

Structural Health Monitoring of a Traffic Signal Support Structure Based on 5.8-GHz Doppler Radar with Median Filter and Revised Circle Fitting

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Abstract— This paper introduces a new technique to obtain accurate measurements of a traffic signal’s mast arm using Doppler radar. A common challenge in extracting oscillatory displacement from the Doppler phase history is examined, and its major cause is also revealed. Consequences of both numerical simulation and experimental validation show that sudden jumps in Doppler radar measurements can be removed through a technique based on median filtering and a revised circle fitting algorithm. The proposed technique can have broad applications in radar-based structural vibration monitoring.

Index Terms — Structural health monitoring (SHM), Doppler radar, median filter, circle fitting.

I. INTRODUCTION

Structural health monitoring (SHM) is the procedure of continuously supervising the integrity of structures, such as bridges, buildings, and dams, in order to extend its lifespan, reduce conservation costs, and improve public safety. For SHM to serve its intended purpose, accurate measurement of the structural deflections is critical. Traffic signal support infrastructures are in strong need for SHM to enable timely maintenance and prevent catastrophic failures. Indeed, bearing the self-weight of a horizontal arm and the dynamic loads from wind excitation, the junction of a traffic signal support structure has been observed to be susceptible to fatigue damage [1].

Accelerometers, linear variable differential transformers (LVDT), and strain gauges have been used in SHM [2]-[3]. However, these conventional sensors have their respective limitations. For example, the structural displacement provided by accelerometers is obtained by numerical integration, and the integration process can artificially amplify the errors, particularly, low frequency noises. Non-contact sensors, such as Eddy current displacement sensors, laser displacement sensors, and vision-based sensors have been used as alternative solutions for structural vibration measurements in SHM. However, these sensors also have practical limitations. Eddy current displacement sensors and laser displacement sensors are both sensitive to the measurement range and the surface condition of objects,

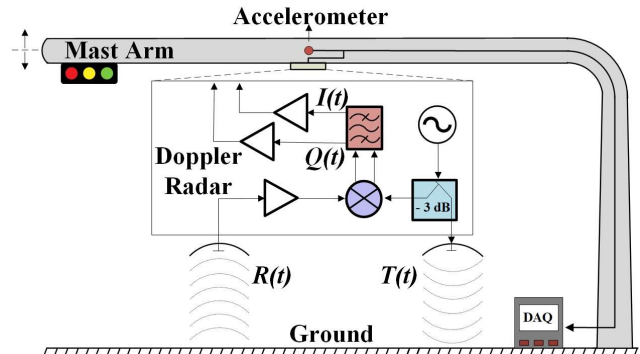


Fig. 1. Block diagram for structural health monitoring of a traffic signal support structure based on Doppler radar.

and vision-based sensors require significant computational resources for image recognition [4].

More recently, radar sensors based on the interferometry technique have emerged as a potential solution for SHM [5]. Microwave radar sensors are more robust against extreme weather conditions and have a longer monitoring ranges. However, many studies related to radar-based SHM were carried out in laboratory or well-controlled environments, so that the robustness and long-term performance of radar SHM sensors in a realistic operating environment have not been fully examined.

In this paper, the performance of a 5.8-GHz Doppler radar sensor for the field SHM of a traffic signal support structure is studied. A simulation and an experiment show that sudden jumps will sometimes be introduced to the vibration measurement if a conventional phase demodulation method is adopted. The main cause of the jumps is analyzed, a solution is proposed, and its effectiveness is also validated in field tests.

II. THEORY AND SIMULATION

The block diagram for the SHM of a traffic signal support structure is illustrated 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

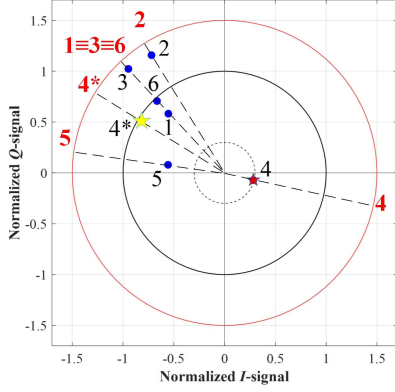


Fig. 2. I/Q constellation graph for the sampling points between $t = 4.702$ s and $t = 4.707$ s.

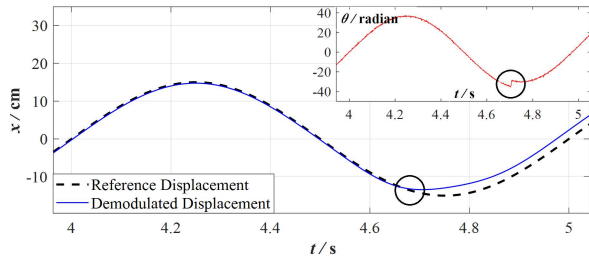


Fig. 3. Sudden jump in a period of simulated vibration displacement with the unwrapped measured phase shown in the inset.

toward the ground, where it is phase-modulated due to the mast arm motion. The reflected signal $R(t)$ is amplified and converted to baseband $I(t)$ and $Q(t)$ signals by a quadrature mixer. Using the nonlinear algorithm of arctangent demodulation, the two baseband channels are normalized and plotted in a constellation graph, and the algebraic displacement increment during each sampling interval is obtained by calculating the change in the phase angles of two adjacent sampling points.

Multiple reflections on the surroundings and the long distance between the mast arm and the ground surface couple clutter noises into the radar system, which results in low signal-to-noise ratio (SNR) at the receiver. In addition, the instantaneous magnitude of the noise level might be high at times. For these reasons, the corresponding point in the constellation graph may occasionally deviate greatly from the unit circle, and the abnormal point can produce an incorrect estimation of the phase changes during sampling intervals. This manifests as an unexpected jump in the curve of vibration displacement.

A simulation was conducted to explain the issue and illustrate its solution. The 1.0 Hz oscillatory equation is expressed as $x = 15 \cdot \sin(2\pi t)$, where x and t are *displacement* and *time*, with units of *centimeter* and *second*, respectively. Gaussian white noise with a 7.0-dB SNR is added to the I

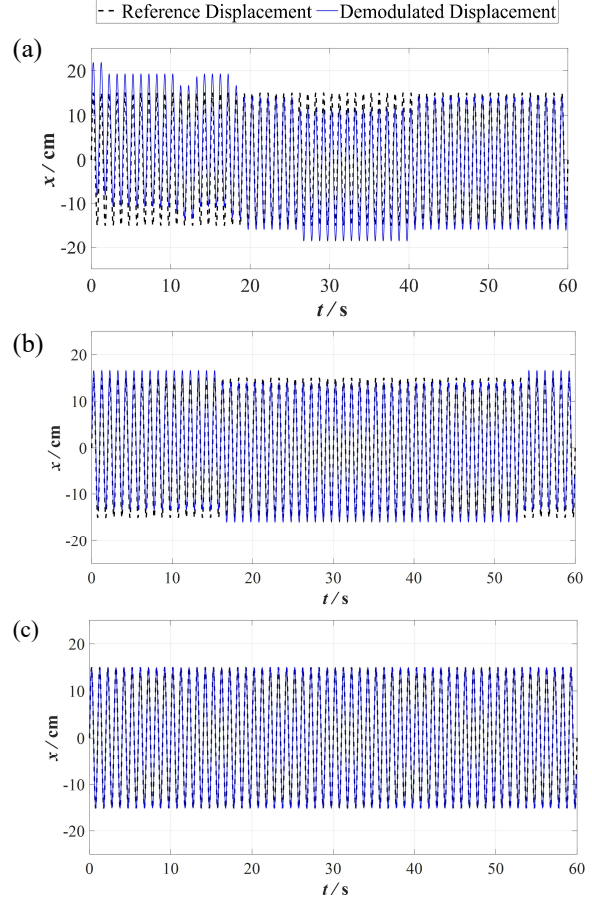


Fig. 4. Simulation results of the demodulated displacements vs. the ground truth. (a) Arctangent demodulation. (b) Arctangent demodulation with median filter. (c) Arctangent demodulation with median filter and revised circle fitting.

and Q channels. The sampling rate and the duration of the simulation are 1000-Hz and 60 seconds, respectively.

Fig. 2 displays a short segment of the constellation graph for the I/Q sampling points placed ordinarily between $t = 4.702$ s and $t = 4.707$ s. In Fig. 3, a jump can be seen in the demodulated displacement, and in the unwrapped measured phase shown in the inset. Fig. 2 also shows that the sampling points 1~6 deviate from the unit circle because of the additive Gaussian white noise. They are projected in the red circle to better visualize the phase change between them. Since points 1, 3, and 6 are collinear, the projections of these points coincide on the red circle. Therefore, the absolute phase difference between points 1 and 2, and that between points 2 and 3 are identical. From point 1 to 2, the displacement increment is negative, since the movement between them is clockwise. On the other hand, from point 2 to 3, the displacement increment is positive. However, since the instantaneous noise level is high, point 4 is placed far away from point 3. This leads to a failing in the correct

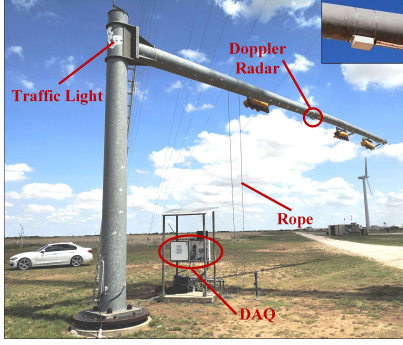


Fig. 5. Experimental setup, with the radar sensor shown in the inset.

direction of rotation, and, consequently, to a large absolute displacement increment that manifests as a sudden jump in the unwrapped phase measured and in the demodulated displacement, as highlighted in Fig. 3.

A median filter is used to reduce the excessive noise level. However, its window width must be properly chosen, so that the I/Q baseband signals may not suffer from severe attenuation, particularly in high amplitude motions.

In addition, a revised circle fitting is necessary to remove the remaining jumps. For instance, in Fig. 2, the point 4 lies close to the origin. Due to the very low SNR, it tends to move randomly around the four quadrants, implying that its phase angle may fluctuate significantly. To address this drawback, the revised circle fitting identifies all the points whose magnitudes are less than a specific threshold (e.g. $r_{TH} = 0.3$, denoted by the inner dashed-dot circle shown in Fig. 2), and, then, each of the deviant points is replaced by the midpoint of line segment connecting its two neighboring points. As an illustration, the revised result of the sampling point 4 is denoted by 4* in Fig. 2.

The performance of the median filter and the revised circle fitting is exhibited in Fig. 4. Most of the sudden jumps are eliminated by the median filter with a 1×9 window. The remaining jumps are subsequently removed by the revised circle fitting with a 0.3 threshold. After the elimination of all the jumps, the standard deviation of the absolute error between the demodulated displacement and the reference displacement decreases from 1.44 cm to 0.18 cm, demonstrating the effectiveness of the proposed method.

III. EXPERIMENTAL VALIDATION

To validate the performance of the proposed technique in field applications, an experiment was conducted in the Reese Technology Center in Lubbock, Texas, USA. The measurement was carried out on a traffic signal support structure. The experimental setup is exhibited in Fig. 5.

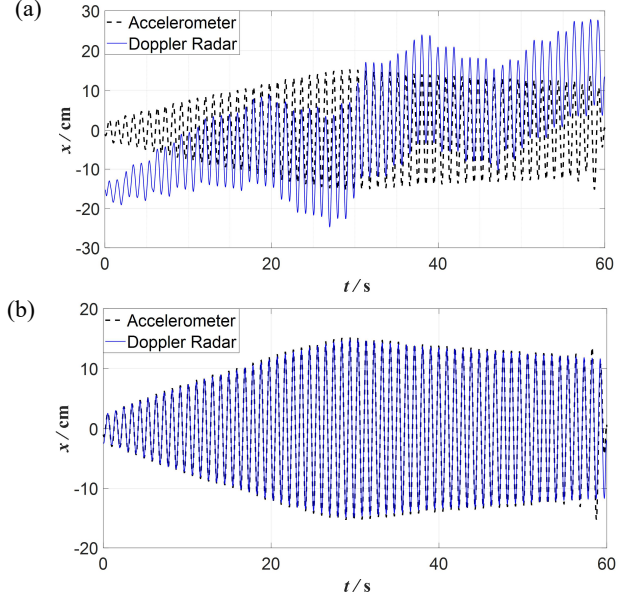


Fig. 6. Experimental results of the demodulated displacements vs. the ground truth. (a) Arctangent demodulation. (b) Arctangent demodulation aided with median filter and revised circle fitting.

The traffic signal support structure used in the test is six meters in height, and the vertical vibration of its twelve-meter-long horizontal arm was stimulated manually by pulling a rope attached to it. When the vibration reached certain amplitudes, the manual excitation was stopped, and the vibration of the arm was allowed to decay freely. The entire process was monitored by the Doppler radar and an adjacent accelerometer installed on the mast arm that provided the reference measurements.

Fig. 6 shows the presence of several sudden jumps in the displacement measurement obtained using the conventional arctangent demodulation. By contrast, all the jumps are eliminated using the median filter with a 1×15 window and the revised circle fitting with a threshold of 0.3 the normalized magnitude. The displacement measured by the radar is consistent with the accelerometer measurement result, since the standard deviation of the absolute error between the radar demodulated displacement and the ground truth is 0.64 cm.

IV. CONCLUSION

This paper presented a new method for eliminating sudden jumps in phase-demodulated Doppler radar data for field structural health monitoring applications. Both a simulation and experiments validated the effectiveness of this method. Future studies will focus on the optimal window width of median filter for various patterns of vibration, as well as dynamic adjustment of the threshold of revised circle fitting based on the radar output SNR.

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