Liquid Height Measuring in Industry Based on Sine plus Noise FMCW Radar

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Summary
In view of the advantages of the Sine plus Noise FMCW radar over short range, in this paper, we presented a novel liquid height measuring system based on it. The principle of this system is analyzed in detail. Considering the liquid to be measured usually with high volatility, temperature, pressure, causticity or toxicity, we utilize trihedral corner reflector floating on the liquid to enhance the accuracy of the measurement. The numerical simulation and the results of on-the-spot survey both validate the affectivity of this kind of liquid height measuring system.
Key words:
Random noise radar, liquid height measuring

1. Introduction

With the development of industry automation, the height of liquid is needed to be measured accurately in many situations. However, the liquid to be measured is usually with high volatility, temperature, pressure, causticity or toxicity. It is very inconvenient to adopt tangent instrument to measure the liquid height. Radar systems for range measurement can apply in these cases. The Sine plus Noise FMCW radar show many promising advantages over short range. For example, it can suppress the leakage effectively while obtain high range resolution and precision with adequate parameters and simple signal processing methods [1]-[4]. In view of these, this paper applied the theory of the Sine plus Noise FMCW radar into liquid height measuring in industry. The transmitted signal is microwave noise with ideal "thumbtack" ambiguity function. Considering the liquid to be measured usually with high volatility, temperature, pressure, causticity or toxicity, we utilize triangle reflector floating on the liquid to enhance the accuracy of the measurement. The numerical simulation and the results of on-the-spot survey both validated the affectivity of this kind of liquid height measuring equipment.

Manuscript received July 25 2006.
Manuscript revised August 10 2006.

2. Theoretical Base and System Architecture

Because liquefied petroleum gas is volatile, there is thick fog on the oil surface. The echo of the Sine plus Noise FMCW radar is attenuated and interfered badly by it. As a result, the virtual oil surface is wavy with random break and the measured liquid height varied with time violently. To overcome the adverse effect of thick oil fog and improve the accuracy of measurement, we utilize the trihedral corner reflector floating on the liquid to enhance the performance of liquid height measuring system. The block diagram of the liquid height measuring system is shown in Fig. 1 and the technicality of it is detailed in our patent "Liquid height measurement by radar with the trihedral corner reflector".

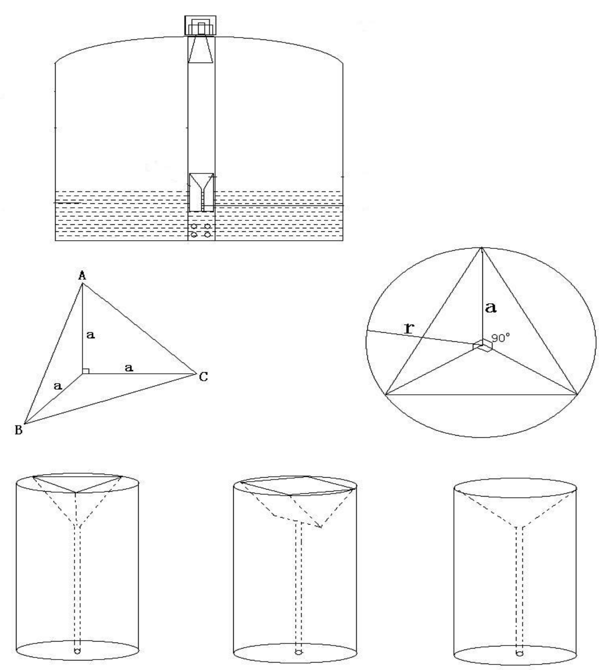

Fig.1. The sketch map of the liquid height measuring system and the applied floating trihedral corner reflector

The main subsystem of liquid height measuring system, that is, the Sine plus Noise FMCW radar is shown in Fig. 2. The modulating signal is a combination of a sinusoidal component (ω_m) and bandpass filtered white noise. The wide bandwidth of the transmitted signal ensure precise range finding. A portion of the transmitted signal is used as local oscillation, mixing with the received target echo signal in the mixer. The spectrum of the mixer output widens with increasing target range and contains the noise from components for all harmonics of the sinusoid. By the Winner and Khintchine Theorem, it can be proved that the post-mixed spectrum is a stationary process. The preamplifier is a wideband AGC circuit with a large dynamic range. The output characteristic with AGC does not change with range or with the extent of the target. The output is then split and passed two bandpass filters. Here, bandwidths of the two filters are $(nf_m - B) \sim (nf_m + B)$ and $(nf_m + B) \sim (nf_m + 3B)$, where f_m is the sine signal frequency and n represents n th resonance wave of the radar received target signal. It is known that output of the selected n th resonance wave of the target echo sine signal is always equal to zero for the case of $n \neq 0$ and zero-range target, that is, the Sine plus Noise FMCW radar can suppress CW leakage near zero range .Thus the power outputs and the difference output for the Sine plus Noise FMCW radar have the special performance named "HOLE" shown in (a), (b) and (c) of Fig.3 [4]. The signal of each channel passes through the bandpass filter, power detector and the radar output is the difference of the two channels.

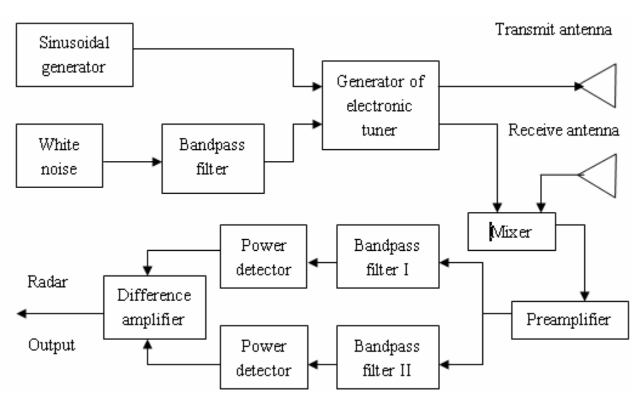

Fig.2 Block Diagram of the Sine plus Noise FMCW radar

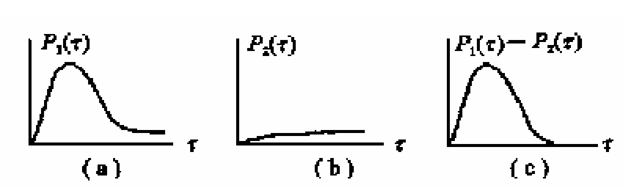

Fig.3 Characteristic Curves of the Sine plus Noise FMCW radar

3. Spectrum analysis on the output of the system

Suppose the transmitted signal for the Sine plus Noise FMCW radar is

$$e(t) = E_c \cos[\omega_0 t + \theta_1(t) + \theta_2(t)] \quad (1)$$

where

$$\theta_1(t) = \int_0^t \Delta\omega_c \cos\omega_m t \, dt = D_1 \sin\omega_m t \,, \quad (2)$$

$$\theta_2(t) = \int_0^t D_f V(t) dt \,, \; D_1 = \frac{\Delta\omega_c}{\omega_m} \quad (3)$$

are the sinusoidal modulated index.

$V(t)$ is the modulated noise voltage, which possesses zero mean and is a normal stationary process. Its power spectrum is

$$W_{N_1}(f) = \begin{cases} \psi, F_1 \le f \le F_2 \\ 0, elsewhere \end{cases} \quad (4)$$

The echo signal of the liquid surface is

$$e(t) = E_r \cos[\omega_0(t-\tau) + \theta_1(t-\tau) + \theta_2(t-\tau)] \quad (5)$$

where E_r is the amplitude of the echo, and τ is the delay between the echo and the transmitted signal.

The autocorrelation function of the post-mixed signal is

$$R_i(t) = \frac{A_c^2}{2} \sum_{n=0}^{\infty} \varepsilon_n J_n^2(D) \cos n\omega_m t \times \exp[-(R(0) - R(t))] \quad (6)$$

Therefore, the post-mixed spectrum is [5]

$$W_i(f) = \frac{A_c^2}{2} \sum_{n=0}^{\infty} \varepsilon_n \exp(-P_N) J_n^2(D)[\delta(f) + P_N W_{N_1}(f) + \frac{P_N^2}{2!} W_{N_1}(f) * W_{N_1}(f) + \dots$$
$$+ \frac{P_N^{K+1}}{(K+1)!} W_{N_1}(f) \overset{K+1}{\underset{*}{}} W_{N_1}(f)] \quad (7)$$

where A_c depends on the transmitted signal, the echo signal and the mixer gain. $P_N = R(0)$, $\varepsilon_0 = 1$, $\varepsilon_n = 2$, $n > 1$, $D = 2D_1 \sin(\omega_n \tau / 2)$, and $W(\cdot) \overset{K}{\underset{*}{}}$ represents the self-convolution of the k th order.

4. Experiments and Discussion

According to the aforementioned principle, we constructed real liquid height measuring system [6] and applied it in the petrochemical industry enterprise. The modulated signal bandwidth is 200MHz. We tested the output of the liquid height measuring system placed on the top of liquefied petroleum gas oilcans with two hours space. Partial experimental results compared with those obtained by accurate tangent measurement are represented in Table 1. The modulating noise is 3.5V (peak to peak) and the sinusoidal component is 0.6V (peak to peak) respectively.

The characteristic curves of the system's practical output are shown in Fig. 4. As shown in Table 1, the short ranging precision of the proposed measuring system can reach $\pm 2cm$, that is satisfying.

Table 1. The partial experimental results compared with manual measurement on liquefied petroleum gas oilcans

Date	Time	Height (mm)	Measured Height (mm)	Error (mm)
6.12	0:00	5300	5291	9
6.13	2:00	5990	5992	-2
6.13	4:00	5990	5995	-5
6.13	6:00	4770	4785	-15
6.13	8:00	3280	3282	-2
6.13	10:00	1600	1610	-10
6.13	12:00	2176	2178	-2
6.13	14:00	3520	3518	2
6.13	16:00	4900	4889	11
6.13	18:00	4880	4886	-6
6.13	20:00	4880	4874	6
		4360	4370	-10

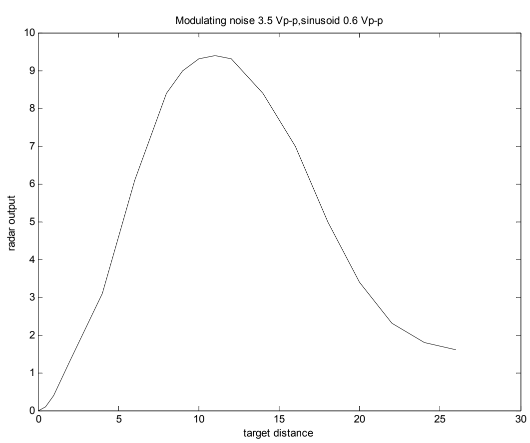

Fig. 4 The characteristic curve of the Sine plus Noise FMCW radar

5. Conclusions

As discussed, the liquid height measuring system based on the Sine plus Noise FMCW radar is especially suited to be applied in industrial liquid height measurement. It can obtain precise liquid height with simple structure. To overcome the adverse effect of thick oil fog and improve the accuracy of measurement, the trihedral corner reflector floating on the liquid is also applied to enhance the performance of it. The numerical simulation and the results of on-the-spot survey both validated the affectivity of this kind of liquid height measuring system. We intend to improve it by improving the method of signal processing and enhancing the RCS of reflectors.

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