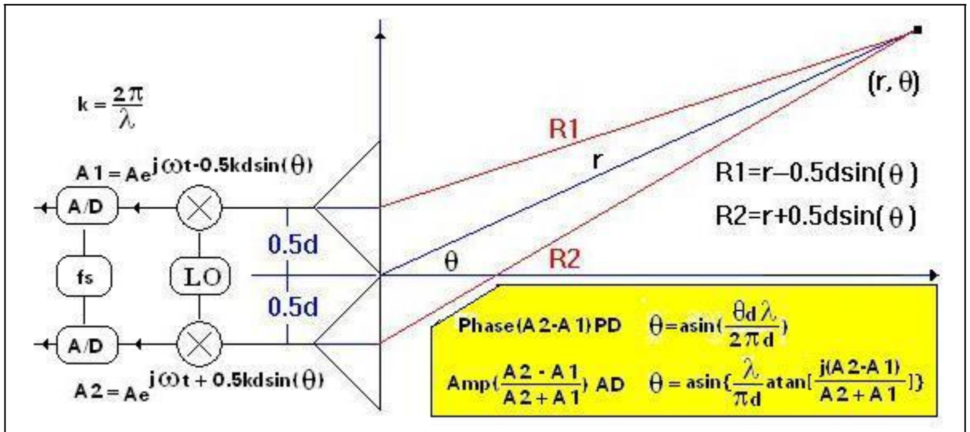
FMCW Mono-Pulse System Basics

Basic Model and Analysis

Two antennas having identical specifications are separated and placed along y-direction with space d. The center of the two antennas is the coordinate zero point. When a target is at position (r, θ) each antenna detects target with distance R1 and R2, respectively. When r is much larger than d (100 times, for example), the signal amplitude of the two channels is equal, but phase difference maybe larger than 360 degrees.

R1 and R2 are represented by:

R1=[r^2+(0.5d)^2-rdcos(π/2 -θ)]^0.5 = r - 0.5dsin(θ)
R2=[r^2+(0.5d)^2-rdcos(π/2+θ)]^0.5 = r +0.5dsin(θ)



Principle Diagram for Digital Mono-Pulse Antennas

Electromagnetic waves may be represented by A EXP[j(ωt+kr)], where A is amplitude, ω is angular frequency, k is the wave number (which is equal to **k = 2π/λ),** λ is carrier wavelength, t is time parameter, and r is distance parameter. The receiver uses the same local oscillator (LO) to down-convert both RF channel signals to the IF band. Using this method, the processing of amplitude and phase is simplified. At the IF band, each channel output is:

A1 = A EXP[j(ωt – 0.5kdsin(θ))]
A2 = A EXP[j(ωt + 0.5kdsin(θ))]

There are two basic approaches to find the target angle θ. The first method is phase detection method (PD). The second method is amplitude detection (AD).

Method 1) Compare phase P2 to P1; the IF phase gap $\theta d=P(A2)-P(A1)$, the target angle θ is

$$\theta = \mathrm{asin}\,[\theta d\ \lambda\ /(2\pi d)]$$

Method 2) Subtract A1 from A2. Then divide by j(A2+A1), the angle is

$$\theta = \mathrm{asin}\,\{\lambda\ /(\pi d)\ \mathrm{atan}\ [(A2-A1)/j(A2+A1)]\}$$

The angle resolution is $d\theta 1 = 0.45\varphi/(S/N)^{0.5}$,

where φ is the 3dB beamwidth of each antenna; S/N is carrier signal to noise ratio.

The following is illustration for an actual application

1) The maximum size of antenna is d. Antenna 3dB beam angle is estimated at $57.3d/\lambda$, which is the maximum angular coverage of a mono-pulse system

2) PD range is limited to +/-(π). Then target angle range is limited by $(+/-)\mathrm{asin}[\lambda\ /(2d)]$, (the practical value will be about times 0.8), which is less than the antenna 3dB beam width.

3) Either the PD or AD method takes place in the digital processor after signals are converted by ADC. Digit phase tolerance $d\theta d$ is a function of the A/D sample frequency. The addition tolerance of PD is:

$$d\theta 2= d\theta d/\{\pi[(2d/\lambda)^2\ -1]^{0.5}\}$$

4) AD approach just uses amplitude only of the sum and difference channels. Amplitude is some function of the target angle θ. The amplitude values are not related to the digital phase error. That is, phase error from ADC samples does not affect the result.

5) FMCW radar detects all possible targets in every triangle wave transmitter modulation period. The IF beat signal parameters are amplitude, frequency and phase in digital format after AD conversion and FFT processor. The amplitude of mono-pulse system is

$$[|A2-A1|^2+|A2+A1|^2]/4.$$

Frequencies coming from transmitter up and down slope period are used to calculate range and speed. Phase is used to calculate target angle when PD method is used. Two channel signals are also used to get target angle in the AD method. In one triangle period, the output is called one unit-radar-data.

6) Usually FMCW radar processor will average Nc times of object return signal to improve S/N sensitivity of radar. The averaged output is called one radar-data-cell. To calculate R and V by a frequency pair is the same for before or after averaging. However, target angle by amplitude or phase must be calculated before averaging.

Calculation Results

The variable in the attached table is the ratio d/λ from 2 to 42.

The first function is antenna 3db beam angle φ. A larger size antenna results in a narrower beam angle. Mono-pulse antenna angle coverage range is limited by the antenna beam. This is the antenna design limitation. Another limitation is by phase detection, which imposes limitation of the phase difference value of +/-180deg. Thus the PD range is the second limitation. This is very close to the antenna beam limitation.

Signal to noise minimum ratio is set to 15dB. The function of angle resolution dθ1 is calculated. This is about 6.5% of the antenna beam angle. Larger S/N will result in improved angle resolution.

The phase tolerance from the ADC specification is calculated. The minimum sample frequency should be two times the maximum beat (IF) frequency to retain original beat signal frequency information. However, phase tolerance limitation is 180deg error at the maximum signal frequency. Table 2 sets phase tolerance (dθd) at 30deg, 90 deg, and 120 deg. Digital sample tolerance dθ2 values are tabulated.

For example, let the antenna size be d/λ=10, the 3dB beam of the antenna be about 6deg. Mono-pulse angle cover range is thus limited to 6 degrees. This will be reduced to 4.8 degrees (+/-2.4degree) when PD method us used. The angle resolution is then 0.48 degree when S/N is 15dB. The corresponding additional tolerance is 0.5deg, 1.4deg, and 1.9deg, when digital phase error is 30deg, 90 deg, and 120deg, respectively.

FMCW Radar Analysis

Typical automotive FMCW radar specifications are: Fc=76.5GHz, B=400MHz, and Fm=1KHz. The maximum return frequency is 1066.8KHz for maximum range 200m. Considering Doppler frequency shift, it is set at 1100KHz. Every 5.334KHz return signal frequency represents one meter.

Assume the maximum sample frequency of ADC is 2.5MHz with antenna size d/λ=10 and S/N =15dB and antenna beam 6deg. Table 1 lists estimated results for target range from 10m to 200m. The return beat frequency fb is from 53.3Khz to 1067KHz. The digital phase error is from 7.7 deg to 153.6deg. The mono-pulse system then can cover 4.9degree angle range with 0.48degree resolution. The resolution will degrade if PD method is used. The additional tolerance is from 0.12deg (@10m) to 2.45deg (@200m).

R	fb		PD range	AD	PD
(m)	KHz	deg	Deg	deg	deg
10	53.33	7.68	4.8722	0.481	0.12
20	106.7	15.36	4.8722	0.481	0.24
30	160	23.04	4.8722	0.481	0.37
40	213.3	30.72	4.8722	0.481	0.49
50	266.7	38.4	4.8722	0.481	0.61
60	320	46.08	4.8722	0.481	0.73
70	373.3	53.76	4.8722	0.481	0.86
80	426.7	61.44	4.8722	0.481	0.98
90	480	69.12	4.8722	0.481	1.1
100	533.3	76.8	4.8722	0.481	1.22
110	586.7	84.48	4.8722	0.481	1.35
120	640	92.16	4.8722	0.481	1.47
130	693.3	99.84	4.8722	0.481	1.59
140	746.7	107.52	4.8722	0.481	1.71
150	800	115.2	4.8722	0.481	1.84
160	853.3	122.88	4.8722	0.481	1.96
170	906.7	130.56	4.8722	0.481	2.08
180	960	138.24	4.8722	0.481	2.2
190	1013	145.92	4.8722	0.481	2.33
200	1067	153.6	4.8722	0.481	2.45

Table 1 FMCW angle Calculation Results

Conclusion: Unless the sample frequency is large enough to reduce the digital phase error and the signal to noise is 15dB or higher, the AD method is preferred over the PD method.

d/		PD range	S/N	PD/AD		PD		PD		PD
	deg	deg	dB	deg	deg	deg	deg	deg	deg	deg
2	30.08	24.61179	15	2.407	30	2.47	90	7.4	120	9.87
4	15.04	12.2073	15	1.204	30	1.2	90	3.61	120	4.81
6	10.03	8.126333	15	0.802	30	0.8	90	2.4	120	3.2
8	7.521	6.091652	15	0.602	30	0.6	90	1.79	120	2.39
10	6.017	4.872177	15	0.481	30	0.48	90	1.43	120	1.91
12	5.014	4.05963	15	0.401	30	0.4	90	1.2	120	1.59
14	4.298	3.479415	15	0.344	30	0.34	90	1.02	120	1.37
16	3.76	3.044336	15	0.301	30	0.3	90	0.9	120	1.19
18	3.343	2.705984	15	0.267	30	0.27	90	0.8	120	1.06
20	3.008	2.435326	15	0.241	30	0.24	90	0.72	120	0.96
22	2.735	2.213893	15	0.219	30	0.22	90	0.65	120	0.87
24	2.507	2.029374	15	0.201	30	0.2	90	0.6	120	0.8
26	2.314	1.873248	15	0.185	30	0.18	90	0.55	120	0.74
28	2.149	1.73943	15	0.172	30	0.17	90	0.51	120	0.68
30	2.006	1.623457	15	0.16	30	0.16	90	0.48	120	0.64
32	1.88	1.521982	15	0.15	30	0.15	90	0.45	120	0.6
34	1.77	1.432447	15	0.142	30	0.14	90	0.42	120	0.56
36	1.671	1.352862	15	0.134	30	0.13	90	0.4	120	0.53
38	1.583	1.281654	15	0.127	30	0.13	90	0.38	120	0.5
40	1.504	1.217568	15	0.12	30	0.12	90	0.36	120	0.48
42	1.433	1.159586	15	0.115	30	0.11	90	0.34	120	0.45

Table 2 general analysis for mono-pulse antenna