Spectrum Correlation of Beat Signals in the FM-CW Radar Level Meter and Application for Precise Distance Measurement

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Abstract — **In this paper, we analyze spectrum correlation of beat signals in the microwave level meter based on the FM-CW radar. For industrial applications, level meters must have high precision, which requires a good linearity of VCO. But, in practice, it is very complicated or very expensive to make VCO linear enough to be acceptable in the industrial field. We propose a measurement algorithm using the fact that there exists a peak in the spectrum correlation of beat signals when range difference is adequately small. This makes it possible to determine the range difference in a precise manner even using a practical VCO. We develop the background theory of correlation and show some results using this algorithm.**

I. INTRODUCTION

The FM-CW radars are widely used for the measurement of distance or velocity in many applications, such as automotive cruise control [1] and tank level measurement [2]-[3]. Although the basic theory of the FM-CW radar is simple and well described in many books [4]-[5], there is an essential problem in the implementation of an FM-CW radar for industrial applications where high precision is required. That is, the VCO (Voltage-Controlled Oscillator) used in the system must have quite a good linearity for output frequencies. If the VCO has some degree of nonlinearity, the width of the IF spectrum is broadened, and it becomes difficult to determine distance in precision [5]. Several methods and algorithms are proposed to solve this problem [6]-[9]. In [6], dynamic feedback loop is used to improve the linearity of VCO. And memory-based linearization technique is applied in [7]. Another solution is to use a reference line to apply relative period counting method or constant phase interval sampling as reported in [8]-[9].

In this paper, we propose an algorithm to determine the distance between antenna reference plane and target, based on the spectrum correlation of beat signals. We explain in detail the background theory in Section II. This algorithm can be applied with IF signals from a reference delay line or the previously measured target.

II. CORRELATION THEORY

The basic block diagram of an FM-CW radar is shown in Fig. 1. If the slope of the VCO frequency sweep is constant for a triangular modulation as shown in Fig. 2, the target range d is calculated as

$$d = \frac{c\, f_b}{4\, f_m \Delta f} \tag{1}$$

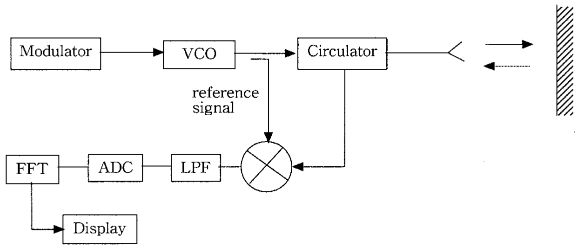

Fig. 1. Typical block diagram of an FM-CW radar system

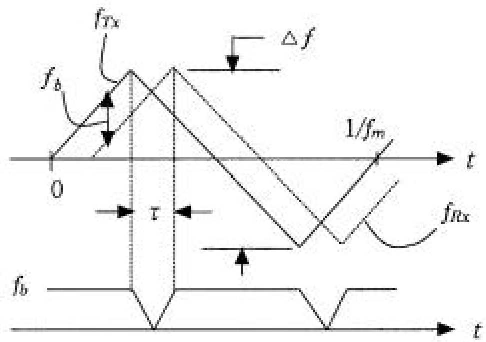

Fig. 2. Frequency-time relationship in FM-CW radar

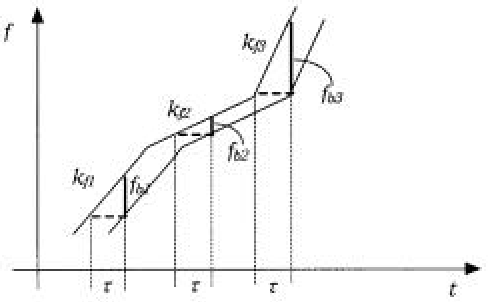

Fig. 3. Nonlinear model of VCO frequency modulation

where c is the speed of light, f_b and f_m are the beat frequency and the modulation frequency, respectively, and Δf is the frequency deviation. In the ideal case, the beat frequency f_b can be obtained from the frequency difference between the transmitted and received signals.

$$f_b = f_{Tx}(t) - f_{Rx}(t) = f_{Tx}(t) - f_{Tx}(t-\tau) \quad (2)$$

where $f_{Tx}(t)$ and $f_{Rx}(t)$ are frequencies of the transmitted and received signals, respectively, and $\tau = 2d/c$ is the delay time of the received signal.

Now, consider that the frequency characteristic is nonlinear in a piecewise manner as shown in Fig. 3. This assumption is reasonable for real VCOs because the slope of frequency modulation will be linear in the short interval. In an ith interval where the modulation slope is constant, a beat frequency is represented as

$$f_{bi} = k_{fi}\tau \quad (3)$$

where

$$k_{fi} = \left.\frac{df}{dt}\right|_i \quad (4)$$

and f means the output frequency of VCO. From this, we can see that there occur many frequency components in the IF signal if k_{fi} is not constant over the measurement period. For two target ranges of which delay times are τ_1 and τ_2, and $\tau_1 \cong \tau_2$, beat signals can be described as

$$v_1(t) = \sum_i A_i^1 \cos(2\pi k_{fi}\tau_1 t) U_i(t) \quad (5)$$

$$v_2(t) = \sum_i A_i^2 \cos(2\pi k_{fi}\tau_2 t) U_i(t) \quad (6)$$

where A_i^1 and $U_i(t)$ represent an amplitude of $v_1(t)$ and a window function for ith interval having the slope k_{fi}, respectively. Then the magnitudes of Fourier transforms for these signals can be expressed as

$$|V_1(f)| = \sum_i |A_i^1| \delta(f - k_{fi}\tau_1) \quad (7)$$

$$|V_2(f)| = \sum_i |A_i^2| \delta(f - k_{fi}\tau_2) \quad (8)$$

Thus, when $\tau_2 = \rho\tau_1$, the relationship of beat frequencies observed in the linearized interval can be expressed as

$$f_{bi}^2 = \rho\, f_{bi}^1 \quad (9)$$

We can find a frequency offset Δf_b^{21} at which the cross correlation between $|V_1(f)|$ and $|V_2(f)|$ is maximum.

$$\Delta f_b^{21} = \left\{f_{bi}^2 - f_{bi}^1\right\}_{average} = (\rho - 1)\left\{f_{bi}^1\right\}_{average} \approx (\rho - 1) f_b^1 \quad (10)$$

where f_b^1 represents the average frequency for f_{bi}^1. Finally, from eq. (10), the difference of target ranges, Δd^{21}, is calculated as

$$\Delta d^{21} = d^2 - d^1 = \Delta f_b^{21} \frac{c}{4 f_m \Delta f} \quad (11)$$

The above procedure can be applied recursively with IF signals from a reference delay line or the previously measured target. Furthermore, a distance d^3 can be determined from previously measured distances d^1 and d^2.

$$d^3 = d^2 + \Delta d^{32} = d^2 + \Delta f_b^{32} \frac{\Delta d^{21}}{\Delta f_b^{21}} \quad (12)$$

III. Experimental Results

Microwave level meters have some advantages over other types of sensors using ultrasound or optical signals, especially for the range measurement inside a steel blast furnace, being operated in adverse environments such as thermal gradients, dust, smoke and so on [3]. We have applied the correlation algorithm to a microwave level meter developed for the application in the steel company. VCO used in the experiment is YTO (YIG-tuned oscillator) of Micro-Lambda with the frequency modulation range

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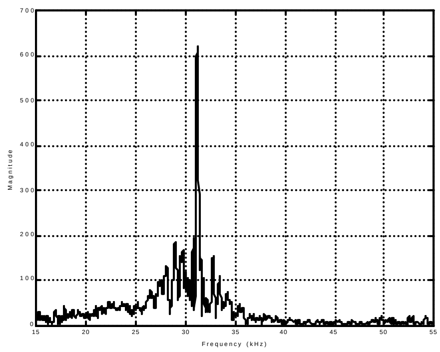
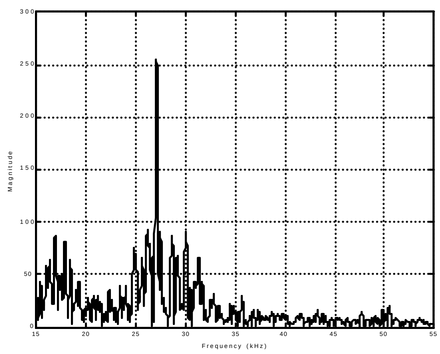
from 8 GHz to 10 GHz (Δf=2 GHz). The modulation frequency is f_m=125 Hz, sampling time is 0.4 μs, and the number of sampling is 10,000.

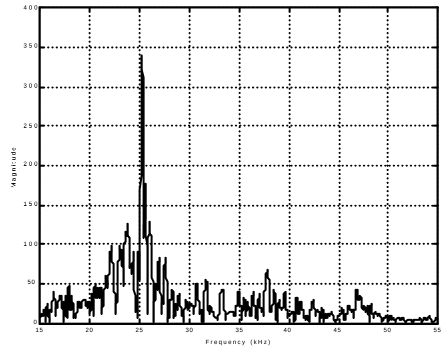
Several results of Fourier transforms of beat signals are presented in Fig. 4. We can observe the nonlinear effect of frequency sweep, especially in Fig. 4(d). Reference targets are in Fig. 4 (a) and (b) which correspond to distances 8.343 m and 7.113 m, respectively. Fig. 5 shows the results of the cross correlations for beat signals in Fig. 4. The frequency offset from Fig. 5 (a) is 4.11 kHz, which is calculated to a distance of 1.233 m from eq. (11). Although this is quite a good result, comparing with the actual range difference of two references, 1.230 m, a correction can be applied based on eq. (12) for a better measurement. Fig. 5 (b)-(d) give offset frequencies of 1.86 kHz, 830 Hz, and 400 Hz, which are transformed with compensations to range differences of 0.557 m, 0.248 m, and 0.120 m, respectively. It is noted that a peak value in the correlation result can be detected even for spread beat frequencies, referring to Fig. 4 (c) and (d), and Fig. 5 (c). The distance resolution is improved up to 3 mm by the method of padding with zeros in the discrete Fourier transform (DFT) [10].



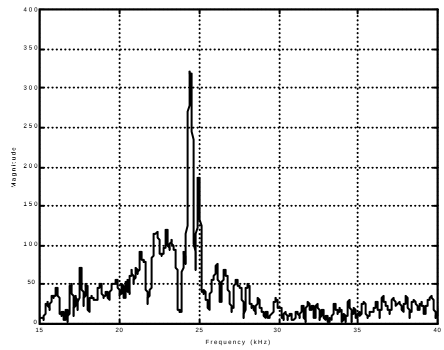
(a) Reference 1 (8.343 m)



(b) Reference 2 (7.113 m)

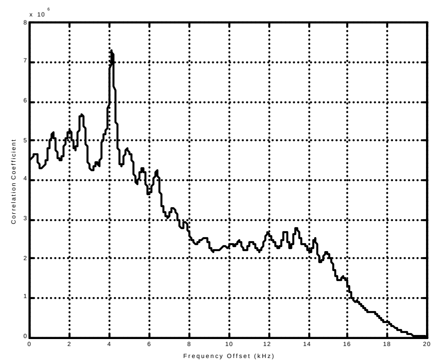


(c) Target range 1

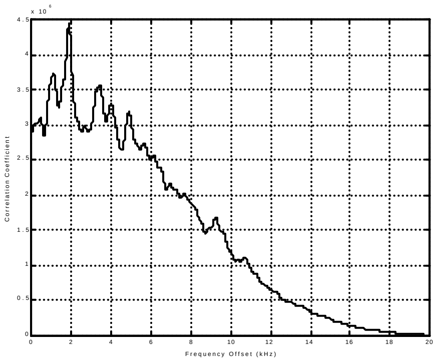


(d) Target range 2

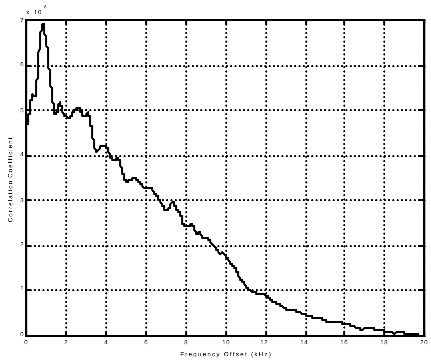
Fig. 4. Fourier transforms of beat signals



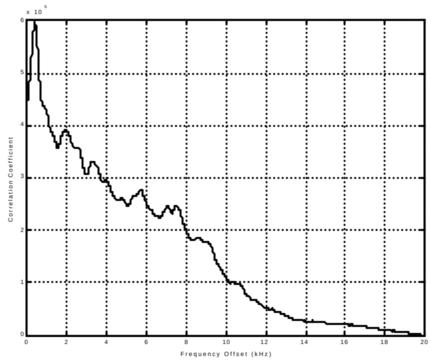
(a) Frequency offset is 4.11 kHz, corresponding to a range difference of 1.233 m for an actual difference of 1.230 m (correlation of Fig. 4 (a) and (b))



(b) Frequency offset is 1.86 kHz, corresponding to a range difference of 0.557 m (correlation of Fig. 4 (b) and (c))



(c) Frequency offset is 830 Hz, corresponding to a range difference of 0.248 m (correlation of Fig. 4 (c) and (d))



(d) Frequency offset is 400 Hz, corresponding to a range difference of 0.120 m

Fig. 5. Correlation results for beat signals in Fig. 4

We have also performed another experiment in the open field with a range up to 30 m. The results are not shown in this paper on account of limited space, but good results were obtained by applying the correlation algorithm.

IV. CONCLUSION

In this paper, we have presented in detail the relationship between spectrum correlation and range difference in the FM-CW radar level meter. The correlation algorithm based on this theory is very useful in the range measurement when beat frequencies spread due to the nonlinearity of VCO. Experimental results for a steel blast furnace are given to confirm the validity of this algorithm. The range resolution is achieved to be 3 mm using the method of padding with zeros in DFT.

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