Small displacement detecting method based on multifrequency continuous wave radar system

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Abstract. A small displacement becomes important indicator in identifying a problem that may rises in several systems. Non-Contacting sensor is needed for small displacement detection in several field such as structure health monitoring, landslide monitoring and human vital sign detection. Radar system is potentially implemented as non-contacting sensor for previous mention problems. Detection of small displacement on a target using a radar system requires high accuracy and resolution which gives the consequence of a wide bandwidth requirement. The method of multi-frequency continuous wave radar is then investigated and proposed as a method for detection of small displacement with low bandwidth requirements. Cross correlation and IQ demodulation techniques are applied in post processing. Theoretical analysis and simulation were conducted to study the concept of the proposed method. The results show that the proposed method can determine the location and magnitude of small displacement.

1. Introduction

Small displacement in millimeter or centimeter scale is observed to identify a problem that may arise in several fields such as structure health monitoring, landslide monitoring and detection of human vital signs. For several cases, a non-contacting sensor is more precise to be implement than contacting sensor in detecting small displacement. Contacting sensor have some practical difficulties when to be used in detecting a vibration on boiler tank or large mechanical structure. For this case, the development a non-contacting sensor based on reflection coefficient measurement was studied [1]. However, the method can’t be used to measure at a large distance. The non-contacting sensor must be placed near the target. The radar system potentially to overcome the measurement distance problems in previous method. Radar system has also been studied in developing non-contacting sensor in many problems such as structure health [2], landslide [3] and human vital signs monitoring (respiration, heart beat) [4, 5]. The small displacement is used as indicator of the problem that may rise on the previous mention cases. For small displacement in a millimeter or centimeter scale, high resolution radar is required. Wider bandwidth of radar signal is required for high resolution detection in the conventional radar point of view. In the other side, the complexity will rise in realization the radar system with wider bandwidth and the interference problem possibility should be carefully considered in the radar operation.

Processing of phase data of radar signal has been studied as a method for high accuracy detection. However, the phase repetitions for a target distance which larger than wavelength becomes limitation in detection capability that need to be overcome. There are several radar technologies that can be used...
in detecting object including impulse, continuous wave (CW) and frequency modulated continuous wave (FMCW) [6]. FMCW radar has widely studied for many applications. Several methods for improving the radar resolution by enhancing the spectral computation [7-9]. However, it still difficult to achieve the detection accuracy for small displacement cases. CW radar is the simplest radar system which requires lower bandwidth in comparison with impulse and FMCW. However, the CW radar is only capable to determine the speed of movement but can’t determine the distance or displacement. Impulse and FMCW have more complex system that require a larger bandwidth. Considering the advantage of CW radar that requires a smaller bandwidth, modify CW radar system to develop its capability in detecting a displacement will give a significant contribution in the development of radar system for small displacement detection.

This paper proposes a modification of CW radar to establish its capability in detecting a small displacement. The modification is done by generating multi frequency sinusoidal signal in transmitter side and developing appropriate post processing in software side. The results showed that the multi frequency CW radar system that proposed could detect small displacement in millimeter scale.

This paper is organized as follows. The first section discussed about the background that motivates the proposed method and problems that addressed in this research. The second section described theoretical perspective of the multi frequency CW radar that proposed for small displacement detection. The third section contains an analysis of the simulation results undertaken to assess the ability of the proposed system and the last is the conclusion.

2. Proposes multi-frequency CW system

The CW radar basically is consisted of sinusoidal signal generator, power splitter, power amplifier and transmitting antenna at transmitter side and low pass filter, mixer, low noise amplifier and receiving antenna at receiver side. Block diagram of CW radar system is shown on figure 1. CW radar system transmits electromagnetic waves with a single frequency of \( f_1 \) and target distance to the radar will affect the phase shift in the reflected wave that received by radar. If the distance between target and radar is \( d_0 \), then the transmitted waves that reflected by the target will arrive at the receiver with phase shift of \( 4\pi d_0/\lambda_1 \). \( \lambda_1 \) is the wavelength of transmitted waveform. The received waveform can be written as (1). The reflected wave is then mixed with the transmitted signal in the mixer. Furthermore, the component of phase difference from mixer output is selected using lowpass filter (LPF) and the LPF output is the dc signal that related to phase shift (2). When a small displacement (\( d_t \)) occurred on the target, the target distance to the radar and corresponding phase shift change respectively to \( d_0 + d_t \) and \( 4\pi(d_0 + d_t)/\lambda_1 \). Furthermore, the LPF output can be written as (3).

![Figure 1. Block Diagram of CW radar system.](image)

Information on target distance and is difficult to estimate using phase data in (2) and (3) because the phase repeats periodically corresponding to the wavelength of the CW signal. The distance information that allows to be estimated with phase data is a limited shift in the wavelength range.
However, the output of LPF such as (2) and (3) is a dc value consisting of amplitude and phase data which difficult to be extracted.

\[ S_{RX}(t) = A_R \cos(2\pi f_1 t + \theta_1 + \frac{4\pi d}{\lambda_1}). \]  

(1)

\[ S_{LPF}(t) = A_L \cos \left( \frac{4\pi d_0}{\lambda_1} \right). \]  

(2)

\[ S_{LPF}(t) = A_L \cos \left( \frac{4\pi(d_0+d_f)}{\lambda_1} \right). \]  

(3)

This paper proposes a several modifications of CW system, both in hardware and post processing parts. In order to overcome the phase repetition problem in CW output, the multi frequency sinusoidal signal generator is employed at transmitter side. The non-periodic signal then can be formed by combining the multi frequency sinusoidal signal. LPF2 is added at receiver side to extracted reference signal for demodulation and cross-correlation calculations. The block diagram of the multi frequency CW radar that proposed in this paper is depicted in figure 2. IQ demodulation technique usually was employed in estimating the phase of signal. Therefore, the IQ demodulation technique is used to estimate the phase data. However, in several previous researches, the IQ demodulation is located at radio frequency (RF) part [10, 11]. To avoid the significant modification in hardware side, we proposed performing the IQ demodulation in postprocessing side.

The proposed method uses a multi-frequency sinusoidal signal generator on the transmitter, but only one of the frequencies is used as a reference signal for the mixer process at the receiver. The signal that chosen as the reference is the lowest frequency sinusoidal signal. Multi-frequency CW radar signal which is then transmitted from the transmitter is then written as (4) where \( N, A_n \) and \( \theta_n \) are respectively as the number of frequencies used, the amplitude of each sinusoidal signal and he initial phase of each sinusoidal generator. The transmitted signal that reflected by the target and received by the receiver can then be written as (5) with \( \lambda_n \) is the wavelength of corresponding to each sinusoidal signal. Afterward, the signal is then mixed with a reference signal and the mixer output can be written as (6). The frequency difference components are then selected using LPF1 and the output of LPF1 can be expressed as (7). The LPF1 output is a sum of sinusoidal signals whose frequency is the frequency difference between each sinusoidal signals and reference signal. In each element of the sinusoidal signals there is a phase shift that corresponding to the distance between the target and the radar (d).

\[ S_{TX}(t) = \sum_{n=1}^{N} A_n \cos(2\pi f_n t + \phi_n). \]  

(4)

\[ S_{RX}(t) = \sum_{n=1}^{N} B_n \cos(2\pi f_n t + \phi_n + \frac{4\pi d}{\lambda_n}). \]  

(5)

\[ S_{rf}(t) = \sum_{n=1}^{N} C_n \cos(2\pi(f_n + f_1)t + \phi_n + \frac{4\pi d}{\lambda_n}) + \sum_{n=1}^{N} D_n \cos(2\pi(f_n - f_1)t + \phi_n + \frac{4\pi d}{\lambda_n}). \]  

(6)

\[ S_{LPF1}(t) = \sum_{n=1}^{N} E_n \cos(2\pi(f_n - f_1)t + \phi_n + \frac{4\pi d}{\lambda_n}). \]  

(7)

\[ S_{loopback}(t) = \sum_{n=1}^{N} F_n \cos(2\pi(f_n - f_1)t + \phi_n). \]  

(8)

\[ r_{LR}[k] = E[S_{LPF1}[k], S_{loopback}[l-k]] \]  

(9)

\[ S_{LPF2}(t) = G_n \cos(2\pi(f_2 - f_1)t + \phi_n + \frac{4\pi d}{\lambda_n}). \]  

(10)

Switch that connecting between the transmitter and receiver sections are used to determine the loop back signal which is then stored and used as reference in determining the initial distance (d_0) between the target and radar. The initial distance is determined by performing calculation of the cross
correlation between the loop back signal and the target signal as written in (9). Afterward, the target distance can be estimated from the peak position of normalized cross-correlation result.

**Figure 2.** Block Diagram of proposed Multi-frequency CW radar for small displacement detection.

The displacement that may occurred on the target is determined from the phase data of LPF2 output signal. The phase data of LPF2 output can be determined by applying IQ demodulation processing that also discussed in [10, 11]. A sinusoidal signal with the same frequency as low pass filter output is needed in IQ demodulation method. After detecting the frequency of low pass filter output using FFT in numerical computation domain, then the reference sinusoidal signal that needed in IQ demodulation is easily synthesized. Further, the low pass filter output then mixed with sinusoidal signal that has synthesized before.

The theoretical analysis that discussed in this section indicated that the proposed method has capability to estimate the location ($d_0$) and small displacement ($d_1$) that happen on the target. The proposed method, basically is a modification and improvement in CW radar system to make the CW radar system has an ability to detect small displacement while maintaining low bandwidth.

### 3. Results and analysis

Computer simulation was performed to verify the theoretical analysis that discussed in section 2. Superposition of multi-frequency sinusoidal signal result a radar signals with pulse shapes with a certain period. In this section the simulation is performed with multi-frequency signal of $[f_1, f_1 + \Delta, f_1 + 2\Delta, ..., f_1 + (N - 1)\Delta]$, where $f_1 = 10$ GHz is the lowest frequency, $\Delta = 1$ MHz and $N$ is the number of frequency that used in multi-frequency. 10 GHz is selected Considering to the small displacement resolution scale that need to be achieved. The pulse width is determined by the number of frequencies that used ($N$). From the radar signal then there is an opportunity to detect a target position through cross-correlation computation.
The figure 3 shows the effect of $N$ on the shape of the radar transmitted waveform. $N$ must be greater than 2 to obtain a pulse signal. Increasing of $N$ cause the pulse signal that reconstructed has narrower pulse width. It can be understood that increasing of $N$ means the increasing the bandwidth. Therefore, the pulse associated to the multi frequency signal has narrower pulse width. The initial position of the target (small displacement) that monitored is then determined by the cross-correlation between the LPF1 output of the reflected signal with the loopback signal. The cross-correlation results of three different target positions are shown in figure 4. According to the result in figure 4, the distance of the target from the radar can be determined and then becomes important information that indicates the location of the small displacement ($d_0$).

Figure 3. Transmitted signal from multi-frequency CW radar with four different N value.

Figure 4. Cross correlation of $S_{LPF1}$ with $S_{loopback}$ that used to determine the target distance ($d_0$) for three different target locations.
Consider to the ability of the proposed method in detecting the location of the target, this concept allowing the radar system that proposed having capability for detecting small displacement on multiple targets. However, the accuracy of estimating the target distance from cross-correlation result is limited to the sampling frequency that used to discretize the LPF output. It causes the small displacement at the order of millimetre or centimetre is difficult to detect. In the proposed method, the small displacement ($d_t$) is determined by computational IQ demodulation as shown in figure 2 against the LPF2 output. The results in figure 5 show the results of small displacement detection for different values at a target with 6 m from the radar. The cross-correlation is used to estimate the location of small displacement and the IQ demodulation is used to estimate the small displacement that occurred at the target. IQ demodulation that is performed in postprocessing side can minimize the change in hardware part.

4. Conclusion

The multi-frequency CW radar was proposed as a method for detecting small displacement. The theoretical and simulation analysis were conducted to investigate the proposed method. The proposed method is a modification of the CW radar by using a multi-frequency generator and two post processing methods. Cross correlation computation is applied to determine the target position whereas IQ demodulation computation is applied to determine the small displacement that occurs. In order to obtain a loopback signal as reference in determining the target distance, a radio frequency switch is added to connect transmitter and receiver section. Switch activation is only done once when starting the measurement and then the loopback data can be stored in memory. Performing the IQ demodulation process in postprocessing part can avoid or minimize the change in hardware part. The results show that the proposed method has ability to detect small displacement at a certain location and possible realized with low bandwidth requirements.

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