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Doppler Compensation of MISO Range Response in Subband Division LFM Pulse MIMO Radar

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Abstract - **Doppler compensation technique for range response in subband divided LFM pulse MIMO radar waveforms is proposed in this paper. Given bandwidth for single LFM transmission in normal radar operation is divided into subbands for multiple LFM pulse transmission in MIMO radar operation. Theoritical range response of the subband LFM MIMO radar waveform is derived and degradation of the response for a moving target is discussed. Dopper compensation technique for slow moving targets is proposed to mitigate the degradation. Range responses of the MIMO waveform and the Doppler compensated range response are validated by numerical simulations.**

Index Terms — **MIMO radar, MIMO radar waveform**

1. Introduction

MIMO (Multiple Input Multiple Output) radar emits orthognal radar waveforms simultaneously from different antenna elements and enables trasmit and receive beamforming, i.e. MIMO beamforming, at signal processing stage. Since MIMO beampattern is identical with 2-way beampattern of SIMO radar [1], where coherent radar waveform is emitted from all antenna elements, beamwidth of MIMO beampattern would be narrower than that of SIMO receive beampattern. This could allow MIMO radar to have improved angular resolution, angular accuracy and clutter mitigation performance [2].

In design of MIMO radar waveforms, the orthogonality of the waveform as well as other system requirements such as limited timeline for full volume search, high power amlification at saturation mode for maximizing radiating power and Doppler tolerance of the waveforms for detecting moving target should be considered to optimize radar system multifunctionality and performance. To those requirements end, the orthgonal radar waveform is realized by low cross-correlation radar waveforms in practical MIMO radar.

MIMO radar waveform design is active research area in recent radar community. Typically, cross-correlation of those waveforms is minimized by exploiting orthogonality in time, code, carrier and/or Doppler frequency domain division [3]. Pros and cons for those divisions are discussed in [4]. In this paper, we focus on frequency division MIMO radar waveforms.

In MIMO radar operation, a few MHz bandwidth for single LFM (Linear Frequency Modulation) pulse transmission from all antennas for normal radar operation is divided into subbands for transmission of multiple LFM pulses. Theoritical MISO (Multiple Input Single Output) range response of the subband LFM MIMO radar waveforms is derived and degradation of the response by moving target is discussed. To minimize the degradation, Dopper compensation technique is proposed and MISO range responses of the MIMO radar waveform with/without the Doppler compensation are validated by numerical simulations.

2. Proposed Compensation Technique

(1) Subband LFM MIMO Radar Waveform and the MISO Range Response

In the subband LFM MIMO radar waveform, total N LFM pulses with different carrier frequency given by $f_n^{(RF)}\left(=f_0^{(RF)}+\Delta f_n\right)$ where are the n-th carrier frequency, center frequency and frequency offset respectively are simultaneously emitted from corresponding the n-th transmit antenna. Backscattered signals from single target in far-field are simultaneously received at the m-th receive antenna.

In the n-th subband pulse compression at the m-th receive channel, the received data is matched with a replica of the n-th LFM pulse to extract the n-th range response. By repeating the subband pulse compression for all N LFM pulses, range responses for N transmit channels are obtained so that transmit beamforming on the m-th receive channels is realized. MISO range response $z_m^{(\theta_b)}(R)$ obtained from the transmit beamforming is described as [1]

$$z_m^{(\theta_b)}(R)=a_m^{(RX)}\exp\left(-j\frac{4\pi R_0}{\lambda}\right)\sum_{n=1}^{N}\mathbf{a}(R)^H\mathbf{W}_n\mathbf{a}(R_0) \quad (1)$$

where θ_b, R, and R_0 are steering direction of transmit beam, range, and target range respectively. $a_m^{(RX)}$ is given by $a_m^{(RX)}=\exp\left(-j2\pi d_m^{(RX)}\sin\theta_0/\lambda\right)$ where θ_0 and $d_m^{(RX)}$ are angle of the target and the m-th antenna position respectively. λ is wavelength given by $\lambda=c/f_0^{(RF)}$. $\mathbf{a}(R)$ is range steering vector defined as $\left[\mathbf{a}(R)\right]_l=\exp\left(-j4\pi Rf_l/c\right)$ where c and f_l are the speed of light and the l-th frequency component of LFM pulse spectrum. $\mathbf{W}_n$ is a diagonal matrix for gating the n-th LFM pulse spectrum where the bandwidth is described as B.

$z_m^{(\theta_b)}(R)$ by (1) clearly indicates that the rangre response is given by a linear combination of total N subband pulse compression response $\mathbf{a}(R)^H\mathbf{W}_n\mathbf{a}(R_0)$. By introducing stepped-frequency steering vector $\mathbf{b}(R)$ defined as $\left[\mathbf{b}(R)\right]_n=\exp\left(-j4\pi R\Delta f_n/c\right)$, (1) is manipulated as

$$z_m^{(\theta_b)}(R)=a_m^{(RX)}\exp\left(-j\frac{4\pi R_0}{c}f_0^{(RF)}\right) \quad (2)$$
$$\mathbf{b}^H(R)\mathbf{b}(R_0)\mathbf{a}(R)^H\mathbf{W}_0\mathbf{a}(R_0)$$

$z_m^{(\theta_b)}(R)$ by (2) reveals that the range response is interpreted as product of range responses of subband pulse

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[1] It should be noted that single target signal arriving at the m-th receive antenna is assumed in the discussion. Multiple signals and receiver noise are discarded in (1) without loss of generality. Futhermore range response due to cross-correlation as well as off-boresight angle and Doppler frequency of the target is discarded to simplify the discussion.

compression $\mathbf{a}(R)^H \mathbf{W}_0\mathbf{a}(R_0)$ and stepped frequency waveform $\mathbf{b}^H(R)\mathbf{b}(R_0)$. Range response of the subband pulse compression has coarse range resolution given by $c/2B$ and range sidelobes within $\pm c\tau/2$ about target range R_0. Range response of the stepped frequency waveform has fine range resolution given by $c\Big/2\left|f_N^{(\mathrm{RF})}-f_1^{(\mathrm{RF})}\right|$. If the carrier frequency $f_n^{(\mathrm{RF})}$ is uniformly allocated at Δf space, there are range grating lobes at $c/2\Delta f$ interval. Those grating lobes are, however, mitigated by multipication of $\mathbf{a}(R)^H \mathbf{W}_0\mathbf{a}(R_0)$ if no windows for achieving lower range sidelobes are applied. Specifically locations of the grating lobes and range nulls of subband pulse compression are coincident so that the grating lobes are cancelled out.

(2) Proposed Doppler Compensation Technique

Received signals are modulated by Doppler frequency of the target. Doppler frequency induces range Doppler coupling effect on subband pulse compression and thus range shift of the range response as well as mismatch loss and degradation of the range sidelobes are occured in $\mathbf{a}(R)^H \mathbf{W}_0\mathbf{a}(R_0)$. Range response of $\mathbf{b}^H(R)\mathbf{b}(R_0)$, however, remains the same since Δf is independent from Doppler frequency provided that difference of the Doppler frequency by different carrier frequency is negligible. This leads to degradation of $z_m^{(\theta_b)}(R)$ such as range shift of mainlobe and increase of sidelobes level. It is clear that Doppler compensation should be applied prior to the subband pulse compression to avoid the degradation. To this end, we proposed to set Doppler filter bank prior to the subband pulse compression. Typically the filter bank could be realized by slow-time FFT (Fast Fourier Transform). Doppler compensation corresponding to respective Doppler bin is applied for uncompressed received signal in fast-time domain. Doppler compensated received signal are sebsequently fed to subband pulse compression followed by MIMO beamforming. It should be noted that Doppler frequency to be compensated is limited to Doppler ambiguity determined by the Doppler filter bank.

3. Computer Simulation

To valiate the discussion in the previous section, results of computer simulation is presented in this section. Two LFM pulses, i.e. $N=2$, with $B=2\,\mathrm{MHz}$ and $\tau=128\,\mu\mathrm{s}$ are used. Two carrier frequencies are spaced at $\Delta f=2\,\mathrm{MHz}$ so that two LFM pulses are contiguous in frequency domain. PRF (Pulse Repetition Frequency) and coherent pulse number are $1\,\mathrm{kHz}$ and 32 respectively.

Range response for stationary target is presented in Fig.1 where blue solid line, green dot line and red dot line are for range response of the subband LFM MIMO radar waveform $z_m^{(\theta_b)}(R)$, stepped frequency waveform $\mathbf{b}^H(R)\mathbf{b}(R_0)$ and subband pulse compression $\mathbf{a}(R)^H \mathbf{W}_0\mathbf{a}(R_0)$ respectively. It is observed that range resolution of MISO range response is finer than that of the subband pulse compression. There are no grating lobes in MISO range response because locations of the grating lobes in $\mathbf{b}^H(R)\mathbf{b}(R_0)$ and range nulls in $\mathbf{a}(R)^H \mathbf{W}_0\mathbf{a}(R_0)$ are coincident.

Range response for moving target is presented in Fig.2. Doppler frequency of the target is $0.969\,\mathrm{kHz}$ which is smaller than PRF and could be compensated. In Fig.2, it is observed that range response of the subband pulse compression is slightly shifted to the left due to the Doppler modulation and thus MISO range response is degraded. The degradation is mitigated by the proposed Doppler compensation and compensated MISO range response is shown in black solid line in Fig.2.

4. Concluding Remark

Theoritical range response of the subband LFM MIMO radar waveform is derived and degradation of the response for moving target was discussed. Dopper compensation technique was proposed to mitigate the degradation. Range responses of the MIMO waveform and the Doppler compensated range response were validated by numerical simulations.

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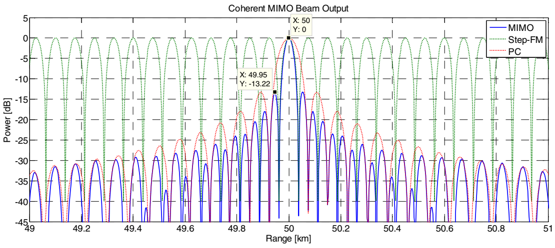

Fig. 1. MISO radar range response for stationary target.

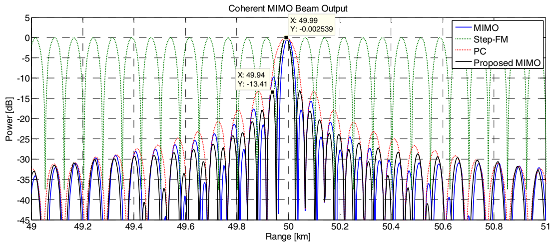

Fig. 2. MISO radar range response for moving target.