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A microwave radar system based on carrier modulation and heterodyne phase difference detecting with time-to-digital converter

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Abstract: To solve the problems of the major kinds of microwave radars to meet the ranging needs of vibrating constructions, a new type of radar system for ranging is proposed based on the carrier modulation and heterodyne phase difference detecting with time-to-digital converter (TDC). In the radar system, an intermediate frequency (IF) signal is used to modulate the amplitude of radio frequency (RF) carrier signal to produce transmitting signal, and radar system receives the back-reflected signal from the target and demodulates the IF signal to expand the unambiguous range. Then, the heterodyne processing and phase detector with TDC device are adopted to detect phase shift of IF signal for ranging to improve the ranging resolution and ranging speed. In addition, the ranging experiment results proved the feasibility and validity of the presented radar system.

Keywords: microwave radar, carrier modulation, heterodyne phase difference detecting, unambiguous range, ranging resolution, ranging speed

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

In order to identify early structural damage and enable remedial actions to be taken, monitoring the displacements and vibrations of civil engineering constructions such as bridges, buildings, and towers is very important [1, 2], in which ranging is the basis and key of great importance. Hence, ranging system should be insensitive to abrupt changes of environmental conditions such as dust and rain because the constructions are almost built in outdoor environment. Besides, it is needed that the unambiguous range of ranging system could be as large as possible for the large size of constructions such as 100 m or even 1 km etc [1, 2]. Moreover, in order to identify the structural damage accurately and quickly for vibrating constructions, ranging system should have a ranging resolution of mm or sub-mm and a ranging speed quicker than the vibrating rate of constructions (e.g. a dozen hertz) [1, 2].

Hence, the microwave radar is an ideal and practical ranging system as microwave is insensitive to environmental changes and can penetrate through rain and fog etc. Currently, pulse radar, single and multiple frequency continuous wave (CW) radar, frequency modulation continuous wave radar (FMCW) and spread spectrum (SS) radar are major kinds of microwave radars [3, 4, 5, 6].

However, there are some problems for them to meet the ranging needs simultaneously above. Usually, the ranging resolution of pulse radar is several centimeters or decimeters as it is very difficult to improve time measurement precision for pulses especially anamorphic echo pulse [3]. Moreover, the single frequency CW radar (SFCW) has a disadvantage of small unambiguous range (several centimeters or decimeters) equal to half of wavelength of the transmitted microwave [4]. Although multi-frequency CW radar (MFCW) could offer a large unambiguous range, its time consuming in switch of multiple frequencies will reduce ranging speed to seconds [7], and ranging error will increase sharply if the multiple frequencies are not transmitted simultaneously before the constructions vibrate or move [4]. Limited by FM bandwidth, the ranging resolution of FMCW radar is only several centimeters or decimeters, so it is similar to SS radar [5, 6].

In brief, the major microwave radars above can only meet one or two needs of large unambiguous range, high ranging resolution and rapid ranging speed for vibrating constructions, thus, to meet all the ranging needs above simultaneously, a new type of radar is proposed in this letter based on carrier modulation and heterodyne phase difference detecting with time-to-digital converter (TDC) [8, 9].

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2 Description of radar system

Shown in Fig. 1 is the schematic diagram of the proposed radar system. The system mainly consists of modulator, demodulator, transmitter, receiver, radio frequency (RF) source and phase detector with TDC device. In modulator, the intermediate frequency (IF) signal $V_0(t)$ is used to modulate the amplitude of carrier signal $V_c(t)$ from RF source. Transmitter sends out the modulated and amplified microwave signal $V_t(t)$, and receiver detects the back-reflected signal $V_r(t)$ from the target of distance R. The demodulator is adopted to demodulate the IF signal $V_\varphi(t)$ from RF signal to expand unambiguous range. Phase detector with TDC is used to detect the phase difference between $V_\varphi(t)$ and $V_0(t)$ to accomplish high precision and rapid ranging (Fig. 1, 2) [8, 9].

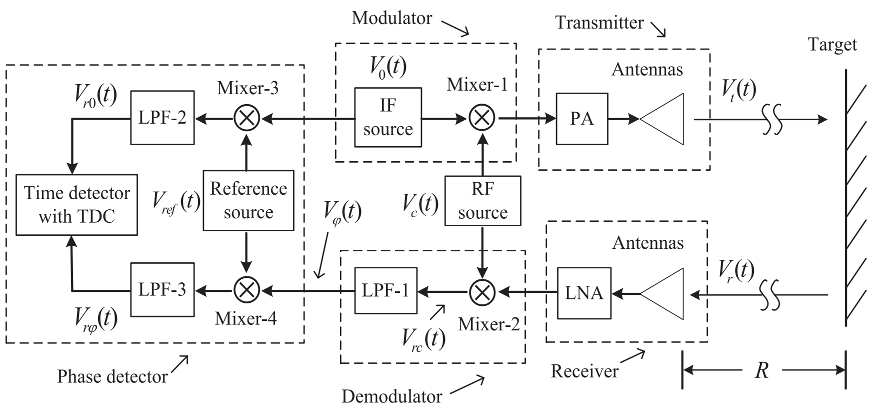

Fig. 1. Schematic diagram of the proposed microwave radar system

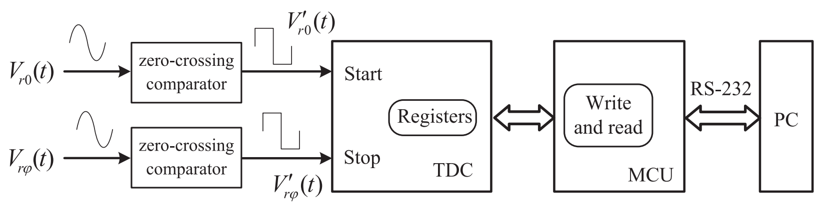

Fig. 2. Schematic diagram of the time detector with TDC device

Detailedly, supposing $V_0(t)$ and $V_c(t)$ are both continuous cosine signals, and that A_0 and A_c are amplitudes and f_0, f_c are frequencies ($f_c \gg f_0$), and the initial phase is zero for facilitating discussion, thus, $V_0(t)$ and $V_c(t)$ are given by

$$V_0(t) = A_0 \cos 2\pi f_0 t \tag{1}$$

$$V_c(t) = A_c \cos 2\pi f_c t \tag{2}$$

Assuming G_{PA} is the gain of power amplifier (PA), the transmitted signal $V_t(t) = V_0(t) \cdot V_c(t) \cdot G_{PA}$ and reflected signal $V_r(t) = \alpha_0 V_t(t - \Delta t)$ are obtained orderly, where α_0 is attenuation coefficient and $\Delta t = 2R/c$ is time delay (c is the light velocity). Supposing G_{LNA} is the gain of low noise amplifier (LNA), the signal $V_{rc}(t) = G_{LNA} \cdot V_r(t) \cdot V_c(t)$ is gained detailedly by

$$\begin{aligned} V_{rc}(t) = A_{rc} \cdot \{&\cos 2\pi[(2f_c + f_0)t - (f_c + f_0)\Delta t] + \underline{\cos 2\pi[f_0 t - (f_c + f_0)\Delta t]} \\ &+ \cos 2\pi[(2f_c - f_0)t - (f_c - f_0)\Delta t] + \underline{\cos 2\pi[f_0 t + (f_c - f_0)\Delta t]}\} \end{aligned} \tag{3}$$

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where $A_{rc} = \alpha_0 A_0 A_c^2 G_{PA} G_{LNA}/4$, clearly, $V_{rc}(t)$ consists of three AC signals of frequencies at $(2f_c + f_0)$, $(2f_c - f_0)$, f_0. According to $f_c \gg f_0$, the IF signal $V_\varphi(t)$ of f_0 underlined in (3) can be demodulated after low pass filtering by

$$V_\varphi(t) = A_\varphi \cdot \cos 2\pi f_0(t - \Delta t) \tag{4}$$

where $A_\varphi = 2A_{rc}\alpha_{LPF1}\cos(2\pi f_c \Delta t)$ (α_{LPF1} is attenuation of LPF-1). Clearly, A_{rc} and A_φ are both determined if the distance R and radar parameters are determined including signals $V_0(t)$ and $V_c(t)$ etc. Thus, after measuring the phase difference $\varphi_R = 2\pi f_0 \Delta t$ between $V_0(t)$ and $V_\varphi(t)$ from (1) and (4), the distance R and its unambiguous range $R_{\max}$ can be gained by

$$R = c\varphi_R/4\pi f_0 \tag{5}$$

$$R_{\max} = c/2f_0 \tag{6}$$

Eq. (6) indicates that reducing f_0 is the only way to expand $R_{\max}$, while f_0 can be easily got at a few MHz or hundreds of KHz because f_0 is in IF band, thus the unambiguous range $R_{\max}$ can be easily gained at a few kilometers from Eq. (6). Moreover, a rapid ranging speed can be also obtained because there is no time consuming in switching of multiple ranging frequencies like multi-frequency CW radar due to the only frequency f_0 to detect R from Fig. 1 and (5).

Besides, in order to achieve a high ranging resolution, neglecting frequency drift at f_0 for facilitating discussion due to the standard IF source with temperature compensation, we can take the differentiation of (5) and get the ranging resolution

$$\delta R = \frac{c}{4\pi f_0} \cdot \delta\varphi_R \tag{7}$$

Eq. (7) shows there are two ways to upgrade δR. One is increasing f_0 while it is opposed to expanding unambiguous range $R_{\max}$ according to Eq. (6), and another is improving phase resolution $\delta\varphi_R$. Clearly, improving $\delta\varphi_R$ is a viable way and the key to upgrade δR when f_0 is determined to ensure a large $R_{\max}$ in (6).

To this end, a sample and useful phase difference detector is adopted with an adjustable and high phase resolution based on heterodyne processing and TDC device (Fig. 1, 2). The heterodyne processing is used to convert the phase difference of high frequency signal to that of a lower frequency signal [10], i.e. let $V_0(t)$ and $V_\varphi(t)$ mix with reference signal $V_{ref}(t) = A_{ref}\cos(2\pi f_{ref} t + \phi_{ref})$ respectively, where A_{ref} is the amplitude, f_{ref} is the frequency and ϕ_{ref} is the initial phase. Assuming that $f_0 > f_{ref}$, the following signals are got after mixing and low pass filtering by

$$V_{r0}(t) = \frac{A_{ref}A_0}{2} \cdot \cos[2\pi(f_0 - f_{ref})t - \phi_{ref}] \tag{8}$$

$$V_{r\varphi}(t) = \frac{A_{ref}A_\varphi}{2} \cdot \cos[2\pi(f_0 - f_{ref})t - \phi_{ref} - \varphi_R] \tag{9}$$

It is seen that $V_{r0}(t)$ and $V_{r\varphi}(t)$ retain the phase difference φ_R, but the signal frequency $(f_0 - f_{ref})$ is lower than f_0 and it is therefore easier to obtain higher phase detecting resolution. Further, zero-cross comparators are used to convert cosine wave signals $V_{r0}(t)$ and $V_{r\varphi}(t)$ into square waves $V'_{r0}(t)$ and $V'_{r\varphi}(t)$ to detect φ_R (Fig. 2), and the time interval Δt_m between $V'_{r0}(t)$ and $V'_{r\varphi}(t)$ is detected by TDC [8, 9], which can lead to the phase difference φ_R and distance R obtained from (5) by

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$$\varphi_R = 2\pi(f_0 - f_{ref}) \cdot \Delta t_m \tag{10}$$

$$R = c \cdot (f_0 - f_{ref}) \cdot \Delta t_m / 2 f_0 \tag{11}$$

Similarly, we can also neglect the frequency drifts of f_0 and f_{ref}, and take the differentiations of (10) and (11) to get

$$\delta\varphi_R = 2\pi(f_0 - f_{ref}) \cdot \delta(\Delta t_m) \tag{12}$$

$$\delta R = c \cdot (f_0 - f_{ref}) \cdot \delta(\Delta t_m) / 2 f_0 \tag{13}$$

Clearly, (12) and (13) indicate that decreasing the frequency $(f_0 - f_{ref})$ is a useful way to improve $\delta\varphi_R$ and upgrade δR when f_0 is determined for $R_{\max}$ and the time resolution $\delta(\Delta t_m)$ of TDC is selected. Besides, When $f_{ref} \to f_0$, it can be got that $(f_0 - f_{ref}) \to 0$, $\delta\varphi_R \to 0$ and $\delta R \to 0$ from (12) and (13). Moreover, TDC is a special timing circuit starting and stopping its timing operation by square waves and measures the time delay between square waves, and it has a high time resolution $\delta(\Delta t_m)$ as high as sub-ns such as 50 ps, and has a rapid measuring speed at us level due to its super-speed gates working in the sequence [8, 9]. Thus, the ranging resolution δR can easily reach millimeters such as $\delta R = 1.0$ mm when $f_0 = 1.5$ MHz, $f_{ref} = 1.3$ MHz and $\delta(\Delta t_m) = 50$ ps from (13), and it is also easily to upgrade δR further by reducing $(f_0 - f_{ref})$ with adjusting f_{ref} in (13).

In brief, from the analysis above, it is obtained the proposed radar has a few better advantages of large unambiguous range (km level), high ranging resolution (mm level) and rapid ranging speed (us level) in theory to meet the ranging needs for vibrating constructions, compared with the major microwave radars above.

3 Experiment and analysis

Ranging experiment should be done to verify the validity of the proposed radar system. As the size of most civil constructions are tens or hundreds of meters, for facilitating discussion, the theoretical unambiguous range of ranging experiment is adopted as $R_{\max} = 100$ m and ranging resolution $\delta R = 1.0$ mm. Hence, $f_0 = 1.5$ MHz and $(f_0 - f_{ref}) = 0.2$ MHz are obtained from (6) and (13) according to the time resolution $\delta(\Delta t_m) = 50$ ps of TDC [8, 9], which produces $f_{ref} = 1.3$ MHz from $f_0 = 1.5$ MHz. Meanwhile, RF carrier frequency f_c is selected to be 2.41 GHz in the ISM band for its correlative devices are abundant and cheap such as mixers and amplifiers. Otherwise, the gain of transmitter and receiver antenna is 14 dBi, and the half-power beam width is 12 degrees, while the power of transmitted signal is 22 dBm. Thus, radar system is set up as below: IF source (RIGOL, DG4102) and mixer-1 (mini, ZX05-83+) compose the modulator, while demodulator consists of mixer-2 (mini, ZX05-83+) and LPF-1 (mini, BLP-5+). PA (mini, ZX60-33LN+), LNA (mini, ZX60-272LN+) and 2.4 GHz antennas customized are used to constitute transmitter and receiver. Phase detector consists of mixer-3/mixer-4 (mini, ZX05-1MHW+), LPF-2/LPF-3 (customized, cut-off frequency 0.8 MHz), reference source (Agilent, 33220a), zero-crossing comparator (ADI, AD8564), TDC module (Acam, TDC-GP2), MCU (STC89C52) and PC (DELL). RF is supplied by a 2.41 GHz source customized with frequency stability of ±3.0 ppm.

As shown in Fig. 3, the radar system is fixed on a stable basis, and the target is a metal reflector of rectangular (600 mm × 600 mm × 2 mm) with a good reflection

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property to microwave, which is fixed on a moving stage of a linear guide rail (Beijing sofn, 7STA02600) and well aligned to antennas. The moving stage is driven by a lead screw controlled by actuator (Beijing sofn, 7SC306) programmed to provide desired motion [11], whose resolution is 0.01 mm.

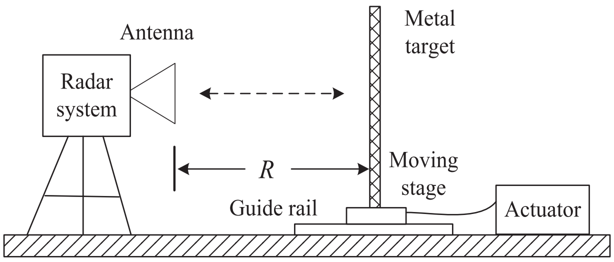

Fig. 3. Experiment of the proposed radar system

In experiment, the reflector target moves from original distance of 2.0 m to 3.1 m with a step of 0.1 m. At each step, 100 samples are averaged to reduce the effect of random noise. The ranging results are got by (5), (11) and shown in Fig. 4 where the linear fitting correlation coefficient is 0.999. Moreover, Fig. 5 shows the 100 samples at 2.0 m, whose standard deviation is 1.04 mm, and those of other 11 positions are all less than 1.09 mm. The difference of 0.04 mm between 1.04 mm of experiment and 1.0 mm of theoretical resolution may be caused by the instability and uncertainty of the circuits including amplifier, LNA, mixers, and so on.

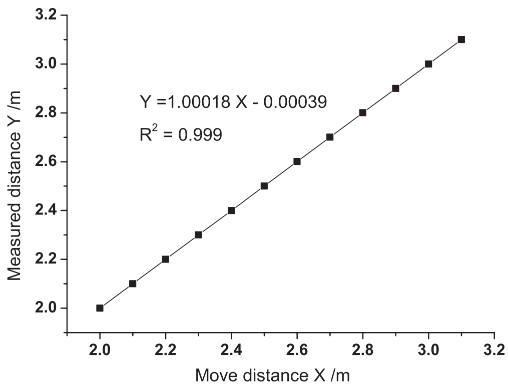

Fig. 4. Ranging results from 2.0 m to 3.1 m.

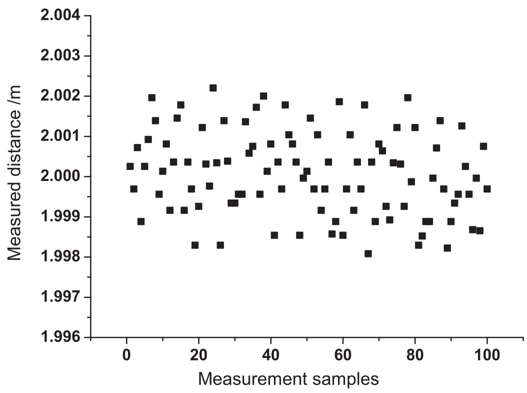

Fig. 5. 100 samples of ranging at 2.0 m

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Therefore, results in Fig. 4 verify the validity of (1)~(13) of the proposed radar and theoretical selection of parameters above, which shows the unambiguous range of the radar is $R'_{max} = 100$ m from (6). Moreover, the ranging resolution can be considered as $\delta R' = 1.04$ mm at 2.0 m from Fig. 5, and each ranging costs averagely 12~13 ms (76.9~83.3 Hz), which shows the ranging speed is quicker than the vibrating rate of most civil constructions (a dozen hertz) [1, 2].

In brief, the ranging results show that the proposed radar has an unambiguous range of 100 m larger than that of SFCW radar [4], a ranging resolution of 1.04 mm higher than that of pulse, FMCW and SS radar [3, 5, 6], and a ranging speed of 12~13 ms quicker than that of MFCW radar [4, 7] mentioned above, which verifies the validity of proposed radar system and shows it is more adaptive to vibrating constructions compared with the major radars mentioned. If the ranging needs are upgraded, we can also upgrade R_{max} and δR easily in (6) and (13) to meet the needs.

4 Conclusion

In this letter, a new type of microwave radar system is proposed based on carrier modulation and heterodyne phase difference detecting with TDC. The experiments proofed the ranging principle of the radar system and showed that the system has an unambiguous range of 100 m, a ranging resolution of 1.04 mm and a ranging speed at 12~13 ms, which verifies the validity of the radar system with the three ranging needs simultaneously, which is adaptive to vibrating constructions.

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