A Viewpoint of Time Variant Dielectric Effect in Vital Sign Detection Using Microwave Radar

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Abstract— Through theoretical analysis and data examinations for a continuous microwave radar system, it is pointed out that there are some inconsistencies when using Doppler radar theory to explain the mechanism of vital sign detection. Meanwhile a time variant dielectric hypothesis viewpoint based on bioelectrical effects is presented, and a simple system model is established. Comparing to the traditional Doppler radar theory explanation, this viewpoint is more reasonable.

1. INTRODUCTION

As early as 1970's, Doppler radar system was applied to detect human body's vital sign like respiration and heartbeat. Up to now, the main principle of microwave radar for vital sign detection is still based on Doppler theory [1]. It says that when a human body is exposed under the incidence of a microwave, the reflected signal will be phase modulated (PM) due to movements caused by respiration and heartbeat, and the frequency or phase of the incident wave can be changed. So by appropriate demodulation techniques, one can obtain the vital sign signal from the change of reflected wave.

Most of us take it for granted that Doppler radar theory is the foundation of vital sign detection. However, with further researches we find there are some inconsistencies between the theory and measurements. So we try to write this paper to show our considerations and give a hypothesis. Firstly, after a short review of Doppler radar theory we analyze two significant contradictions between this theory and measurements. Secondly, we present a new viewpoint or a hypothesis based on time variant dielectric effects in human body and in virtue of electromagnetic scattering theory. Finally, we give a comparison for the viewpoint to traditional Doppler radar theory explanation to show that it can be more reasonable to explain the mechanism.

2. DISCUSSIONS FOR DOPPLER RADAR THEORY OF VITAL SIGN DETECTION

2.1. A Short Review of Vital Sign Detection Based on Doppler Radar Theory

The classic explanation for this topic is Doppler theory [1]. According to this theory, the incident wave that is reflected off human's chest with a periodical varying displacement would result in a narrowband PM reflected wave:

$$S(t) = \cos(\omega_0 + \phi(t)) \tag{1}$$

where ω_0 is the angular frequency and the phase shift is:

$$\phi(t) = 4\pi \cdot x(t)/\lambda, \tag{2}$$

where $x(t)$ is the displacement of the target to be measured. In receiver part of the radar $\phi(t)$ can often be obtained by coherent detection. The principle is shown in Figure 1. To obtain $\phi(t)$, one should adjust the phase of phase-shifter to make $\theta = 90°$. In a small phase shift condition, we have $\sin(\phi(t)) \sim \phi(t)$. So by low pass filtering and baseband amplifying, $x(t)$ will be displayed on the oscillograph. When the phase shift is large enough, this linear approximation is not valid. So this case has led researchers to further deeper study [2, 3]. However, their works are still based on a cosine function baseband signal model that is derived from classical Doppler radar theory. Although they can improve the detection accuracy to some extent, the following doubt points we put forward still keep remained.

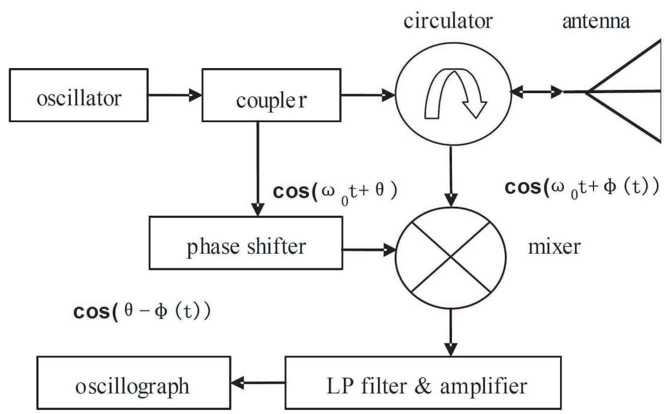

Figure 1: The simple diagram of continuous wave Doppler radar.

2.2. The Baseband Signal Difference between Theory and Experiments

The first contradiction is that the baseband signal detected in lab experiment is different from the theory. Referring to Figure 1, to obtain $\phi(t)$ from $\cos(\phi(t))$, two conditions must be satisfied: (a) Coherent local oscillation signal should be orthogonal to the received RF signal; (b) The reflected signal should be modulated with small phase shift to the carrier wave, that is:

$$\max \phi(t) \ll \pi/6 \tag{3}$$

If these two conditions cannot be satisfied, ordinarily an inverse cosine operation to the output signal will be needed. If condition (b) is satisfied but condition (a) is not, we can obtain the approximate results by differentiating to the output signal. Otherwise the demodulation baseband signal is just $\cos(\theta - \phi(t))$, not the target movement signal $\phi(t)$ (so is $x(t)$). But the fact is contrary: almost all the experiment results show that one can directly obtain the heartbeat and/or respiration signal $x(t)$ waveform after demodulation. Actually, most of the experiments didn't meet the two conditions described above (we have confirmed this). Here we cite a typical test results in Figure 2 to explain the problem [4]. We can clearly verify this observation from the figures.

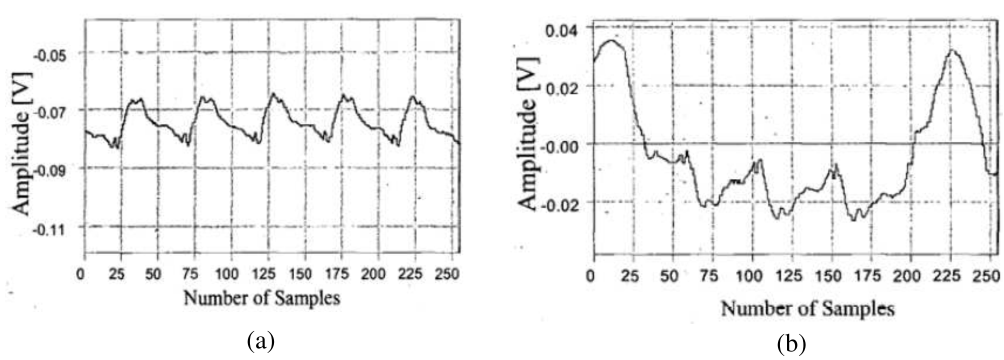

Figure 2: The test results [4], $f = 10.353\,\mathrm{GHz}$, 50 samples per second. (a) The heartbeat signal; (b) The combination signal of the respiration and heartbeat.

2.3. The Amplitude Difference between Heartbeat and Respiration Signals

The second important problem is that Doppler radar theory cannot explain the amplitude difference between heartbeat and respiration signals. We can see also from Figure 2 and test results mentioned in other papers that they are basically in a same decimal order [5]. But according to Doppler theory, the difference should be much bigger, as we prove as follows.

Firstly, we consider this problem from the surface movement made by heartbeat and respiration. According to Equation (2), the maximum amplitude of modulated signal should be determined by maximum target's displacement $x(t)$. Directly comparing the displacement of respiration and heartbeat, we can find the displacement of breast and abdomen caused by respiration is much larger than that by heartbeat. For a healthy adult man, the displacement caused by respiration can reach up to 10 millimeters even more. However, for displacement caused by heartbeat, we can hardly observe it even the testee hold the breath. Therefore, in the view point of Doppler theory, respiration signal should be much larger than that of heartbeat signal.

Secondly, if considering that the movement displacement caused by heartbeat inside chest is larger than that on the surface, we can analyze the RF loss in human body to explain the problem. Here we only present the result because of the paper length limitation: a detailed calculation by ADS simulation shows that heartbeat signal is about 96 dB smaller than the respiration signal at 10 GHz [6].

Therefore, in view of Doppler radar theory, no matter how we analyze the problem from either aspect, respiration signal should be much larger than heartbeat signal. However, the fact isn't like this as we pointed out.

3. THE MECHANISM OF VITAL SIGN DETECTION BASED ON TIME VARIANT DIELECTRIC EFFECTS IN HUMAN BODY

As is known, bioelectricity is an electrical phenomenon of organism. The sinoatrial node controls heartbeat of a healthy people. The bioelectrical pulses produced by sinoatrial node pass through special transmission tissues, atria, and atrioventricular node (the node between atria and ventricle), finally reach the ventricle, and result in contraction of the atria and ventricle. The regular repetitions of this process become the heartbeat and rhythm of heart.

There is another character of bioelectricity that the vital information it carries can be transmitted to outer skin through electric tissues and body fluid around the heart and nerve cells. So testing electrode put on the skin can detect the change of the voltage in human's body. Because of this character, the biological electric fields caused by every action in human's body exist on human's skin. According to electromagnetic theory, the body can be regarded as a time varying dielectric coefficient ε and conductivity σ, which can carry the information of biological electric field:

$$\varepsilon = \varepsilon_0 \varepsilon_r f(t), \quad \text{and} \quad \sigma = \sigma_0 f(t). \tag{4}$$

where ε_0 is the permittivity in vacuum, ε_r and σ_0 is the normally defined human body's dielectric constant and conductivity, respectively; $f(t)$ is a hypothetical function that represents time variant dielectric effects in human body. Comparing with the variation of incident field, $f(t)$ varies much slowly. When a human body is exposed under the incidence of microwave radar shown in Figure 1, the Maxwell equation has the form by (4)

$$\nabla \times H = j\omega\varepsilon(t)E + \sigma(t)E = j\omega\varepsilon_e f(t)E \tag{5}$$

where ε_e is the ordinary complex dielectric constant,

$$\varepsilon_e = \varepsilon_r \varepsilon_0 - j\frac{\sigma_0}{\omega}. \tag{6}$$

The field in (5) is a total field, involving incident field $\mathbf{E}^{inc}$ and scattered field $\mathbf{E}^s$. We can use the concept of equivalent polarization current and integral equation method to solve the scattered field [7]. Therefore we can derive

$$\mathbf{E}^s = \varepsilon_e f(t) e^{j\phi(t)} \left(\delta\omega^2 \mu_0 \varepsilon_0 \iint_S \mathbf{E}^{inc} G(r, r') ds' + \iint_S (n \cdot \mathbf{E}^{inc}) \nabla' G(r, r') ds' \right) / \varepsilon_0 \tag{7}$$

where δ is the thickness of human body's surface layer skin; G is Green function in free space; the integrals are performed both on human's surface with a unit normal vector n. The Equation (7) is derived under following approximations: The field in human body attenuates rapidly, $|\varepsilon_e| \gg \varepsilon_0$, and $|\mathbf{E}^{inc}| \gg |\mathbf{E}^s|$.

When the incident field is scattered by human body, referring to (7), the scattered field will have a product form of $f(t)$ and incident field. This is equivalent to that the incident carrier wave is modulated in amplitude by the bioelectrical signal. Therefore, the scattered field has the character not only of PM wave with Doppler phase shift, but also of amplitude modulated (AM) wave. Namely, the scattered field is an AM-PM signal. So in a radar receiver, we can use coherent demodulation method to get the function $f(t)\cos(\theta - \phi(t))$, and adjust θ only for getting maximum amplitude, but not for restoring the signal information itself. This is an essential difference from the Doppler theory mentioned in Section 2.1.

The model in Figure 3 shows above work principle. The main difference of Figure 3 and Figure 1 is that the former includes a time variant dielectric function $f(t)$, so the demodulated result is completely different.

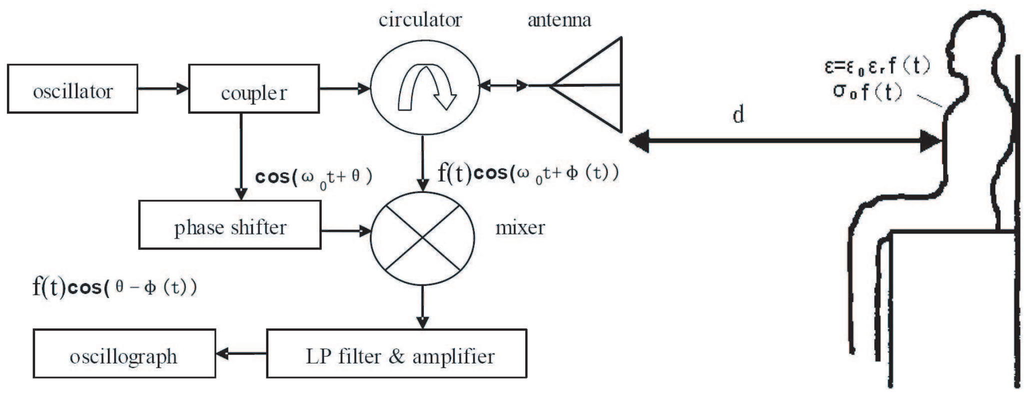

Figure 3: Time variant dielectric effect models of vital sign detection using microwave radar.

Referring to Figure 3, the model has several characters. Firstly, the scattered signal can be equivalent to an AM-PM wave, which has less dependency on the movement of human body. After coherent demodulation to the AM wave we can get the baseband signal both of respiration and heartbeat. Secondly, from Equation (7), since the solution of the scattered field can be carried out only on the surface of human body, the microwave loss problem is avoided. Finally, since AM signal satisfies the principle of linear superposition, this model can process multi-signal detection problem, which is difficult to solve in Doppler radar theory.

It is worthy to indicate that in the past, people used to consider organism as an inhomogeneous loss medium only, and the dielectric characteristics of all biological organization do not change along with organism's status. In fact, as human body is a complex organism, its metabolism process is fulfilled by a series of complex biochemical response. Yan Liping et al., who are in Sichuan University, China, have made a research on this topic and published their paper [8]. They made an experiment to show the behavior of time-variable dielectric coefficients and conductivity. According to their research report, the experiment takes about 10 seconds from time of beginning to stable status, and the relative variation rate of complex dielectric coefficients and conductivity in human body can be reached up to 37%. Detailed information of their contribution and our further work will be described in the future.

4. CONCLUSION

This paper analyzed the inconsistencies between Doppler radartheory for vital sign detection and known measurements. It also provides a new mechanism and an AM-PM wave model for microwave radar vital sign detection based on time variant dielectric effects, which is essentially caused by bioelectrical phenomena of human body in our opinion. Comparing with the traditional Doppler radar model, the advantages of this model are:

1) It avoids the inconsistencies between theoretical analysis and experiment results.
2) Because a variety of time variant dielectric effects is on human's skin, so whether we detect any vital sign, we just need to consider the reflection of the incident wave on human's skin surface, and the detection will have less dependency on movement. Besides, as vital sign signals satisfy the principle of linear superposition, it makes easy to detect the heartbeat and respiration at same time.
3) The simulation model can be more similar to the reality, and can be constructed by more rigorous electromagnetic theoretical analysis.

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