SCIENCE CHINA
Information Sciences

• LETTER •

October 2016, Vol. 59 109301:1–109301:3
doi: 10.1007/s11432-016-0028-y

Accurate non-contact retrieval in micro vibration by a 100GHz radar

Rui WANG, Aolin LI, Cheng HU* & Tao ZENG

Beijing Institute of technology, Beijing 100081*, China*

Received January 8, 2016; accepted February 18, 2016; published online May 11, 2016

Citation Wang R, Li A L, Hu C, et al. Accurate non-contact retrieval in micro vibration by a 100GHz radar. Sci China Inf Sci, 2016, 59(10): 109301, doi: 10.1007/s11432-016-0028-y

Dear editor,

Owing to good accuracy and ability to isolate the desired target from clutter, the applications of radar technique in vibration measurement have attracted many researchers' interests in recent years. One of the main applications is heartbeat detection [1]. The measurement accuracy of heart rate using a Ka-band radar is fully evaluated, where different body orientations relative to the radar were tested. In addition, the radar has been used in human vocal vibration signal detection [2], where a speech radar system is presented to extract speech information from the vocal vibration signal of a human subject. The radar has also been used in monitoring engineering constructions [3, 4]. Natural frequencies and mode shapes are able to be identified from radar data. However, in most cases, the radar systems are only used to detect vibration frequency.

A method based on nonlinear Doppler phase modulation effect has been proposed to measure the amplitude of a single tone periodic movement [5]. The radar baseband output for the periodic vibration target can be expanded into a series of harmonics whose harmonic magnitudes are determined by the vibration amplitude. Li et al. take the magnitude ratios between two even-order or two odd-order harmonics to obtain the estimates of the vibration amplitude. However, the target is only 1.65 m away from the radar, thus, the received signal is in high SNR and the influence of noise is negligible. Moreover, vibration amplitude of the target is 2 mm which is not small enough in some applications.

In this letter, we propose a modified non-contact retrieval method for micro vibration with submillimeter amplitude. Utilizing one harmonic pair of backscattered signal, the amplitude of vibrational target can be retrieved. However, the noise may cause a bias of harmonic magnitude and thus decrease the estimation accuracy of vibration amplitude. In order to suppress the noise's influence, all the available harmonics are utilized based on least squares estimation to improve the accuracy. The main contributions of this letter are as follows: (a) a modified non-contact retrieval method for micro vibration; (b) an experimental validation to measure the micro vibration of a corner reflector attached to a calibrator 8.5m away from the radar.

Method of the vibration amplitude retrieval. In this letter, the frequency-modulated continuous-wave(FMCW) is adopted and thus the transmitted signal can be expressed as

$$s_T(t) = P \exp\left\{j\left(2\pi f_c t + \pi k_r t^2 + \phi_0\right)\right\} \quad (1)$$

where P is the transmitted power, f_c is the carrier frequency, t is the fast time, k_r is the chirp

* Corresponding author (email: cchchb@163.com)
The authors declare that they have no conflict of interest.

rate, and ϕ_0 is the initial phase. If this signal is reflected by a target at a nominal distance R_0 with the vibration displacement of $x(\tau)$ in the range direction, where τ is the slow time, the total distance travelled from the transmitter to the receiver is $2R(\tau) = 2R_0+2x(\tau)$. Then, after down-conversion, the received signal can be expressed as

$$s_B(t) = P\sigma \exp\left\{ \begin{array}{l} j\pi k_r\left(t - \frac{2R(\tau)}{c}\right)^2 + \\ j\frac{4\pi R(\tau)}{\lambda} + j\phi \end{array} \right\} \quad (2)$$

where σ is the radar cross section of the target, c is the speed of light, λ is the radar wavelength in air. After dechirp processing, the received signal can be represented as

$$\begin{aligned} s_D(t) =& P\sigma \mathrm{sinc}\left\{\pi B\left(t - \frac{2R_0}{c}\right)\right\}\cdot \\ & \exp\left\{j\left(\frac{4\pi x(\tau)}{\lambda} + \phi\right)\right\}, \end{aligned} \quad (3)$$

where B is the bandwidth of the signal, $2x(\tau)/c \ll 1/B$, ϕ is the constant phase. For a single tone vibrating target, its displacement can be denoted as $x(\tau) = A\sin(2\pi f_v \tau)$. The target signal can be extracted from (3) at $t = 2R_0/c$ and further expressed as Fourier series:

$$\begin{aligned} s_v(\tau) &= P\sigma \exp\left\{j\left(\frac{4\pi A \sin(2\pi f_v \tau)}{\lambda} + \phi\right)\right\} \\ &= P\sigma \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi A}{\lambda}\right) \exp\{j(2\pi n f_v \tau + \phi)\} \end{aligned} \quad (4)$$

where $J_n(.)$ is the n-th order Bessel function of the first kind [1]. The absolute value of ratio between l-th and k-th order harmonics is

$$\frac{H_l}{H_k} = \frac{\left|P\sigma J_l\left(\frac{4\pi A}{\lambda}\right)e^{j\phi}\right|}{\left|P\sigma J_k\left(\frac{4\pi A}{\lambda}\right)e^{j\phi}\right|} = \left|\frac{J_l(4\pi A/\lambda)}{J_k(4\pi A/\lambda)}\right|. \quad (5)$$

The ratio is only determined by the vibration amplitude at a fixed carrier frequency as shown in Figure 1(a). Different vibration amplitudes may correspond to same ratio. Considering A/λ is small for submillimeter amplitude and W band, we select the range of $0 \sim 5$ for A/λ as the effective vibration amplitude detection range. The effective detection ranges for J_2/J_1 and J_3/J_2 are marked by the red solid lines in Figure 1(a). Then, vibration amplitude can be extracted from one harmonic ratio based on the monotonous curve [5].

However, the harmonic ratio is quite sensitive to the signal noise. In order to minimize the effect of the noise, a modified amplitude retrieval method is proposed utilizing all available harmonic pairs. Assuming N harmonics are used, the magnitudes of N harmonics can be obtained based on the Fourier transformation(FT) of (4). Then, we can construct the harmonic ratio vector as

$$\boldsymbol{x} = (H_2/H_1, ..., H_l/H_k, ..., H_N/H_{N-1}),\ l > k. \quad (6)$$

In the vector, there are $N(N-1)/2$ harmonic pairs in total. The vibration amplitude detection range $A_b \sim A_e$ for $\boldsymbol{x}$ is determined by the intersection of the effective detection range for all harmonic rations. Then, the detection range $A_b \sim A_e$ is sampled into A_1, ..., A_i, ..., A_m with the step interval of ΔA which is determined according to the expected accuracy.

According to (5)(6), for each A_i, a harmonic ratio vector $\boldsymbol{x}_i$ can be obtained. Taking all of them, we obtain the ratio matrix G:

$$G = \begin{bmatrix} H_{12}/H_{11} \ ... \ H_{1l}/H_{1k} \ ... \ H_{1N}/H_{1(N-1)} \\ H_{22}/H_{21} \ ... \ H_{2l}/H_{2k} \ ... \ H_{2N}/H_{2(N-1)} \\ ... \\ H_{m2}/H_{m1} \ ... \ H_{ml}/H_{mk} \ ... \ H_{mN}/H_{m(N-1)} \end{bmatrix} \quad (7)$$

where $H_{il}/H_{ik} = |J_l(4\pi A_i/\lambda)/J_k(4\pi A_i/\lambda)|$.

Calculate the sum of squared error between every row of G and the measured harmonic ratio vector, we get

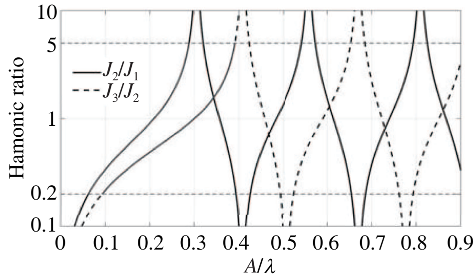
$$e_i(A) = \sum_{k=1}^{N-1}\sum_{l=k+1}^{N} (H_{il}/H_{ik} - H_l/H_k)^2 \quad (8)$$

where $i = 1, 2, \ldots, m$. Finally, we can derive the estimate of vibration amplitude $\widehat{A}$ which corresponds to the minimum $e_i(A)$ based on least squared error.

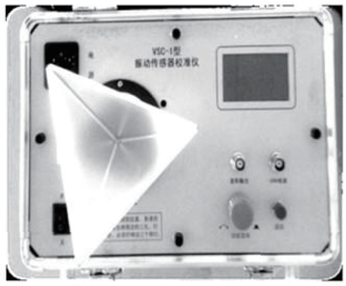
Theoretically, the more harmonic pairs we use, the accuracy will be higher. However, the increasing N will narrow the effective detection range as shown in Figure 1(a). In addition, because the harmonic magnitudes generally become weaker with increasing the orders, the high-order harmonic pairs are limited by low SNR.

Experimental validation. In the experiment, a W-band FMCW radar was used to measure the vibration of a corner reflector with the edge length of 8cm attached to a vibration calibrator(see Figure 1(b)). The calibrator can generate a single tone vibration with 10 Hz $\leqslant f_v \leqslant$ 2000 Hz and 0.5 μm $\leqslant A \leqslant$ 1000 μm. Parameters of the radar are shown in Figure 1(c).

In the experiment, the calibrator generated a single-tone vibration with f_v = 40 Hz and A = 500 μm and at about 8.5 m away from the radar.



(a)



(b)

Parameters	Wavelength	PRF	Resolution
Value	3 mm	2 kHz	0.125 m

(c)

Frequency (Hz)	Amplitude (mm)	Estimate (mm)	Error (mm)
40	0.25	0.2586	0.0086
40	0.5	0.4986	0.0014
60	0.25	0.2625	0.0125
60	0.5	0.489	0.011

(d)

Figure 1 (a) Theoretical harmonic ratios of 2nd-to-1st pair and 3rd-to-2nd pair; (b) a corner reflector attached to the calibrator; (c) parameters of the radar; (d) experiment results.

We compare the results for $N = 3$ and $N = 4$ since only 4 harmonics are available as a result of SNR limitation. A is in the detection range of the harmonic ratio vector. The amplitude step ΔA is defined to be 0.3 μm.

The magnitudes of the first 4 harmonics are obtained from the spectrum of complex radar baseband output. According to the method in [5], we take the harmonic pair H_2/H_1, H_3/H_1 or H_3/H_2, and then obtain the estimates of vibration amplitude $\widehat{A}_{21} = 494.0$ μm, $\widehat{A}_{31} = 501.9$ μm and $\widehat{A}_{32} = 512.0$ μm, respectively. The corresponding errors are 6, 1.9 and 12 μm. If the proposed method is taken, the estimate for $N = 3$ is $\widehat{A}_{321} = 498.6$ μm with the error 1.4 μm, while for $N = 4$ is $\widehat{A}_{4321} = 510.3$ μm with the error 10.3 μm. Thus, it indicates that the optimal N is 3 in this experiment. More results obtained through the proposed method for $N = 3$ are shown in Figure 1(d).

From the experimental results, it can be found that the proposed method has better estimation accuracy of micro vibration than the one in [5] where only one harmonic pair is used.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 61427802).

References

1 Li C, Xiao Y, Lin J. Experiment and spectral analysis of a low-power Ka-band heartbeat detector mesuring from four sides of a human body. IEEE Trans Microw Theory Tech, 2006, 54: 4464–4471

2 Lin C S, Chang S F, Chang C C, et al. Microwave human vocal vibration signal detection based on doppler radar technology. IEEE Trans Microw Theory Tech, 2010, 58: 2299–2306

3 Gentile C. Deflection measurement on vibrating stay cables by non-contact microwave interferometer. NDT and E International, 2010, 43: 231–240

4 Pieraccini M. Monitoring of civil infrastructures by interferometric radar: a review. The Scientific World J, 2013, 2013: 1–8

5 Li C, Lin J. Non-contact measurement of periodic movements by a 22-40GHz radar sensor using nonlinear phase modulation. IEEE MTT-S Int Dig, 2007: 579–582