FMCW Radar Sensors

Frequency Modulated Continuous Wave Radar

Basic operating principles and theory

FMCW (Frequency Modulated Continuous Wave radar differs from pulsed radar in that an electro-magnetic signal is continuously transmitted. The frequency of this signal changes over time, generally in a sweep across a set bandwidth. The difference in frequency between the transmitted and received (reflected) signal is determined by mixing the two signals, producing a new signal which can be measured to determine distance or velocity. A sawtooth function is the simplest, and most often used, change in frequency pattern for the emitted signal.

FMCW radar differs from classical pulsed radar systems in that an RF signal is continuously output. Consequently, time of flight to a reflecting object can not be measured directly. Instead, the FMCW radar emits an RF signal that is usually swept linearly in frequency. The received signal is then mixed with the emitted signal and due to the delay caused by the time of flight for the reflected signal, there will be a frequency difference that can be detected as a signal in the low frequency range. A schematic presentation is shown in Figure 1.

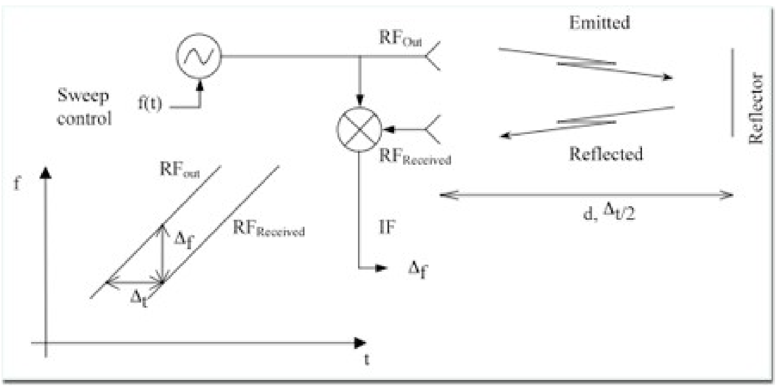

Figure 1. Schematic presentation showing how a low frequency signal is generated by mixing the received RF signal with the output RF signal. Due to the delay, Δt, caused by emitted signal travel-

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ing the distance to the reflector and back to the receiver, there will be a small difference in signal frequency between the two RF signals. This is output as an IF-signal with frequency Δf.

A simplified derivation of the intermediate frequency (IF) signal with the frequency Δf can be made in the following way: assume that the RF signal generator will output a frequency that is changing linearly over time as:

$$f_{RFOut} = f_{RF0} + k_f * t,\ 0 \le t < T \qquad \text{eq. 1}$$

where f_{RF0} is the starting frequency, T is the frequency sweep time and k_f is the slope of the frequency change, i.e. the sweep rate:

$$k_f = \frac{BW}{T} \qquad \text{eq. 2}$$

where BW is the frequency sweep bandwidth. The delay caused by the round-trip of the emitted signal to the reflector is calculated as:

$$\Delta t = 2\frac{d}{c} \qquad \text{eq. 3}$$

where d is the distance between the radar antenna and the reflector and *c* is the speed of light. Due to the delay, the frequency of the received signal compared with the emitted signal will be:

$$f_{RF\,Received} = f_{RF0} + k_f * (t - \Delta t),\ \Delta t \le t < T + \Delta t \qquad \text{eq. 4}$$

The difference in frequency, Δf, between $f_{RF\,Received}$ and f_{RF0} is thus:

$$\Delta f = k_f * (-\Delta t) \qquad \text{eq. 5}$$

This is the signal that is output from the detector. The minus sign can be omitted since the real signal frequency output from the radar detector is wrapped to a positive frequency. Thus the expression can be written as:

$$\Delta f = \frac{BW}{T} \cdot 2\frac{d}{c}, \qquad \text{eq. 6}$$

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Typical values for the RS3400 series modules would be a frequency sweep, BW, of 1500 MHz over T=75 ms corresponding to a sweep rate, k_f, of 20 000 MHz/s. A distance, d, between the radar and a reflector of 15 m would give a delay, Δt, of 0.1 µs and the IF signal frequency, Δf, would then be 2000 Hz. This signal is easily sampled with a high resolution ADC in order to be detected. If several reflectors are appearing in the measurement setup, the resulting IF signal will contain superpositions of the individual IF-signals from the echoes.

Different echoes are distinguished by their unique IF signal frequency and a Fourier transform of the sampled signal can be used to extract the distances to the different targets. The measurement range of the system is limited by the sensitivity of the detector and the sampling rate of the ADC. For the RS3400 series a sampling rate of 20 kHz gives a maximum detectable IF signal frequency of 10 kHz, which corresponds to a range of 75 m. Longer ranges are easily achievable by either increasing the sample rate or lowering the sweep rate. In addition, antenna gain needs to be fairly high in order to provide sufficient signal levels for the detector.

Theoretical performance

The fundamental range measurement resolution of the system can be estimated as follows. The Fourier transform of a time limited signal can only detect an IF signal frequency with a resolution of 1/T, keeping in mind that Δt<<1/T; thus the sampling time can be approximated by T. Using equation 6, this gives the minimum change in d, Δd, as:

$$\frac{1}{T} = \frac{BW}{T} \cdot 2\frac{\Delta d}{c}, \qquad \text{eq. 7}$$

which can be transformed to:

$$\Delta d = \frac{c}{2BW}, \qquad \text{eq. 8}$$

showing that the range measurement resolution is only limited by the sweep bandwidth. This is an important observation since it is says that resolution is not dependent on the frequency of the RF signal itself, but rather only on the sweep bandwidth. There are methods of increasing the resolution of the measurements by a factor of 10 to 100 using fitting algorithms. These find a peak in the

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IF signal spectrum which is not at an integer frequency point defined by the sampling rate and sweep bandwidth.

The range detection and FMCW radar principle may also be derived using a characterization of the IF signal phase rather than the frequency. This is recommended in order to understand the possibilities of a discrete system where the frequency sweep really is generated by a discrete set of frequencies. This derivation also lends itself more directly to high resolution range measurements. For the simplicity of understanding the measurement principle it is however unnecessary and is thus included as an appendix.

Detailed operating principles and theory

FMCW radar principles using phase measurement (time discrete version).

FMCW radar functions by outputting a continuous RF signal, whose frequency is swept over a specific frequency band. Synthesized modules, like RS3400, are in fact not sweeping the frequency continuously, but rather step the frequency with a set of discrete frequency points. Thus, these systems are also called Stepped Frequency Continuous Wave (SFCW) radar. The synthesized signal source assures very precise frequency control, which is important for the accuracy and repeatability of measurements.

The RF signal will be radiated and reflected against different objects. The echo is then received and compared (mixed) with the radiated RF signal. Had the system been measuring time-of-flight for a pulsed signal, the sensor output could be linear with distance. In an FMCW, however, the sensor output corresponds to the cosine of the phase difference between the echo signal and the radiated signal.

$$s = \cos(\Phi) \qquad \text{eq. 9}$$

where *s* is the output signal from the sensor and Φ denotes the phase difference between the echo RF signal and the radiated signal.

In other words, the measurement signal from the sensor will be a cosine signal indicating the round-trip electrical distance which the radiated signal has traveled.

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$$s = \cos\left(2\pi \frac{2d}{\lambda}\right)$$ eq. 10

or

$$\Phi = 2\pi \frac{2d}{\lambda}$$ eq. 11

where d is the distance to the reflecting object and λ is the electrical wavelength of the RF signal. The multiplication by 2 accounts for the round-trip.

The expression for Φ can also be written as

$$\Phi(f_{RF}) = 2\pi \frac{2d}{c} f_{RF}$$ eq. 12

where λ has been substituted with, *c*, the speed of light and f_{RF} is the frequency of the RF signal.

For any measurement (except for those at very short distances) the electrical distance will exceed one wavelength and there will be ambiguities about the measurement result. Fortunately, the RF signal can be stepped in frequency and several measurements can be performed. From eq. 12, it is clear that Φ will increase linearly with f_{RF} and thus the detector output will be a cosine shaped signal. A small value of d, meaning a close echo, will create a slowly varying detector signal and a distant echo will create a quickly varying detector signal. The frequency of the RF output signal, f_{RF}, is stepped over the available band (BW). For the RS3400S, this band is from 4625 MHz to 5375 MHz, with BW = 750 MHz. For the RS3400X, this band is from 9250 MHz to 10750 MHz and for the RS3400K this band if from 24000 MHz to 25500 MHZ, i.e., BW = 1500 MHz. The expression for Φ is then:

$$\Phi(n) = 2\pi \frac{2d}{c}\left(f_{RF_0} + \frac{n}{N} BW\right)$$ eq. 13

where n indicates each unique measurement, n = 0, 1, ..., and (N-1) and N is the number of frequency points used for the measurement sequence. The term f_{RF0} denotes the starting frequency. Recalling that the detector output is the cosine of Φ, the equation will be as follows:

$$s(n) = \cos\left(2\pi \frac{2d}{c}\left(f_{RF_0} + \frac{n}{N} BW\right)\right)$$ eq. 14

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Since the cosine function only is unique over the range [0, π], the expression can be simplified to:

$$s(n) = \cos\left(\Phi_0 + 2\pi \frac{2d}{c} \frac{n}{N} BW\right) \qquad \text{eq. 15}$$

where Φ0 accounts for the phase value at the starting RF signal frequency of the sweep. It should be noted that Φ0 can be limited between 0 and π. To extract the value of the distance to the reflector, d, one needs to estimate how much Φ changes over the frequency sweep. One simple way is to take the Fourier transform of the signal s(n).

$$S(m) = fft(s(n)) \qquad \text{eq. 16}$$

Here m denotes the normalized index in the transformed domain, m=0, 1, ..., (N-1).

With the detector signal being a time varying signal, m can be seen as the index in the frequency domain for the detector signal. As an alternative, this domain may be seen as a distance domain. For simplicity, this domain will be called frequency domain or spectrum in this text since in most cases it is the typical interpretation of a Fourier transformed signal.

Recalling that the Fourier transform of a cosine yields two Dirac-delta functions, the transform of s(n) becomes:

$$S(m) = \frac{1}{2}\left(\delta\left(m - \frac{2d * BW}{c}\right) + \delta\left(m + \frac{2d * BW}{c}\right)\right) \qquad \text{eq. 17}$$

The second term on the right hand side refers to a peak at a negative value of m, this can be easily converted to a positive value by adding N, but is of no further interest here. The first term on the right hand side will have a peak at m=(2d*BW/c). Conversely, if a peak is identified at $m=m_0$, the corresponding distance to the reflector can be calculated as:

$$d = m_0 \frac{c}{2BW} \qquad \text{eq. 18}$$

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Thus, a ranging function is achieved.

It is worth noticing that eq. 18 is completely independent of the center frequency of the RF signal. In fact, to get an impression of the resolution that is available from only extracting a measurement of the distance based on the maximum peak found in the frequency domain, the difference between two integer values of m is c/2BW. This shows that the resolution is only depending on the sweep bandwidth of the RF signal and not of its specific frequency. A frequency sweep from 9250 to 10750 MHz will give the same resolution as a frequency sweep from 24000 to 25500MHz.

For the specified frequency sweep with BW = 1500M Hz, the integer range measurement resolution will be 0.10 m.

In order to achieve higher resolution in range measurements, a weighted average of several frequency points can be used to find a peak location that is positioned between integer points in the spectrum. Additionally, when a single echo is available in a local part of the spectrum, it is possible to estimate d based on the slope of the phase angle Φ. Using only the first term in the right hand side of eq. 17, recall that the inverse Fourier transform of a Dirac-delta function is a complex exponential:

$$ifft\left(\delta\left(m - \frac{2d * BW}{c}\right)\right) = e^{-i2\pi \frac{2d}{c} \frac{mBW}{N}} \quad \text{eq. 19}$$

Here, the right hand side is a complex series of N points. In a real-life measurement, the signal will not be an ideal complex exponential like in eq. 19. However, an inverse Fourier transform of only a section of the spectrum around a peak of interest will give a complex signal whose phase angle may be extracted. Using this phase angle, the slope may, for example, be found using a least squares fit to a linear expression.

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