NARROWBAND TRACKING FILTERS IN FMCW RADAR SENSORS

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Abstract

The need for spectral analysis of the signal received by frequency modulated continuous wave (FMCW) radar sensors (FMRS) is inevitable in many applications of FMRS. It can be effectivelly performed using only digital signal processors, based on the fast Fourier transform (FFT). To make the signal analysis by FFT processor easier, it is necessary to separate the received signal (which generally varies in amplitude and in frequency) from the broadband noisy background at the microwave mixer output by the narrowband tracking filter. Besides a brief desription of the performance and application of FMRS, the analysis of FMCW signal, with respect to moving target indication (MTI), and the function of a suitable tracking filter system is presented in this paper.

Keywords :

frequency modulation, radar sensor, spectral analysis, tracking filter, moving target indication

1. Introduction

FMCW radar sensors (Fig.1), rather than pulse radar sensors, represent the most versatile type of sensors at the present time. They are used for detection of stable or moving targets, distance (range) measurement (altimeters), obstacle avoidance (cars, ships, helicopters,...), cruise control, terminally guided munition, etc. Compared to other sensor systems (infrared, ultrasonic, laser, etc.), radar sensors are more advantageous as they can make direct measurement of range and velocity, they are less influenced by interferencies and climatic restrictions, and they make signal processing easier to apply, etc.

Frequency modulation in microwave (not millimetric) radar systems has also been used over the past few decades (e.g., altimeters). The technology of microwave systems (units of GHz) can hardly be applied to reliable radar sensors of small size, small weight, low cost, etc. The realization of such a sensor is possible only with millimetric waves. Frequencies near 35GHz, 70GHz, 94GHz, 144GHz are used here because atmospheric attenuation of propagated electromagnetic waves is relatively small at these frequencies [3],[4]. The realization of millimetric wave radar sensors was made possible not long ago thanks to the ever - improving hf qualities of components like Gunn diodes, mixer diodes, circulators, etc.

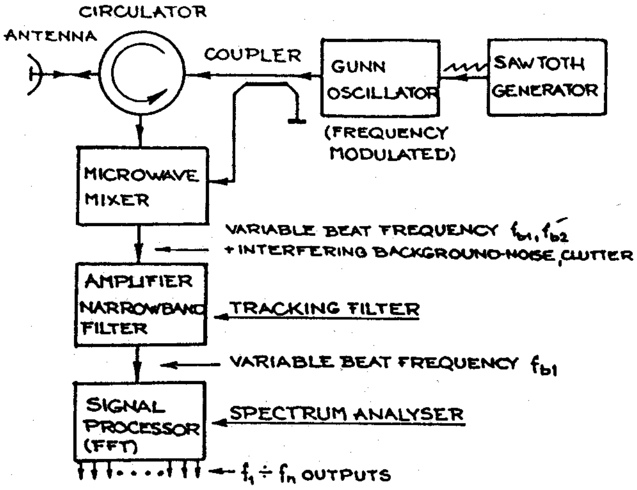

Fig. 1

2. Basic principles of FMRS

Because of their simple construction, their reliability, low cost, etc, all types of millimetric FMRS work almost exclusively as homodynes (Fig.1). Rf signals for transmission, and also for mixing usually of power of units of mW only - is generated in a varactor- tuned Gunn oscillator (GO), in which linear frequency modulation by sawtooth (Fig.2) or triangular waveform is performed. The range resolution ΔR/R (R = distance of target) of FMRS depends on the degree of nonlinearity in the time interval $T_m = 1/f_m$ of modulated waveform. For precises measurements, the sweep is generated digitally so that ΔR/R can be realized at better than 0.05%.

FM signal from the GO is transmitted through circulator (diplexer) by a parabolic antenna (usual gain G_a = 35 - 40 dB). The reeived signal at frequency f_r diplexed by the circulator to the mixer, gives, after mixing with the transmitted signal at frequency f_0 from the coupler, a IF signal at a beat frequency of $f_{b1} = |f_0 - f_r|$.The local oscillator (LO) signal is derived from the GO by the coupler, working as a nonreflecting power divider.

For more detailed target characteristic determination (Doppler effects, MTI, pattern recognition, etc), it is convenient to perform spectral analysis of the received signal (IF signal) digitally by FFT processors. However, different disturbances may be critical to the operation of the analysing system. Particularly the phase noise of the GO (e.g., 80 - 90 dBc/Hz at 100kHz) broadens the noise spectrum at the mixer output, making spectral analysis more difficult. This means, for example, that close targets are more difficult to distinguish and that small Doppler shifts caused by a moving target are sometimes nondiscernable.

Therefore the useful IF signal (with widely variable frequency f_{b1}) is separated from the broadband background interference by the narrowband tracking filter before FFT signal processing. The configuration of one type of a tunable tracking filter is shown in Fig.4.

IF frequency f_{b1} and the distance to target R are related by the well known expression [1],[3]

$$R = \frac{c}{2\Delta f \cdot f_m} \cdot f_b \tag{1}$$

where c is the light velocity. Frequency deviation Δf (Fig.2) and sweeping modulation frequency f_m are kept constant in the system illustrated in Fig.4. It is, of course, possible to determine the distance R with help of f_m($\Delta f, f_{b1}$= const) or Δf (f_m, f_{b1}=const), but it is difficult to apply such systems in small FMRS. To avoid the range ambiguity given by the beat frequency f_{b2} (>>f_{b1}) (Fig.2) during the

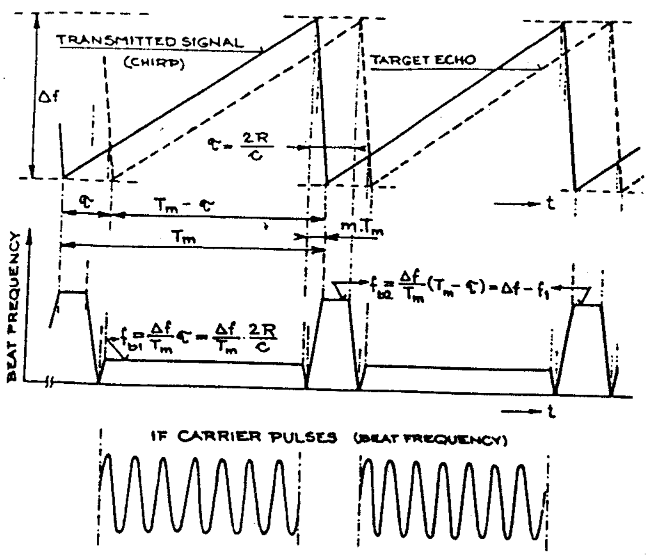

Fig. 2

section (τ+ $2mT_m$) of sweeping waveform, the receiver in FMRS should be blocked during that part of the period T_m. Section mT_m should be as short as possible ($mT_m << T_m$). From Fig.2 it is apparent that the maximum time τ_{max} = $2R_{max}/c$ beetwen the transmitted and received signal should be much shorter than the T_m period duration ($\tau_{max} << T_m$). The longer is the τ_{max}, the lower is the energy of frequency pulses (Fig.2). The energy of the received signal P_r also decreases as τ_{max} increases (~R_{max} -see radar eqn. $P_r \sim 1/R^4$). For the determined R_{max} (i.e., τ_{max}) it is desirable to make the lenght of the period T_m as long as possible and, hereby, also the bandwidth product $\Delta f.T_m$. This contributes to the higher processing gain of the receiver and, in turn, to the higher range resolution.

2.1 Analysis of FMCW signal with respect to MTI

Moving target indication (MTI) is one of the most important capabilities of radar. Though the circuit MTI processing in FMCW is rather different than that in pulse radars, its basic principle is the same. MTI is based on the well known moving target Doppler (MTD) [1]. MTD processing in FMCW is implemented by measuring the rate of change of phase of output at each range bin from one sweep to the other [Fig.2] - likewise in pulse radars.

There is, of course, Doppler cross coupling in FMCW radar, whereby the Doppler shift due to a moving target (with radial velocity v) changes the apparent range of the target. This causes so called "MTI blind speeds", where the first blind speed of FMCW radar occures at frequency f_d = $2vf_t/c$ (f_t is instantaneous transmitted frequency). In our system, at Fig.1,it means that the Doppler shift causes a range error of exactly one range cell at the output of the FFT processor. The beat frequency (IF) in homodyn has been increased by just one cycle per sweep.

The relationship between the range Doppler cross coupling and the MTI blind speed is analysed in the following section, taking into consideration the signal of only a single target. The effect of multiple targets can be easily extrapolated because the system is linear with respect to the received signals. The end effect due to flyback, when IF is equal to f_{b2}, need not to be considered. Besides the above mentioned target velocity v, light velocity c, sweep repetition T_m and transmitted frequency f_t, further symbols will be used: t=t_o is time since start of sweep; f_o is transmitter frequency at the time t =0; $\alpha = \Delta f / T_m$ is chirp rate; τ is time of flight of the signal to the target and back; R_o is mean range of the target during sweep; and R_1 is range of the target at time t=0.

Using the relation $f_t = f_o + \alpha t$ (see Fig.2) and asuming radial velocity of the target to be constant, the standing phase ψ of the transmitted signal is (for ψ= 0 at time = 0)

$$\psi = 2\pi \int_0^t f_t dt = 2\pi(f_o t + \alpha t^2/2). \tag{2}$$

This standing phase has to do with the transmitted signal

$$A(t) = A_o \sin 2\pi(f_o t + \alpha t^2/2) \tag{3}$$

as well as with the received signal

$$B(t) = B_o \sin 2\pi\left[f_o(t-\tau) + \alpha(t-\tau)^2/2\right]. \tag{4}$$

The IF signal as a product of a mixing of the signals given by (3) and (4)

$$C(t) = C_o \cos 2\pi(f_o\tau + \alpha t\tau - \alpha\tau^2/2) \tag{5}$$

where A_o, B_o, C_o are the amplitudes of presented signals which have no effect on the analyzed problem. A change in indication of the range R(t) caused by the moving target

$$R(t) = c\tau/2 = R_1 + vt \tag{6}$$

yields

$$\tau = 2R(t)/c = (R_1 + vt)/c. \tag{7}$$

Substituting (7) for expression (5), $[f_o = f_t - \alpha t]$ after some manipulation, becomes :

$$C(t) = C_o \cos 2\pi[\frac{\alpha t R_1}{c}(1 - \frac{v}{c}) + \frac{f_o vt}{c} + \frac{\alpha v t^2}{c}\left(1 - \frac{v}{2c}\right. + \frac{R_1}{c}\left(f_o - \frac{\alpha R_1}{2c}\right) \tag{8}$$

The sense of the single "frequency" and "phase" terms in expression (8) is: the first frequency term $\alpha t R_1(1 - v/c)/c$ is the range beat proportional to the range of the target. The second frequency term $f_o vt/c$ is the well known Doppler shift. The third frequency term $v\alpha t^2(1 - v/2c)/c$ is a cross term interpreted as the chirp on range beat, due to the changing range. It can be interpreted also as the chirp on the Doppler, due to the changing transmitter frequency. The fourth term $R_1(f_o - R_1\,\alpha/2c)/\,c$ is a constant phase term.

The range Doppler cross coupling is expressed explicitly in eqn.(8). Besides this, it can be shown that MTI with FMCW radar can be performed without having to resolve the range Doppler cross coupling. Considering the IF signal (eqn.5) for two succesive sweeps

$$C_1(t) = C_o \cos 2\pi\left(f_o\tau_1 + \alpha\tau_1 t - \alpha\tau_1^2/2\right. \tag{9}$$

and

$$C_2(t) = C_o \cos 2\pi\left(f_o\tau_2 + \alpha\tau_2 t - \alpha\tau_2^2/2\right) \tag{10}$$

one of the simplest forms of MTI processing is to perform the subtraction of signals defined by (9) and (10)

$$D(t) = C_2(t) - C_1(t). \tag{11}$$

Using standard trigonometrical identities when substituting (9) and (10) into (11), it is convenient for further derivation to define the mean time of flight $\tau_o = (\tau_1 + \tau_2)/2$ and half the change in time of flight between two sweeps: $\delta\tau = (\tau_1 - \tau_2)/2$. Then

$$D(t) = 2\cos 2\pi[f_o\tau_o + \alpha\tau_o t - \alpha\tau_o/2 - \alpha\delta\tau^2/2]\times$$
$$\times \sin 2\pi[f_o\delta\tau + \alpha\delta\tau t - \alpha\tau_o\delta\tau/2]. \tag{12}$$

similarly to (7) it can be defined

$$\tau_1 = 2(R_1 + vt)/c \tag{13a}$$

$$\tau_2 = (R_1 + v\tau + vT)/c \tag{13b}$$

where $T = \delta\tau c/v$ is obtainable from the relation

$$\delta\tau = Tv/c. \tag{14}$$

As the velocity v is assumed to be constant, the expression for $\delta\tau$ is not the function of time, and the term $-\alpha\delta\tau^2/2$ from (12) can be considered as a constant phase Φ so that the form of eqn.(12) changes slightly

$$D(t) = C_o \sin 2\pi\left[f_o\tau + \alpha\tau_o t - \alpha\tau_o^2/2 - \Phi\right]\times$$
$$2\sin 2\pi[f_o\delta\tau + \alpha\delta\tau t - \alpha\tau_o\delta\tau/2]. \tag{15}$$

The first part of the right-hand side of eqn.(15) is the same as that of eqn.(5), which describes the single sweep (except for constant phase Φ). Then, the second part of eqn.(15) is the effect of the MTI filter, having much to do with the tracking filter discussed in the next section.

Comparing the MTI term in conventional pulse radar, which equals 2 sin $2\pi f_o\,\delta t$ [3],[4], the expression for FMCW radar contains two aditional terms. The first term, $+\alpha\delta\tau t$, varying with the time, represents the change in transmitted frequency varying during the sweep. The second term, $-\alpha\tau_o\delta\tau/2$, expresses the fact that the range beat frequency is slightly different between one sweep to the next because the range has changed. Since both of these terms are functions of $\delta\tau$, they do not influence the static cancellation, for which $\delta\tau=0$.

If no strict parameters for MTI processing are required, the influence of both terms need not be considered, and the above derived analysis shows that the simple MTI canceler behaves the same for an FMCW as for pulse radar.

3. Narrowband tracking fiter

Configuration of one type of analog tracking filter used in FMRS at, for example, 94GHz which is tuned from 1MHz to 12MHz (Δ f = 100MHz) f_m = 100kHz) is shown in Fig.4. The system consist of: a signal searching loop (SSL), an automatic tuning loop (ATL), and a tunable narrow band filter (TNF) (B = 120kHz) working as a superheterodyne (SH) with double mixing. Sawtooth-shaped searching voltage (e.g, 1kHz) is applied in SSL via electronic switch (ES) to the varicap of the local oscillator LO1 of SH, where it changes the oscillator frequency f_{01} so that all signals at the input of the first SH mixer M1 at frequences from 1MHz to 12MHz are mixed to fixed intermediate frequency (IF) $f_{IF} = 46.3MHz$. The second SH mixer M2 converts the frequency f_{IF1} to the second IF at frequency $f_{IF2} = 1.7MHz$ with the help of the second oscillator frequency $f_{o2} = 48MHz$. The signal of f_{o2} is generated in the crystal controlled oscillator LO2. The signal at frequency f_{IF2} is amplified by the gain controlled IF amplifier and filtered by the bandpass filter into the frequency band $B_{IF2} = 120kHz$. More than 75% of the energy of IF carrier pulses (Fig.2) is concentrated in the band B_{IF2} as is illustrated by energy spectrum |S| in Fig.3.

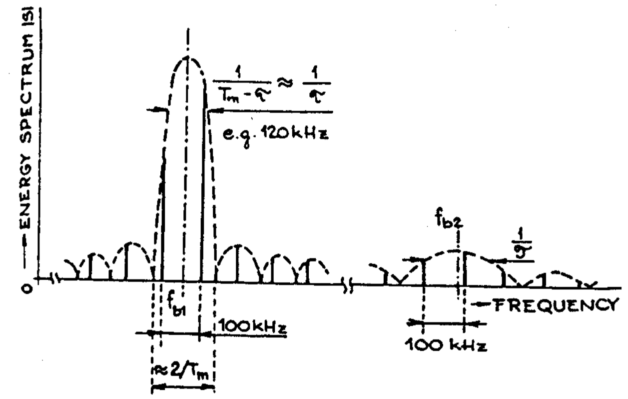

Fig. 3

If the frequency bandwidth at the input of TNF is $B_i = 12MHz - 1MHz = 11MHz$ and the bandwidth $B_{IF2} = 120$ kHz, then the achievable noise reduction of noise N_o at the output of TNF to noise N_i at its input is approximately

$$\frac{N_o}{N_i} = \frac{4k\delta R_o B_{IF2}}{4k\delta R_i B_i} = \frac{B_{IF2}}{B_i} = \frac{120 \cdot 10^3}{11 \cdot 10^6} = 1.09 \quad (20.8dB). \qquad (16)$$

Such noise reduction substantially facilitates the following digital signal processig.

In the case that the signal reflected from the target is received during the search process, it appears amplified at the output of TNF. Here the signal is rectified to DC voltage which switches the system via ES into the automatic tuning mode. The automatic tuning loop consists of the limiter, the frequency/voltage converter (FUC), the PLL frequency diskriminator (PD), and the summing circuit. The tuning voltage $U_T \pm \Delta U$ from the output of the summing circuit adjusts the LO1 to a frequency which ensures continual tracking of TNF into variable frequency f_{b1}. The branch of ATL operates in the whole frequency range 1MHz - 12MHz (rough tracking), while the branch with PD puts IF frequency 1.7MHz (nearly) into the middle of frequency band 120kHz.

4. Conlusion

The work of the whole tracking filter has been experimentally tested and results have shown - among other things - its ability to work in a much broader frequency band than in the paper presented. For experimental purposes, most of the blocks of the tracking

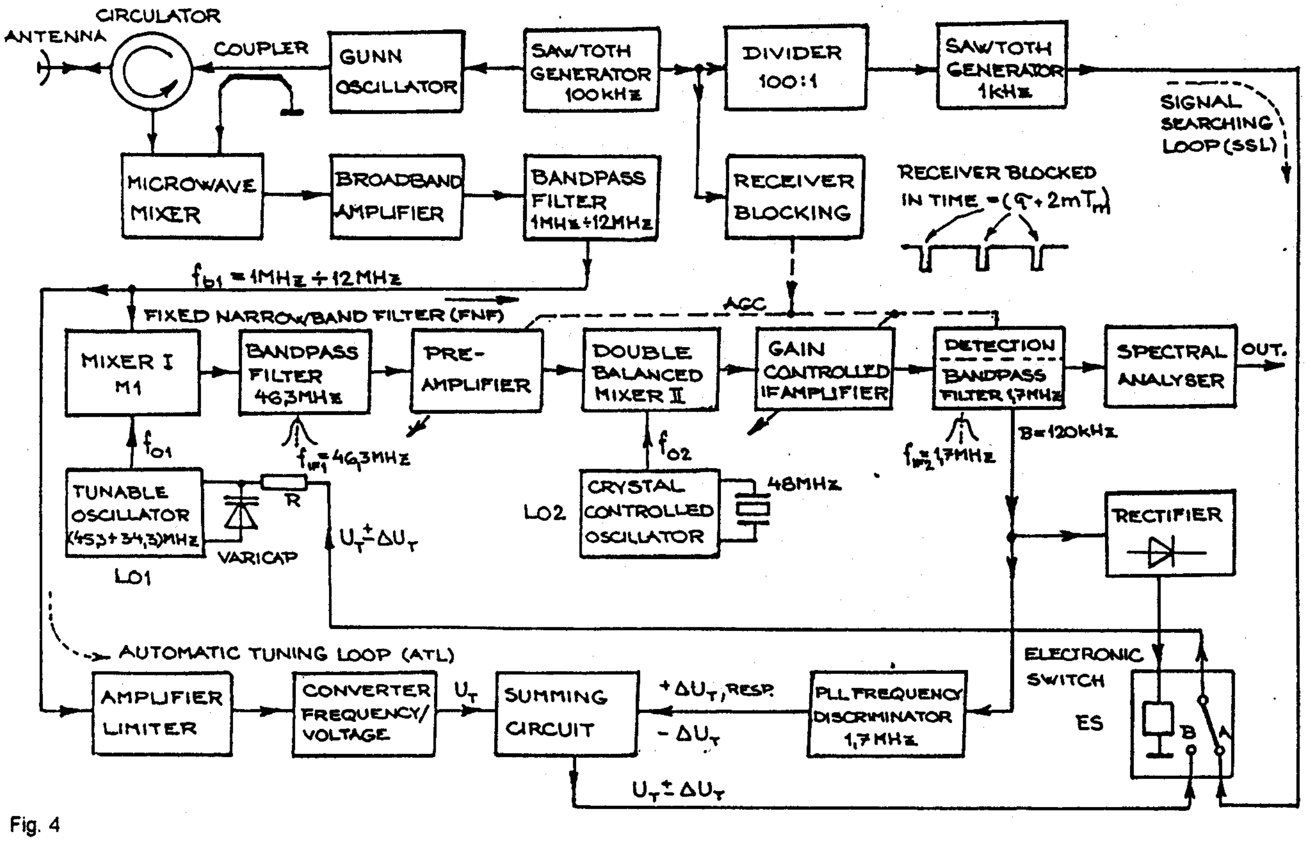

Fig. 4

filter were realized with ICs. But, for the final version of filter, it is assumed that digital ICs will be used where possible, e.g. a frequency synthesizer for LO_1, a digital FUC, etc.

5. References

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About author, ...

Břetislav Syrovátka was born in Moravia in 1935. He graduated in radioeletronics from CTU Prague in 1958. After his apointment in Tesla Kolín (1958 - 1962) he joined the staff of the Department of Radioelectronic, CTU Prague where he received PhD. in 1972 and Assosiate Professor in 1990. Most of his research activities are intented on experiments. He is focussed to developing and constructing electronic and especially radioelectronic equipments. He is author of about 20 technical paper, 9 printed lectures for students.

100TH ANNIVERSARY OF THE CZECH ENGINEERS' FOUNDATION

The Czech Engineers' Foundation (ČMT - ČESKÁ MATICE TECHNICKÁ) was established during a Plenary session in the Great Hall of the Old Town Hall in December 1895. Its aim was to remove financial obstacles from the way of the optimum development of the Czech engineering literature. The principal decision was to put to operation an editorial house for inexpensive engineering publications. Many selfless workers made a steady development possible.

The most prominent part of activity of the ČMT was always centred in publications. An edition of Foundation Papers was responsible for the fame of ČMT. Important was the "Engineers' Guide" edition, since 1914, and the popular library "The World of Labour", since 1917. All in all they represent dozens of volumes highly valued both in this country and abroad.

The care for engineering publications was taken over in 1953 by the State Publishing House of Technical Literature (SNTL), with a continuation of publishing of Papers and Guides preserved. Meanwhile the significance of association to the ČMT (total membership 24000 in 1955) declined to a certain extent. Yet the ČMT continued to influence the editing policies, the establishment of the Engineering Readers' Club and the awarding of prizes for important engineering Papers.

The Market Economy Mechanism also took hold in the publishing policies of engineering books in 1989. The ČMT targets its activities to hold up the Czech engineering publications, to support the creativity of Czech authors and to help in finding suitable sponsors and editors. This means that its activities are about the same as a century ago. There is no other institution in this country which would develop and popularise the Czech engineering literature today. A permanent high quality engineering education is clearly impossible through studies of foreign language literature and translations only, as long as we wish to keep our national identity. The ČMT wishes, as an edition to the activities mentioned above, to be engaged in reviewing, assessments and consultancy and take care of development of the Czech engineering terminology. All this is true of course for electrical engineering, electronics and radio engineering as well.

We appeal to all scientists, engineers, scholars, managers and students take an active part in the development of these noble traditions.

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