Harmonics Cancellation in Noncontact Microwave Doppler Radar Cardiopulmonary Sensing

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Abstract

This paper addresses the challenge of respiration harmonics cancellation in microwave Doppler radar cardiopulmonary sensing. A new signal processor based on adaptive noise cancellation is proposed. When the heartbeat signal is easily overwhelmed by the respiration harmonics, the traditional band-pass filters are used to separate heartbeat signal from the respiration signal, then the LMS-based multi-notch filter is implemented to filter the respiration harmonics. Experimental results from a 2.4GHz continuous wave Doppler radar show that the respiration harmonics can be effectively removed and more accurate measurement of heartbeat rates can be obtained.

Keywords: Microwave Doppler Radar, Adaptive Notch Filter (ANF), Vital Sign Detection (VSD), Respiration and Heartbeat.

1. Introduction

Respiration and heart rates have been monitored for more than a century to aid in the diagnosis of pathological conditions in medicine and related fields. While traditional medical devices for monitoring respiration and heart rate are performing with electrodes and sensors touching the subject, the novel non-contact Doppler radar has been introduced to sense human cardiopulmonary activities remotely since 1970s [1]. As the Doppler radar can detect respiration and heartbeat rates in a non-invasive way, it is no longer painful to some patients, especially the burned victims, and can minimize disruption of the subject’s activity, thus, is more suited to applications where extended monitoring is needed, such as health monitoring. In addition to the potential use in healthcare, Doppler radar can be applied to emergency rescue situations, such as earthquake and fire rescue where it is impossible to approach the subject trapped under debris, and can provide a quick tool to locate the victims. Furthermore, due to its through-wall nature, Doppler radar can be used for security applications where non-cooperated subjects are present, such as airport security, military checkpoints.

In the last decade, great efforts are made to accurately detect respiration and heartbeat rates using noncontact Doppler radar. To avoid “null” point problem in single-channel receiver Doppler radar, quadrature I/Q receiver has been proposed and better output of two channels is used to detect the required frequencies [2]; then two commonly demodulation methods, namely arctangent demodulation and complex demodulation are further introduced [3-4]. To achieve robust penetration performance, Chen et al. designed and investigated Doppler radars operating at 450 MHz, 1150 MHz and 10 GHz [5-6]; other Doppler radars operating at frequencies such as L, Ka-band were also reported to get higher detect sensitivity [2-3, 7]. Recent years, advanced signal processing and radar technologies that include multiple-input, multiple-output technique for detection of multi-subjects [8-9], cancellation of body movement and fidgeting [4, 10], robust spectral RELAX algorithm for accurately discriminating the heartbeat and respiration frequencies [11], adaptive noise cancellation for extracting heartbeat signal [12], reassigned joint short time Fourier transform for heart rate variation detection [13] were also presented.
Most existing frequency estimation techniques above are based on Fourier transform. After transforming the received radar signal into its spectrum, the frequency estimates correspond to the locations of dominate peaks of spectra. However, when respiration and heartbeat rates are simultaneously measured, the heartbeat signals suffer from the respiration harmonics or inter-modulation interferences, and are sometimes overwhelmed by the respiration harmonics, making it impossible to detect the heartbeat rates accurately [11].

The aim of this paper is to filter out the respiration harmonics mixed with heart signal. When the traditional IIR or FIR is not appropriate, we propose to subtract these harmonics from the filtered heartbeat signals in the time domain. The harmonics are not precisely known, but their frequencies can be obtained after respiration rate is measured, this fact motivates us to use the adaptive noise canceling (ANC) technique to iteratively adjust the phase and amplitude of reference inputs to approach the harmonics. This is actually the adaptive notch filter (ANF) process. Experimental results from a real continuous microwave Doppler radar show that the harmonics can be effectively filtered and more reliable measurement of heartbeat rates can be produced.

The rest of paper is organized as follows. Section 2 gives the signal model to describe the harmonics problem. Section 3 presents the signal processing techniques, where the simple description of Doppler radar is also given. In section 4, experimental results are presented to validate the signal processor, and section 5 gives the discussion. The last section concludes the paper.

2. Signal model

Assume a stationary man is seating in front of a radar with the distance $d_0$, the periodical body movement caused by respiration and heartbeat can be modeled as $x_r(t) = m_r \sin(\omega_r t)$ and $x_h(t) = m_h \sin(\omega_h t)$ with amplitudes $m_r$ and $m_h$ and angular frequencies $\omega_r$ and $\omega_h$, then the total distance between human body and radar is

$$d(t) = d_0 + x_r(t) + x_h(t).$$

According to Doppler Effect, when radar transmits a signal to human body, the Doppler phase shift of the reflected signal is

$$\phi(t) = \frac{4\pi d(t)}{\lambda} = \frac{4\pi}{\lambda} d_0 + \frac{4\pi}{\lambda} x_r(t) + \frac{4\pi}{\lambda} x_h(t),$$

where $\lambda$ is the wavelength of the transmitted signal.

If the transmitted signal is $T(t) = \cos(\omega t)$, the I/Q baseband outputs of Doppler radar after direct downconverting can be expressed as

$$B_I(t) = \cos \left( \frac{4\pi}{\lambda} x_r(t) + \frac{4\pi}{\lambda} x_h(t) + \phi_0 \right)$$

$$B_Q(t) = \sin \left( \frac{4\pi}{\lambda} x_r(t) + \frac{4\pi}{\lambda} x_h(t) + \phi_0 \right),$$

where $\phi_0 = \frac{4\pi d_0}{\lambda}$ is the constant phase shift induced by the distance $d_0$.

Based on Bessel expansion, Equation (3) can be rewritten as [4]

$$B_I(t) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_k \left( \frac{4\pi m_r}{\lambda} \right) J_l \left( \frac{4\pi m_h}{\lambda} \right) \cos(k\omega_r t + l\omega_h t + \phi_0)$$

$$B_Q(t) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_k \left( \frac{4\pi m_r}{\lambda} \right) J_l \left( \frac{4\pi m_h}{\lambda} \right) \sin(k\omega_r t + l\omega_h t + \phi_0).$$
where \( J_k \) is the \( k \)th-order Bessel function of the first kind.

It can be shown in Eq.(4) that the baseband outs of quadrature I/Q channel are a sum of sinusoidal components with frequencies \( \omega_{l,j} = k \cdot \omega_s + l \cdot \omega_h \), where components with \( \omega_{h,0} \) and \( \omega_{h,1} \) are the respiration and heartbeat component to be extracted, other components are the harmonics or inter-harmonics of cardiopulmonary components, their amplitudes are determined by the real value \( J_k \left( \frac{4\pi m_k}{\lambda} \right) J_l \left( \frac{4\pi m_l}{\lambda} \right) \). Fortunately, our experiments show that the amplitudes of most of harmonics components are much smaller than those of cardiopulmonary components. The normal ranges of human respiration and heartbeat rate are 0.1–0.3 Hz and 0.8–2 Hz, so the respiratory signal and heartbeat signal can be separated by band-pass filters. However, since the respiration signals are much stronger than heartbeat signals, the respiration harmonics, mainly the 4th, 5th and 6th respiration harmonics, can fall into the frequency range of heartbeat signal and easily interfere with heartbeat signals.

As an example, Fig.1 shows the spectrum of 40 s baseband output of Doppler radar which will be described in the following section. The peak value of respiration \( \omega_{h,0} \) is the largest; the peaks of respiration harmonics, mainly \( \omega_{h,4} \), \( \omega_{h,5} \) and \( \omega_{h,6} \) fall into the frequency range of heartbeat (0.8–2 Hz) and can exceed the peak of heartbeat \( \omega_{h,1} \). Thus, the harmonics components must be removed from the heartbeat signal to make the measurement of heartbeat rate reliable.

3. Methodology

3.1. Doppler radar system

For laboratory experiments, a continuous wave Doppler radar operating at 2.4 GHz was designed and implemented. While most of cardiopulmonary Doppler radars in references are presented in laboratory environments, the Doppler radar system is based on commercially available broadband direct quadrature demodulator Analog AD-8347 and 16 bit Advantech data acquisition card USB-4716 [14-15], the radiated power of the radar is 20 dBm, and the antenna gain is 70 dBi.

![Figure 1. An example of the spectrum of a baseband output collected from the Doppler radar introduced in this paper.](image)

Fig.2 (a-b) shows the Doppler radar structure. The Doppler radar system is shown in Fig.2 (c), thereturned signal is amplified by LNA and then down converted by AD-8347. The outputs of
quadrature baseband are digitized by USB-4716, and then transported to PC through the USB data cable. The matching software WaveScan 2.0 of USB-4716 can be used to observe the raw signal and save the discrete data as text files. The text files can be conveniently processed further by MATLAB software for technological research.

### 3.2 Adaptive notch filter

There exist many adaptive notch filters; one of most used adaptive notch filters is LMS-based notch filter. The block diagram of the LMS adaptive notch filter is depicted in Fig.3, where \( d(k) \) is the primary input signal, \( x(k) \) is the reference signal with frequency \( \omega_0 \), amplitude \( A \), \( x_1(k) = A \cos(\omega_0 k) \) and \( x_2(k) = A \sin(\omega_0 k) \) are the two quadrature reference inputs of \( x(k) \), \( w_1(k) \) and \( w_2(k) \) are the iterative weights, \( \varepsilon(k) \) is the residual output, \( k = 1, 2, \ldots L \).

Assume that the adaptive step is the constant \( \mu \), the filter output is \( y(k) \), and then the adaptive noise canceling can be realized by

\[
y(k) = w_1(k)x_1(k) + w_2(k)x_2(k),
\]

\[
\varepsilon(k) = d(k) - y(k),
\]

\[
w_1(k+1) = w_1(k) + \mu \varepsilon(k)x_1(k),
\]

\[
w_2(k+1) = w_2(k) + \mu \varepsilon(k)x_2(k).
\]

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**Figure 2.** The pictures of Doppler radar. (a – b) The radar architecture. (c) The Doppler radar system.
Figure 3. The diagram of single-frequency adaptive notch filter.

It has been already proved that the transfer function from the primary input to residual output is [16]

\[ H_z(z) = \frac{z^2 - 2 \cos \omega_0 z + 1}{z^2 - (2 - \mu A^2) \cos \omega_0 z + (1 - \mu A^2)}. \]  
(9)

The \( H_z(z) \) has a zero point at \( \omega = \omega_0 \) approximately, and it equals to a notch filter with 3-dB bandwidth [16]

\[ BW = \frac{\mu A^2 f_s}{2\pi} \text{ Hz}, \]  
(10)

where \( f_s \) is the sampling rate. By properly selecting step size \( \mu \) and \( A \), narrower bandwidth and deeper notch can be adaptively obtained compared with traditional notch filter. Furthermore, multi-notch filter can be easily extended by substitution of single-frequency reference signal with a sum of sinusoidal ones, which can be used to reject multi-sinusoidal interferences with good performance as well.

3.3 Signal processor

The cardiopulmonary rates can be obtained from the combined two channel signals or signal-channel signal. The most common two methods of the combined signals are arctangent demodulation and complex demodulation [3-4]. In arctangent demodulation method, the Doppler phase is directly obtained by arctangent function on I/Q outputs. For complex demodulation, the complex signals are combined. The main merits of quadrature methods are that they have no “null” problem. However, they are more complicated and also suffer from DC problem or harmonics problem [11]. The single-channel method, though suffers from the “null” problem, is simple. So we simply use single-channel method in our experiment, the better output of I/Q channels is selected as the method proposed in reference [2].

Fig.4 shows the block diagram of signal processor in this paper. The single-channel raw data is firstly filtered to separate respiration component from heartbeat component by band-pass filters. Depending on the ranges of normal human cardiopulmonary rates, the 600-tap band pass digital FIR Kaiser filter with cutoff 0.1-0.6 Hz, \( \beta = 6.5 \) is used to extract the respiration component and 600-tap band pass digital Kaiser filter with cutoff 1-2 Hz, \( \beta = 6.5 \) is used to extract the heart component.

The respiration signal is very strong compared with heartbeat and harmonics; it can be directly windowed and transformed by power spectrum methods. The frequency estimates are realized by dominate peak finding of the power spectral density (PSD). The extracted heartbeat signal, however, is mainly interrupted by 4th, 5th and 6th respiration harmonics. Without the harmonics precisely known, the LMS-based ANC is used to iteratively generate the true harmonics signals with initial signals \( \sin(4\omega t), \sin(5\omega t) \), and \( \sin(6\omega t) \). The adaptive process is just the extension of the adaptive notch filter shown in Fig.3, but with 3 reference inputs signals. If the three qudrature inputs signal is assumed to be
Then, the adaptive iteration procedure is
\[ y_i(k) = w_{i1}(k)x_{i1}(k) + w_{i2}(k)x_{i2}(k), \]
\[ \epsilon(k) = d(k) - \sum_{i=1}^{3} y_i(k), \]
\[ w_{i1}(k+1) = w_{i1}(k) + \mu \epsilon(k)x_{i1}(k), \]
\[ w_{i2}(k+1) = w_{i2}(k) + \mu \epsilon(k)x_{i2}(k). \]
As a result, the 3-notch filter is generated.

After the harmonics are removed, the filtered heartbeat signal is also transformed to the spectrum, and the heartbeat rates can be estimated by the dominant peaks of PSD.

4. Experimental Results
This section will present experimental results to verify the signal processor. It should be remembered that this paper just focuses on the signal processing of harmonics interference suppression. The statistic results such as experimental results of many different human samples are not investigated here. All the experimental data are recorded from a 28-year-old male stationary target located in the front of radar. The sample frequency is set to be 100 Hz.

4.1 Experiment 1
The target is located in front of radar at a distance of about 0.5 m. Fig.5 shows the experimental results of signal processor without harmonics cancellation. In Fig.5 (a), the 50 s raw signal is filtered to separate the respiration and heartbeat component. The corresponding PSD of the cardiopulmonary signals is depicted in Fig.5 (b). The peak of respiration is obvious; however, the heartbeat peak is located between two larger peaks of respiration harmonics, as is shown in Fig.5 (b). Thus, if the frequency maximum peak located is considered to be heartbeat rate, the estimated heartbeat rate is not accurate any more. The estimated respiration rate is 0.22 Hz, and the heartbeat rate 0.88 Hz. The heartbeat rate is actually the 4th harmonics rate of respiration.
From (10), we can see that the bandwidth of adaptive notch filter is dependent on harmonics amplitude $A$, sampling rate $f_s$ and step size $\mu$. After $A = 1$ and $f_s = 100$ Hz are set, the performance of ANC mainly depends on $\mu$. The bandwidth of notch filter should be carefully selected so that it is larger than spectrum frequency resolution, but smaller than frequency interval between heartbeat and adjacent harmonics rate so that they can’t be filtered together. The estimated frequency interval is about 0.1 Hz and frequency resolution is $1/50 = 0.02$ Hz, so we get

$$0.02 \leq BW \leq 0.1 \tag{16}$$

Substitute values $A = 1$, $f_s = 100$ into (10), and from (16), the range of $\mu$ can be obtained

$$0.0013 \leq \mu \leq 0.0063 \tag{17}$$

The value $\mu = 0.003$ is adopted here.

After the adaptive notch filter, the experimental results can be seen in Fig.6 (a-b). It can be seen from Fig.6 (b) that the 4th, 5th, and 6th harmonics are successfully removed. The heartbeat peak is dominant. There are also some smaller peaks around the heartbeat peak; they are mainly caused by noise and inter-harmonics between respiration and heartbeat, they don’t influence the detection of heartbeat rate. The heartbeat rate after ANC is detected as 1.18 Hz compared with 0.88 before ANC.

As the spectral power of cardiopulmonary signal is relative the signal length, the performance of proposed algorithm is dependent on processed time length. The time length determines not only the frequency resolution but also the peak power. As the cardiopulmonary signal is easily affected by some interference such as random
body movement and is actually time-varying. The relative ratio of peak values between harmonics and heartbeat randomly differs within different time intervals.

Fig.7 shows the estimated heartbeat rates versus time lengths without and with ANC. The 4th and 5th harmonics are relatively strong compared with the 6th harmonics, furthermore, the harmonics amplitudes are time varying, their spectral peaks are randomly detected as the heartbeat peak until the processed time length is larger than 70 s, the value of heartbeat peak is sufficiently larger than those of harmonics. After the respiration harmonics are cancelled by ANC, the heartbeat rate detected is always around the 1.2 Hz. In order to further demonstrate the performance of the algorithm on the time length, another experiment will be presented in the following subsection.

4.2 Experiment 2

In this experiment, the same stationary target is located in the front of radar at the distance of about 1.8 m. The processed window length is 90 s. The frequency resolution of spectrum is higher compared with that in Experiment 1, so the smaller value of $\mu=0.02$ is set. Similarly to Experiment 1, the experimental results are plotted in Fig.8. As is shown in Fig.8 (a – b) without ANC, the respiration signal is also very strong and the respiration rate can be easily extracted, the heartbeat signal is mixed with the 4th, 5th and 6th respiration harmonics. The respiration rate is 0.23 Hz, and “heartbeat rate” is about 0.92 Hz, which is actually the 4th harmonic rate of respiration. In Fig.8(c – d), the heartbeat rate is 1.25 Hz after the harmonics are removed.

This experiment indicates larger time length can enhance the frequency resolution, but the peak value of heartbeat is still possibly smaller than that of the harmonics. The harmonics problem cannot be solved by signal accumulation. In fact, larger time length is not advised because the heartbeat rate is slightly time-changing and longer observing time will result in the higher possibility of outer interferences in complex environment.

5. Discussion

The performance of the proposed algorithm is mainly limited by adaptive noise canceling. In this paper, the traditional LMS algorithm is used; some other improved LMS algorithms are open for further investigation, such as normalized least mean square (NLMS) [17]. Furthermore, if the heartbeat rate is very close to the harmonics rate of respiration, the heartbeat signal may be filtered together, the performance of proposed signal processor will degrade. While larger time length for higher frequency
resolution is not advisable especially in medical diagnosis, more robust spectral estimation techniques should be used to distinguish the harmonics from heartbeat [11], meanwhile, the improved narrower notch filter must be carefully designed. It should be also note that the traditional band-pass filters are used to separate heartbeat component from noise and respiration signals. Empirical mode decomposition (EMD) is known as a powerful tool to analyze non-stationary signals, and can decompose the signals into a series of intrinsic mode functions with different bandwidths, it can be also used to separate signals [18-19], the EMD-based technique for extract heartbeat signals will be discussed in other work.

Although the harmonics problem can be modeled by (4), the relative amplitudes ratio of sinusoidal components is still unknown especially under complex environments such as earthquake rescue. The arctangent demodulation method for quadrature I/Q outputs has better harmonics suppression than complex demodulation method and channel-selection method [4]. However, as the Doppler phase shift can not be ideally obtained by arctangent demodulation method, the harmonics problem still exists [12], and the harmonics cancellation is necessary as well. The amplitude of respiration harmonics is related to the carrier frequency of Doppler radar. Higher carrier frequency may lead to higher sensitivity of the radar; as the result, the heartbeat signal can be strong enough, not to be overwhelmed by the harmonics [20].

6. Conclusion

This paper investigates the harmonics cancellation in Doppler radar for accurate heartbeat detection. After separating the heartbeat signal by band-pass filter, we propose the LMS-based ANC to remove the respiration harmonics overlapped with heartbeat signal. The performance of the algorithm is
validated by experimental results. When the harmonics amplitudes are precisely unknown, more investigation will be done in future.

7. References


