Microwave Radar with Transponder for Displacement Measurement in Structural Health Monitoring

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Abstract:
Having combined the advantages of ground-based interferometric radar and Global Position System (GPS), a microwave radar with transponder for three-dimensional displacement monitoring method has been proposed. In this system, the active reflector ensures the long measurement distance at low antenna radiation power; the transponder provides the total solutions to antenna microwave leakage and multipath reflection problems; the phase demodulation with FFT (Fast Fourier Transform) make sure that the accuracy approach to submillimeter level. The experiment results show that the system measurement error is less than 0.32mm within 400 meters at 1.6W transmitting power, measuring speed is 10ms per time, and the displacement measurement range can reach 60mm.

Keywords: structure health monitoring (SHM); microwave radar, displacement measurement; transponder; active reflector

1. INTRODUCTION

SHM Research Situation
Large infrastructures such as bridges, dams and skyscrapers are the vital facilities to guarantee the economic development and human lives, so it’s of great importance to monitor the structures’ health status on line while they are at service[1]. Being a key parameter of structural health monitoring, structural displacement/deformation indicates the damage status of infrastructures [2].

Numbers of methods are applied to monitor the structure displacement/deformation, such as linear variable differential transformer (LVDT), inclinometer, imaging system for displacement, Total Station, GPS, etc [3-6]. Among them, Total Station and GPS are two dominating methods which are widely used in construction monitoring and structural health monitor respectively. On the other hand, ground-based interferometric radar is newly introduced in structural health monitor [7, 8]. The performance comparison of them is listed in table 1.

<table>
<thead>
<tr>
<th>Sensor types</th>
<th>Precision</th>
<th>All-weather measurement</th>
<th>Installation on the Target</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>Centimeter</td>
<td>Yes</td>
<td>GPS Receiver</td>
<td>low accuracy; high price;</td>
</tr>
<tr>
<td>Total station</td>
<td>Millimeter</td>
<td>No</td>
<td>Reflector</td>
<td>Affected by bad weather; unsuitable long-term monitoring;</td>
</tr>
<tr>
<td>Interferometric radar</td>
<td>Submillimeter</td>
<td>Yes</td>
<td>Antenna</td>
<td>high price;</td>
</tr>
</tbody>
</table>

Table 1. Performance comparison of different sensors

According to Table 1, for some steel structure, millimeter defects should be detected and given the warning information, so the accuracy of GPS is poor; the
continuous monitoring is necessary whether raining or snowing, so the total station doesn’t meet the requirement because the optical lens is sensitive to the bad weather[6, 9]. From the above, radar system has a good performance for displacement monitoring, but the high cost puts it out of reach of many infrastructure applications[10]. Thus, the exploitation of radar system for one-dimensional displacement monitoring is imperative.

Current methods based on radar system for displacement measurement have been listed clearly in table 2 in the respects of accuracy, measurement distance range, and application area.

<table>
<thead>
<tr>
<th>Radar types</th>
<th>Measurement distance range</th>
<th>Accuracy</th>
<th>Application area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impulse Radio Ultra-Wideband, IR-UWB</td>
<td>Decameters</td>
<td>Centimeter</td>
<td>Positioning; heartbeat detection; Displacement measurement;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>heartbeat detection; Displacement measurement;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance measurement; displacement measurement;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance measurement; heartbeat detection;</td>
</tr>
<tr>
<td>Doppler Interferometry</td>
<td>Meters</td>
<td>Micrometer</td>
<td>Positioning; heartbeat detection; Distance measurement;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>heartbeat detection; Distance measurement;</td>
</tr>
<tr>
<td>Stepped Frequency Continuous Wave, SFCW</td>
<td>Hectometers</td>
<td>Submillimeter</td>
<td>Distance measurement; displacement measurement;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance measurement; heartbeat detection;</td>
</tr>
<tr>
<td>Linear Frequency Modulation Continuous Wave, LFMCW</td>
<td>Meters</td>
<td>Submillimeter</td>
<td>Distance measurement; heartbeat detection;</td>
</tr>
</tbody>
</table>

Table 2. Performance comparison of different radar systems

Infrastructures, like bridges, always stretch over hectometers, even kilometers, so the measurement distance should be far enough. What’s more, millimeter accuracy is necessary at the same time. Taking the distance and accuracy into consideration, the SFCW method is the priority. IDS company applied SFCW into Interferometric radar system already. However, high cost is the obstacle for general applications. In order to apply the microwave technology into SHM, developing the measuring instrument with high accuracy and lower cost is necessary. For microwave methods, antenna leakage and multi-path interference are two main problems, which limit the measurement distance and accuracy. Analysis is as following.

The Problem Description of the Antenna Leakage and Multi-Path Interference
The radar system radiates a single-frequency electromagnetic wave and receives the target echo signal, and there is a phase difference $\Phi$ between the transmitting signal and receiving one as shown in figure 1. The relationship between the displacement and $\Phi$ will be discussed later.

![Figure 1. Phase Difference between the Transmitted and Received Signal](image.png)

There is a common radiation pattern for directional antenna as shown in figure
Actually, the transmitting antenna is close to the receiving antenna in a radar system as shown in figure 1. It’s obvious the vertical side-lobe $S_2(t)$ of the transmitting wave can be received by the receiving antenna. The side-lobe leakage will have a much more serious impact on the target echo signal as the measuring distance getting farther. The measurement accuracy gets worse because of the antenna microwave leakage.

The multi-path interference means the receiving antenna is not only sensitive to echo signal of the target but also the objects near the target[12-14]. What’s more, the echo signal reflected by the passive target reflector attenuates with the measuring distance, so the measuring distance is limited. Thus, combining the advantages of ground-based interferometric radar and GPS, microwave radar with transponder for one-dimensional displacement monitoring method has been proposed. And it is suitable for long distance and high accuracy measurement with the elimination of the antenna leakage and multi-path interference.

2. SYSTEM PRINCIPLE

Microwave Radar with Transponder System

Here is the system principle diagram as shown in figure 3. From the figure 3, the system includes two parts. The active reflector part will be installed on the target. Supposing the initial distance is R before the target has the displacement, the radio source 1 $s_1(t)$ is divided into $s_{R1}(t)$ and $s_{11}(t)$. The former $s_{R1}(t)$, as the transmitting signal, comes into being $s_{R1}(t)$ when it’s received by antenna A1. And $s_{00}(t)$ can be obtained in the same way from $s_0(t)$.

For the part microwave radar, the two inputs of the mixer are $s_{11}(t)$ and $s_{00}(t)$, the latter is the divide of the $s_0(t)$. The mixer output will be filtered by low pass filter (LPF), and then comes into being $s_R(t)$. $s_R(t)$ is the reference signal for displacement measurement. On the other hand, for the part active reflector, $s_d(t)$ can be obtained in
the same way as $s_0(t)$, $s_i(t)$, passing through the frequency modulation (FM), comes into being the $s_d(t)$. Finally, the displacement information can be demodulated from phase difference between the $s_0(t)$ and $s_d(t)$ by the data process unit. Strict derivation is following. Supposing the radio source signals $s_0(t)$, $s_i(t)$ have the expressions:

$$s_0(t) = A_0 \cos(2\pi f_0 t + \phi_0)$$  \hspace{1cm} (1)
$$s_i(t) = A_i \cos(2\pi f_i t + \phi_i)$$  \hspace{1cm} (2)

Where the $f_0$, $f_i$ are the frequencies; the $\phi_0$, $\phi_i$ are the initial phases, the $A_0$, $A_i$ are the amplitudes. So the radiation signals $s_{r0}(t)$, $s_{ri}(t)$ are followings without consideration of the hardware delay influence.

$$s_{r0}(t) = A_0 \cos(2\pi f_0 t + \phi_0)$$  \hspace{1cm} (3)
$$s_{ri}(t) = A_i \cos(2\pi f_i t + \phi_i)$$  \hspace{1cm} (4)

Where the $A_0$, $A_i$ are the amplitudes.

According to the electromagnetic transmission pattern, the receiving signals $s_{r0}(t)$, $s_{ri}(t)$ are:

$$s_{r0}(t) = A_0 \cos[2\pi f_0 (t - \Delta t_R) + \phi_0]$$  \hspace{1cm} (5)
$$s_{ri}(t) = A_i \cos[2\pi f_i (t - \Delta t_R) + \phi_i]$$  \hspace{1cm} (6)

Where the $\Delta t_R$ is the time delay. $\Delta t_R = R/c$, and $c$ is the light speed. Supposing $f_i > f_0$, the differential frequency signals $s_d(t)$:

$$s_d(t) = A_0 \cos[2\pi (f_i - f_0) t + (\phi_i - \phi_0) - 2\pi f_0 \Delta t_R]$$  \hspace{1cm} (7)
$$s_d(t) = A_i \cos[2\pi (f_i - f_0) t + (\phi_i - \phi_0) + 2\pi f_0 \Delta t_R]$$  \hspace{1cm} (8)

Based on the FM pattern, $s_d(t)$ will be modulated as $S_{FM}(t)$:

$$S_{FM}(t) = A_{FM} \cos[2\pi f_c t + 2\pi k \int_0^1 s_d(t) \, dt + \phi_c]$$  \hspace{1cm} (9)

Where the $A_{FM}$ is the amplitude, $f_c$ is the carrier frequency of the modulator, $k$ is the modulation coefficient, $\phi_c$ is the initial phase of the carrier wave. And the $S_{DM}(t)$ is the $S_{FM}(t)$ with a $\Delta t_R$ time delay.

Applying the FM-DM system, signal $s_{ri}(t)$ and receiving one $S_{DM}(t)$ have the different frequencies from each other, which provides solutions to the elimination of the antenna wave leakage and multi-path interference.

Finally the FM demodulator outputs the signal $S_m(t)$:

$$S_m(t) = A_m \cos[2\pi (f_i - f_0) t + (\phi_i - \phi_0) + 2\pi (f_0 - f_i) \Delta t_R]$$  \hspace{1cm} (10)

Make a comparison between equation (10) and (7), the phase difference between the $s_d(t)$ and $s_m(t)$ is $\Phi = 4\pi f_0 \Delta t_R$. Combining $\Delta t_R = R/c$, it’s obvious that:

$$R = c\Phi / 4\pi f_0$$  \hspace{1cm} (11)

Where the $\lambda = c/f_0$ is wavelength of the electromagnetic wave.

When the target has a displacement, the phase difference between the $s_0(t)$ and $s_{ad}(t)$ $\Phi$ will have a increment $\Delta \phi$. The displacement can be calculated by equation (12):

$$\Delta R = \frac{\lambda}{4\pi} \Delta \phi$$  \hspace{1cm} (12)

In conclusion, the displacement of the target can be demodulated by the phase difference between the transmitting and receiving signal.

For each target, at least three microwave radar stations are used to monitor the one-dimensional displacement at the same time, and the one-dimensional displacement can be demodulated with the three one-dimensional displacements.
Displacement Measurement Performance of the System

The accuracy of the displacement measurement depends on the resolution of the phase difference demodulation. According to the equation (12), the relationship is expressed as following:

$$\delta(\Delta R) = \frac{\lambda}{4\pi} \delta(\Delta \phi)$$ (13)

The measurement distance depends on the performance of the antennas and the transmitting power. Here is the friss-equation for electromagnetic wave transmitting in free space.

$$P_{rm} = (\frac{\lambda}{4\pi R})^2 P_t G_t G_r$$ (14)

Where the $P_{rm}$ is the receiving power, $\lambda$ is the wavelength, $R$ is the distance, $P_t$ is the transmitting power, $G_t$ and $G_r$ are the gain of the transmitting and receiving antenna.

In terms of the equation (13) and (14), the accuracy and distance can be given in table 3 when the frequency of the electromagnetic wave varies from 0.43GHz to 5.8GHz.

<table>
<thead>
<tr>
<th>Frequency $f_0$/GHz</th>
<th>0.43</th>
<th>1.4</th>
<th>2.4</th>
<th>4.4</th>
<th>5.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy/mm</td>
<td>0.97</td>
<td>0.3</td>
<td>0.17</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>Measurement distance R/km</td>
<td>139</td>
<td>43</td>
<td>25</td>
<td>14</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3. The Performance of the System at Certain Frequency. The accuracy is calculated with the $\delta(\Delta \phi)=1^\circ$, and the distance with $P_{rm}=-80$dbm, $P_t=20$dbm, $G_t=G_r=14$dbi

According to regulations from the ITU-Radio communication Sector, the ISM (Industrial Scientific Medical) free band can be used without application. The 433MHz, 2.4GHz and 5.8GHz are some of free frequency bands.

From the table 3, some conclusions are following:

A. The accuracy is within 1 millimeter if the resolution of the phase difference demodulation is within 1 degree.

B. The measurement distance has the potential to reach to kilometers.

3. EXPERIMENTS

The Measurement Accuracy Experiments

For real application, the data-process unit includes the DAQ (Data Acquisition Card) and a computer, and the DAQ will obtain the two signals of $s_R(t)$ and $s_M(t)$ for computer to demodulate the phase difference. It is indispensable to test the resolution of the phase difference demodulation. Here is the schematic diagram and pictures illustrated in figure 4. And table 4 gives the experimental parameter.

From the figure 4, two signals with adjustable phase difference generated by the standard source serve as the $s_R(t)$ and $s_M(t)$. And then the DAQ acquires the data for computer to demodulate. The results are shown in figures 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>$f_1$</td>
<td>2.400150GHz</td>
</tr>
<tr>
<td>$f_c$</td>
<td>5.8GHz</td>
</tr>
</tbody>
</table>

Table 4. The Experimental Parameter Setting
The increment of the phase difference is 1 degree and 25 points has been measured at each step. From the figure 5 (B), it indicates that 1 degree resolution can be achieved by the phase difference demodulation system, which means that the submillimeter-accuracy for displacement measurement can be realized from equation (13).

**Displacement Measurement with Whole System at Long Distance**

The whole experiment system consists of two parts illustrated in figure 3. One is a microwave radar, the other is an active reflector. And only the circuit composition is different from each other. For each part, the setup is demonstrated in figure 6 as following.

The gunsight and the target are for collimation of the microwave radar and active reflector at long distance, levelling for angle adjustment. Millimeter-displacement coming from the translation stage is the substitute of the deformation of real measurand. Field experiment pictures are demonstrated in figure 7.
Figure 7. The Field Experiment Pictures. The Left is the Microwave Radar and the Right is the Active Reflector at long distance beyond sight.

Five experiments are carried out at five different distances (19m, 110m, 200m, 400m) to test the performance of the system. The displacement increment is 1 millimeter by translation stage and 8 points are measured for each step. The results are listed in figure 8-11.

Figure 8. Results of the displacement measurement while the active reflector is 19 meters away (A) 8 single-point measurements for each step (B) Average of the 8 single-point measurements.

Figure 9. Results of the displacement measurement while the active reflector is 110 meters away (A) 8 single-point measurements for each step (B) Average of the 8 single-point measurements.

Figure 10. Results of the displacement measurement while the active reflector is 200 meters away (A) 8 single-point measurements for each step (B) Average of the 8 single-point measurements.
Comparing the five results, it can be concluded that the system is capable of displacement measurement at long distance.

The system error at each distance has been processed in this procedure: (1) Calculate the standard deviation of eight single-point measurements for each step. (2) Regard the averages of the standard deviations at each distance as the systems errors. The system errors of the results are given in Table 5.

<table>
<thead>
<tr>
<th>Distance</th>
<th>System Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>19m</td>
<td>0.14mm</td>
</tr>
<tr>
<td>110m</td>
<td>0.06mm</td>
</tr>
<tr>
<td>200m</td>
<td>0.09mm</td>
</tr>
<tr>
<td>400m</td>
<td>0.32mm</td>
</tr>
</tbody>
</table>

Table 5. Comparison of the system error of the experiment

It’s obvious that the system errors doesn’t have a serious deterioration when the distance is farther away, and also the accuracy is within submillimeter.

4. CONCLUSIONS

A microwave radar with transponder for one-dimensional displacement monitoring method for SHM (Structure Health Monitor) is presented in this paper. In order to realized the one-dimensional displacement with high accuracy, wide range, long distance, all-weather and low cost, the principle of displacement measurement using microwave radar system is analyzed especially, so is the performance of the system. Finally, corresponding experimental facility is setup, and experiments have been conducted. The results show that the system measurement error is less than 0.32mm within 400 meters at 1.6W transmitting power, measuring speed is 10ms per time. Furthermore, the total system hardware cost is within 1,500 dollars, which is much cheaper than GPS and Ground-based interferometric radar. In short, the microwave radar with the active transponder reflector has a great potential for SHM at kilometers measurement distance with submillimeter accuracy if the system parameters are further optimized.

5. REFERENCE

[9]. Gonzalez-Aguilera, D., J. Gomez-Lahoz, and J. Sanchez, A new approach for structural


