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FM-CW 레이더 거리계의 비트 신호 스펙트럼 상관성을 이용한 고정밀 측정 알고리듬

(Correlation Algorithm for High-Precision Measurement in FM-CW Radar Level Meters)

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요 약

본 논문에서는 FM-CW 레이더의 원리를 이용한 마이크로파 거리계에서 비트 신호(beat signal)의 스펙트럼 상관도(correlation)를 해석하고, 이를 이용하여 고 정밀도를 실현할 수 있는 거리 측정 알고리듬을 제안한다. 산업 자동화용과 같이 고 정밀도를 요구하는 경우, 거리계에 사용되는 VCO의 주파수 선형도가 매우 우수하여야 한다. 그러나 실제 VCO의 선형도를 높이기 위해서는 고가의 VCO나 복잡한 선형화 회로가 필요하며, 이는 장비 자체의 제작 비용을 높이는 요인이 된다. 거리 차가 충분히 작은 표적물에 대한 두 비트 신호의 주파수 스펙트럼간에는 상관도에서 첨두치를 나타내는 주파수 옵셀(offset)이 존재하게 되며, 본 논문에서는 이를 바탕으로 일반적인 VCO를 사용하더라도 정밀한 측정을 할 수 있는 상관 알고리듬을 제안한다. 제안된 알고리듬의 타당성을 검증하기 위한 측정 결과를 제시하였다.

Abstract

In this paper, for the microwave level meter based on the FM-CW radar, we analyze the spectrum correlation of beat signals and propose a measurement algorithm using the theory. 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 sufficiently small. This makes it possible to determine the range difference in a precise manner even using a practical VCO. We present some experimental results to show the validity of this algorithm.

I. Introduction

The FM-CW (frequency modulated continuous wave) 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]. This is mainly for the reason that microwave level meters have several advantages over other types of sensors, for example, using ultrasound or optical signals, being operable in

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adverse environments such as thermal gradients, dust, smoke and so on[3]. Although the basic theory of the FM-CW radar is simple and well described in many books[4,5], there is a critical 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 method as reported in [8] and [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 implemented with IF signals from a reference delay line or the previously measured distance. In Section III, measurement results are presented to show the validity of this algorithm.

II. Correlation Theory

The basic block diagram of an FM-CW radar[4] 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

$$d=\frac{cf_b}{4f_m \triangle B} \tag{1}$$

where c is the speed of light, f_b and f_m are the beat frequency and the modulation frequency, respectively, and ΔB 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.

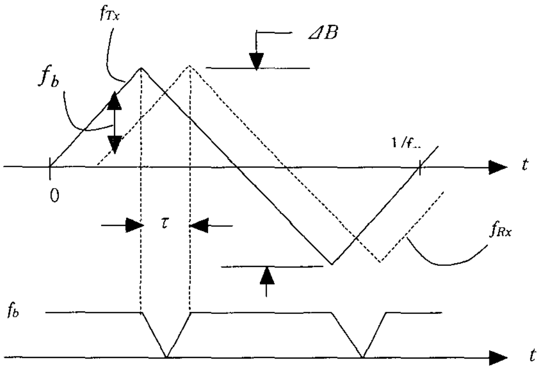


Fig. 2. Frequency-time relationship in FM-CW radar.

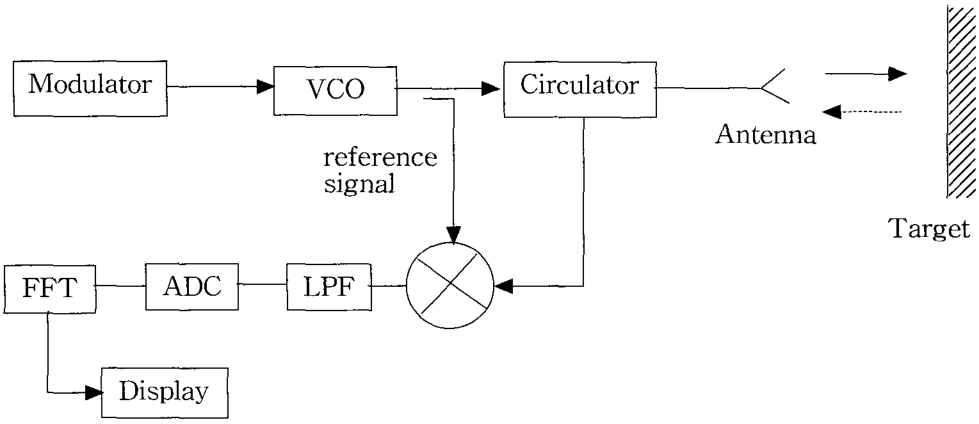


Fig. 1. Typical block diagram of an FM-CW radar system

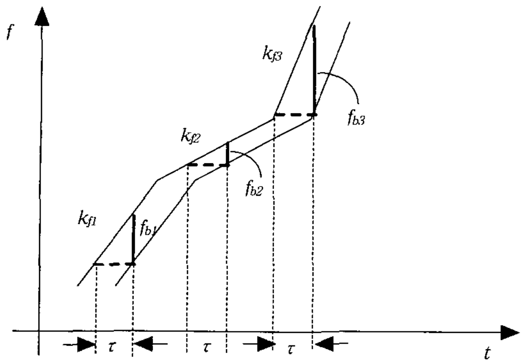


Fig. 3. Nonlinear model of VCO frequency sweep characteristics.

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

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. The nonlinear effect of VCO causes the IF spectrum broadening, as described in [5] and [10]. That is, there exist several frequency components in the beat signal for one target range, which degrades the measurement accuracy. In an i th interval where the modulation slope is constant, a beat frequency is represented as

$$f_{b_i} = k_{f_i}\tau \qquad (3)$$

where

$$k_{f_i} = \frac{df}{dt}\bigg|_i \qquad (4)$$

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, as indicated in [5]. For two target ranges of which delay times are τ_1 and τ_2, and $\tau_1 \approx \tau_2$, beat signals can be described as

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

$$v_2(t) = \sum_i A_i^2 \cos(2\pi k_{f_i}\tau_2 t)\,U_i(t) \qquad (6)$$

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

$$|V_1(f)| = \sum_i |A_i^1|\,\delta(f - k_{f_i}\tau_1) \qquad (7)$$

$$|V_2(f)| = \sum_i |A_i^2|\,\delta(f - k_{f_i}\tau_2). \qquad (8)$$

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

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

Let us define the cross correlation $R_{21}(\varDelta f_b)$ between $|V_1(f)|$ and $|V_2(f)|$ as

$$R_{21}(\varDelta f_b) = \sum_{j=0}^{N-1} V_1(j\varDelta f - k\varDelta f)\,V_2(j\varDelta f) \qquad (10)$$

where N is the number of sampling, $\varDelta f = 1/N\varDelta t$ is the frequency resolution in the Fourier transform with a sampling time $\varDelta t$, and $\varDelta f_b = k\varDelta f$ represents a frequency shift to calculate the correlation. We can find a frequency offset $\varDelta f_b^{21}$ at which the cross correlation between $|V_1(f)|$ and $|V_2(f)|$ becomes maximum.

$$\varDelta f_b^{21} = \{f_{b_i}^2 - f_{b_i}^1\}_{\text{average}} = (\rho - 1)\{f_{b_i}^1\}_{\text{average}} = (\rho - 1) f_b^1 \qquad (11)$$

where f_b^1 represents the average frequency for f_{bi}^1. Finally, the difference between two target ranges, $\varDelta d^{21}$, which includes the effect of VCO nonlinearity, is calculated as

$$\varDelta d^{21} = d^2 - d^1 = \varDelta f_b^{21} \frac{c}{4 f_m \varDelta f}. \qquad (12)$$

Eq. (12) implies that a range difference is proportional to the frequency offset producing a maximum correlation coefficient. Therefore, if we know the actual difference between two reference lines, $\Delta d^{21}_{\mathrm{ref}} = d^{2}_{\mathrm{ref}} - d^{1}_{\mathrm{ref}}$, the calculated difference Δd^{21} given in eq. (12) can be scaled correctly to compensate the nonlinearity of VCO sweep. That is, a distance d^3 can be determined from previously measured distances d1 and d^2,

$$d^3 = d^2_{ref} + \Delta d^{32} = d^2_{ref} + \Delta f_b^{32} \frac{\Delta d^{21}_{ref}}{\Delta f_b^{21}}. \qquad (12)$$

This procedure can be applied recursively with IF signals from a reference delay line at the first measurement and the previously measured target later on.

Ⅲ. Experimental Results

We have performed measurements on coaxial cables to verify the validity of the correlation algorithm described in Section Ⅱ. A level meter has been developed using a VTO (varactor-tuned oscillator) of Magnum Microwave (model no. HV113T-1) of which sweep characteristic is measured in Fig. 4. The linearity L of VCO describes how closely the frequency characteristic approximates a straight line, which is defined as:[11]

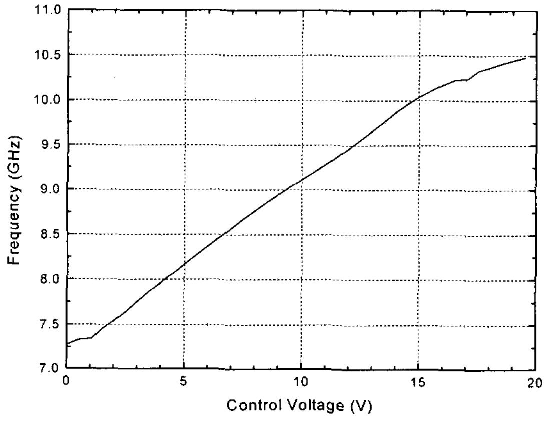
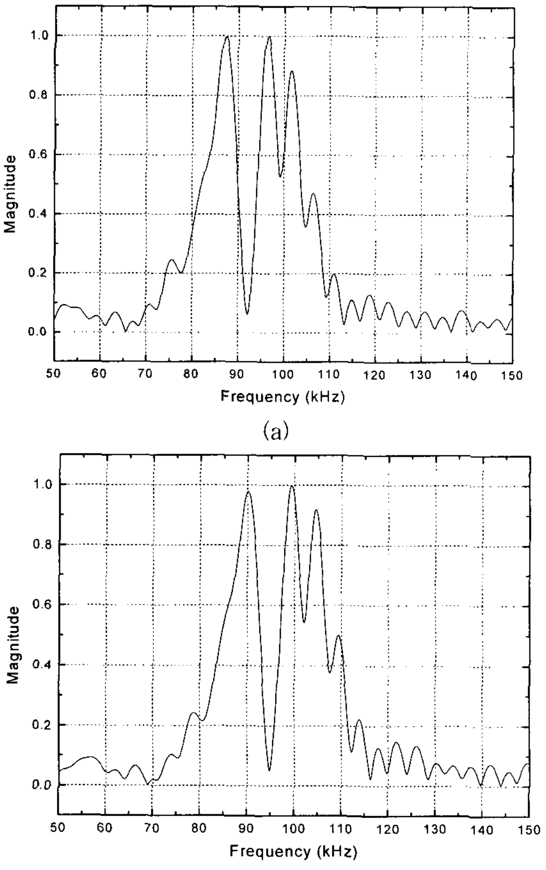


Fig. 4. Frequency sweep characteristics of Magnum VCO (HV113T-1)

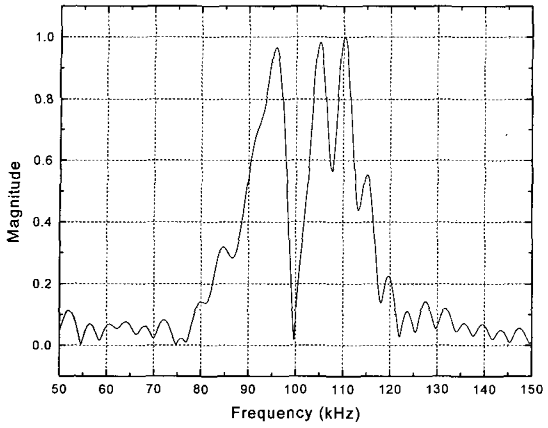
$$L = \frac{S_{\max} - S_{\min}}{S_{\max} - S_{\min}} \times 100\,\% \qquad (13)$$

where $S_{\max}$ and $S_{\min}$ are the maximum and minimum values of the sensitivity over the VCO's tuning range. The linearity of this VCO is measured to be 12.1%. The frequency sweep range is 8.177-9.670 GHz (ΔB=1.493 GHz), the sweep time is T_s=0.25 ms, and the number of sampling is 1,000. Results of Fourier transform of beat signals are shown in Fig. 5. Frequency spectrums for reference lines are plotted in Fig. 5 (a) and (b) which correspond to distances of 157.0 cm and 162.0 cm, respectively. Fig. 5 (c) and (d) show frequency spectrums for test lines of which actual lengths are 171.5 cm and 176.5 cm, respectively. We can see that beat signals contain lots of frequency components. Fig. 6 shows the results of the cross correlations for



(a)

(b)



(c)

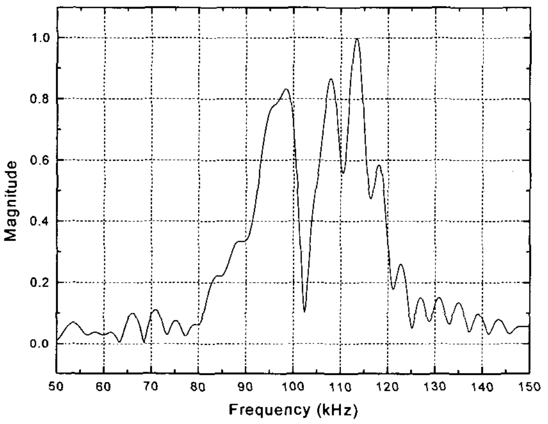
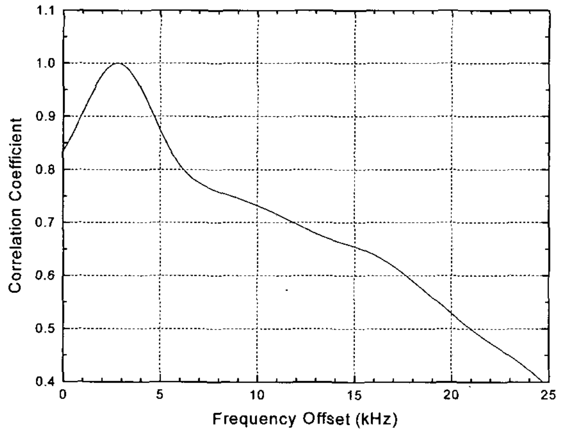
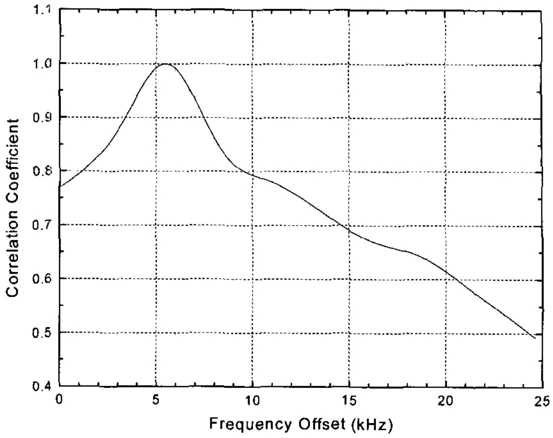


Fig. 5. Frequency spectrums of beat signals
(a) reference line 1 (157.0 cm),
(b) reference line 2(162.0 cm),
(c) test line 1 (171.5 cm),
(d) test line 2 (176.5 cm)



(a)



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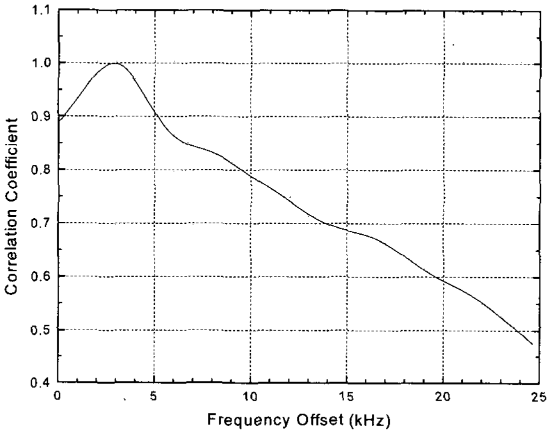

(c)

Fig. 6. Correlations of frequency spectrums plotted in Fig. 5.
(a) correlation between reference line 1 and 2 (peak at 2.88 kHz), (b) correlation between reference line 2 and test line 1 (peak at 5.44 kHz), (c) correlation between test line 1 and 2 (peak at 2.88 kHz)

frequency spectrums plotted in Fig. 5. From Fig. 6 (a), the frequency offset showing a peak is 2.88 kHz, for which the actual range difference is 5.0 cm. With these reference lines, the offset frequency from Fig. 6 (b), 5.44 kHz, leads to a range difference of 9.444 cm and that from Fig. 6 (c), 2.88 kHz, represents a range difference of 5.000 cm from eq. (12). Actual range differences and measured results are compared in Table 1.

It is noted that peak values in the correlation results can be detected even for the broadening in

Table 1. Measurement results using the correlation algorithm.

targets	reference line 1 and 2 (Fig. 6 (a))	reference line 2 and test line 1 (Fig. 6 (b))	test line 1 and 2 (Fig. 6 (c))
frequency offset	2.88 kHz	5.44 kHz	2.88 kHz
measured difference	-	9.444 cm	5.000 cm
actual difference	5.000 cm	9.500 cm	5.000 cm

beat frequency spectrums, referring to Fig. 5 and Fig. 6. The range resolution can be improved by the method of padding with zeros in the discrete Fourier transform (DFT) [12]. In this paper, 25,000-point DFT is computed, resulting in the range resolution of 4.0 mm. So the measurement error boundary becomes ±2.0 mm. We can see that the maximum measured error is 0.56 mm, in Table 1, which is within the error boundary. We have also performed other experiments in the open field with a range up to 30 m[13]. The results are not shown here, but good results have been obtained.

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 can be used to achieve high precision in the range measurement where spectrum broadening of beat signals occurs due to the nonlinearity of VCO. Experimental results measured for coaxial cables are given to confirm the validity of this algorithm.

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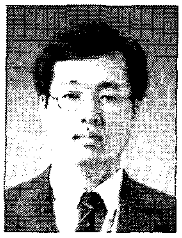

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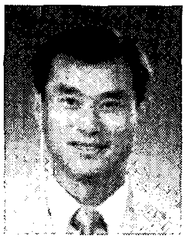

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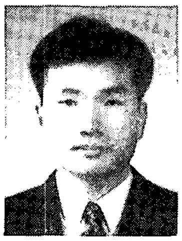

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