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PERFORMANCE OF CONTINUOUS WAVE RADAR FOR LOW FREQUENCY VIBRATION AND STATIC DEFLECTION TESTING

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ABSTRACT

Structural health monitoring (SHM) technology has developed rapidly in the last few decades in an effort to improve infrastructure service and maintenance. Most structures, especially long-span bridges, have very low natural frequencies (less than 10 Hz). Detecting the low frequency vibration and static deflection is a critical measurement to understand the characteristics of these structures. Many existing approaches are not practical for full-scale structure testing. Continuous wave (CW) radar offers a good solution for the detection of low frequency vibration and deflection of structures. In this paper a DC coupled CW radar for distributed bridge monitoring is introduced. Structural system identification methods tailored for the distributed radar network are developed and evaluated in a simulation model of the radar network and a scaled seven story building model. To characterize the radar low frequency vibration measurement performance, a series of laboratory tests are conducted. The performance of measuring static deflection is demonstrated by a simple supported beam test. Finally, conclusions and ongoing research are summarized.

KEYWORDS

DC coupled radar, continuous wave radar, system identification, low frequency vibration, static deflection.

INTRODUCTION

Structural health monitoring (SHM) plays an important role in structural characterization and maintenance. Various technologies have been developed to enable practical and effective SHM; however many practical considerations must still be addressed. In particular there is a need for accurate and low-cost bridge deflection sensors (Chan *et al.* 2009) that are appropriate for use in wireless sensor networks. Currently laser-based systems provide accurate measurements but are quite costly (Raghavan and Cesnik 2007). GPS has been used successfully for deflection detection but has sampling rate and resolution limitations (Ko and Ni 2005). The ability to accurately capture bridge displacements in a spatially dense network of wireless sensors with integrated structural system identification has the potential to improve SHM strategies.

Continuous wave (CW) radar detection sensors offer an effective solution for capturing structural displacement measurements in a low-cost, easily deployable sensor package. The radars transmit a continuous microwave that is reflected by a moving target and captured by the receiver. By comparing the phase information difference between transmitted and reflected signals, the target's motion may be determined. For the practical SHM applications such as bridge monitoring, the CW radars can be attached to the bottom of the bridge deck. The ground under the bridge is used to reflect the radar's signals. By measuring the relative displacement of the deck, the dynamic vibration or static deflection of the bridge can be detected. Previous research has focused on an AC coupled CW radar, which has shown promising results for measuring structural motion in a variety of measurement conditions (Guan *et al.* 2013). The AC coupled radar removes any DC component in the raw RF signals, thereby simplifying the necessary signal processing to extract displacement data. The primary drawback of the AC coupled radar is its inability to measure static deflections and low-frequency structural vibrations (<1 Hz), both of which are of interest in many SHM applications.

To enable a broader range of SHM applications, this paper presents a DC coupled CW radar that is capable of both dynamic and static structural displacement measurements. The additional challenges associated with retaining the DC component of the measured signals are discussed. The low frequency motion measurement performance of the radar is demonstrated by series of laboratory tests. In addition, the capability of this CW

radar to measure static deflection is shown using a simply supported beam test. To extend the experimental results, a network of CW radars is simulated to measure the response of a building model and perform structural system identification using the simulated radar measurements. Finally, the conclusions and ongoing research are summarized.

BACKGROUND

While there are many types of radars which may be used to measure the distance or the motion of objects, many have drawbacks in accuracy, device size, and cost. This research focuses on CW radars for their wide range of measurement capabilities and the potential for a small sensor package. In contrast to other radar types, such as pulse radars, CW radar can measure the velocity of a target at any range and moving at any velocity. The CW radar has been successfully used in a range of applications, including vital sign detection (Ascione et *al.* 2013).

The radar presented in this paper, shown in in Figure 1, transmits the continuous 2.4 GHz wave by one of the two patch antennae. The signal is reflected by objects and the reflected signal is captured by the second antenna. The transmitted and received signals are combined in a quadrature mixer to convert the RF signals to lower-frequency baseband signals that can be sampled by the analog-to-digital converter (ADC). These baseband signals contain all of information present in the modulated reflected signal necessary to obtain the target displacement.

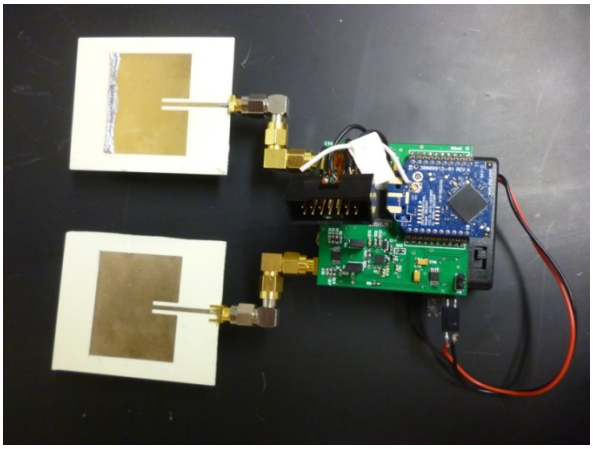


Figure 1. 2.4 GHz DC coupled radar sensor

One of the primary challenges associated with using the DC coupled radar is that the DC offset present in the measured signals is often two to three orders of magnitude larger than the signal amplitude (Droitcour 2006), making it difficult to amplify the signals without saturating the limits of the ADC. To eliminate DC offset, AC coupled radar is commonly used, which implements a high pass filter in hardware to eliminate the DC components prior to signal digitization. This is a reasonable approach for many applications where static and low frequency motion are not important; however, to detect motion less than 1 Hz without signal attenuation and distortion, a DC coupled radar must be used.

The DC component of the signal will change based on the target distance and other environmental factors. To adaptively adjust the amplifier bias to the desired level that allows both high gain and maximum dynamic range, DC tuning must be performed. This process centers the DC offset within the ADC measurement range using two steps: RF coarse-tuning and baseband fine-tuning (Gu and Li 2012). The RF coarse-tuning chain includes a phase shifter and an attenuator at the RF front end. It adds part of the transmitter signal to the receiver signal to remove part of the DC offset. The block diagram of the DC coupled radar is shown in Figure 2. After completion of DC tuning, the baseband signals (I and Q) are given by:

$$B_I(t) = A_I \cos\left[\theta + 4\pi x(t)/\lambda + \Delta\varphi\right] + DC_I \tag{1}$$

$$B_Q(t) = A_Q \sin\left[\theta + 4\pi x(t)/\lambda + \Delta\varphi\right] + DC_Q \tag{2}$$

where A_I and A_Q are the amplitudes of the I and Q signals, θ is a constant phase shift, $x(t)$ is the target movement, λ is the carrier wavelength (2.4 GHz), $\Delta\varphi$ is the total residual phase noise of the radar, and DC_I and DC_Q are the DC offsets in I and Q baseband signals, respectively.

Then the baseband signals are transmitted wirelessly using a Zigbee radio and collected by the receiver connected to the PC. The baseband signals contain the DC offsets which need to be removed before obtaining displacement measurements. Several DC offset calibration methods can be applied to do this signal processing (Zakrzewski et *al.* 2007). The corrected baseband signals are given by:

$$B_I(t) = \cos\left[\theta + 4\pi x(t)/\lambda + \Delta\varphi\right] \tag{3}$$

$$B_Q(t) = \sin\left[\theta + 4\pi x(t)/\lambda + \Delta\varphi\right] \tag{4}$$

After DC offset calibration a process called arctangent demodulation is applied on the new baseband signals to obtain the displacements.

$$\psi(t) = \arctan\left[B_Q(t)/B_I(t)\right] = \theta + 4\pi x(t)/\lambda + \Delta\varphi \tag{5}$$

$$\varphi(t) = 4\pi x(t)/\lambda \tag{6}$$

where θ is dependent on the initial position of the target. $\varphi(t)$ is proportional to the relative displacement between the subject and the radar. Given the known carrier wavelength, λ, the relative displacement can be obtained as $x(t)= x_0+\varphi(t)\lambda/4\pi$, where x_0 is the initial distance to the target.

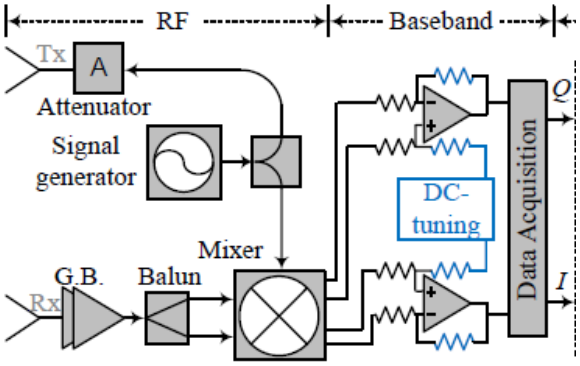
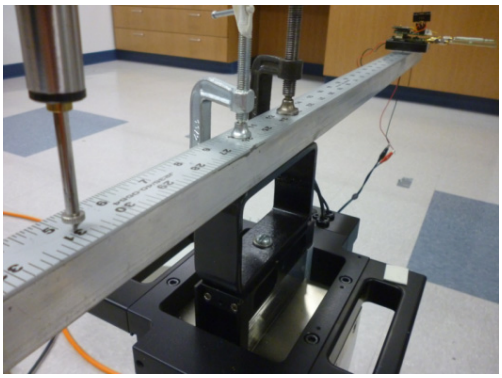


Figure 2. Block diagram

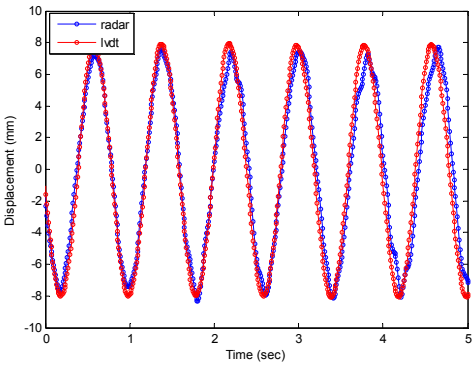
LOW FREQUENCY VIBRATION TESTING

A series of laboratory tests were conducted to characterize the low-frequency measurement performance of the DC coupled radar. A Labview controlled vertical shake table was used to generate low frequency (< 2Hz) sinusoidal motions. The radar was mounted to the shaker with a rigid cantilever beam and pointed towards the floor below. In these experiments, the radar moves while the target (the floor) remains stationary. The distance between the floor and the radar's antennae is about 50 cm. This setup simulates the proposed bridge-mounted application of the sensor and is shown in Figure 3a. To quantify the errors of the DC coupled radar measurements, an LVDT was used to measure the motion of the shaker simultaneously with the radar. The results of the LVDT and radar sensor for a 1.25 Hz sinusoidal motion are shown in Figure 3b. The absolute amplitude error between the radar and the LVDT is less than 1 mm.

To evaluate the performance of the radar sensors under different testing conditions, the frequency and amplitude of the shaker motions are varied. In the first series of tests, the 1.25 Hz sinusoidal motion is generated by the shake table while the motion amplitude is varied from 6.5 mm to 10 mm. The second series of tests varies the motion frequency range from 0.25 Hz to 2Hz while the motion amplitude is fixed at 6.5 mm. For all tests, the measured motion frequency was correctly measured by the radar; however, differences in the measurement amplitude of the LVDT and the radar were observed. For each test scenario the percentage error between the radar and LVDT amplitude are calculated.

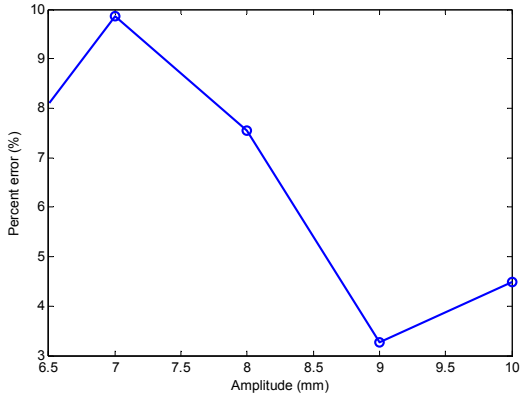


(a)

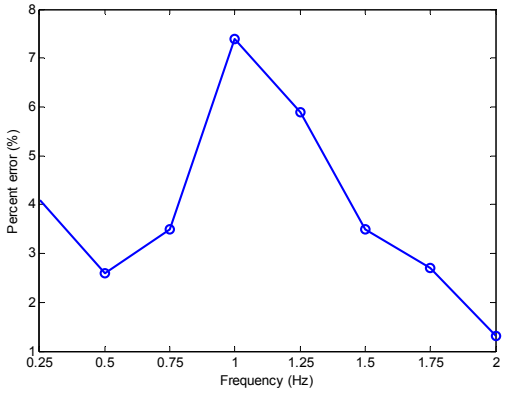


(b)

Figure 3. (a) Experiment setup, (b) 1.25 Hz motion measured results



(a)



(b)

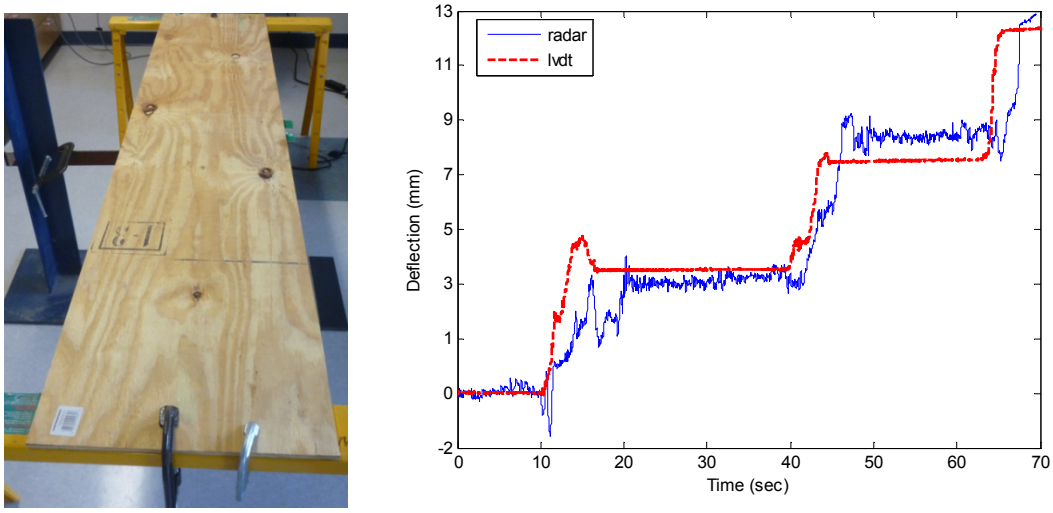
Figure 4 (a). Percent error vs amplitude of the motion, (b) Percent error vs frequency of the motion

The summary of results is shown in Figure 4. For the errors caused by the different motion amplitudes, except the 7 mm amplitude case, the trend is that the percent error becomes smaller with increasing amplitude. This behavior is expected since the increased motion amplitude results in a higher signal power of the baseband signals, enabling more accurate demodulation. There is no trend in the measurement amplitude error due to different motion frequencies. For most cases, the errors are less than about 8%.

STATIC TESTING

The DC coupled radar has the capability of detecting static structural deflections. A preliminary test on a simply supported beam was performed to evaluate the static deflection measurement ability, as shown in Figure 5a. The span of the beam is 2 m. The radar was attached to the underside of the mid-span to measure the beam deflection. An LVDT was installed at the same position to provide a reference measurement. The floor below the beam, covered with a patch of foil, was used as the reflection surface for the radar signal. The distance between the radar and the reflection surface was about 50 cm. To induce static deflection in the beam, three masses were applied one at a time to the mid-span of the beam, with time gaps between the addition of each mass. The radar and LVDT measured the time history of the static deflection changes simultaneously.

The results from both the radar and the LVDT are shown in Figure 5b. The DC radar results have the similar shapes as the LVDT and detect all three additions of mass. The deflection measurements from radar are close to the results from the LVDT, with slightly more signal disagreement when the second mass was added. The total deflection results (approximately 13 mm) from the radar are close to the results from the LVDT. Although the results from the radar are noisier than the LVDT in this preliminary test, the DC coupled radar shows promising performance for measuring static deflection. Further signal processing enhancements are expected to improve the signal quality.



(a) (b)

Figure 5 (a). Experiment setup, (b) Static deflection measurement results

THE RADAR SENSOR NETWORK SIMULATION MODEL

To predict the performance of multiple DC coupled radars making up a monitoring sensor network, a simulation model of the radar sensors has been created. To accurately capture the performance of the radars within the simulation model, the parameters of the radar are obtained from hardware information and experimental results. A scaled seven story building model is used in the network simulation model as the measurement test bed. The stiffness and mass distribution of this model are based on an existing scaled seven story building model used for laboratory experiments at the University of Florida (Guan *et al.* 2013). The natural frequencies of the building model are 2.18 Hz, 6.46 Hz, 10.45 Hz, 13.98 Hz, 16.91 Hz, 19.09 Hz and 20.44 Hz. For the network measurement simulation each floor of the building model is excited with a random excitation. After the responses at each floor of the building model are simulated, the vibration of each floor is measured by the simulated radar sensor which is put on the same floor. To represent practical measurement conditions, three different cases of the signal noise are simulated in the baseband signals. These noise levels represented as signal-to-noise ratios (SNRs) are 10 dB, 6.99 dB and 5.229 dB which correspond to the ratio of the noise levels to the signal power of 30%, 20% and 10% respectively. This simulates the testing conditions when the distance between the radar and the target increases, thereby decreasing the SNR. After DC offset calibration and arctangent demodulation, the simulated radar sensor measurement is obtained. Finally, the Eigenvalue Realization Algorithm (ERA) is applied to the measured displacements to extract the measured natural frequencies and mode shapes of the building model. The flow chart of the simulation process is shown in Figure 6.

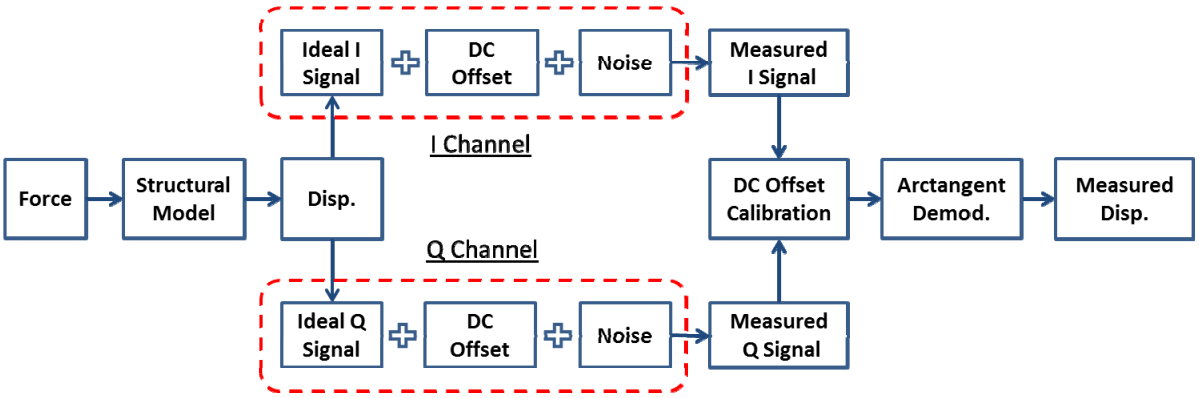


Figure 6. Simulation process

The natural frequencies measured in the simulation model of all three cases match with the ideal results. The mode shape results of three different noise cases of the simulation model are shown in Figure 7. For the lower frequency modes of the structure (mode 1 to mode 4), the radar sensor network can detect the mode shape

accurately. For the higher frequency modes, the mode shape errors increase with lower SNRs. The results demonstrate that with a lower SNR (resulting from increasing distance between the radar and the target) there is reduced accuracy in the mode shape measurements.

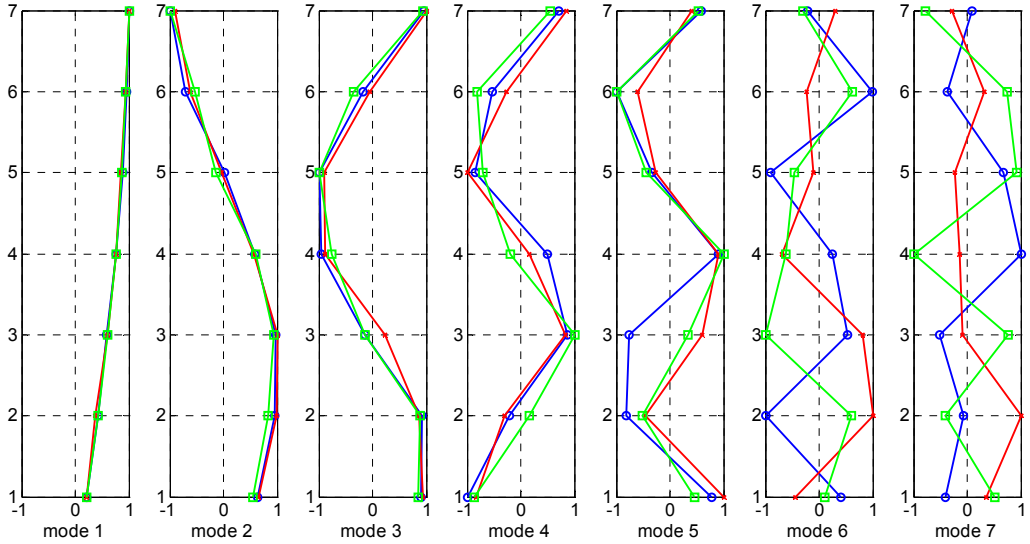


Figure 7. Mode shapes with different noise levels, green line is the result from SNR = 5.229 dB, red line result is from the case SNR = 6.99 dB, blue line is from the case SNR = 10 dB

CONCLUSION

In summary, the newly developed DC coupled radar demonstrates good performance for low frequency motion detection. Although the results from the static deflection tests exhibit higher noise levels than the reference sensor, the DC coupled radar shows promise for accurate static deflection measurements. The simulation model is a useful tool for the prediction of the performance of a network of DC coupled radar sensors. Even in the presence of realistic measurement noise, the simulated radar network has the ability to detect the natural frequencies and mode shapes of a building model.

Determining the working distance range between the target and the DC coupled radar will be the next step in the development of this radar technology for structural monitoring applications. Reducing the noise levels in the static measurement cases through improved signal processing will be the subject of ongoing research. Current efforts are underway to integrate the DC coupled radar with the WiseMote wireless sensor platform. The embedded algorithms on the WiseMote will enable a robust and functional sensor node appropriate for SHM applications (Hoover *et al.* 2012). Finally, a network of WiseMote/DC coupled radars will be deployed on a full-scale bridge structure for distributed deflection measurements and embedded system identification.

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