology behind phase detection offers a complex solution to an ever more complex problem. To reach the beam energies necessary to fuel the high-energy collisions of a particle accelerator, the beam is accelerated using electric fields. These accelerating cavities use a sinusoidal RF signal. Because of the alternating nature, the phase of the signal and the resonant frequency of the cavity is crucial to accelerating the beam. For instance, if the signal is 180˚ out of phase, it would effectively decelerate the beam instead of accelerating it. This effect can also allow for "bunching" of particles in the beam. This means that the particles don't travel in a steady, constant beam, but instead travel in small discrete packets of particles. Therefore, a signal's phase is important to both acceleration, and beam manipulation. This paper will discuss the design and assembly of a phase detector built using the ADCMP572 ultra-fast comparator, along with identifying further objectives that developed over the course of the design.

Design

To create our phase detector, we were first tasked with identifying the conditions at which it would operate. These conditions included the frequency range, voltage input/output, and drive range to power the mixer. While the information obtained from the phase detector built using the ADCMP572 could allow for the design of high-frequency phase detectors, it would first be tested at a lower frequency range. Also, our standards led us to design one with both a 4 V peak to peak and 20 V peak to peak output, which meant the output would need to be amplified after the mixer in two stages. Then, due to ease of operation concerns, it was desired that the detector have zero output voltage when the two input signals were phase matched. This would allow for any output from the detector to be interpreted as meaning the signals are out of phase. This output voltage could then be directed to some other feedback loop to make corrections to the RF system.

The basic components for the phase detector are two-way 90° power splitters, comparators, a mixer, a low-pass filter and two amplifier stages. A two-way 90° splitter forces one of the signals to be 90° out of phase and, while it may seem counterintuitive, it is necessary for creating the desired response. When two signals are put into a mixer, if they are phase matched, the output will be at its maximum. This is undesirable in application because no output is wanted when the signals are in phase. This is corrected by the two-way 90° splitter. Since two signals that are 90° out of phase will produce zero output when fed through a mixer, by forcing one signal 90° out of phase, it can then be assumed that zero output from the phase detector indicates that the signals were originally in phase. However, it is worth mentioning that, when dealing with phase detection applications, it is necessary that circuit length matching be maintained. This is done because any disparity in length that the signals must travel before they reach the mixer will display a phase error. Therefore, the distance that the two signals travel must be exactly the same. Because of this, it is necessary that *both* signals pass through a two-way 90° splitter before arriving at a comparator. Fortunately, in consideration of this, the two-way 90° splitters are designed to have both a 0° and 90° output to allow for circuit distance matching. Therefore, even though both signals will pass through a two-way 90° splitter, only one of them will have its phase altered 90° and the other will pass through unaltered.

The next basic component of the phase detector is the comparators. These components are crucial in phase detection as they convert the signals to a square wave before they reach the mixer. Since the mixer is sensitive to phase difference and amplitude difference, a comparator is used to produce a square wave with fixed output amplitude. This way the mixer is only sensitive to phase changes. To maintain accuracy in phase detection, it is necessary that the output from the mixer be completely linear. To achieve this, a triangle wave output from the mixer is necessary, and is only obtainable with two square-wave input signals. The comparator was configured to work as a zero crossing detector. If the input voltage is greater than the zero volts, the output from the comparator will be at its maximum output voltage. Also, if the input voltage is below zero volts, the output will be at its minimum [2].

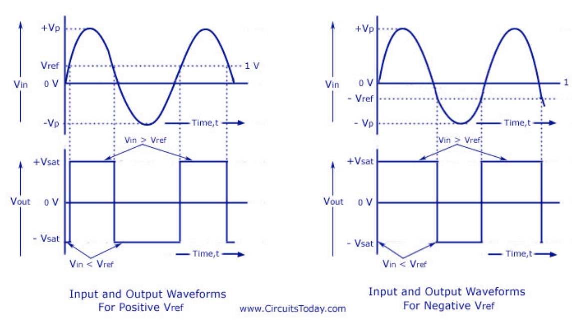

Figure 1
As the signal crosses the x-axis the comparator's output changes in response.

However, voltage change is not instantaneous, so it is impossible to obtain a perfect square-wave (figure). This delay is referred to as the comparators propagation delay, and, for a high-frequency phase detector, it is desired that it be as short as possible due to the high frequency of the input signals.

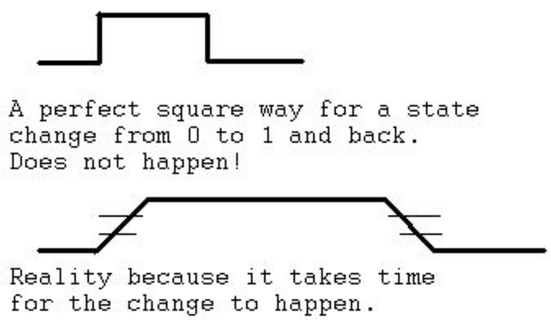

Figure 2
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Therefore, Analog Devices' ADCMP572 ultra-fast comparator was selected due to its low propagation delay (150 picoseconds). The ADCMP572 is capable of switching logic states at least three times quicker than the next fastest comparator on the market (MAX9600), which made it the best choice for a high frequency phase detector.

After the signals are converted to a square wave, they are put through a mixer. The mixer performs the vital function of the phase detector and allows us to compare the phase of the two signals. The output from the mixer generates new signals that include the sum and the difference of the two signals according to the equation: $\cos(\omega_1)\cos(\omega_2) = [\cos(\omega_1 + \omega_2)]/2 + [\cos(\omega_1 - \omega_2)]/2$ [3]. Since the signal generated by the sum of the two frequencies will be much higher frequency than the difference signal, it can be filtered out with a low-pass filter, allowing only the difference signal to pass through. If filtered correctly, any output means that the output voltage is directly proportional to the difference in phase only.

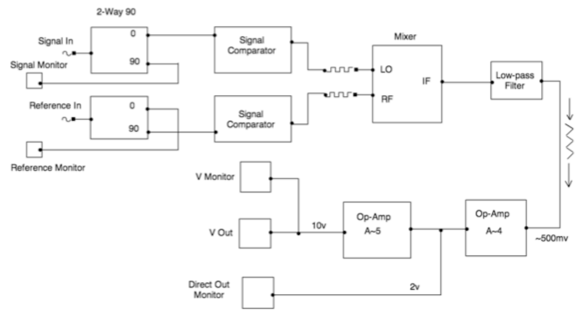

Figure 3
Basic block diagram of planned circuit

Development

Once the phase detector was designed, we then began evaluation of our circuit. First, the comparator evaluation boards were wired and terminated as necessary. Then the square wave output from the comparators was tested with an oscilloscope. Due to the short propagation delay that was seen from the signal (see Figure 1 in appendix), it was confirmed that the comparator would be sufficient for our phase detector. However, it was still possible that the comparator's response could change as more components were added. It was also observed that the signal had a direct current (DC) component. This would have to be removed before the signals could be fed into the mixer. To fix this, a DC blocking capacitor was added to the circuit after each comparator. The signals were then fed into the mixer and the output was measured using an oscilloscope. After seeing irregularities in the output of the mixer, it was apparent that there wasn't sufficient power to drive the mixer. Therefore, it was necessary to amplify the signals before they reached the mixer. After calculating the gain needed to drive the mixer, amplifiers were added following the comparators. These were successful in amplifying the signals to the level necessary to drive the mixer (7 dBm), and as a result, the desired linearity was seen from the mixer output. However, the signal still contained higher order harmonics that would need to be filtered for an accurate reading. A Butterworth low-pass filter was designed with a cutoff frequency of 5 megahertz (mHz). This was then added to our circuit after the mixer, and produced the desired filtering of any higher order harmonics present in the signal (appendix Figure 2). The output from the mixer at this point was roughly 630 millivolts (mV) peak to peak. However, we wanted to amplify this output and generate two outputs. One would have an output of 4 V peak to peak, and the second would have an output of 20 V peak to peak. This amplification would be achieved in two stages to allow for a researcher to use either output, depending on the application. A used circuit board was repurposed for the phase detector, and, using the potentiometers (variable resistors) already present within it, the necessary amplification was achieved with great precision.

Testing

With the phase detector assembled, further testing was required. It was observed that a significant DC offset was present from our mixer. This meant that with only one signal feeding the mixer, an output voltage was still present. To correct this, additional circuit length was added to one signal path before it reached the mixer. Also, overshoot in our signal was observed following the DC blocking capacitors (appendix Figure 3). This was leading to a very slight curve in the signal following the mixer. To rectify this, a different output was used from one of the comparators, which caused the overshoot in one signal to precisely mirror the other. Once fed through the mixer again, these irregularities canceled each other out, producing the desired linearity. It should be noted, however, that this correction is not ideal in all situations and this capacitance issue may require further research for future projects.

Conclusion

The phase detector designed using the ADCMP572 shows promise in its application. The comparators performed according to expectations in regard to their propagation delay. This performance could allow for more accurate and reliable phase detection in future high-frequency applications, along with better performance in standard phase detection. However, due to the time frame available for the design and assembly of the phase detector, there is still much to be determined. For instance, due to some of the components present in our phase detector, it was not possible to test its response to frequencies larger than 100 Mhz. Further research would involve replacing these components with ones that would operate at the higher frequencies. However, due to the proof of concept obtained here, these objectives could be realized with little delay and a high-frequency phase detector could be designed quickly in response to a researcher's need for one.

Acknowledgements

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References

[1] Analog Devices. "*Analog Devices* ADCMP572 Datasheet." N.p., 2009. Web. 22 July 2013.

[2] "Comparator." *Wikipedia*. Wikimedia Foundation, 25 July 2013. Web. 26 July 2013

[3] Breed, Gary. "The Mathematics of Mixers: Basic Principles." *High Frequency Electronics*. N.p., Jan. 2011. Web. 26 July 2013.

Appendix

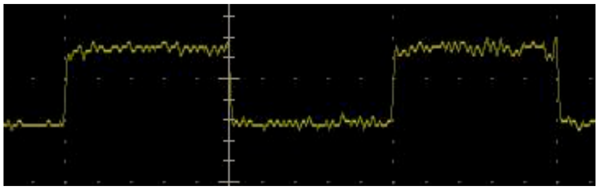

Figure 1: Scope reading displaying the comparator response signal.

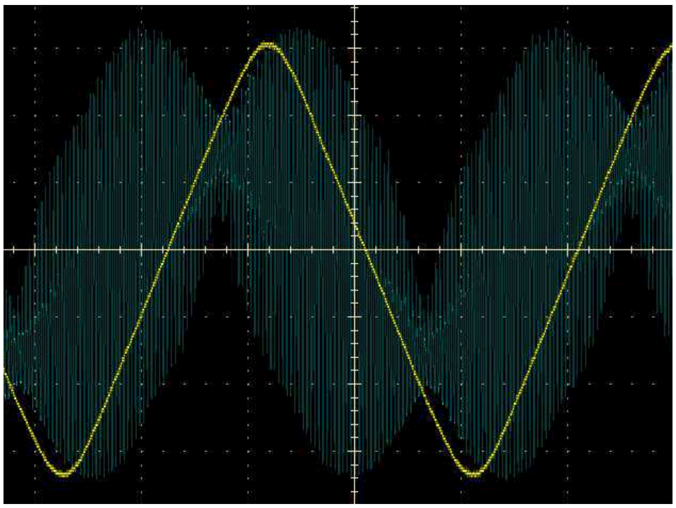

Figure 2: Signal is shown before filtering (blue), and after (yellow).

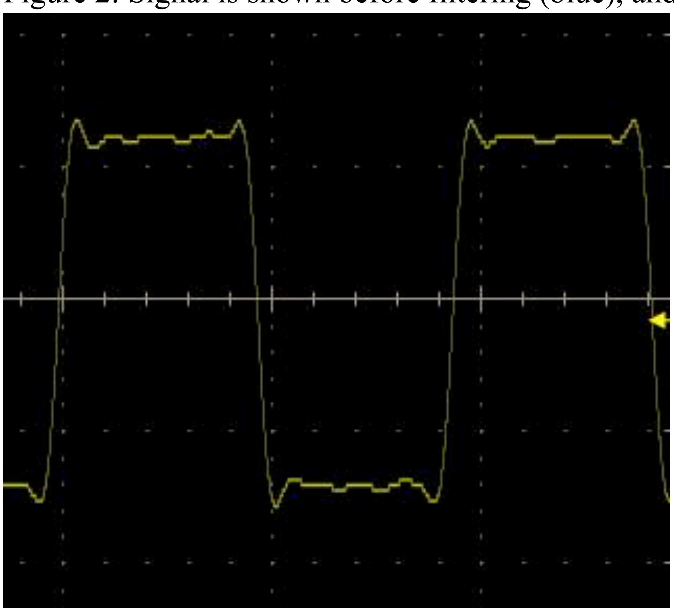

Figure 3: Overshoot in the rise/fall response of the signal following the DC blocking capacitor.