SMCW Radar for Low IF Sensing Applications

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***Abstract*—Quadrature monostatic direct conversion receivers (homodyne) have been extensively studied for detecting slow, small amplitude motions such as vital signs. The main advantage of direct conversion monostatic receivers is the straightforward coherent sensing that mitigates the oscillator phase noise. However, any imbalance between the two channels introduce significant errors in the recovered displacement and additional flicker noise is introduced during direct down-conversion to DC and in the baseband amplification circuit. To overcome these problems, low intermediate frequency radars have been proposed. Nevertheless, they exhibit increased hardware complexity and non-straightforward coherent detection. A sinusoidally modulated continuous wave radar is proposed to combine the benefits of the homodyne and heterodyne architectures. A theoretical analysis has been presented and experimentally verified. Measurements using mechanical targets demonstrate signal to noise ratio improvements of up to 21.45 dB, when a 10 µm motion was measured at a distance of 100 cm.**

Keywords—Doppler radar, low-IF, mechanical vibration, physiological signals, radar sensors.

I. Introduction

Doppler and interferometric radars have been widely studied for sensing applications. These sensors have shown great potential for speed monitoring, non-contact and unobtrusive cardio-respiratory motion sensing, and structural health monitoring [1]. The most widely used architecture in continuous wave (CW) Doppler radar is the quadrature monostatic direct conversion (homodyne) architecture, since it has less hardware complexity, coherent down-conversion, and solves the optimal/null point problems. However, it suffers from DC offset, I/Q channels imbalances, and flicker noise due to impurities in the transceiver components [2]. To overcome these limitations, low intermediate frequency (IF) receivers (heterodyne) have been proposed [3]-[5]. Nevertheless, coherent detection is not straightforward in heterodyne receivers, which is essential for phase information extraction [4]. For instance, when different signals are used in the IF stage of the receiver (RX) and transmitter (TX) paths, it results in the loss of the coherent detection, since the oscillators' phase noises are uncorrelated. For coherent digital low-IF demodulation, heterodyne radars require co-designing the baseband digital processing unit (i.e., the digital IF demodulation clock should be coherent with the RF local oscillator) and the RF front end, which is not straightforward to achieve. Even though coherent heterodyne architectures have been proposed [3]-[5], additional hardware such as mixers and oscillator are required, which increases the system's hardware complexity, power consumption, and cost [2].

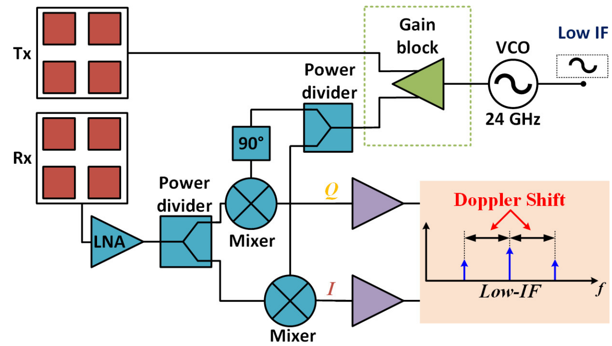

Fig. 1. Block diagram of the proposed SMCW radar.

For a non-stationary conventional Doppler/interferometric radar, the detected baseband signal can be obtained as the convolution between the radar and the target's motion. It is well known that a signal can be up-converted when a periodic phase shift is applied [6]. Therefore, if a periodic mechanical motion is applied to the radar (e.g., using a linear actuator), a frequency shift equal to the inverse of the motion's period will be applied, generating a low-IF in the recovered signal. However, applying a mechanical motion to the radar is inconvenient and increases the system's form factor, complexity, and cost. Heterodyne architectures have been widely used for vital signs and slow vibration detection (in the range of 0.1 to 1.5 Hz), since the performance of the homodyne structures significantly degrades at frequencies close to DC. Improvements of up to 15 dB in the signal to noise ratio (SNR) have been reported for motion frequencies below 1 Hz [5]. Additionally, for heterodyne architectures, the I/Q channels can be digitally generated, removing the imbalances present in homodyne receivers. However, heterodyne structures usually need a mixer to up-convert the TX/RX signals, a signal generator for the low IF, and an extra RF filter to avoid the double side band (DSB) global null point problem [5]. Several modulations to the radar's TX signal have been proposed to sense both range and speed using radar system. For instance, linear (LFMCW) and step (SFMCW) frequency modulated continuous wave, and frequency shift keying (FSK) radars have been widely studied for range and speed sensing. However, the feasibility of modulating the radar's TX signal to overcome the limitations of homodyne interferometric radars has not been explored yet.

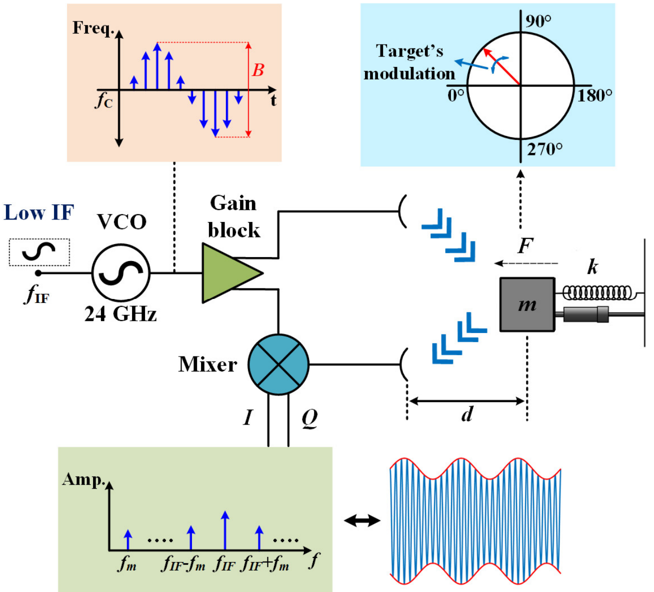

Fig. 2. Illustration of the proposed SMCW low-IF sensing technique.

In this paper, a sinusoidally modulated continuous wave (SMCW) radar is proposed as depicted in Fig. 1. By periodically changing the radar's transmitted frequency, the target's motion is successfully up-converted. Moreover, the straightforward coherence of monostatic direct-conversion receivers is preserved, since a single signal source is used for the TX/RX paths and an exact copy of the TX signal is used for down-conversion on the receiver side. Therefore, combining the benefits of the homodyne and heterodyne architectures at the cost of increased bandwidth (BW).

II. Theory

A typical Doppler/interferometric radar transmits a single-tone continuous-wave signal towards the target and down-converts the generated echo. The phase of the reflected down-converted signal is directly proportional to any movement performed by the target (e.g., cardio-respiratory motion) [1], [6]. The normalized baseband signals obtained from a quadrature homodyne receiver can be modeled as $S_I(t) = \cos(4\pi x(t)/\lambda + \phi)$ and $S_Q(t) = \sin(4\pi x(t)/\lambda + \phi)$, where ϕ is the total residual phase accumulated in the circuit and along the transmission path, λ is the wavelength of the wireless signal, $x(t) = m\sin(\omega_m t)$ is the mechanical movement, and m and ω_m are the motion's amplitude and frequency, respectively. If the radar's TX frequency is sinusoidally modulated, the normalized baseband signals could now be modeled as:

$$S_{ISM}(t) = \cos\left(\frac{4\pi m \sin(\omega_m t)}{c/(f_c + B\sin(\omega_{IF} t))} + \phi(t)\right) \quad (1)$$

$$S_{QSM}(t) = \sin\left(\frac{4\pi m \sin(\omega_m t)}{c/(f_c + B\sin(\omega_{IF} t))} + \phi(t)\right) \quad (2)$$

where $\lambda(t) = c/(f_c + B\sin(\omega_{IF} t))$, c is the speed of light, B is the modulation BW, f_c is the center frequency of the TX signal, and $\omega_{IF} = 2\pi f_{IF}$ is the angular frequency of the desired low-IF signal, as depicted in Fig. 2. The time varying residual phase accumulated in the circuit and along the transmission path is $\phi(t) = 4\pi d/\lambda(t) + \theta(t)$ where d is the distance between

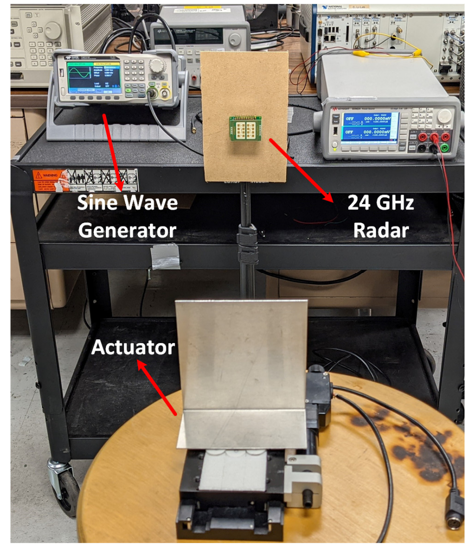

Fig. 3. Experimental setup.

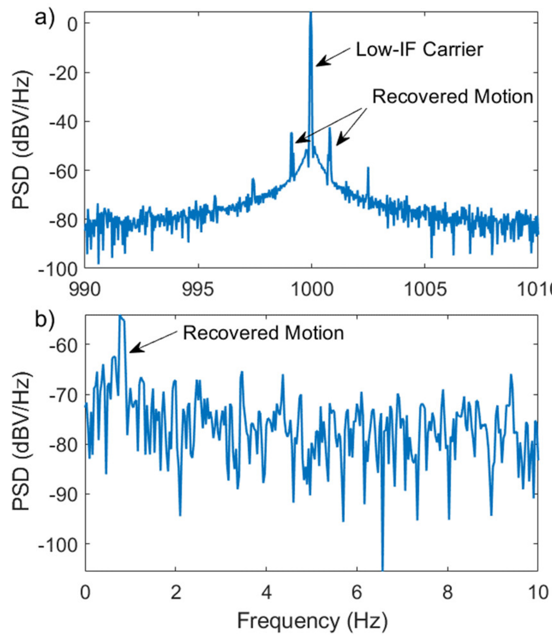

Fig. 4. SMCW radar recovered spectrum for a) low-IF and b) fundamental response.

the target and the radar and $\theta(t)$ is the total residual phase accumulated in the circuit. After dividing $4\pi x(t)/\lambda(t)$, performing polynomic expansion, and taking $4\pi m/c$ as a common factor, the generic recovered signal for an SMCW radar can be modeled as:

$$S_{SM}(t) = \cos\left(\frac{4\pi m}{c}[f_c \sin(\omega_m t) + B\sin(\omega_m t)\sin(\omega_{IF} t)] + \phi(t)\right). \quad (3)$$

From (3), it can be deducted that due to the sinusoidally time varying wavelength $\lambda(t)$, a DSB up-conversion is applied to the target's motion when an SMCW radar is used. In other words, two tones located at $\omega_{IF} - \omega_m$ and $\omega_{IF} + \omega_m$ will be added to the radar's recovered signal compared with the conventional

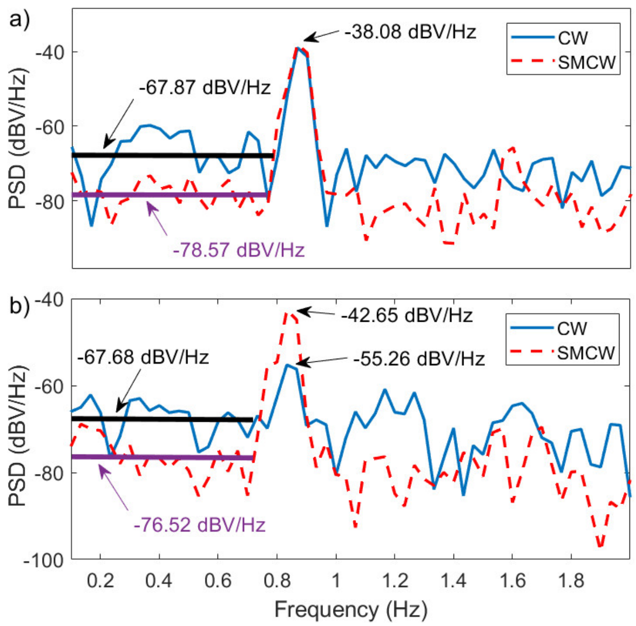

Fig. 5. SMCW and CW radar recovered spectrum comparison for a 10 μm motion at a) 80 and b) 100 cm using envelope detection.

CW case, as depicted in Fig. 2. The introduced frequency shift is very important for measuring slow motions, since the flicker noise rapidly decays as the frequency increases. From (3), it also can be deducted that the system's sensitivity depends on the BW used for the detection, since *B* directly affects the phase shift applied by the generated low-IF to the recovered baseband signals. However, if the used BW is large enough to perform large angular modulation to the signal, harmonics will be created in the recovered spectrum [2].

III. Experimetal Results

To verify the feasibility of using an SMCW radar for low-IF sensing, experiments were carried to measure the mechanical motion of an actuator (Zaber T-NAO8A50) using a 24 GHz radar (InnoSent IVS-162), as depicted in Fig. 3. A 1 kHz sine wave was used to modulate the radar's TX signal with a total BW of 102 MHz. Experiments were carried out at two different distances between the radar and the actuator (80 and 100 cm). Additionally, the experiments were repeated using the radar in CW mode to compare the performance. The actuator was programed to produce a periodic movement of 0.9 Hz with an amplitude of 10 μm to evaluate the radar's sensitivity. Finally, power spectral density (PSD) was used to compute the recovered spectrum, 30 seconds windows were used for all the experiments with a sampling frequency of 20 kHz.

To understand the sensing mechanism, the actuator was placed 80 cm away from the radar and was set to perform a 10 μm motion. The recovered spectrum is depicted in Fig. 4(a)-(b), as predicted by the authors' analysis, the recovered motion was successfully up-converted to around 1 kHz and the fundamental response is still present on the spectrum. However, as depicted in Fig. 2, to analyze the obtained results in comparison with the ones obtained using the radar in CW mode, envelope detection needs to be applied to the recovered low-IF signals. Fig. 5(a)-(b) show the recovered spectrum of an SMCW radar after envelope detection is applied. The actuator was placed 80 cm away from the radar and a 10 μm motion was measured using the same radar system configured in both SMCW and CW modes. The obtained results are depicted in Fig. 5(a). As can be seen, a 10.7 dB improvement was achieved for the SMCW radar case, due to the flicker noise reduction at 1 kHz. Then, the actuator was placed 100 cm away from the radar and the same experiment was repeated. As depicted in Fig. 5(b), this time a 21.45 dB SNR improvement was achieved for the SMCW radar case, showing the effectiveness of the proposed modulation to improve the Doppler/interferometric radar sensitivity for the slow motion case. However, a higher improvement was observed when the actuator was placed 100 cm away from the radar, compared with 80 cm case. To better understand this difference, five experiments were carried out for the 80 and 100 cm case, where similar results were obtained. This difference could be caused due to systematical error, or the complex relationship between the TX/RX signals. Therefore, in the continued research, a deeper theoretical analysis should be performed to better understand the sensing mechanism and analyze the impact of the proposed modulation on the well-known limitations of interferometric radars, such as large angular modulation, and optimal/null point detection.

IV. Conclusion

The feasibility of using sinusoidal modulation to generate a low-IF on conventional direct conversion radars was studied and experimentally verified. A 10 μm motion was successfully recovered using both CW and SMCW radars, when the actuator was placed 80 and 100 cm away from the radar. SNR improvements of 10.7 and 21.45 dB were obtained for each case, respectively. The SNR improvement was achieved at the cost of a 102 MHz BW. Further analysis will be performed to study the feasibility of using this technique for digital *I*/*Q* generation and range detection. Additionally, the large angular modulation and optimal/null point limitations should be studied for the proposed modulation.

Acknowledgment

The authors wish to acknowledge National Science Foundation (NSF) for funding support under Grant 1808613 and 2030094.

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