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RF-Tag-Referenced Structural Displacement Measurements With Multiple Moving Interferers

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***Abstract*—Doppler radars have potential for accurate structural displacement measurements by transmitting radio frequency (RF) waves that are phase-modulated by the motion of a vibrating target. Existing works have considered the use of active and passive tags to improve the measurement accuracy by either increasing the signal to noise ratio of the received signal or by doubling the frequency of the returned signal. However, structural displacement estimation using Doppler radars in scenarios with strong interferences has not been reported. In this paper, the feasibility of using Doppler radars assisted by active RF tags to estimate structural displacement when multiple moving objects are also illuminated by the same sensor is investigated. Leveraging an active tag, the signal associated with the structural vibration is upconverted to allow easy frequency discrimination for the signal of interest. By applying a digital filtering-based approach, interference rejection is achieved, and an accurate tag-referenced displacement can be retrieved.**

Keywords— clutter rejection, displacement measurement, Doppler radar, remote detection, RF tag, structural health monitoring (SHM).

I. Introduction

The remote estimation of structural displacements based on radars has caught significant attention in recent years. Low-cost homodyne Doppler radars are a suitable choice for the non-contact detection of periodic vibrations because they have relatively simple front-end architecture and require relatively low computational resources for signal processing [1]-[3]. In [2], a Doppler radar was employed to monitor the health condition of a traffic light structure. The radar was mounted on the true target (mast arm of the traffic light structure) and the ground was used as a reference to reflect the radar signal. However, the presence of moving clutters/objects on the radar's field of view, including vehicles and pedestrians, is a major challenge for the estimation of the structure's displacement, because their Doppler frequencies are combined with the frequencies associated with the structural vibration.

RF tags have gained popularity in the literature for its ability to track and differentiate tagged targets from environmental clutters and other untagged subjects/objects [3]-[4]. However, active RF tags have not been used as an alternative for the SHM based on the displacement measurements retrieved by Doppler radars. For example, in a practical SHM scenario, with the continuous flow of moving objects with relatively large radar-cross section (RCS), strong interferences may be introduced to the radar's baseband signals, which would deteriorate the accuracy of the displacement measurements and compromise the effectiveness of the radar-based SHM. This issue might be addressed by employing active microwave tags on the measurement setup.

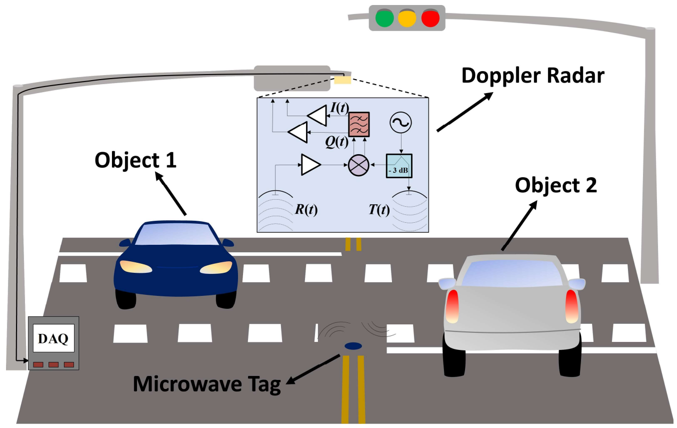

Fig. 1. Block diagram for the remote displacement measurements in scenarios with multiple moving objects using Doppler radars and active RF tags.

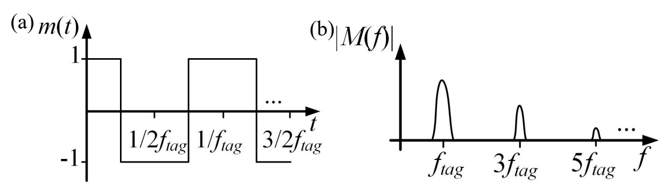

Fig. 2. Modulating signal of the microwave tag. (a) Time-domain representation of the square wave with fundamental frequency f_{tag}. (b) Frequency-domain representation of the tag's square wave.

In this work, the remote displacement measurement of a periodic vibration in the presence of multiple moving clutters using Doppler radar and active RF tag is investigated. The frequency up conversion capability of RF tags is key to enable the discrimination of the signal of interest against unwanted spectral components introduced by other interferers. A signal processing technique used to extract the tag-based measurement is also proposed. Simulation results obtained in this paper demonstrate the advantages of this tag-assisted approach to remotely estimate displacement measurements in a complex environment.

II. Theory of Tag-Referenced Doppler Displacement Estimation

The block diagram for the remote displacement measurement in scenarios with multiple moving objects using

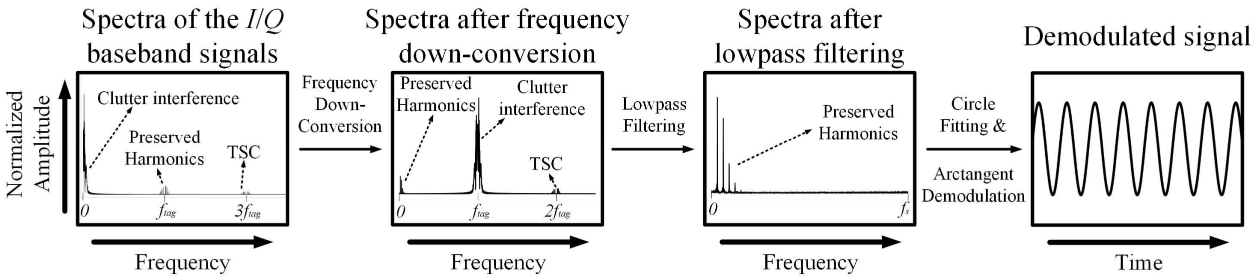

Fig. 3. Flowchart of the signal processing approach proposed to extract the tag-based displacement.

Doppler radars and active RF tags is shown in Fig. 1. The Doppler radar is installed on the mast arm with its two antennas pointing downwards. A continuous-wave signal $T(t)$ is transmitted towards the ground and then phase-modulated due to the mast arm motion and the potential movement of multiple clutters in the radar's field of view (FoV). The received signals $R(t)$ are amplified and down converted to $I(t)$ and $Q(t)$ signals by a quadrature mixer using a copy of the transmitted signal.

Fig. 2(a) and (b) exhibit the time-domain and the frequency-domain representation of the modulating signal generated by the microwave tag placed below the radar. The modulating signal $m(t)$ introduces a constant phase shift to the radar carrier signal. The difference between the two phase shifts should be chosen as 180° to achieve double-sideband suppressed carrier modulation. As a consequence, the frequency up-conversion of the harmonic component(s) introduced by the Doppler phase modulation due to the structural motion is done [4]. Since the Fourier expansion of $m(t)$ is composed of a sum of spectral components of odd frequencies (f_{tag}, $3f_{tag}, \ldots$), the collection of harmonic component(s) become(s) two sidebands around the fundamental frequency f_{tag} and the frequencies of the other tag's spectral components (TSC). Fig. 3 details the signal processing approach used to extract the displacement of the mast. The Doppler frequencies associated with other moving objects remain on the lower side of the spectra of the baseband signals along with other interferences introduced by the radar's signals that were not tag-modulated. The radar's signals that were amplitude-modulated by the tag appear in the upper side of spectra, which allows the preservation of the harmonic components associated with the structural motion. After down-converting the I/Q baseband signals using a copy of the tag's square wave ($f_{downconversion} = f_{tag}$), the harmonic components that were centered around f_{tag} and $3f_{tag}$ are now centered at 0 Hz and $2f_{tag}$, respectively. The low-frequency interferences introduced by other untagged moving objects are moved to f_{tag}. A lowpass filter is then applied to the down-converted signals to obtain the desired signal. The cutoff frequency is set to f_s, which is the sampling frequency required to sample the baseband signals when the structural displacements reach the maximum amplitude. Finally, a circle fitting routine followed by the arctangent demodulation are applied to the lowpass filtered signals to retrieve the displacement of interest.

III. Simulation Results

To validate the feasibility of the proposed application and the effectiveness of the corresponding signal processing

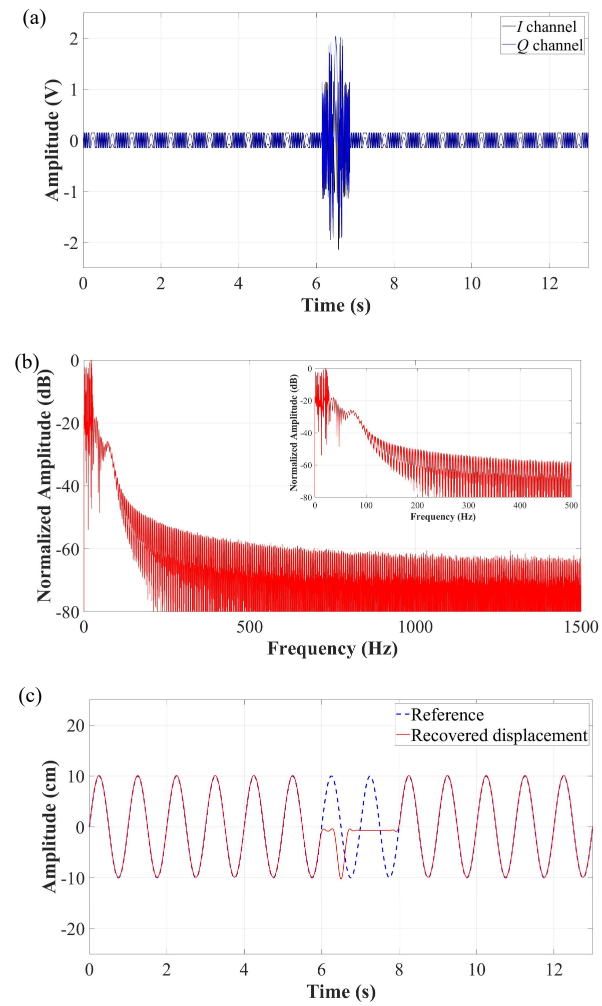

Fig. 4. Simulation results for the scenario where no active RF tag is placed on the radar's illumination scene. (a) I/Q baseband signals. (b) Spectra of the I/Q baseband signals. The distorted harmonic components are shown in the inset. (c) Recovered displacement.

approach, baseband signals were computer-generated to replicate the scenario depicted in Fig. 1. Consider that two cars travelling on opposite directions simultaneously approached a 5.8-GHz Doppler radar attached to the bottom side of a traffic light structure with horizontal velocities of 4.5 m/s (~10 mph) and 9 m/s (~20 mph), respectively. An active RF tag was placed on the ground at a nominal distance of 6 m, just in the middle of the radar's illumination area. The TX/RX antennas' beamwidth were set to 30°. The 1.0-Hz mast arm's vibration motion can be expressed as $x(t) = 10 \cdot sin(2\pi t)$, where x and t

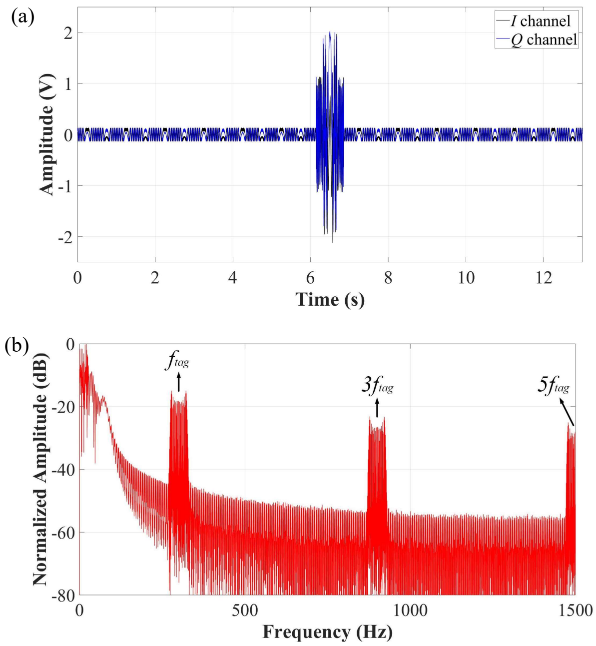

Fig. 5. Simulation results for the scenario where one active RF tag is placed on the radar's illumination scene. (a) *I*/*Q* baseband signals. (b) Spectra of the *I*/*Q* baseband signals.

refer to displacement and time, respectively. In this simulation, the frequency of the square wave generated by the tag was set to 300 Hz. Note that the frequency of the square wave used to upconvert the harmonics components of interest can be adjusted accordingly. The simulation duration was around 13 s and the *I*/*Q* baseband signals were sampled at 3000 Hz. White Gaussian noise with 45-dB SNR is added in the simulation.

Fig. 4 illustrates the simulation results when there is no active RF tag on the radar's illumination scene. In Fig. 4(a), the *I*/*Q* baseband signals are shown. By analyzing the variations of the time-domain signals, it can be roughly identified the instants when both moving objects travel through the Doppler radar's FoV (from ~6.1 s to ~6.9 s). One car moving at 4.5 m/s enters the radar's FoV at ~6.1 s and leaves at ~6.9 s, while the other is first illuminated by the radar at 6.3 s and remains reflecting the radar's transmitted signals until around 6.7 s. The Doppler signatures associated with both moving objects and the vibration traffic light mast arm are combined. Fig. 4(b) shows the corresponding spectra of the recorded *I*/*Q* signals. The inset reveals the distorted harmonic components. Because of the simultaneous phase modulation of the two moving clutters and the vibrating target, the harmonic components associated with the vibration motion are deteriorated, and the mast arm's displacement cannot be estimated. Fig. 4(c) shows the recovered displacement when there is no active RF tag on the radar illumination scene. The corrupted displacement measurements, which are caused by the interferences introduced by the two point-scattered moving objects, can be clearly seen from ~5.9 s to ~8.1 s.

On the other hand, Fig. 5(a) and (b) depict the *I*/*Q* baseband signals and its corresponding spectra, respectively, when there is an active RF tag placed on the ground. Again, the presence of the two point-scattered moving objects can be flagged

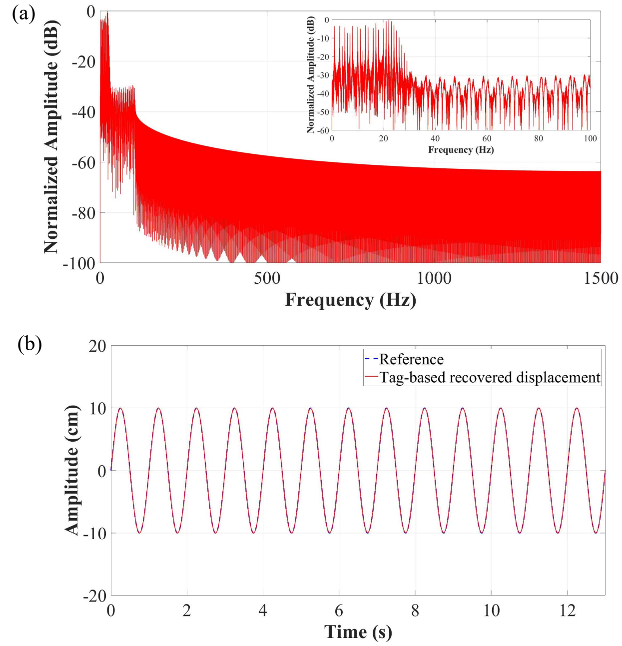

Fig. 6. Simulation results for the scenario where one active RF tag is placed on the radar's illumination scene. (a) Spectra of the baseband signals after the lowpass filtering. The preserved harmonic components associated with the vibrating motion of interest are shown in the inset. (b) Tag-based recovered displacement.

between ~6.1 s and ~6.9 s. However, part of the radar's transmitted signals is now upconverted by an active RF tag placed on the ground. The collection of harmonic components of the motion of interest become two sidebands around the fundamental frequency f_{tag} and the frequencies of the TSC ($3f_{tag}$, $5f_{tag}$) as shown on Fig. 5(b). Since only the ground is tagged, the harmonic components associated with the mast arm motion are preserved. Fig. 6(a) details the spectra of the *I*/*Q* baseband signals after being downconverted using the tag's square wave signal as reference and lowpass filtered with a cutoff frequency fixed at 100 Hz. The preserved harmonic components associated with the vibrating motion of interest are shown in the inset. The circle fitting routine is applied to the time-domain signals obtained after the removal of the clutter interferences and the isolation of the harmonic components of interest in the frequency domain. The tag-based displacement measurement is then recovered after applying the arctanget demodulation algorithm. As depicted on Fig. 6(b), there are no distortions on the estimated tag-based displacement.

IV. Conclusion

This paper investigated the feasibility of the remote displacement measurements in scenarios with multiple moving interferers using homodyne Doppler radars and active RF tags. Benefiting from upconverting the harmonic components of interest, the proposed radar-based setup can easily eliminate the interferences caused by other moving objects. In addition, the signal processing approach used to extract the displacement of interest was explained and its effectiveness was demonstrated with simulation results. Future work will focus on the design of active RF tags, and the test of the proposed scheme in real scenarios.

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