High-Precision Vital Signs Monitoring Using FMCW Millimeter-Wave Radar

Digital Signal Processing (DSP) techniques for non-contact detection of respiration and heart rate.

Why This Research?

- **Non-contact vital sign monitoring** is crucial for:
    - Burn patients, newborns, elderly, and infectious disease monitoring.
    - Applications like home healthcare and driver fatigue detection.
- **Challenges**:
    - Hardware noise → **Low SNR** (signal-to-noise ratio)
    - Extracting small motions like breathing/heartbeat accurately.

Proposed System Overview

FMCW Radar-Based Monitoring System

- **Radar Type**: 77 GHz FMCW millimeter-wave radar.
- **Scenario**: Monitor a person sitting in an office environment.
- **Data Acquired**:
  - **Respiration rate**
  - **Heart rate**
- **DSP Chain**: Key innovation of the paper.

Signal Processing Chain

Steps in DSP Workflow

1. **Signal Preprocessing**:
    - Static clutter removal (background interference).
    - DC offset compensation (correct hardware bias).
2. **Phase Extraction In Range Window**:
    - Use extended DACM algorithm to extract phase.
3. **Noise Reduction**:
    - Iterative VMD Wavelet-Interval-Thresholding.
4. **Feature Extraction**:
    - Respiration: FFT-CZT hybrid algorithm.
    - Heartbeat: Time-domain peak-seeking & FFT.
5. **Final Output**:
    - Accurate respiration and heart rate with low relative errors.

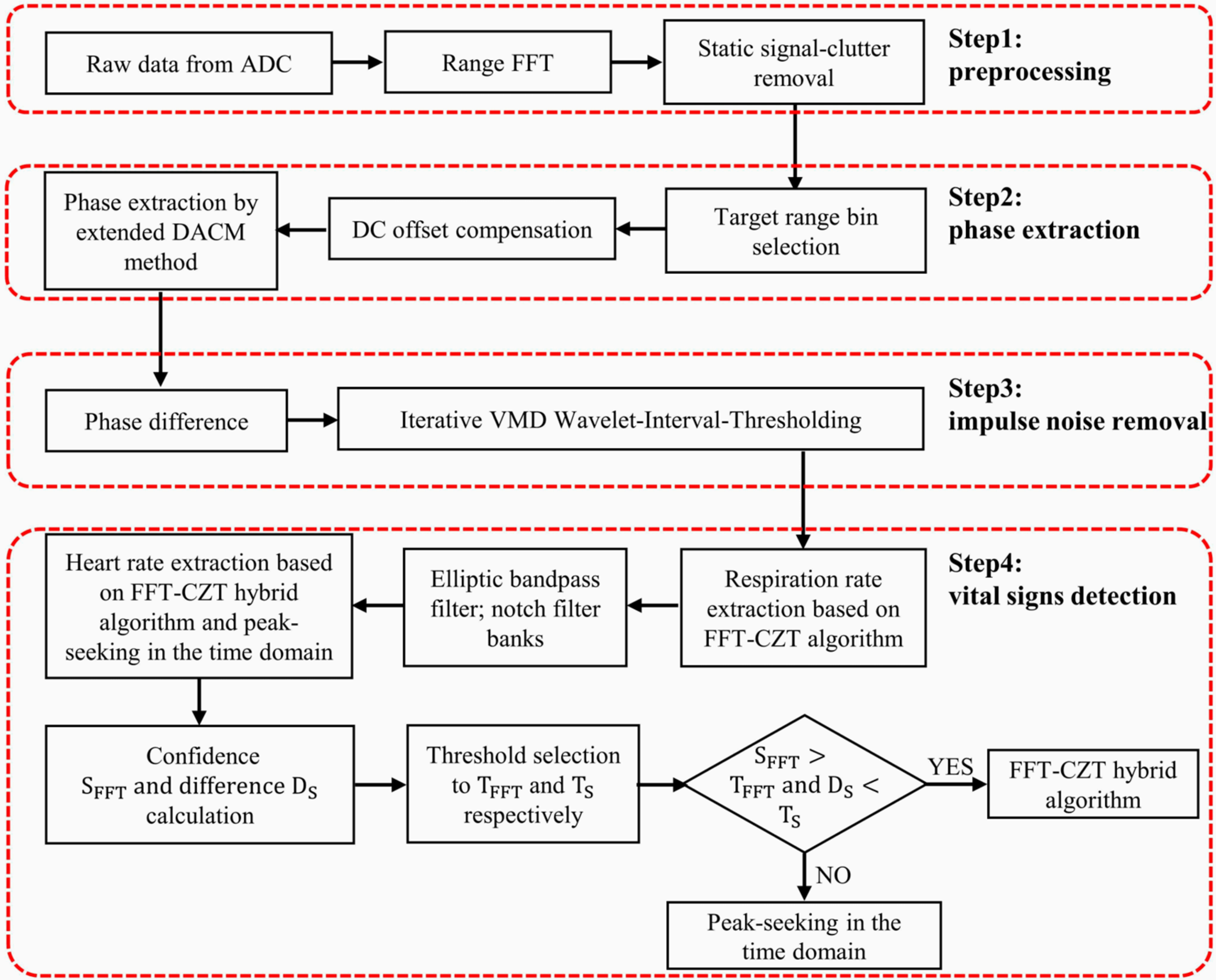


Figure 1. The proposed signal processing algorithm chain.

Range FFT and Static Clutter Removal

Range FFT

- Converts radar raw data (in time domain) into frequency domain.
- Identifies the **distance (range)** of targets by analyzing signal frequencies.

Static Signal Clutter Removal

- Eliminates interference from stationary objects (e.g., walls or furniture).
- Focuses only on signals reflected from moving targets (e.g., human breathing or heartbeat).

Range FFT

Key Concepts:

- **Radar Signal:** Reflected signals contain time delays proportional to the distance of objects.
- **FFT (Fast Fourier Transform):** Converts the time-delay signal into frequencies to calculate distances.

Steps:

1. **Raw Data:** Radar captures signals over multiple fast-time intervals.
2. **Apply FFT:** Transforms time-domain data into frequency domain.
3. **Identify Range:** The frequency peaks correspond to the distances (ranges) of objects.

Static Signal Clutter Removal

Key Concepts:

- Stationary objects (e.g., walls, furniture) cause "clutter" in radar data.
- Moving targets (e.g., human chest movements) create dynamic signals.

Method:

$$y[m,n] = y_0[m,n] - \frac{1}{N_{\text{frames}}} \sum_{n=1}^{N_{\text{frames}}} y_0[m,n]$$

where $m = 1, 2, 3, \ldots, N_{\text{samples}}; n = 1, 2, 3, \ldots, N_{\text{frames}}$. N_{samples} means the number of sampling points of each chirp; and N_{frames} means the number of frames.

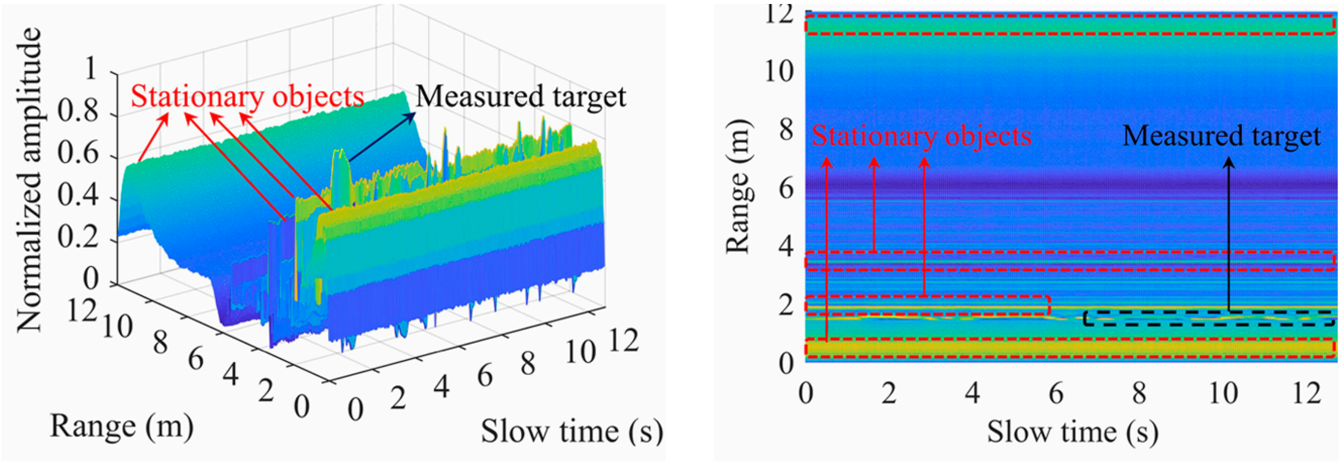
Why Are These Steps Important?

Range FFT:

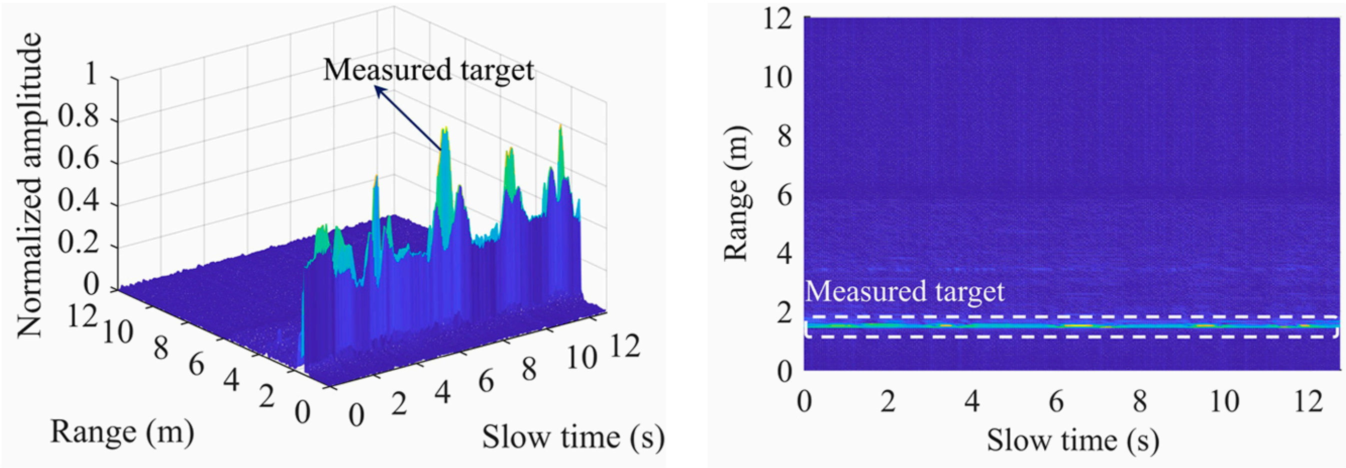
- Determines **where** the targets are located (distance).
- Creates the **range bins** for further processing.

Static Signal Clutter Removal:

- Focuses on **dynamic movements** of interest.
- Improves signal-to-noise ratio (SNR) for vital signs detection.



(**a**)



(**b**)

Figure 2. Range-FFT: (**a**) before static signal-clutter removal; (**b**) after static signal-clutter removal.

DC Offset Compenstation

Definition

- DC offset is an unwanted constant or low-frequency component in a signal that shifts it away from its baseline (zero level).
- This offset occurs due to hardware imperfections such as ADC or amplifier imbalance.

Purpose

- Remove the DC component to center the signal around zero.
- Improve analysis of dynamic signal variations caused by respiration and heartbeat.

Process

1. **Calculate the DC Component**:

$$\mathrm{DC}_{\mathrm{value}} = \frac{1}{N} \sum_{n=1}^{N} x[n]$$

2. **Subtract the DC Component**:

$$x_{\mathrm{adjusted}}[n] = x[n] - \mathrm{DC}_{\mathrm{value}}$$

3. **Result**:
    - Signal is centered around zero, eliminating static bias.

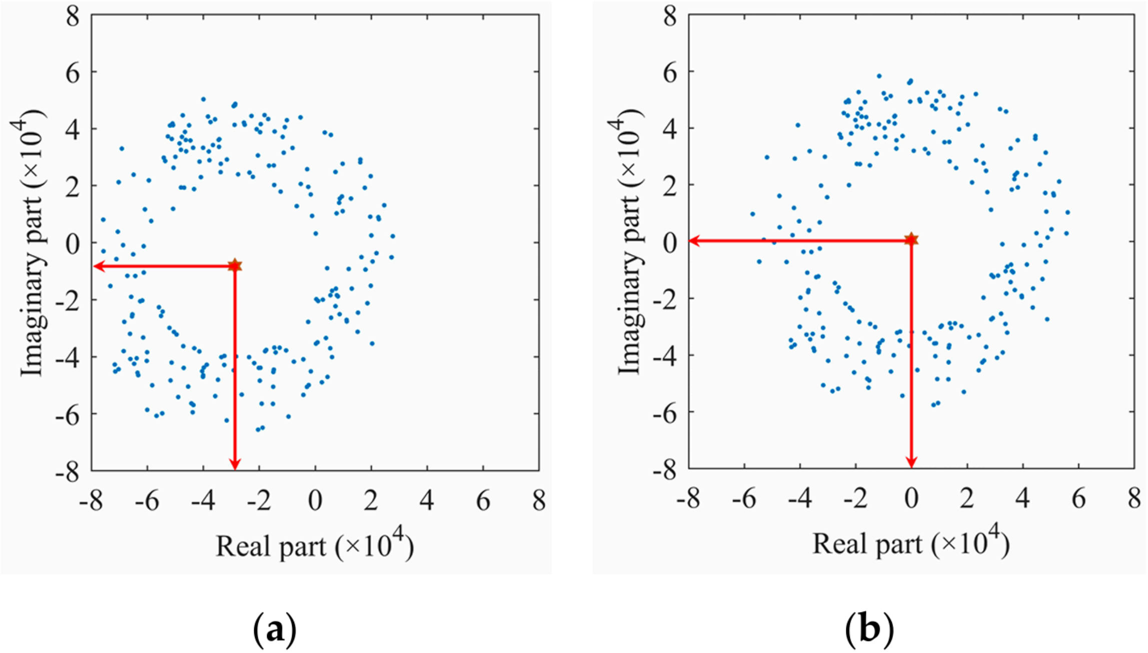


Figure 3. The complex data at the selected range bin: (**a**) before DC offset compensation; (**b**) after DC offset compensation.

DACM (Differentiate and Cross Multiply)

Definition

- A method to extract dynamic phase changes from radar signals by focusing on short-term variations and removing static noise.

Purpose

- Isolate dynamic phase signals caused by physiological movements (e.g., breathing, heartbeat).
- Remove static phase noise or low-frequency interference.

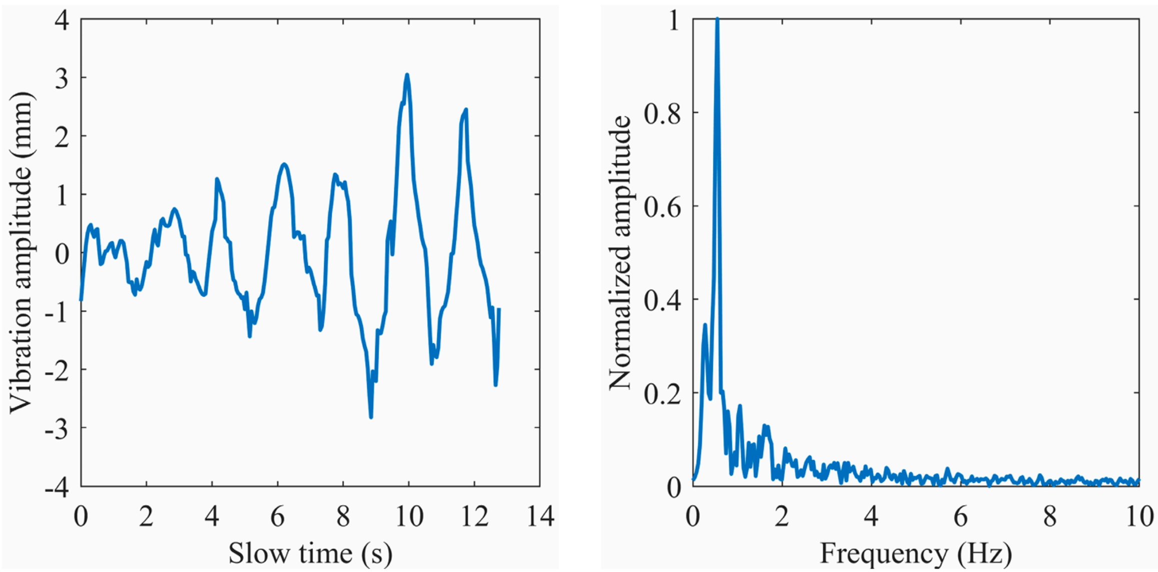
Steps

1. **Phase Extraction**:
   - Calculate the instantaneous phase from I (in-phase) and Q (quadrature) components: $\phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right)$
2. **Differential Phase Calculation**:
   - Compute the change in phase over time: $\Delta\phi(t) = \phi(t) - \phi(t-1)$
3. **Accumulation**:
   - Reconstruct the dynamic phase signal by accumulating differential values: $\phi_{\text{DACM}}(t) = \sum_{k=1}^{t} \Delta\phi(k)$
4. **Filtering**:
   - Apply high-pass filtering to remove residual low-frequency noise.

1. $$\frac{d}{dt}\phi(t) = \frac{d}{dt}\left[\arctan\frac{Q(t)}{I(t)}\right] = \frac{I(t)Q'(t) - Q(t)I'(t)}{I(t)^2 + Q(t)^2}$$

2. $$\phi(n) = \sum_{k=2}^{n} \frac{I(k)\left[Q(k) - Q(k-1)\right] - Q(k)\left[I(k) - I(k-1)\right]}{I(k)^2 + Q(k)^2}$$

We transform the extracted phase into **the waveform of chest vibration amplitude varying with slow time** and obtain **its spectrum information** through FFT.



(**a**) (**b**)

Figure 4. Extracted phase by the extended DACM: (**a**) in the time domain; (**b**) in the frequency domain.

We found that the heartbeat frequency is covered in the spectrum in ***Figure 4b*** because the chest fluctuation caused by the heartbeat is very weak relative to breath

The first-order phase difference operation is adopted to enhance the heartbeat signal. ***Figure 5*** shows the time domain waveform and frequency domain spectrum of the differential signal, where the spectral amplitude in the heart rate range is increased.

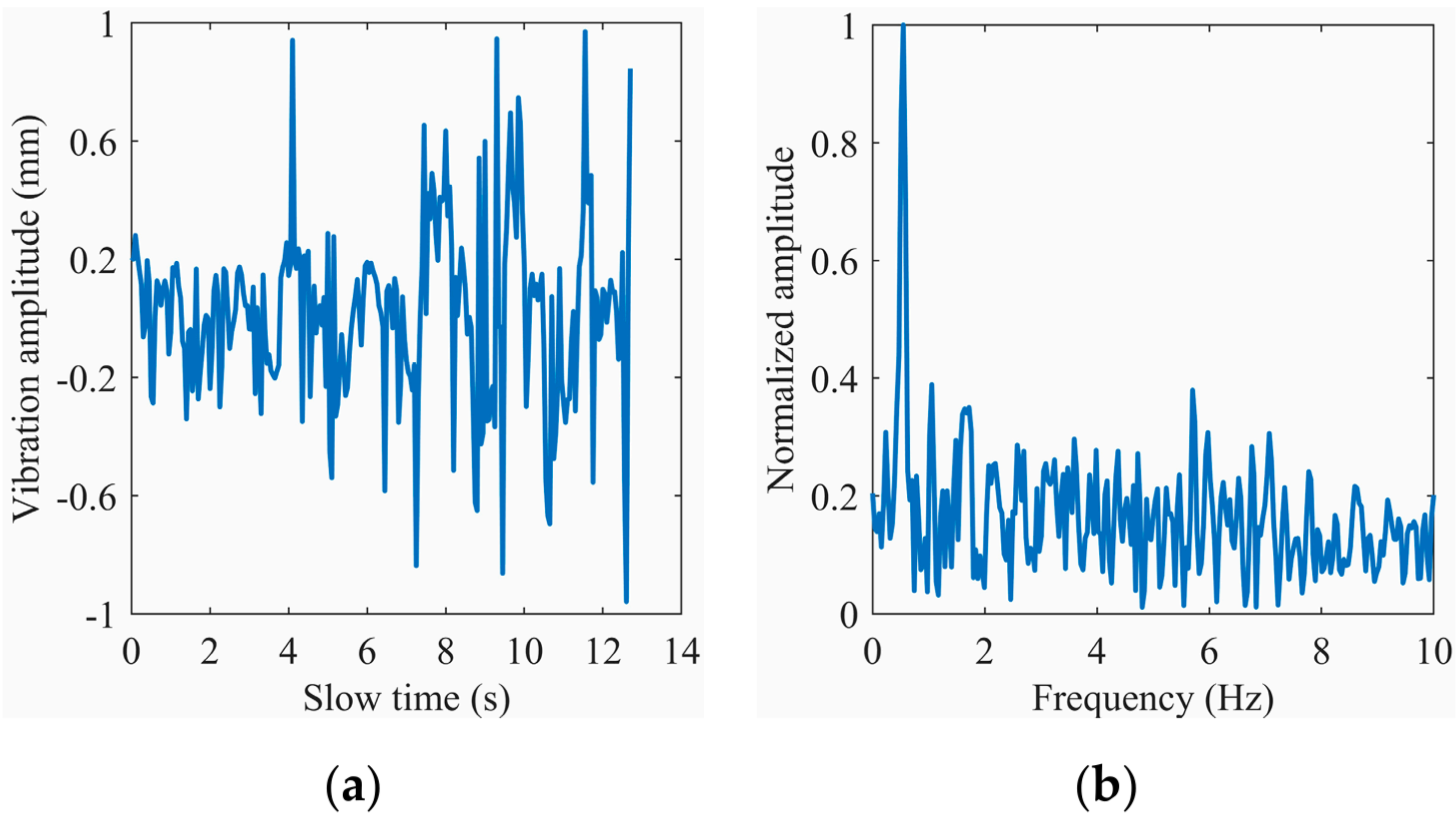


Figure 5. Phase difference: (**a**) in the time domain; (**b**) in the frequency domain.

Examples

DC Offset Compensation:

- Input Signal: $x(t) = 3 + \sin(t)$
- After Compensation: $x(t) = \sin(t)$

DACM:

- Input Phase:
  $\phi(t) = \text{static component} + \text{dynamic signal}$
- After DACM: Only dynamic signal remains (e.g., breathing signal at 0.2 Hz, heartbeat at 1 Hz).

Key Applications

- DC Offset Compensation: Preprocessing radar signals for accurate phase analysis.
- DACM: Extracting precise dynamic phase components for physiological monitoring.

Experiments and Results

Experimental Setup

- **Radar Used**: TI AWR1642 with DCA1000 acquisition board.
- **Subjects**: 11 people, 2 groups.
    - Group 1: Normal respiration & heart rates.
    - Group 2: Accelerated breathing/heart rates.
- **Test Scenarios**: Distances of 0.8m, 1m, 1.3m, 1.5m.

Results

- **SNR Improvement**:
  - Respiration: +1.89 dB.
  - Heartbeat: +1.44 dB.
- **Accuracy**:
  - Respiration: Avg. error = 1.33%.
  - Heartbeat: Avg. error = 1.96%.

Contributions of the Paper

Why This Paper Matters

- Combines FMCW radar with advanced DSP techniques.
- Demonstrates non-contact vital sign monitoring with high accuracy.
- Addresses challenges like:
    - Low SNR.
    - Hardware imperfections.
    - Small motion extraction.
- **Applications**:
    - Healthcare monitoring.
    - Emergency alerts.
    - Home-based elderly care.

Summary and Conclusion

Key Takeaways

- FMCW radar + DSP = High-precision monitoring.
- **DSP Techniques**:
  - Iterative VMD Wavelet-Interval-Thresholding.
  - FFT-CZT hybrid algorithm.
  - DC offset compensation.
- **Results**:
  - Accurate respiration and heart rate monitoring.
  - Applicable in noisy, real-world environments.
- **Future Scope**:
  - Real-time processing.
  - Broader healthcare applications.