A 14 GHz Non-Contact Radar System for Long Range Heart Rate Detection

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***Abstract*-This research presents a 14 GHz CW Doppler radar to measure respiration and heart rate. A leakage cancellation technique is used to detect heart rate of human for long range detection. Arctangent demodulation without the dc offset compensation can be applied because of the heterodyne receiver structure and the leakage cancellation technique. HRV analysis of the radar system and the ECG signal which is measured directly are compared. Based on the measurement results, the radar can detect the respiration and heart rate with a small error rate.**

I. INTRODUCTION

Non-contact biosensor system have been used to detect respiration and heart rate since the early 1970s [1]. Doppler radar can detect the heart and respiration rate through clothing as non-invasive method. As interest in health increases, many research institutions have studied about the radar structure, demodulation technique, detection algorithm to achieve accurate performance. Most studies have focused on a simple structure such as direct conversion and a compact size to detect the signal within a few meters. In this paper, we adopt the heterodyne structure and leakage cancellation technique in order to complement the disadvantage of direct conversion and increase the detectable range of radar system.

II. DOPPLER RADAR SYSTEM

A. Radar Structure

Fig. 1 shows the Doppler radar system structure. The 14 GHz transmitted signal reflected by the subject goes to the receiving antenna. The gain of antenna is 16 dBi at 14 GHz. The received signal at the antenna is amplified by LAN and down converted to 11.7 GHz by mixing the signal with 2.3 GHz local oscillator. And it is down converted to 480 MHz intermediate frequency (IF) again. The IF signal is entered into the demodulator. The I and Q channels which are the outputs of demodulator are filtered, amplified, and converted the digital signal at the A/D converter. Finally, it is divided in heart signal and respiration signal and displayed on the computer.

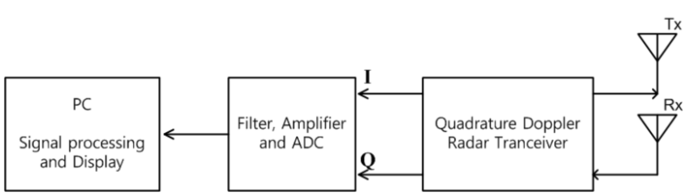

Figure 1. Block diagram of Doppler radar system for detecting heart rate.

B. Arctangent Demodulation

Arctangent demodulation in quadrature receivers can get a high accuracy in demodulation of heart and respiration signals. By applying the arctangent operation to the ratio of I and Q output of radar system, accurate phase demodulation can be achieved regardless of the target's position or motion amplitude [2].

In CW Doppler radar systems the phase displacement $\Delta\varphi$ between the transmitted and received signal is described for range detection [3].

$$\Delta\varphi = \frac{4\pi x(t)}{\lambda} + \varphi_r \tag{1}$$

with x(t) for the time-varying subject range, λ for wavelength, and φ_r for the constant phase shift by the chest movement.

Quadrature channel imbalance and dc offset act as a linear transform on the I and Q components, thus modifying (1) to

$$\begin{aligned}\varphi(t) &= \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) \\ &= \arctan\left(\frac{V_Q + A_e \sin(\theta + \varphi_e + p(t))}{V_I + \cos(\theta + p(t))}\right)\end{aligned} \tag{2}$$

where V_I and V_Q refer to the dc offsets of each channel, and A_e and φ_e are the amplitude error and phase error, respectively [4].

The direct conversion is the simplest architecture, so most of CW radar systems for detecting heart rate have used the direct conversion. But it has the disadvantage which has the dc offset.

Heterodyne architecture can reduce the dc offset, that is V_I and V_Q in (2).

C. HRV Analysis

The heart rate variability (HRV) is the physiological phenomenon of variation in the time interval between heartbeats. It is measured by the variation in the beat-to-beat interval. We compared the value of electrocardiogram (ECG) signal measured by ECG detector with the arctangent demodulation value of I and Q signals measured by radar system. The measured peak points of arctangent and ECG signals can be expressed by mean beat to beat interval, and the standard deviation of normal beat-to-beat interval (SDNN), and the root mean square of successive heartbeat interval differences (RMSSD).

D. Leakage Cancellation

The transmitted power can be more than 100dB higher than the received signal, so if even a small fraction of the transmitted power leaks into the receiver it can saturate the low-noise-amplifier or even damage the sensitive circuitry. This is the disadvantage of CW radar system. For a bi-static radar system, the majority of the leakage comes from the free space coupling between the transmitter antenna and the receiver antenna, where up to 60dB isolation can be achieved [5]. The isolation problem is more dominant when the transmitted power is increased in order to extend the detection range. The arctangent demodulation with dc offset compensation in quadrature Doppler radar has demonstrated in [4]. We can use arctangent demodulation without dc offset compensation because of heterodyne structure which has the low dc offset and leakage cancellation technique which can reduce the dc offset due to the self-mixing.

III. Measurement Results

We obtain the experimental data based on various situations. Fig. 2 shows the measurement results in time domain when the subject is 5m apart from the transmitting and receiving horn antennas. The power at the transmitting antenna is -10dBm, the leakage cancellation technique did not be applied. These signals are obtained simultaneously for the same subject. Data was collected for 20 seconds. The raw data is filtered by the band pass filter with the cut-off frequency of 0.6Hz to 2.5Hz, in order to extract the heart signal information. Fig. 2(c) is the combined arctangent signal of Fig. 2(a) and (b). The magnitude of combined arctangent demodulated output is normalized by the maximum amplitude. Fig. 2(d) shows the ECG signal measured by ECG detector. We can see that heart rate is 24 beats for 20 seconds in both arctangent demodulated signal and ECG. The all peak positions have been successfully detected in Fig. 2(c) and Fig. 2(d).

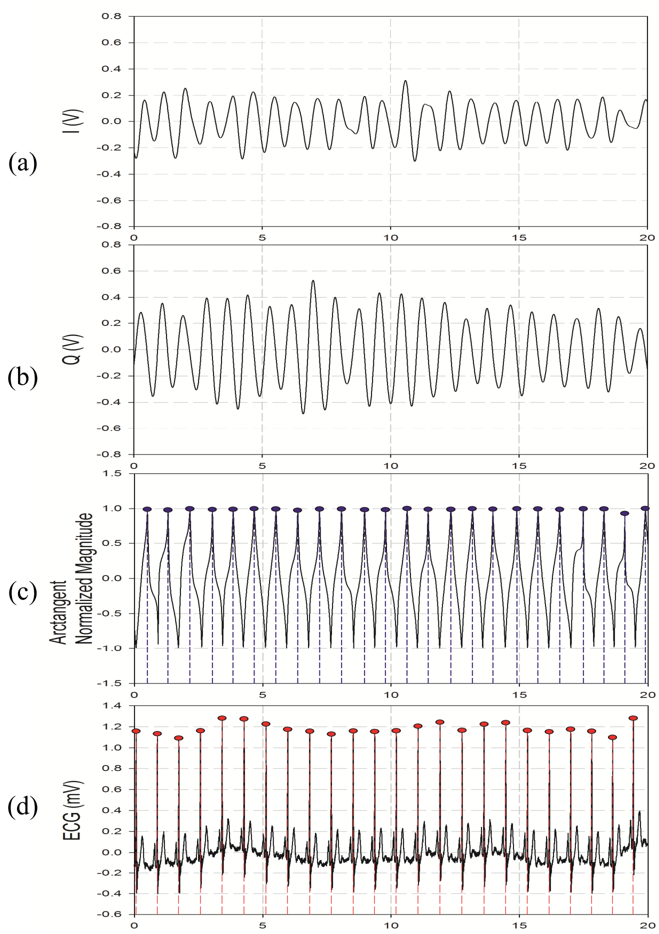

Figure 2. Measured heart signal I (a), Q (b), the combined arctangent demodulated output (c), and ECG signal (d).

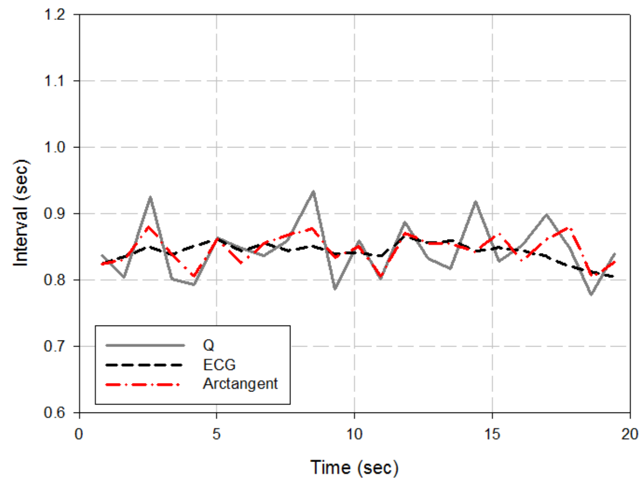

Figure 3. Beat-to-beat interval of Q signal, arctangent signal, and ECG signal.

Fig. 3 shows the beat-to-beat interval of Q, arctangent, and ECG. In order to compare the accuracy improvement of Q with arctangent, HRV analysis is shown in Table I. In case of Q-signal, RMSE is 40.87ms between Q and ECG. But in case of arctangent, RMSE is 21.16ms. The difference between measured by radar and ECG detector is smaller in case of arctangent demodulation. The difference between measured by radar and ECG detector is 19.71ms in case of arctangent demodulation. The error of SDNN and RMSSD is reduced by 16.62ms and 36.11ms, respectively.

TABLE I
HRV ANALYSIS COMPARISON Q, ARCTANGENT, AND ECG

Mean RR (ms)					
Q	ECG	RMSE	Arctan.	RMSE	|△|
845.278	841.726	40.87	845.37	21.16	19.71
SDNN (ms)			RMSSD (ms)		
Q	Arctan.	ECG	Q	Arctan.	ECG
43.20	23.58	14.77	72.87	36.76	10.3

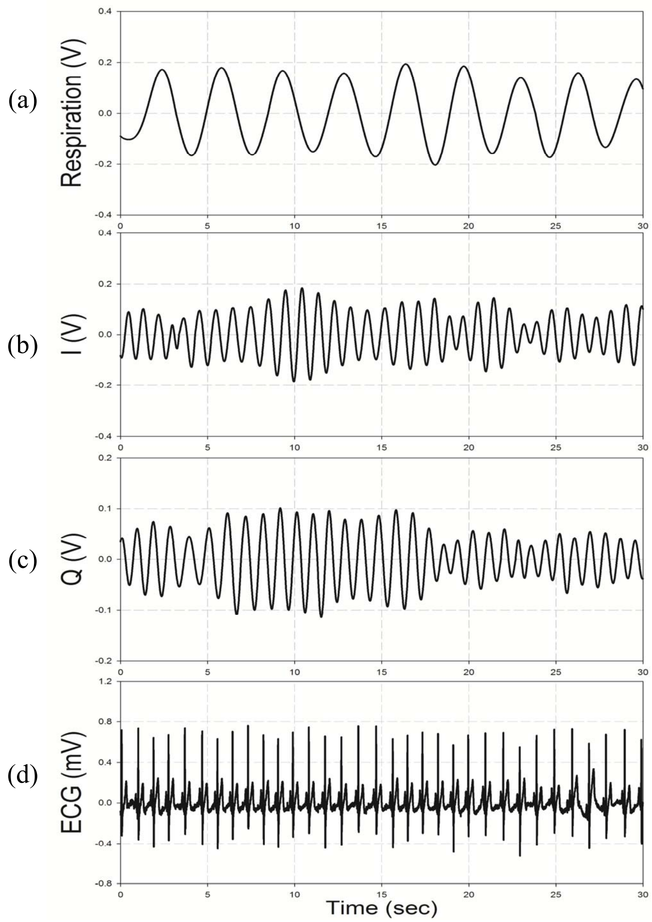

Figure 4. Measured data for respiration (a), I (b) and Q (c) output of the heart signal, and ECG signal (d) at a range of 25m.

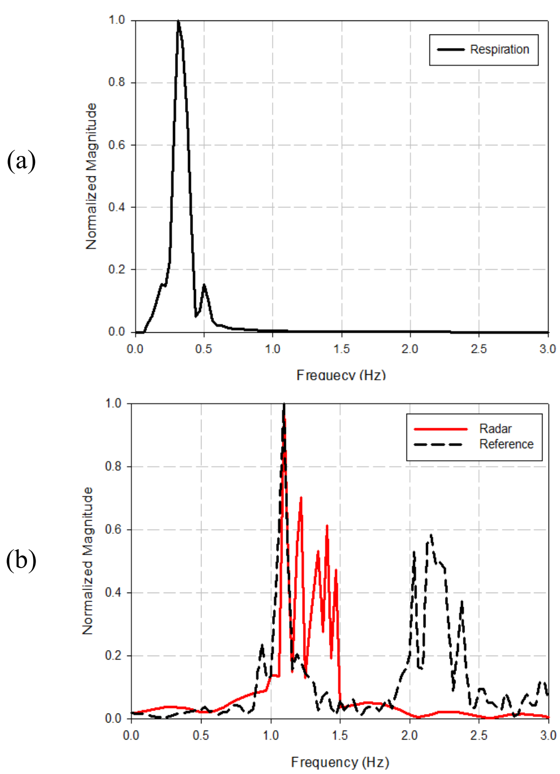

Figure 5. FFT of detected respiration (a) and heart rate (b) at a range of 35m.

To demonstrate the long range detection we increase the output power at the transmitting antenna to 23dBm. When the transmitting power is increased, the isolation between transmitting antenna and receiving antenna is dominant factor of the performance of radar system. By using leakage cancellation technique, we can get 27dB isolation improvement. Fig. 4 shows the measured results during 30 sec for radar signals at the distance of 25m. The raw data from radar have been filtered to respiration signal (a) and heartbeat (b),(c). We can see that heart rate is 33 beats for 30 seconds in both measured signal from radar system and ECG.

The FFT of measured data at the distance of 35m are shown in Fig. 5. The peak position of the respiration spectrum is 0.32Hz, which corresponds to 19.2 breaths per minute. The peak positions of the heart spectrum of radar and ECG are the same as 1.094Hz, which correspond to 65.64 beats per minute.

IV. Conclusion

This paper presents a 14 GHz CW Doppler radar system which can be used for monitoring respiration and heart rate. The Doppler radar system is tested and compared to simultaneous electrocardiogram. An exact heartbeat and respiration signals were measured and verified its accuracy by comparing HRV analysis with ECG signals. Heterodyne structure and leakage cancellation technique are able to use arctangent demodulation without dc offset compensation.

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