2021 International Conference on Emerging Technologies for Communications (ICETC 2021)

A Study on Pre-Filter Design for Improving Accuracy in Heart rate Estimation from Horizontal Multi-direction Using Discrete Wavelet Transform with mm-Wave Radar

Ryosuke Koyanaka†, ***Student member***, **Shunsuke Sato**†, ***Student member,*** **Yaokun Hu**††, ***Member***,
and Takeshi Toda††, ***Member***

SUMMARY We have been considering applying discrete wavelet transform (DWT) to heart rate estimation using 77 GHz band FMCW radar. Moreover, we have proposed using a high pass filter (HPF) in DWT pre-processing in order to reduce respiratory signal and its harmonics included in the DWT results. In this paper, we compared a detection accuracy and signal-to-noise ratio (SNR) improvement in the case of a High-pass Chebyshev Type II and an elliptic HPF, respectively. The experimental result showed that the Chebyshev Type II filter was more effective for back and left directions where body surface movements due to respiration are less than the front and right directions.

key words: *Chebyshev, discrete wavelet transform, FMCW radar, heart rate estimation, respiration, vital sign monitoring.*

1. Introduction

Doppler radar [1-3], impulse Ultra-wide Band (UWB) radar [4], and Frequency Modulated Continuous Wave (FMCW) radar have been used for non-contact vital sign monitoring [5]. 77GHz FMCW radar was used in this study because of its high resolution and accuracy [6]. When using FMCW radar to detect a subject, the interference to the subject's signal can be partially eliminated by selecting an appropriate Range-bin. However, an appropriate algorithm is needed for the extracted signal to remove noise such as interference from other objects in the same range-bin and body shaking. Previously, we performed heartbeat signal extraction utilizing Empirical Mode Decomposition (EMD) for time-domain signal processing and Improved Complete Ensemble Empirical Mode Decomposition with Adaptive noise (ICEEMDAN). ICEEMDAN solves mode mixing, a problem of EMD, by adding white noise [7]. The processing of these methods takes a long time. Considering the application of heart rate estimation with radar, the processing time should be short. Meanwhile, DWT is superior to EMD-based time-domain signal processing in terms of processing time. Therefore, we have been also considering utilizing discrete wavelet transform (DWT) to estimate heart rate [8, 9]. DWT is a signal processing method in the frequency domain. It is possible to decompose the signal and extract small signals buried in the original signal by employing a high pass filter (HPF) and a low pass filter repeatedly for signals. However, the DWT results contain noises such as the respiratory signal and its harmonics, because the frequencies of respiratory signal and heart rate are close. When the heart rate and respiratory frequency are close, HPF reduces the heartbeat frequency together with the respiratory signal depending on attenuation characteristics near the cutoff frequency. However, in general filter design, the steeper the attenuation characteristic near the cutoff frequency, the larger the passband ripple, and vice versa. This paper reports that a Chebyshev type II filter improves both signal-to-noise ratio (SNR) and root-mean-square error (RMSE) comparing without the filter, regardless of subjects, for the backward estimation where body surface movement is less than forward. Moreover, in the left side estimation where body surface movement due to respiration is relatively small, the Chebyshev filter was found to be effective. Even though the improvement depends on subjects. On the other, in frontal estimation, an elliptic filter more effectively improved both SNR and RMSE than the Chebyshev filter. The elliptic filter's roll-off is steeper [10], but the passband ripple is larger than the Chebyshev filter. In the case of the right side estimation where respiratory signals are relatively large compared to heartbeat signals, the elliptic filter was found to be more effective than the Chebyshev filter.

2. Signal Processing

2.1 FMCW Radar Principle

Chirp signal is transmitted whose frequency increases linearly from f_{min} to f_{max} in time T_{c}. The transmitted chirp hits an object and is received after a time T_{d}. If the distance from the radar to the target is R_0 and the speed of light is c, the relation between T_{d} and R_0 is expressed as $T_{\mathrm{d}} = 2R_0/c$. The IF signal is obtained by mixing the transmitted with the received signals. The IF signal is expressed as

$$\begin{aligned} s_{\mathrm{r}}(t) &= A_{\mathrm{t}}A_{\mathrm{r}}\exp\left(j(2\pi f_{\mathrm{min}}T_{\mathrm{d}} + 2\pi K T_{\mathrm{d}}t - \pi K T_{\mathrm{d}}^2)\right) \\ &\approx A_{\mathrm{t}}A_{\mathrm{r}}\exp\big(j(2\pi f_{\mathrm{min}}T_{\mathrm{d}} + 2\pi K T_{\mathrm{d}}t)\big), T_{\mathrm{d}} < t < T_{\mathrm{c}}, \end{aligned}$$

where A_{t} and A_{r} are amplitudes of transmitted and received chirp signals, and $\pi K T_{\mathrm{d}}^2$ can be ignored because it is small. The movement of the chest surface due to the vibration of the heartbeat is small, then the phase information of the IF signal, $\varphi(t) = 4\pi f_{\mathrm{min}}\big(R_0 + x(t)\big)/c$, is used to calculate the displacement, where $x(t)$ is the displacement of the target.

---

† The author is with Graduate School of Science and Technology, Nihon University, Chiyoda-ku, Tokyo, 101-8308 Japan.

†† The author is with College of Science and Technology, Nihon University, Chiyoda-ku, Tokyo, 101-8308 Japan.

3. Proposed Method

Fig.1(a) shows the proposed signal processing chain in which HPF is introduced in DWT pre-processing to reduce the respiratory signal and its harmonics included in the radar vital sign $\boldsymbol{x}(\boldsymbol{t})$. We had to try designing filters for difference in body surface movement and respiratory signals depending on measurement directions and subjects.

3.1 Filter Design

3.1.1 Elliptic High Pass Filter

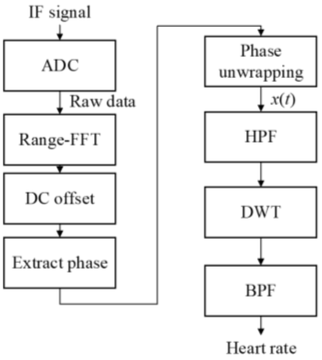
Normally, the respiration frequency is from 0.1 to 0.6 Hz and the heart rate is from 0.8 to 2.0 Hz [11]. Therefore, it was necessary to design an HPF with a passband frequency starting at 0.8 Hz. Moreover, there are two types of filters, IIR and FIR. Compared to IIR filters, FIR filters are simpler to design, but the number of taps must be increased to obtain good attenuation characteristics. However, to obtain good attenuation characteristics, it is necessary to increase the number of taps. Increasing the number of taps increases the computational complexity and delay time of the system. Since the response time is important for applications, an IIR type filter was selected in this study. Fig. 1(b) shows the frequency spectrum of the main IIR HPFs. Elliptic filters have a steeper frequency response in the transition band than Butterworth and Chebyshev filters. The Butterworth and Chebyshev filters may not reduce the respiratory signal enough. In addition, the Elliptic filter has a ripple in the stopband, but -80 dB is already considered to be sufficient attenuation. We then designed an IIR Elliptic HPF with a passband frequency from 0.8 Hz to estimate the heart rate.

3.1.2 High-pass Chebyshev Type II Filter

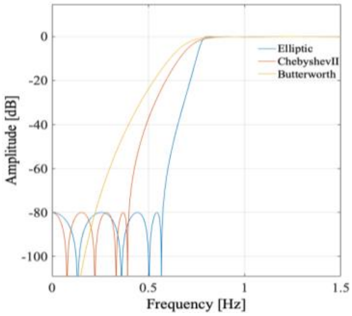
The passband ripple of HPF is shown in Fig. 1(c). As described later in experiments and results, the accuracy of the heart rate measurement from the backside worsened when the elliptical filter was used to reduce the respiratory component. The reason for this is that using a filter with a passband ripple on the data acquired from the back, which is less affected by the respiratory component, has a large impact on the accuracy and SNR. In short, a passband ripple negatively affects the data, which has fewer noises. Therefore, a high-pass Chebyshev type II filter with a flat passband area was used to reduce noise such as the respiratory component. Compared to the elliptic filter, the slope in the transition area is milder. However, it is not a big problem for the data acquired from the backside, which contains a little respiratory component. The accuracy and SNR may be improved due to the less ripple feature.

3.1.3 Band Pass Filter

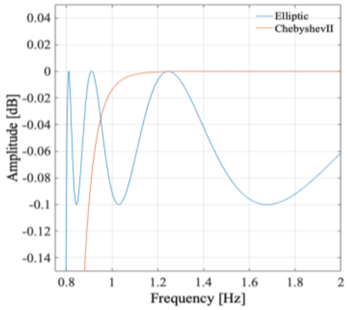
A band-pass filter (BPF) is shown in fig. 1(d), which attenuates signals in frequencies other than heart rate in waveforms reconstructed by the DWT, in which the low and high cutoff frequency was 0.8 and 2.0 Hz respectively, due to the typical heartbeat frequency band.



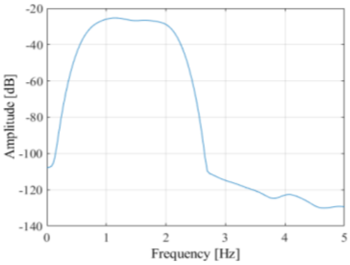
(a) Proposed signal processing chain



(b) HPF frequency spectrum



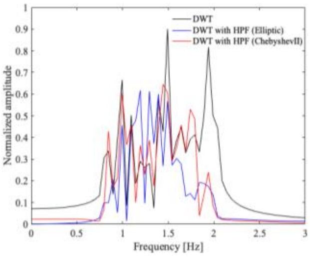
(c) Passband ripple of HPF



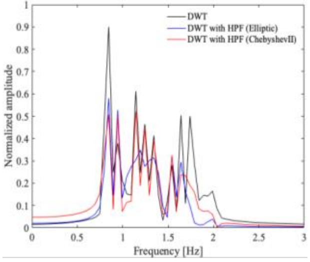
(d) BPF frequency spectrum

Fig. 1. The proposed method

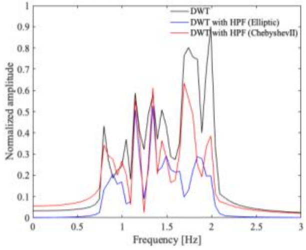
Fig 2. The experimental scene



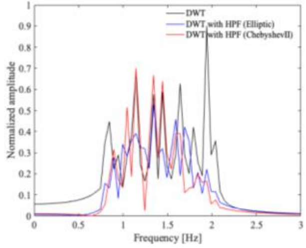
(a) Frontside



(b) Backside



(c) Right side



(d) Left side

Fig. 3. Example of frequency spectrums

Table I. SNR and RMSE

(a) Front

	SNR [dB]			RMSE [Hz]		
	w/o filter	Elliptic	Cheb. II	w/o filter	Elliptic	Cheb. II
Sub. A	-30.749	-29.606	-29.541	0.05036	0.04398	0.03525
Sub. B	-30.864	-30.532	-30.785	0.07035	0.06910	0.03997
Sub. C	-32.181	-29.909	-31.187	0.06582	0.05323	0.03168
Sub. D	-30.111	-29.515	-29.290	0.04334	0.03595	0.03776
Sub. E	-31.869	-30.523	-30.595	0.06508	0.02961	0.02758
Mean	-31.155	-30.017	-30.280	0.05899	0.04637	0.03445

(b) Back

	SNR [dB]			RMSE [Hz]		
	w/o filter	Elliptic	Cheb. II	w/o filter	Elliptic	Cheb. II
Sub. A	-30.722	-31.160	-30.212	0.04512	0.06512	0.04171
Sub. B	-28.788	-29.208	-26.580	0.19715	0.18884	0.03310
Sub. C	-32.082	-33.373	-29.964	0.06497	0.06040	0.05017
Sub. D	-35.601	-36.083	-30.270	0.06710	0.07390	0.04207
Sub. E	-31.888	-29.014	-27.170	0.05760	0.05047	0.03734
Mean	-31.816	-31.768	-28.839	0.08639	0.08775	0.04088

(c) Right

	SNR [dB]			RMSE [Hz]		
	w/o filter	Elliptic	Cheb. II	w/o filter	Elliptic	Cheb. II
Sub. A	-29.915	-29.802	-32.113	0.03846	0.03484	0.00183
Sub. B	-28.119	-27.228	-29.442	0.04690	0.04437	0.00163
Sub. C	-29.773	-28.744	-30.579	0.12783	0.11290	0.00094
Sub. D	-28.614	-28.255	-28.767	0.03868	0.03804	0.00132
Sub. E	-27.549	-27.409	-29.624	0.03759	0.04220	0.00170
Mean	-28.794	-28.288	-30.105	0.05789	0.05447	0.00148

(d) Left

	SNR [dB]			RMSE [Hz]		
	w/o filter	Elliptic	Cheb. II	w/o filter	Elliptic	Cheb. II
Sub. A	-29.041	-32.256	-32.398	0.05567	0.05638	0.00123
Sub. B	-31.639	-29.368	-31.123	0.05722	0.06490	0.00181
Sub. C	-32.315	-31.742	-29.839	0.05624	0.04275	0.00104
Sub. D	-33.480	-32.626	-30.334	0.05545	0.06572	0.00163
Sub. E	-31.279	-30.877	-31.071	0.05914	0.04454	0.00098
Mean	-31.551	-31.374	-30.953	0.05674	0.05486	0.00135

4. Experiments and Results

In the experiment, the radar was placed in two directions, front and back, about 1 m away from five subjects, and the vital signs were acquired for 60 seconds. The carrier frequency, bandwidth, chirp slope, chirp time, and frame time of the FMCW radar used were 77 GHz, 3.99 GHz, 70 MHz/μs, 57 μs, and 100 ms, respectively. In addition, heart rate data was acquired by ECG at the same time as vital sign acquisition by radar. These data were used as reference data. The heartbeat signal is extracted by applying the signal processing described above to the data obtained by radar. The radar vital sign was processed by moving the observation window of 200 frames by 10 frames. Root-Mean-Square Error (RMSE) was used to evaluate the accuracy by comparing the heart rate estimated by DWT with the reference heart rate measured by ECG.

Fig. 2 shows the experimental scene. Fig. 3 (a), (b), (c), and (d) show the effect of the proposed method on the heartbeat displacement data acquired at the front, back, right, and left, respectively. The figures show the comparison between the proposed method with elliptic and Chebyshev HPF and without HPF. For the front, the reference frequency obtained by ECG was 1.2 Hz, and the frequency estimated by DWT was around 1.19 for all filters. The obtained frequencies were the same, but the SNR was improved by employing the Chebyshev type II filter. The SNR was further improved by employing the elliptic filter. The result of DWT without filter includes larger noises than the heartbeat signal around 1.0, 1.4, 1.5, 1.6, and 2.0 Hz. Even though the Chebyshev type II HPF reduced those noises, the heartbeat signal is still smaller than them. While the elliptic HPF reduced those noises, and the heartbeat signal became the largest. Since the noise around 0.85 Hz is reduced. This is probably due to the steep roll-off of the elliptic filter. For the back, the subject's heart rate frequency was around 1.1 Hz in the ECG data, 1.14 in the DWT only and with the Chebyshev type II filter, and 1.19 with the elliptic filter. By reducing the respiratory component with the Chebyshev type II filter, the SNR of the heartbeat signal was improved. For the right, the respiratory signal is relatively large compared to the heartbeat signal because the human heart places on the left side of the human body. The reference frequency is 1.1 Hz, the frequency estimated by DWT is 1.14 Hz for all filters. The results of the without filter and the Chebyshev filter include large noises around 1.9 Hz due to the noise around 0.8 Hz. The elliptic filter reduced the noise by around 0.8 Hz. As a result, in the elliptic filter result, the heartbeat signal became a large signal relatively. For the left, the heartbeat signal is relatively large. The reference frequency is 1.1 Hz, the frequency estimated by DWT is 1.14 Hz for all filters. The results of the without filter and elliptic filter include noises that are larger than the heartbeat signals. While in the Chebyshev filter's result, the heartbeat signal is the largest.

Table I (a), (b), (c), and (d) show the SNR and RMSE of the heart rate estimation using the data acquired from the front, back, right, and left respectively. The SNRs of each subject are the average value calculated from the each SNR of all observation windows. Table I (a) shows that the frontal measurements were better with the Chebyshev type II filter than without the filters. However, the SNR improvement for subjects B, C, and E was higher when the elliptic filter was used. The reason for this is that the slope of the transition area of the Chebyshev type II filter is slower than that of the elliptic filter. Therefore, the Chebyshev type II filter may not be able to reduce noise such as the respiratory component included in the data acquired from the front. As shown in Table I (b), SNR and RMSE were improved by employing the Chebyshev type II filter in the backward measurement compared to the case without HPF and with the elliptic filter for all subjects. Therefore, it was confirmed that the ripple in the passband affected the data acquired from the back, because the respiratory component was hardly included in the data. Table I (c) shows that the elliptic filter is more suitable than the without filter and the Chebyshev filter for all subjects for the right. Table I(d) shows that the elliptic filter improved the SNR over the without filter and Chebyshev filter for subjects A and B in the left. While the Chebyshev filter performed well over the without filter and the elliptic filter for subjects C, D, and E.

5. Conclusion

In this research, heartbeat signals were acquired using a 77GHz FMCW radar, respiratory signals and their harmonics were reduced by high-pass filters, and heartbeat signals were extracted by discrete wavelet transform and finally with a band-pass filter. For the backward estimation, the SNR and RMSE improvement depend on the subjects with the elliptic filter. On the other, the Chebyshev type II filter improved both the SNR and RMSE, regardless of the subjects, that had less passband ripple. For the right side estimation that includes relatively large respiratory signals, the elliptic filter is suitable. For the left side estimation that includes relatively small respiratory signals, the improvements depend on the subjects. For the above results, the Chebyshev type II filter may be effective for the data acquired from the directions, which has little respiratory signal.

References

[1] C. Ye, K. Toyoda, and T. Ohtsuki, “A Stochastic Gradient Approach for Robust Heartbeat Detection with Doppler Radar Using Time-Window Variation Technique” IEEE Trans. on Biomedical Engineering, vol. 6, pp. 1730-1741, Jun. 2019.

[2] T. Okano, S. Izumi, H. Kawaguchi, and M. Yoshimoto, “Non-contact biometric identification and authentication using microwave Doppler sensor,” Proc. of IEEE Bio. Circ. and Sys. Conf. (BioCAS), pp. 392-395, Oct. 2017.

[3] H. Tan, D. Qiao, and Y. Li, “Non-Contact Heart rate Tracking Using Doppler Radar”, 2012 Int’l Conf. on Sys. and Info. (ICSAI2021), pp. 1711-1714, June 2012.

[4] H. S. Cho, Y. J. Park, and H. K. Lyu, “Robust Heart rate Detection Method using UWB Impulse Radar”, 2016 Int’l Conf. on Info. and Commun. Tech. Converg. (ICTC2016), pp. 1138-1142, Oct. 2016.

[5] Y. Hu and T. Toda, “Remote Heart rate Estimation based on Phase Accumulation-Linear Interpolation Method for mm-Wave FMCW Radar,” IEICE Communications Express (ComEX), Nov. 2020.

[6] R. Koyanaka, Y. Hu, and T. Toda,”A Study of Heart rate Estimation with Empirical Mode Decomposition for 77 GHz FMCW Radar,” 2020 Int’l Conf. on Emerging Tech. for Commun. (ICETC2020), A4-4, Dec. 4 2020.

[7] Y. Hu and T. Toda, “The Effect of Multi-directional on Remote Heart Rate Measurement Using PA-LI Joint ICEEMDAN Method with mm-Wave FMCW Radar,” 2021 IEICE Transactions on Commun. Aug. 2021.

[8] M. Li, J. Lin., “Wavelet-Transform-Based Data-Length-Variation Technique for Fast Heart rate Detection Using 5.8-GHz CW Doppler Radar,” IEEE Trans. on Micro. Theory and Techs., Vol. 66 pp.568-576, no. 1, Jan. 2018.

[9] C. Bhagavatula, S Venugopalan, R Blue, R Friedman, M. O. Griofa, Marios Savvides and B.V.K.Vijaya Kumar., "Biometric Identification of Cardiosyn-chronous Waveforms Utilizing Person Specific Continuous and Discrete Wavelet Transform Features,” 2012 Annual Int’l Conf. of the IEEE Eng. in Med. and Bio. Soc., pp. 4311-4314, Nov. 2012.

[10] R. Koyanaka, S. Sato, Y. Hu, and T. Toda, “Respiration Harmonics Suppression by HPF in Heart rate-estimation with Discrete Wavelet Transform” IEICE Gen. Conf. B-19-8, Mar. 2021.

[11] M. Alizadeh, G. Shaker, J. Carlos Martins De Almeida, P. Pelegrini Morita, and S Safavi-Naeini., ‟ Remote Monitoring of Human Vital Signs Using mm-Wave FMCW Radar,” IEEE Access, Vol.7 pp. 54958-54968, Apr 2019.