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# Micro Vibration Reconstruction Under In-Range Large-Scale Dynamic Clutters Using a Bi-Exponential Radar Signal Model

Xujun Ma<sup>\*1</sup>, Pei Wang<sup>\*</sup>, Jie Liu<sup>#</sup>, Daqing Zhang<sup>\*</sup>

<sup>\*</sup>SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris, France

<sup>#</sup>Nanjing Forestry University, China

<sup>1</sup>xujun.ma@telecom-sudparis.eu

**Abstract**—In this paper, a novel micro vibration reconstruction method is proposed to mitigate the influence of in-range large-scale dynamic clutters for radar sensing. In order to understand the impact of dynamic clutters on the target signal, a bi-exponential radar signal model is introduced to explicitly characterize the superposition mechanism between the target and clutter vector signals. Theoretical analysis shows that strong dynamic clutters would overwhelm the target signal and further distort the sensing result when using conventional demodulation methods. To solve this problem, a vector separation technique is proposed via accurate estimation of both vector signals and proper phase unfolding. Leveraging an Impulse-Radio Ultra-Wideband (IR-UWB) radar, experiment results show that the proposed technique could effectively recover the micro mechanical vibration in the presence of a strong in-range dynamic clutter.

**Keywords**—Bi-exponential radar signal model, in-range dynamic clutter, micro vibration reconstruction, vector separation.

## I. INTRODUCTION

Recently advance in high-performance radar architectures and algorithms paves the road to accurate detection of micro vibrations in the presence of various kinds of hardware drawbacks, e.g., flicker noise [1][2], I/Q imbalance[3], and AC distortion issue[4]. However, due to the complexity of environment, clutter signals reflected from ambient objects pose more challenges to robust target sensing. It is easy to remove the influence of the clutters that are far away from the targets by leveraging wideband radar systems, like Frequency-Modulated Continuous-Wave (FMCW) and Impulse-Radio Ultra-Wideband (IR-UWB) radars, which provides sufficient range resolution to differentiate objects from range. However, in real environment (e.g., in the factory scenario), it is also common that some clutters stay close to the target or locate at the same range bin but from different directions. Therefore, the in-range clutters and the target signal will merge with each other, affecting the sensing performance.

According to the Doppler feature of the clutter signals, they could be classified as stationary and dynamic clutters. Usually, in the presence of in-range stationary clutters, it is difficult to accurately locate the position of the target especially when the strength of the clutter signal is greater than the target signal. Conventional solutions filter out the unmoving clutters by leveraging stationary elimination techniques (e.g., moving target indication (MTI) algorithm [6]), and then the moving target could be explicitly identified. Furthermore, to realize high-linear target motion tracking,

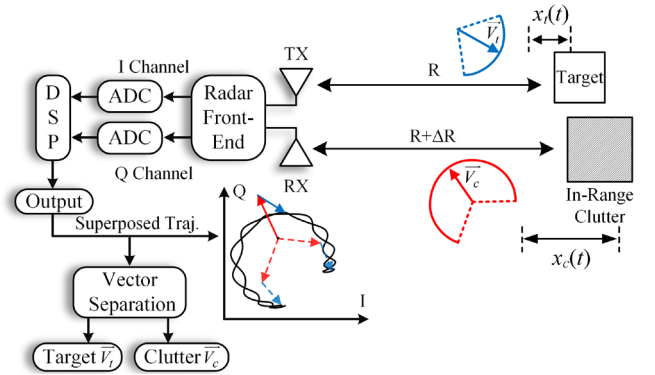


Fig. 1. Micro vibration detection under in-range large-scale dynamic clutter using a radar system.

specific DC cancellation techniques [7] are essentially required to remove the additional DC offset caused by the in-range stationary clutters, so that the linear phase demodulation could work properly without any unwanted phase distortion. In contrast, when the proximity clutter comes from a moving object which is quite common in the factory scenario, the in-range clutter signals become dynamic and inevitably superpose with the target signal. Unfortunately, conventional phase demodulation methods fail to accurately retrieve the target motion due to phase distortion especially when the radar cross section (RCS) of the clutter is significantly larger than that of the target. In [8], a frame subtraction method is proposed to remove the clutter for FMCW radar, whereas huge digital resources are required to process the algorithm in the intermediate-frequency (IF) domain.

In this paper, a novel micro vibration reconstruction method is proposed in the presence of in-range large-scale dynamic clutters. A bi-exponential radar signal model is proposed to depict the superposition mechanism of the clutter and target signals. Based on this model, a vector separation method is further introduced to separate target signal from the clutters based on the estimation of key trajectory parameters. Experiments prove the effectiveness of this method for mechanical vibration detection using an IR-UWB radar.

## II. THEORY

### A. Bi-Exponential Radar Signal Model

Fig. 1 demonstrates the schematic diagram of reconstructing target's micro vibration in the presence of in-range large-scale dynamic clutter using the proposed vector

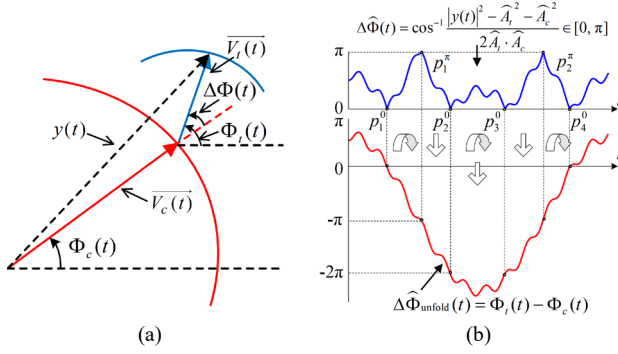


Fig. 2. (a) Bi-exponential radar signal model. (b) Strategy of phase reconstruction by unfolding the signal phase.

separation method. The target performs a micro vibration  $x_t(t)$  in front of the radar system (e.g., CW, FMCW or IR-UWB radar) with a range  $R$ . The in-range clutter possesses a bigger physical size and generates a larger displacement  $x_c(t)$ . The distance between the clutter and the target is  $\Delta R$ , which is too short to be distinguished due to radar's limited range resolution. Therefore, the reflected signals of both the target and clutter are superposed in the baseband, resulting in a complicated I/Q trajectory  $y(t)$ , which could be expressed in a bi-exponential expression:

$$y(t) = \underbrace{A_t e^{j\frac{4\pi}{\lambda_c}[x_t(t)+R]}}_{\vec{V}_t(t)} + \underbrace{A_c e^{j\frac{4\pi}{\lambda_c}[x_c(t)+R+\Delta R]}}_{\vec{V}_c(t)}, \quad (1)$$

where  $\lambda_c$  denotes the wavelength of radar's carrier frequency, the  $A_t$  and  $A_c$  are the amplitudes of the target motion vector  $\vec{V}_t(t)$  and the clutter motion vector  $\vec{V}_c(t)$ , respectively. Given that the clutter occupies a larger physical size (i.e., radar cross section (RCS)) than the target,  $A_c$  is greater than  $A_t$ .

Fig. 2 visualizes the bi-exponential radar signal model which contains two independent dynamic vectors,  $\vec{V}_t(t)$  and  $\vec{V}_c(t)$ . The amplitude and phase of the resultant baseband signal  $y(t)$  could be depicted as:

$$|y(t)| = \sqrt{A_t^2 + A_c^2 + 2A_t \cdot A_c \cdot \cos[\Phi_t(t) - \Phi_c(t)]} \quad (2)$$

$$\angle y(t) = \tan^{-1} \frac{A_t \sin[\Phi_t(t) - \Phi_c(t)]}{A_c + A_t \cos[\Phi_t(t) - \Phi_c(t)]} + \Phi_c(t), \quad (3)$$

where

$$\Phi_c(t) = \frac{4\pi}{\lambda_c}[x_c(t)], \quad \Phi_t(t) = \frac{4\pi}{\lambda_c}[x_t(t) - \Delta R]. \quad (4)$$

It is clear that the resultant baseband amplitude and phase are both demodulated by the target and clutter motions in a non-linear style. Meanwhile, as  $A_c$  is much larger than  $A_t$ , the phase of the baseband signal is dominated by the clutter motion and there comes  $\angle y(t) \approx \Phi_c(t)$ , which causes a distorted target motion in the phase history. By directly leveraging conventional methods (e.g., CSD [9] and AT [10] algorithms) to analyze the baseband vector, one could hardly retrieve the target motion correctly and explicitly in both time and spectral domains.

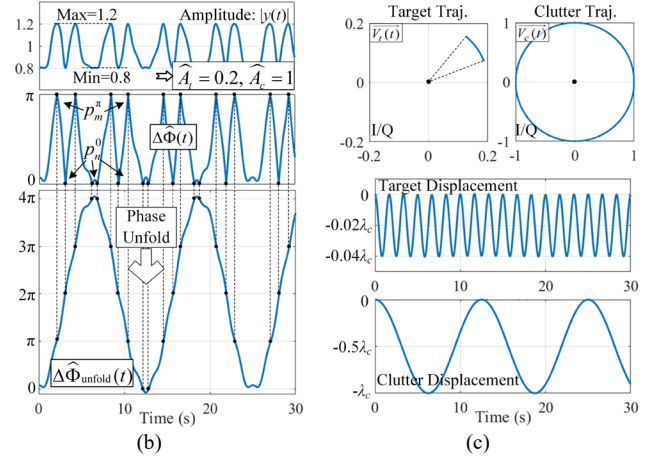
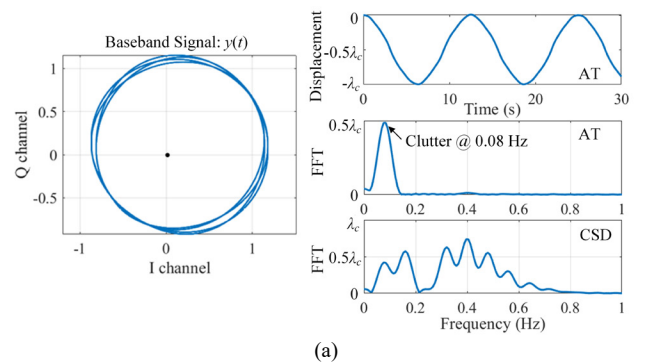


Fig. 3. (a) Simulation results of using conventional methods. (b) Parameter estimation and (c) simulation results of proposed vector separation method for micro vibration reconstruction.

### B. Vector separation for micro vibration reconstruction

To properly reconstruct the target and the clutter motions from the baseband output, vector separation could be realized through accurate parameter estimation and waveform reconstruction.

To simplify the analysis, we assume that both the clutter and target vibrates periodically, and the displacement of the clutter is comparable to  $\lambda_c$ , while the target's motion displacement is much smaller than the wavelength. By observing the baseband signal within one or more clutter periods, the amplitudes of  $\vec{V}_t$  and  $\vec{V}_c$  could be estimated as:

$$\hat{A}_t = \frac{\max|y(t)| - \min|y(t)|}{2}, \quad \hat{A}_c = \frac{\max|y(t)| + \min|y(t)|}{2}. \quad (5)$$

According to the (2), the phase difference  $\Delta\Phi(t)$  between  $\Phi_t(t)$  and  $\Phi_c(t)$  could be estimated as:

$$\Delta\hat{\Phi}(t) = \cos^{-1} \frac{|y(t)|^2 - \hat{A}_t^2 - \hat{A}_c^2}{2\hat{A}_t \cdot \hat{A}_c}. \quad (6)$$

However, due to the phase ambiguity of the inverse cosine function,  $\Delta\hat{\Phi}(t)$  is folded within  $[0, \pi]$ . In order to retrieve the correct phase difference  $\Delta\Phi(t)$ , specific unfolding strategy is utilized as shown in Fig. 2(b). In doing so, the folding points  $\{p_n^0, n \in \mathbb{N}, \text{when } \Delta\hat{\Phi}(t)=0\}$  and  $\{p_m^\pi, m \in \mathbb{N}, \text{when } \Delta\hat{\Phi}(t)=\pi\}$  are first identified. By flipping and shifting the segments between adjacent folding points, the folded phase profile

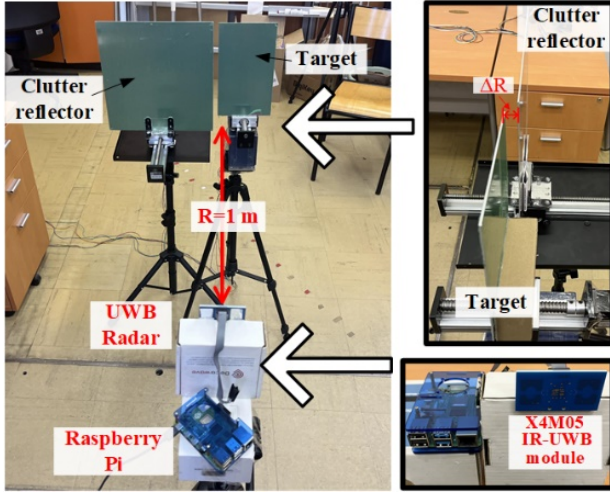


Fig. 4. Experiment setup.

could be expanded properly and the resultant phase turns into  $\Delta\hat{\Phi}_{\text{unfold}}(t) = \Phi_t(t) - \Phi_c(t)$ .

Furthermore, by substituting  $\Delta\hat{\Phi}_{\text{unfold}}(t)$  into  $y(t)$ , the target and clutter vectors could be properly separated as follows:

$$\hat{V}_c(t) = \hat{A}_c \cdot y(t) \cdot \left\{ \hat{A}_c + \hat{A}_t \cdot e^{j\hat{\Phi}_{\text{unfold}}(t)} \right\}^{-1} \quad (7)$$

$$\hat{V}_t(t) = \hat{A}_t \cdot y(t) \cdot \left\{ \hat{A}_c \cdot e^{-j\hat{\Phi}_{\text{unfold}}(t)} + \hat{A}_t \right\}^{-1}. \quad (8)$$

By further extracting the phase information of each vector, both the target and clutter motions could be reconstructed explicitly without any distortion problems.

### III. SIMULATION

Simulations are carried out to validate the proposed vector separation method for micro vibration reconstruction. Specific simulation setups of the target and clutter vectors are listed in Table 1 to indicate the sensing scenario containing an in-range large-scale dynamic clutter with a large physical size.

Table 1. Simulation setups of the target and clutter vectors.

	Motion	Vector Strength	$\Delta R$
$\vec{V}_t(\vec{t})$	$x_t(t) = 0.02\lambda_c \cos(2\pi \cdot 0.6t)$	$A_t = 0.2$	$0.25\lambda_c$
$\vec{V}_c(\vec{t})$	$x_c(t) = 0.5\lambda_c \cos(2\pi \cdot 0.08t)$	$A_c = 1$	

The simulated results are shown in Fig. 3 with a 30-s time window. In Fig. 3(a), the baseband signal deviates from an ideal cycle due to the superposition of two independent dynamic motion vectors. According to Eq. (3), as the strength of the clutter vector is larger than that of the target vector, clutter's phase dominates the signal phase. Spectrum results of AT and CSD algorithms show that conventional methods fail to identify the target signal. In comparison, the simulation results of the proposed vector separation method are shown in Fig. (b) and (c). In Fig. 3(b), since the strength of the target and clutter vectors are properly estimated, the phase difference  $\Delta\hat{\Phi}_{\text{unfold}}(t)$  could be correctly recovered. Then, vector separation is successfully conducted as shown in Fig. 3(c), and

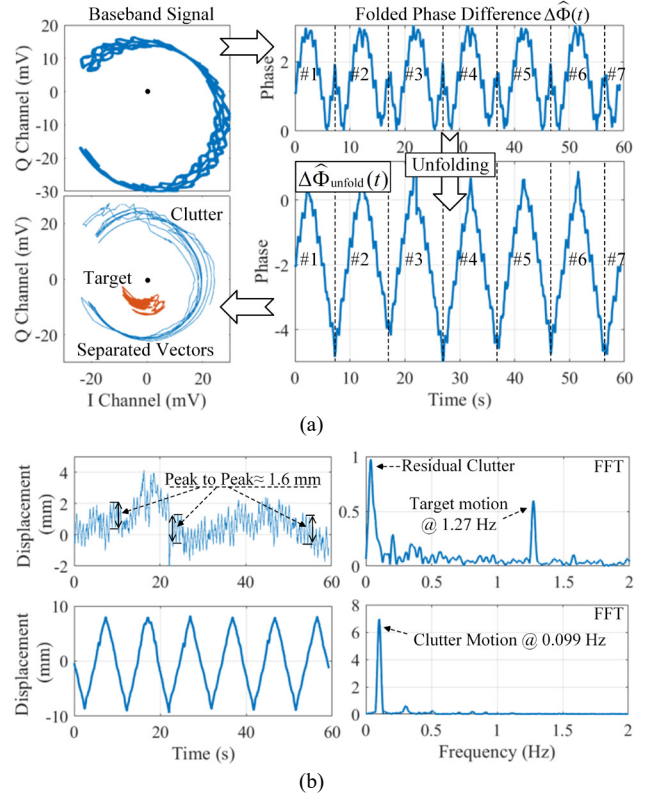


Fig. 5. Experiment results. (a) Intermediate results of vector separation. (b) Recovered waveform and spectrum results of target's and clutter's motions.

both the target and clutter motions are accurately reconstructed, proving the effectiveness of this method.

### IV. EXPERIMENTS AND RESULTS

Experiments were further conducted in the lab environment to verify the proposed method. As shown in Fig. 4, a X4M05 IR-UWB radar module was configured by a Raspberry Pi board to work at 7.29 GHz with a 50-Hz pulse repetition frequency. Following the setup in Fig. 1, two metal reflectors controlled by linear actuators were located 1 m away from the UWB radar. To construct the in-range clutter scenario, the metal reflector (size: 30 cm×30 cm) was placed next to the smaller metal reflector (size: 25 cm×15 cm) with  $\Delta R = 1$  cm. As the bandwidth of the UWB radar is about 1.4 GHz, the radar range resolution is poorer than 10 cm, so it is hard to separate the target and clutter signals from range bins.

During the experiments, the smaller metal reflector was configured as the target to vibrate periodically with a frequency of 1.25 Hz and an amplitude of 0.8 mm ( $\sim 0.02\lambda_c$ ). Meanwhile, the larger metal reflector acted as the clutter and vibrated with a 0.1 Hz frequency and an 8-mm amplitude ( $\sim 0.19\lambda_c$ ). 60-s data were collected for processing. Leveraging the proposed vector separation method in Section II.B, processing results from each step are shown in Fig. 5(a). Instead of grouping all the data to estimate the strength of two vectors, the baseband signal is divided into seven segments based on the periodicity of the clutter and each segment could be treated individually to reduce the noise influence on

parameter estimation. After phase unfolding, the recovered phase difference  $\Delta\hat{\Phi}_{\text{unfold}}(t)$  is utilized to separate the baseband vector into the target and clutter vectors. By further extracting the phase profiles of separated vectors, their waveform and spectrum results are shown in Fig. 5(b). Although partial clutter signal is not fully calibrated, the peak-to-peak displacements of most target motion cycles agree with the ground truth and target frequency is also successfully detected.

## V. CONCLUSION

In this paper, a novel micro vibration reconstruction technique is proposed to mitigate the influence of in-range large-scale dynamic clutters for radar sensing. Based on a bi-exponential radar signal model, both the target and clutter vectors could be linearly separated from the superposed baseband signal. Experimental results prove that the proposed technique could effectively reconstruct the micro mechanical vibration in the presence of in-range dynamic clutter using an IR-UWB radar in the lab environment.

## ACKNOWLEDGMENT

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