Dual Frequency Continuous Wave Radar for Small Displacement Detection

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***Abstract*— In several field such as structure health monitoring, landslide monitoring and medical measurement, small displacement is used as the indicator of any problem that may rise in such fields. High resolution radar system is required for small displacement detection in millimeter of centimeter scale. Continuous wave (CW) radar with its narrow bandwidth feature, has a simpler system comparing with other radar system. However, the modification is needed to present the ability of CW radar in detecting small displacement. In this paper, dual frequency CW radar was investigated and proposed for small displacement detection. Computer simulation has been conducted to study the capability of the proposed radar system. The result shows that the dual frequency CW radar at 10.525 GHz is capable to detect a small displacement in millimeter scale. The frequency difference of the radar signal needs to be adjusted to avoid the ambiguity in the detection result.**

Keywords*— *continuous wave (CW) radar, small displacement, dual frequency.

I. Introduction

Small displacement is used to identify any problem that may rise in several field such as landslide monitoring, structural health monitoring and medical measurement. Radar system was studied to be implemented in detecting small displacement. Some studies have been developing the Synthetic Aperture Radar (SAR) system that applied to detect a landslide [1-3]. SAR technology uses pulse waveform that having ultra-wideband (UWB) characteristic [4]. UWB characteristic provides a fine resolution and an accurate sensing. However, a wideband radar signal usage, gives some consequences, such as increasing the realization complexity and giving interference in mitigations problems.

A feasible way to distinguish between received and transmitted radar signal is by recognizing the change of echo signal frequency in receiver. It is known as doppler effect [5]. The change of this sinusoidal echo signal gives impact to its phase. From the phase data, the displacement is potential to be estimated. Phase component processing have been studied for high accuracy detection in radar system. Phase repetition for large target distance, become limitation that need to be considered. Doppler radar can be realized using Continuous Wave (CW) radar system, Frequency Modulation Continuous Wave (FMCW) radar system and Impulse radar system. CW radar system has a narrower bandwidth and simpler among other radar system that previously mentions.

CW radar can only detect a dynamic target such as vibration. A vibration may be viewed as time varying small displacement event that occurred on an object. According to this fact, on CW radar advantages feature such as narrow bandwidth and simple structure, CW radar system is potential to be developed as the radar system for small displacement detection. However, a modification of CW radar system is required to develop its capability in detecting small displacement. HB100 is a CW radar module that operates at 10.525 GHz [6]. Due to the transmitted frequency, the transmitted signal that has a wavelength of 28.5 mm. The objective of this research is to investigate the potential of HB100 to be used in developing CW radar system for small displacement. The theoretical and simulation investigation is then discussed in this paper as the preliminary step in developing prototype of the proposed radar system that based on HB100.

This paper proposed a modification scheme for CW radar which deals with small displacement detection. The dual frequency CW radar system was investigated and proposed for small displacement detection. The theoretical and computer simulation have been performed to study its ability in detecting a small displacement.

This paper is organized into four sections. Introduction section discusses about the background and problems that addressed in this research. Section II explains the proposed method and the theoretical overview. The simulation and its result are discussed in section III and the last is conclusion.

II. Proposed Method

The proposed modification takes place on transmitter and receiver part. In transmitter part, we used two sinusoidal signal generators with different frequency, respectively as f_1 and f_2. The modification in receiver is mainly done on the postprocessing of Low Pass Filter (LPF) output. The block diagram of the proposed dual frequency CW radar is depicted by Fig.1. Summation of sinusoidal signals from generator is then transmitted to the target and amplified by the power amplifier (PA). The transmitted signal of the proposed radar can be written as (1).

$$S_{TX} = A_0 \cos(2\pi f_1 t) + A_0 \cos(2\pi f_2 t), \qquad (1)$$

A_0 is the amplitude of the transmitted signal and t is the time of since the signal is transmitted until received. The square block in Fig.1 illustrates the target where small displacement is occurred. The transmitted signal that arrived at the target is reflected to the radar and received at receiver

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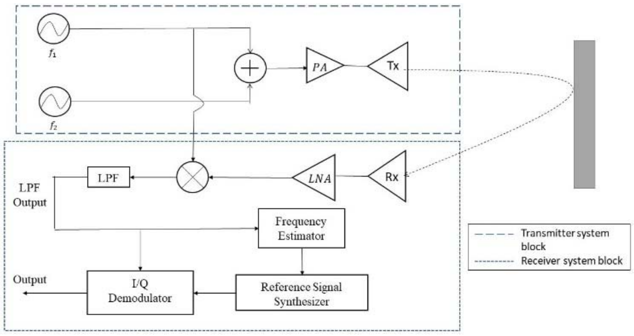

Fig. 1. Block diagram of Dual Frequency Continuous Wave Radar.

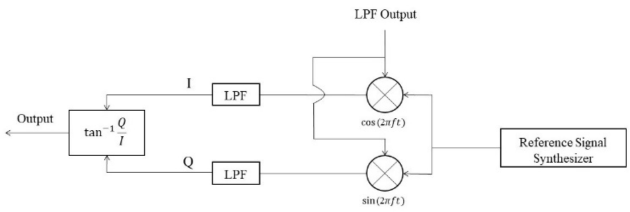

Fig. 2. Block diagram of I/Q demodulator.

side. The received echo signal is amplified by the low noise amplifier (LNA), and can be expressed as (2).

$$S_{Rx}=A_1 \cos\left(\frac{2\pi 2d}{\lambda_1}+2\pi f_1 t\right)+A_2 \cos\left(\frac{2\pi 2d}{\lambda_2}+2\pi f_2 t\right), \quad (2)$$

A_1 and A_2 are the amplitude of the echo signal with the frequency of f_1 and f_2, respectively.

The echo signal is mixed with the signal from oscillator 1 (f_1). Then, the LPF output contains sinusoidal echo signal and direct current (DC) component, it can be written as (3).

$$S_{M0}(t)=A_1' \cos\left[2\pi(f_2-f_1)t+\frac{2\pi 2d}{\lambda_1}\right]+A_2' \cos\left(\frac{2\pi 2d}{\lambda_2}\right), \quad (3)$$

The displacement data can be obtained from the phase shift data $\left(\frac{2\pi 2d}{\lambda_1}\right)$of the sinusoidal echo signal, with d is the displacement range that occurred, and λ_1 is the wavelength of the signal. The sinusoidal echo signal is shown in (4).

$$S_{LPF}(t)=A_L \cos\left[2\pi(f_2-f_1)t+\frac{2\pi 2d}{\lambda_1}\right]. \quad (4)$$

A_L is the amplitude of sinusoidal component of echo signal. The frequency estimator detects the frequency value $(f_2-f_1)t$) or can be written as *df,* of sinusoidal component. Then, the reference signal synthesizer generates sin and cos signal with the value of frequency that has been obtained in the frequency estimator. The frequency estimation can be performed by applying the Fast Fourier Computation of the LPF output. The frequency estimation must be done before the proposed radar is operated to detect the small displacement. The reference signal is a sinusoidal signal of LPF output when the transmitter is directly connected to receiver, this connection named as a loopback connection. The reference signal is decomposed in two orthogonal signals, with the amplitude of A_r, then are written as (5) and (6).

$$S_{ref\_I}(t)=A_r \cos[2\pi(f_2-f_1)t]. \quad (5)$$

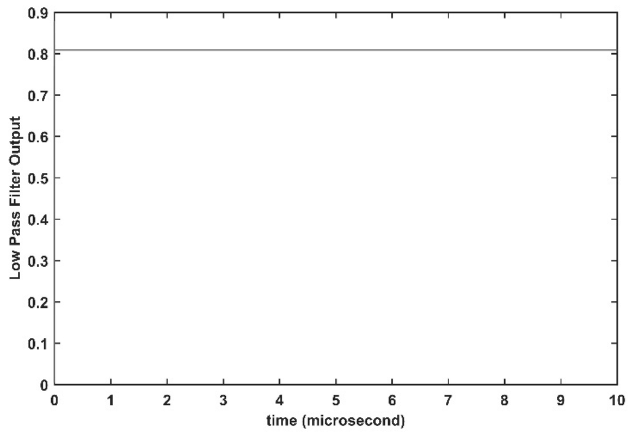

Fig. 3. Single frequency LPF output.

$$S_{ref\_Q}(t)=A_r \sin[2\pi(f_2-f_1)t]. \quad (6)$$

Those sinusoidal signals, sin and cos, are then used in I/Q demodulation process. I/Q stands for in-phase and quadrature, which means there are two sinusoidal signals with 90° phase difference [7]. The block diagram of I/Q demodulator can be shown in Fig.2. The $S_{ref\_I}(t)$ is reference signal for in-phase (I) and $S_{ref\_Q}(t)$ is reference signal for quadrature (Q).

Those two reference signals are then mixed with LPF output in (4) and the results are expressed as (7) and (8), with the value of amplitude are A_I and A_Q for in-phase and quadrature signal, respectively. The LPF at in-phase and quadrature section is used to eliminate the higher frequency component, then the LPF output at both section is written as (9) and (10). These LPF outputs are contain the data of the displacement (d).

$$S_I(t)=A_I \cos[4\pi(f_2-f_1)t]+A_I \cos\left[\frac{2\pi 2d}{\lambda_1}\right]. \quad (7)$$

$$S_Q(t)=A_Q \sin[4\pi(f_2-f_1)t]+A_Q \sin\left[\frac{2\pi 2d}{\lambda_1}\right]. \quad (8)$$

$$S_{LPF\_I}(t)=A_o \cos\left[\frac{2\pi 2d}{\lambda_1}\right]. \quad (9)$$

$$S_{LPF\_Q}(t)=A_o \sin\left[\frac{2\pi 2d}{\lambda_1}\right]. \quad (10)$$

The phase shift degree can be determined by performing arcus tangent calculation of LPF output of in phase and quadrature sections. Finally, the phase detector output computation is done referring to (11).

$$S_{PD}(t)=tan^{-1}\left[\frac{S_{LPF\_I}(t)}{S_{LPF\_Q}(t)}\right]. \quad (11)$$

III. Result and Discussion

This system is simulated by MATLAB software. Refers to HB100 module [6], the transmitted frequency (f_1) of this system is 10.525 GHz. By shifting the second frequency (f_2), the bandwidth of the system is obtained with the value of *df.* The initial distance between target and radar is assumed to be known. In this simulation the initial distance is set to be 2.85 m, as the experiment of the radar are going to be done in a room.

If the system only use a single transmitted frequency (f_1), f_2 is equal to zero, then the LPF output in Fig.1 is in a form of direct current (DC) signal. The DC signal of LPF output is

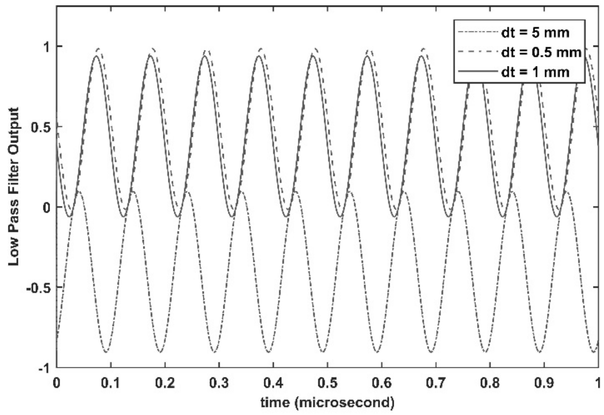

Fig. 4. Dual frequency LPF output.

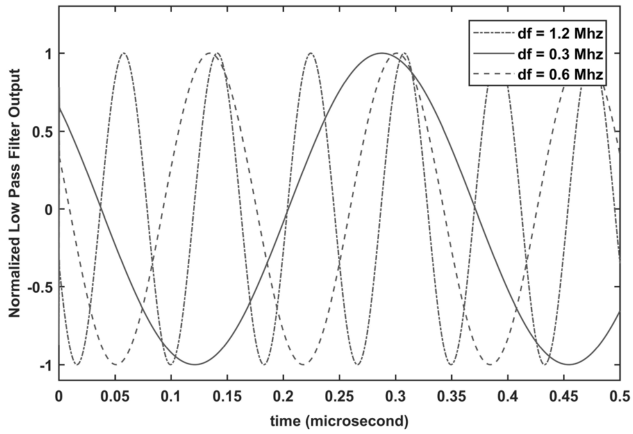

Fig. 5. Normalized dual frequency LPF output.

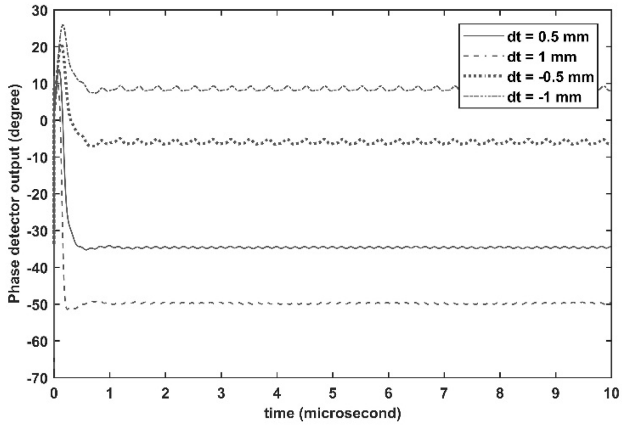

Fig. 6. Phase detector output of dual frequency CW radar.

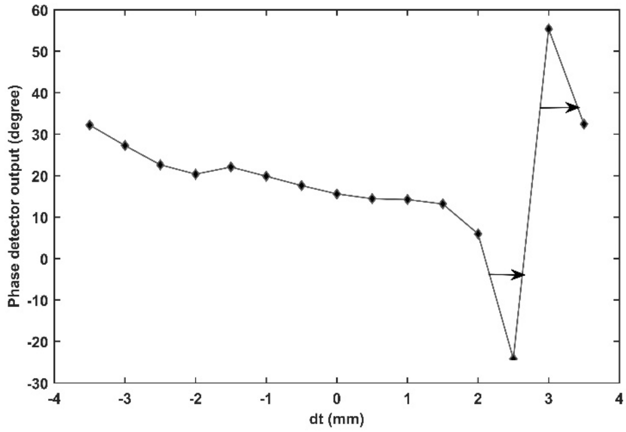

Fig. 7. Phase detector output of dual frequency CW radar with 0.3 MHz bandwidth.

shown in Fig. 3. The phase data is implicitly contained in its DC signal, then the phase data is difficult to be extracted from there. For phase component detection, the sinusoidal output is needed to be generated. By modifying the transmitter with dual frequency, the LPF output on Fig.1 is then in a sinusoidal form. Afterward, the phase data can be determined using I/Q demodulator.

Fig.4 shows the LPF output of Dual Frequency CW radar that proposed. In this result the value of *df* is set to 0.3 MHz and the simulation is performed for three different small displacement values (*dt*). These three LPF output in Fig.4, are having the same frequency with different phase with each other. This phase shift contains the displacement data of the target. But, the displacement data cannot be directly obtained from this LPF output, because the LPF output is still in time domain. In order to make the result clearer and simpler, the normalization of LPF output is done. Normalization is a wave function scaling, so that all the probabilities are add to 1.

The normalized LPF output with different value of *df* is shown in Fig.5. The frequency of LPF output is proportional to *df*. A large *df* , causes a high frequency on LPF output and vice versa. The value of *df* give consequences to the overall bandwidth of the proposed radar system, therefore the value of *df* is expected to be small as possible.

Fig.6 shows the phase detector output for several different value of displacement (*dt*) with the value of *df* is 0.3 MHz. As expecting a small value of *df*, this value is chosen due to the narrowest bandwidth obtained from the simulation result in MATLAB. There are four value of displacements, 0.5 mm, -0.5 mm, 1 mm, and -1 mm. The magnitude of the phase detector output should be the same if the magnitude of *dt* is also the same. For a sample, in Fig.6, the phase detector output of 0.5 mm displacement is around -35°. But, on -0.5 mm displacement, the phase detector output is not 35°, it is around -5 ° . This kind of thing is happened because of the normalization process that affect the phase detector output.

The frequency difference adjustment is done by shifting the f_2. Fig.7 and Fig.8, show the phase value in 0.3 MHz and 1.2 MHz bandwidth, respectively. The ambiguity of the phase degree is shown by the arrow in both figures, where one value of phase detector degree has more than one value of displacement (*dt)*. Linearity relation between phase detector output and displacement (*dt*), determine the range of displacement detection which can be supported by the proposed radar. The relationship between phase detector output and displacement (*dt*) in Fig.8, is more linear than in Fig.7. It is mean that the bandwidth (*df)* affects to the range of displacement detection. For a certain purpose of displacement detection, the difference between dual sinusoidal signal in transmitter should be selected properly to increase the linearity of phase detector output and minimizing the ambiguity in detection result.

IV. Conclusion

In this paper, the dual frequency CW radar was proposed. The proposed radar is developed by conducting system

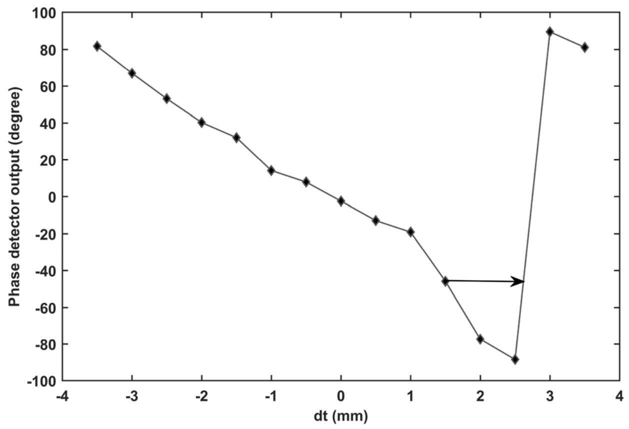

Fig. 8. Phase detector output of dual frequency CW radar with 1.2 MHz bandwidth.

modification of CW radar in transmitter and receiver part. In transmitter part, we used two sinusoidal signal generators with different frequency to obtain the sinusoidal output in conventional CW radar. In receiver part, the modification is done in postprocessing of the LPF output by adding the phase detection computation. Theoretical and simulation were conducted to study the capability the proposed radar system. The result shows that the proposed modification is capable to detect a small displacement in millimeter scale. The result shows that any value of displacement can be detected. In avoiding the ambiguity of phase detector output and arranging the range of small displacement detection, the bandwidth (*df*) needs to be adjusted. The smaller the bandwidth, the higher the ambiguity probability.

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