

Model Study of UWB Bioradar for Respiratory Detection

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Abstract: In terms of parameters selection and detection in measurement of Ultra Wide Bandwidth stepped frequency bioradar model, stepped frequency interval of emission signal, frequency bandwidth of the intermediate filter (IFBW) and sampling integration time of echo signal are discussed in this paper. These factors impact imaging and human respiratory detection. A novel calculation method of parameters is proposed based on both theoretical and experimental results, which are Fourier transformation analysis method and empirical data, respectively. The stepped frequency interval of emission signal is 14.15 MHz, IFBW < 3 kHz and the sampling integration time of echo signal is 15 s which has been shown that reasonable parameter settings can improve image resolution and the echo signal to noise ratio significantly. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Human respiratory detection, Frequency interval, Frequency bandwidth of the intermediate filter, Sampling integration time, Biological radar.

1. Introduction

Non-contact life-detection technology images or penetrates through obstruction directly but it does not contact with body. At the same time, the heartbeat and other parameters may be sensed. Inspired by the medical science engineering development, non-contact life-detection has become highly sophisticated with respect of social development, military applications, one can refer to [1, 2]. Compared with detection technology based on infrared ray, ultrasonic wave and optic ray, radar ray is not affected with weather, temperature and other environmental factors. It is able to penetrate thick

obstacle (smog, wall, grove for example) without couplant. So, it owns superiority, especially in life detecting, namely Life Radar, refer to [3-5].

UWB stepped frequency radar is well known in terms of high resolution, strong penetrating ability, capability of obtaining targets' tiny characteristic. Recently, it is a hotspot in the field of life detection research [6, 7]. Some researchers have already applied it to the research of 2-D and 3-D imaging algorithm for human target and human body micro Doppler feature sense [8-12]. UWB stepped frequency radar emits some successive signals with a certain frequency interval step in a relatively wide frequency range, and the corresponding echo signals

are received. In respect of the life body detection, it often requires the object to be imaged and simultaneously measured breath, heartbeat and other micro Doppler information. Step frequency interval of the transmitting signals, the bandwidth of the intermediate frequency filter and sampling integration time of echo signals may affect the target imaging precision and breathing, heartbeat detection accuracy. However, most existing results are not involved in the above parameters' effects on the target imaging, breathing and heartbeat detection as well as into how to set reasonable parameters.

In this paper, therefore, the respiratory frequency is to be measured, the parameters including stepped frequency interval of emission signal, IFBW and sample integration time of echo signals are set using UWB stepped frequency radar.

2. UWB Stepped Frequency Bioradar Theoretical Model

Biological radar working schematic diagram is shown in Fig. 1. Antenna is fixed while radar is working. Both static and moving targets are taken into account. In some cases, there will be obstacles between radar and imaging areas.

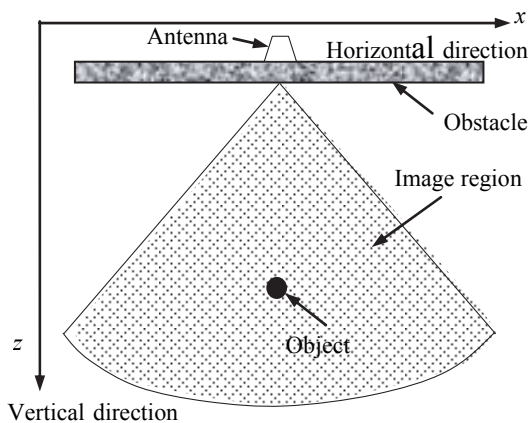


Fig. 1. Diagram of bioradar.

When electromagnetic waves at different frequency go through, detracting is sharply increasing as frequencies of electromagnetic waves are increasing. Heartbeat signal amplitude is set at 10 dB less than respiratory signal amplitude. The biological radar is, therefore, better to detect organism respiratory signal. According to the characteristics of organism respiratory signal, organism can be considered as a reflector doing simple harmonic oscillation at a R_0 distance with radar antenna, referred to [13], as shown in formula (1).

$$R=R_0+a_h\sin(\omega_h t+\varphi_h), \quad (1)$$

where a_h is the respiratory amplitude, generally less than 2 cm, ω_h is a respiratory signal frequency, which

can be expressed as $\omega_h = 2\pi f_h$. And ω_h is affected by the size, age and positions of people. Usually ω_h is 15~45 times corresponding frequency between 0.25~0.75 Hz, t is time, φ_h is initial phase. At a certain frequency of UWB stepped frequency cw radar, emission signal can be expressed as:

$$S_{T,i} = e^{-j\omega_i t_0}, \quad (2)$$

where ω_i is a frequency point signal's angular frequency, the initial time of emission signals is t_0 . Receiving signals are:

$$S_{Rec,i} = \mu_0 \mu_m e^{-j\omega_i(t_0+t_r)}, \quad (3)$$

where μ_0 is the electromagnetic wave propagating loss in air, μ_m is the loss brought by electromagnetic wave penetrating obstacles or human body, t_r is the time for emitting signal reflected from the object it met. The value of t_0 can be determined by the target location:

$$t_r=2R/v, \quad (4)$$

where v is the speed of electromagnetic wave propagating in the medium, because the major transmission medium is air in life detecting, v can be set to a vacuum electromagnetic wave velocity v_0 , 3×10^8 m/s. When signals encounter obstacles, smoke or other mediums, one can do the corresponding compensation at the time of imaging. So, assuming initial time of emission signals $t_0=0$, after bringing (1) and (4) into (3), one can get vector echo signal expression:

$$S_{Rec,i} = \mu_0 \mu_m e^{-j2\omega_i(R_0+a_h \sin(\omega_h t+\varphi_h))/v_0} \quad (5)$$

These echo signal phases at different frequency are different, but if the reflector is fixed (i.e., no harmonic vibration), phase difference of adjacent frequency receiving signal is fixed. Frequency echo phase subtracts adjacent one in order to eliminate different frequency phase difference, which may be expressed as:

$$Pha_i = \text{angle}(S_{Rec,i+1}) - \text{angle}(S_{Rec,i}) \quad (6)$$

Angle ($S_{Rec,i}$) is the echo phase of i^{th} frequency, Pha_i is the phase difference of $i+1$ frequency point and the i^{th} frequency signal. After processing $N+1$ frequency echo signal phases, we can get N phase difference values. Removing the mean value of these phase difference, one can obtain the echo phase cyclical fluctuation, which is introduced by breathing harmonic vibration.

Radar 2-D imaging is designed to track object in a horizontal plane parallel to the ground plane in the radar radiation direction. Image is divided into horizontal and vertical directions (vertical direction may also be defined as the depth direction), see Fig. 1. Image vertical resolution depends on the bandwidth of antenna signal. Horizontal resolution is based on

the antenna synthetic aperture length (i.e., the relative displacement between target and antenna in the horizontal direction) [14]. The detection of moving human's breath, heartbeat information by utilizing biological radar is more difficult. Generally, regarding biological radar work, human body is required at rest or quasi static state. The body has no relative displacement with the radar in the horizontal direction. So the target image can't focus. In this case the radar can detect human breathing, heartbeat information and image only in the vertical direction.

Radar transmitting and receiving continuous wave signals of the single step frequency, which is sampling in the frequency domain, see (5), where ω_i is the sampling angular frequency. Without considering the respiratory signal, all the received signals are in integral form (7).

$$S_{\text{Rec}} = \mu_0 \mu_m \sum_{i=1}^N e^{-j2\omega_i R_0 / v_0} \quad (7)$$

In the imaging, R_0 is unknown, replaced by the R_x , R_x/v_0 is the electromagnetic wave propagation time. If ω is continuous in (7), R_x/v_0 may be correspondingly written as the integral form. As shown in formula (8).

$$S_{\text{Rec}} = \mu_0 \mu_m \int_{\omega_0}^{\omega_N} e^{-j2\omega R_x / v_0} d\omega \quad (8)$$

Eq. (8) is the frequency domain signal, that is, time domain signal is in Fourier transform from. The frequency domain signal does an inverse Fourier transform to get time domain signal. Time domain signal represents the electromagnetic wave propagation time. Propagation time multiplies with the speed of electromagnetic wave propagation in the medium to obtain the distance information, i.e. the distance domain. Distance domain is the coordinate formed by distance between radar antenna and the target. Distance domain 1-D imaging is to determine the object and the radar antenna linear distance, that is to say a target at a distance from the antenna of a fan-shaped arc with R as the radius. Distance imaging resolution ΔR is

$$\Delta R = v_0 / 2B, \quad (9)$$

where B is the bandwidth of the transmitted signal, the coefficient 2 is due to electromagnetic wave from a transmitter to a receiver needed to go back and forth return when imaging.

3. Parameter Setting Discussion and Experimental Verification

3.1. Frequency Interval Effecting the Measurement and its Setting

In section 2.2, it is known that distance domain 1-D imaging is needed to take IFFT of the array

which various received frequency signals. So the frequency interval of the two frequencies determines the time length of time domain, which is the imaging distance, or the imaging range, refer to (10).

$$R = v / 2\Delta f_T, \quad (10)$$

where Δf_T is the step frequency interval.

Without considering the output power and power attenuation, theoretically, smaller frequency interval is the bigger imaging range. But in certain bandwidth, smaller frequency interval desires more transmission frequency points. In working state, biological radar requirements target for synchronous imaging. Therefore, each signal emission time cannot be too long. If there are more frequency points, each frequency transmitting and measuring time would be reduced, the quality of transmitting signal and the stability of receiving signal would decrease. It would affect the imaging resolution and respiratory signal detection accuracy. So for UWB stepped frequency bioradar to determine a suitable frequency interval is necessary.

In some cases biological radar penetrates walls and other obstacles in order to detect target. The dielectric constants of wall and air are different; the velocity of electromagnetic wave is therefore different. (10) may be rewritten as:

$$\Delta f_T = 1 / (2R_a / v_a + 2R_w / v_w), \quad (11)$$

where v_a is the velocity of electromagnetic wave in the air, equals to v_0 , v_w is electromagnetic wave speed in the wall medium, R_a is the electromagnetic wave propagation distance in the air, R_w is the electromagnetic wave propagation distance in the medium of wall, v_w and v_a relation as follows:

$$v_w = v_a / \sqrt{\epsilon_w}, \quad (12)$$

where ϵ_w is the wall dielectric constant, frequency interval Δf , One can obtain:

$$\Delta f_T = v_a / (2R_a + 2\sqrt{\epsilon_w} R_w) \quad (13)$$

Usually, biological radar range is 10 m and building wall thickness is less than 0.5 m. The dielectric constant decided by wall material. If, R_w is 0.3 m and ϵ_w is 9. Substituting these values into Eq. (13) one can get Δf_T for 14.15 MHz.

3.2. IFBW Effecting the Measurement and Settings

UWB stepped frequency bioradar images target and detects its breathing, heartbeat and other life parameters at the same time. It transmits a certain frequency continuous signal. Because breathing, heartbeat and other life signals are very weak, which belong to the measurement of small signal detection

requiring higher stability and accuracy. With respect of the high frequency signal, detection firstly goes down to Intermediate Frequency (IF) in the mixed way. Then, amplified IF signals pass through the intermediate frequency filter. IF filter is a band-pass filter, it selects the required mixing component, suppresses other unwanted signals, sampling after filtering. Biological radar transmits and receives measurements synchronously. The frequency of the transmitted signal determines the frequency of the received signal. So, a group of signal emission time corresponds to frequency bandwidth of the intermediate filter (IFBW).

Smaller IFBW leads to the wider measurement of the dynamic range and improves measuring accuracy and precision. Our group in the experiment uses Agilent vector network analyzer E5071C as the echo receiving terminal instrument. It has a wide frequency band in the test. Dynamic range of test port is greater than 123 dB (IFBW of 10 Hz). This paper measures echo signal S11 parameters using the E5071C vector network analyzer. S11 parameters include the echo signal amplitude values and phase values (or the phase differences of the transmitting signals). Minimum E5071C IFBW is 10 Hz, but if IFBW test for 10 Hz, the time required will be too long. Our group chose 80~2500 MHz band, emission signal frequency interval is 14.15 MHz, the frequency points tested is 121, and measured time is 16.2 s, i.e. 16.2 s is to complete measurement a group of (121) frequency data, which is not able to satisfy the requirement of real time imaging.

In order to meet the measure precision requirements and rapid imaging, biological radar should be set IFBW reasonable values. By looking at the E5071C instrument manual, see reference [15], get the specifications in Table 1.

Table 1. Instrument Indexes of E5071C

Index	E5071C parameter
IFBW	3 kHz
Frequency Range	10~4380 MHz
Dynamic Range	>98 dB
Trace Noise Amplitude	<0.004 dBrms
Trace Noise Phase	<0.035°rms

In this paper, the radar transmitting signal frequency is 800~2500 MHz, emission signal amplitude is 10 dBm. The measured target echo signal amplitude is greater than -60 dBm, dynamic range is within 70 dB. Phase measurement accuracy is considered for respiratory measurement. Respiratory amplitude for 1cm (normal respiratory status), emission signal frequency is 800 MHz (larger signal frequency as well as the smaller wavelengths, the wavelength of a complete respiratory amplitude is greater, namely the phase variation is larger), a complete respiratory phase changes 9.6°, instrument noise phase is 24 dB less than trace phase change,

satisfies the measurement requirements. Measuring dynamic range of instrumentation and the uncertainty of transmission and reflection would not meet the experiment requirement on the condition that is greater than 3 kHz for IFBW. When IFBW is 3 kHz for 800~2500 MHz time required for measurements between 121 step frequency signal is 0.5 s. That is to say an imaging signal transmitting frequency which is less than 2 Hz, satisfies the measurement requirements.

Through the above analysis IFBW decides measurement accuracy and the transmitted signal frequency in each group. Different test instruments and different test requirements should set reasonable IFBW, to meet the accuracy and real-time requirements.

3.3. Sampling Time Integration of Respiratory Frequency

Respiratory frequency detection is a small signal measurement. SNR of echo signal is very low. The general use of long time signal accumulation may improve the SNR to a certain extent; make simple harmonic vibration frequency of the echo signal in the frequency domain is more prominent. In addition, according to Fourier theory, time-domain sampling time length determines the frequency resolution size. Longer time domain sampling time will result in higher resolution in frequency domain. Sampling length of time and frequency resolution relationship is:

$$\Delta f_R = 1/T_L \quad (14)$$

Including Δf_R for frequency resolution (simple harmonic oscillator), T_L for sampling time length.

Human respiratory frequency is not strictly periodic, which will, therefore, fluctuate a little with the human body in stable state, and it can be thought as quasi periodic signals. Additionally, when the human body physiological state changes, the respiratory frequency will change accordingly. The longer time domain sampling time is, the more slowly the radar on respiratory frequency response changes, see reference [16-20]. Respiratory frequency was equal to average when long sampling times was took, then the respiratory frequency sensing makes certain errors. Therefore, a reasonable time domain sampling time can improve signal to noise ratio significantly in respect of the detection of periodic signals, achieve fast detection speed. This paper determines the reasonable length of time domain sampling time by experimental analysis method using our group's instrument settings.

Fig. 2 demonstrates human respiratory frequency amplitude normalized data through the experimental way. In the experiment, the human body sat on the bench, located in place with distance of 2 m with radar antenna, in the stationary state, even breathing,

breathing frequency is 0.5 Hz. Radar emission signal frequency for 800~2500 MHz; an imaging signal emission cycle for 1 s. Each group of emission signal had 121 frequency points. Transmitting and receiving used the same antenna, emission and receiving can be simultaneously, total of 60 s data collection. In Fig. 2 (a~d) were respiratory frequency detection image of continuous 15 s, 12 s, 8 s and 5 s data. According to (14), 15 s, 12 s, 8 s and 5 s time length correspond frequency resolution of 0.067 Hz, 0.083 Hz, 0.125 Hz and 0.2 Hz. To improve the resolution of calculation, our group used 8192 point FFT for the time domain signal Fourier transformation. Due to the human respiratory frequency range is between 0.25~0.75 Hz (see section 2.1 mentioned), the graph is only given 0~1 Hz amplitude diagram.

From the Fig. 2 (a) we can see, 15 s sampling time has the high frequency resolution and SNR is

high, respiratory frequency measured is 0.502 Hz. Measure is accurate. The actual frequency resolution (according to generic algorithm which is -3 dB width of peak amplitude) is 0.031 Hz, breathing rate is 0.517 Hz on the condition of 12 s sampling measure time, here appeared 0.017 Hz deviation, measuring resolution for 0.114 Hz. Compared with 15 s data SNR drops, signal amplitude dropped by 20.8 %. As can be seen from the graph, noise increased significantly, frequency resolution and SNR down is quite obvious when sampling time is 8 s and 5 s in the picture and it is difficult to distinguish respiratory signal.

From the above experimental data it can be concluded that in the measurement of respiratory frequency, using 15 s sampling time length to do accumulation can obtain accurate respiratory signal frequency, and won't make measurement time too long, is more reasonable.

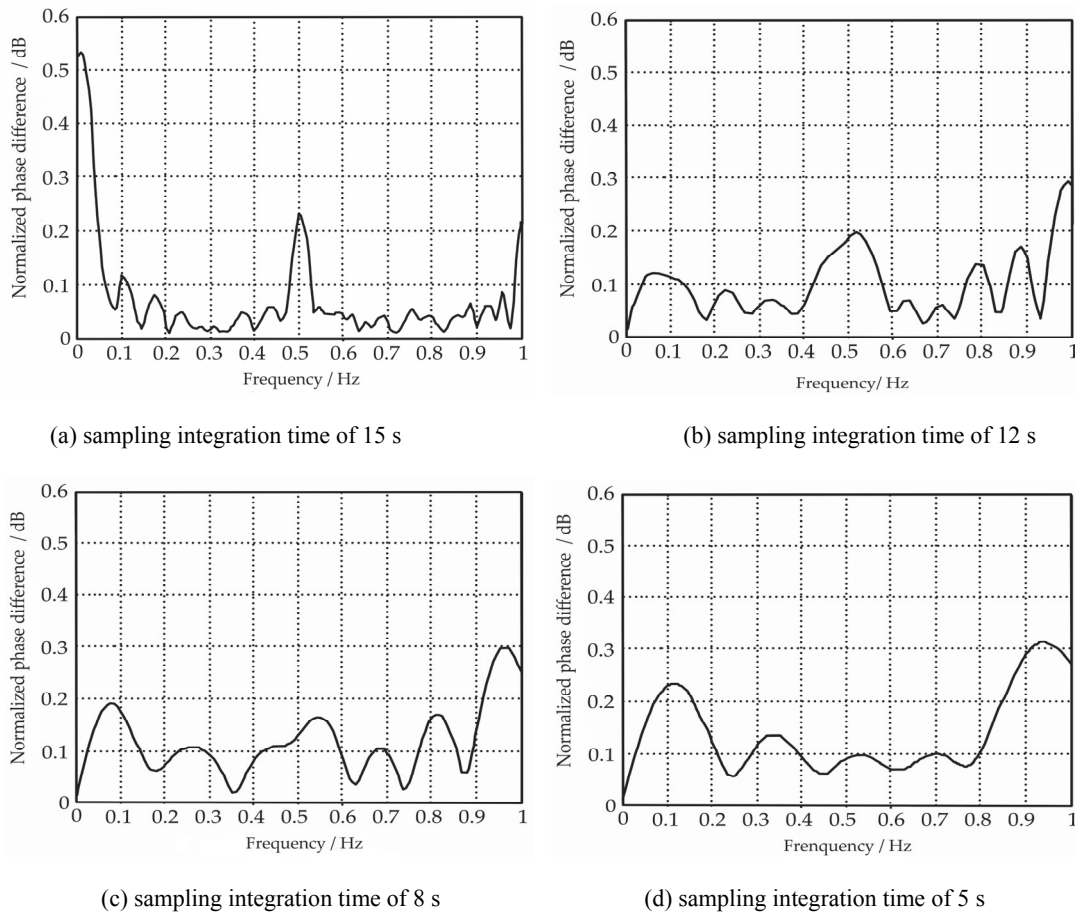


Fig. 2. Amplitude normalized image of human respiratory obtained by integrating different sampling time.

4. Conclusion

Aiming at the ultra-wideband step frequency radar emission signal step frequency interval, intermediate frequency filter bandwidth and sampling integration time of echo signal three problems, this paper analyzed and demonstrated some parameters setting scheme for ultra-wideband step frequency

biological radar target imaging and measuring the respiratory frequency. The conclusion may be drawn based on both theoretical and experimental results:

1) Frequency step interval affects radar measure distance. In this paper, the radar emission signal frequency interval of 14.15 MHz is more appropriate,

2) The intermediate frequency filter bandwidth (IFBW) influences instrument measuring dynamic

range, accuracy and measuring speed. With respect of the instrument adopted in the experiment, demands $IFBW < 3$ kHz to satisfy the measurement requirements.

3) Sampling time length influences respiration signal frequency measurement accuracy and resolution and signal-to-noise ratio. In this test, 15 s sampling time length for accurate and fast measurement respiratory signal frequency is more reasonable.

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