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SELECTED PROBLEMS OF PROCESSING A RADAR SIGNAL WITH A LFM-FSK MODULATION

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Abstract. An operational model of continuous-wave radar designed for detection of stationary and moving objects in the air was built at the Institute of Aviation. The LFM-FSK modulation of radiated signal was selected, due to its advantages (short measurement time, not very complicated algorithm of calculations, the possibility of simultaneous measurement of the range and velocity of multiple objects). The modulation waveform is composed of two intertwined strictly linear or stepwise sweeps. Two adverse phenomena (the mutual influence, resulting from not perfect transmittance of receiver channel, of the samples related to even and odd steps of the transmitted signal and the leakage of transmitted signal into the receiver antenna causing an excessive increase of receiver output dynamic range) were encountered during the development process. The issues relating to them are presented in the paper. The first issue was solved by the use of a pre-compensation digital filter. The dynamics of the leakage signal was reduced by mixing of quadrature output signals of the radar head in a proper proportion, and by using the dome made of foam material, instead of a laminate one, which was designed initially.

Keywords: radar signal, modulation, unmanned aerial vehicle, compensational method.

1. Introduction

Among the projects that have been realized at the Institute of Aviation recently, a need has appeared for mastering the radar measurement of velocity and distance of moving objects relative to a sensor. The measurement range of distance is of a few hundred meters and the range of relative velocity is a dozens meters per second. For such parameters radars with a continuous wave have an advantage over the impulse ones (Meinecke, Rohling 2000). They are able to obtain an established resolution within a comparatively short measurement time and not very great computational complexity while at the same time no high power level of radiation is required. The LFM-FSK (Linear Frequency Modulation with Frequency Shift Keying) modulation has been applied within the radar solutions that were adopted at the Institute of Aviation.

The paper presents a general outline of the measurement method and selected issues which involved proper digital processing of a measured signal.

2. Measurement method

The detection capabilities of a continuous-wave radar depend on of the type of frequency modulation that has been applied. In the absence of a modulation it is only possible to establish object velocity with respect to the radar (based on a change in echo frequency caused by the Doppler effect). In turn, the use of a linear frequency modulation enables to determine the distance of the object, which has zero or a known velocity with respect to the radar (which enables to take into account the Doppler effect). A simultaneous measurement of distance and relative velocity of the object requires the use of a more sophisticated form of the modulating signal. One of the frequency modulated signals which gives such a possibility is combined of two linear frequency modulated up-chirp signals (strictly linear or stepwise) transmitted in an intertwined manner (ABABAB...), where signal B is shifted relatively to signal A in frequency. Two different variants of the shape of FM waveform are shown in Figure 1 (Meinecke, Rohling 2000; Monod *et al.* 2009).

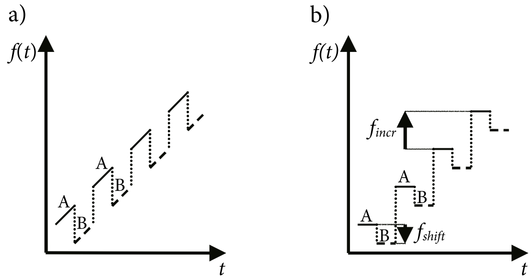


Fig. 1. The LFM-FSK modulating signal: a) strictly linear b) stepwise

The received HF (high frequency) echo signal together with a fraction of the transmitted one is applied to the mixer, and regardless of which variant of the LFM-FSK modulating signal is chosen, the resultant LF (low frequency) signal is sampled near the end of every step (or linear segment). In case of a single object (steady or moving) the A and B samples look similar to those presented in Figure 2.

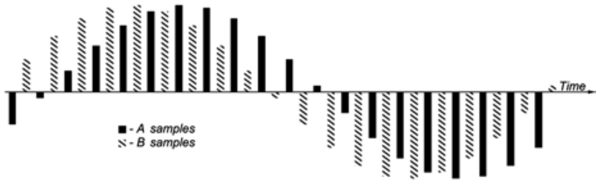


Fig. 2. An example of a sampled echo signal from a single object in the LFM-FSK radar

Each sequence of samples A or B is processed separately by using the Fourier transform in order to determine the frequency and phase of its sinusoidal envelope, which is seen as a peak in the spectral domain. After determining the frequency and phase shift between the two sinusoids, the range and relative radial velocity of the object can be unambiguously determined. Assuming that the condition $f_{shift} = -0.5 f_{incr}$ is fulfilled (when the measurement is the most precise), the proper formulas are expressed in the following form (Meinecke, Rohling 2000):

$$L = \left(\frac{N-1}{2\pi} \Delta\varphi - \frac{i}{2} \right) \Delta L \,, \tag{1}$$

$$v = \left(\frac{N-1}{2\pi} \Delta\varphi + \frac{i}{2} \right) \Delta v \,, \tag{2}$$

where N is the number of samples A or B; L – the range of the object; ΔL – range resolution; v – the radial velocity of the object; Δv – velocity resolution; $\Delta\varphi$ – the difference between the phases of spectral peaks B and A; i – the index of spectral peak (A or B). The resolutions ΔL and Δv are obtained by the following equations:

$$\Delta L = \frac{c}{2 f_{Sweep}} \,, \tag{3}$$

where c denotes the velocity of electromagnetic waves, f_{Sweep} – the overall frequency sweep of A or B segments, and

$$\Delta v = \frac{\lambda}{2 T_{Chirp}} \,, \tag{4}$$

where λ denotes the wavelength used and T_{Chirp} – the period of modulation waveform (A and B segments altogether).

The spectra of A and B samples can include more than one peak. This corresponds to the situation when two or more targets occur within the radar range. It allows to perform a simultaneous measurement of several targets' parameters (though in rare cases it could happen that two targets have such combinations of range and velocity that their echoes give peaks with the same index, thus only one joint peak is formed in the signal spectrum). To determine the indexes of the peaks, i.e. to detect maxima in the spectrum, appropriate algorithms are used. They enable to detect the peaks in the background of interferences and noises or in the background related to the surface, over which the object equipped with the radar flies. For one of the radar solutions that were developed at the Institute of Aviation the GOSGO CFAR algorithm has been used (GOSGO – *generalized order statistic greatest of,* CFAR – *constant false alarm rate*). A general scheme of most of these algorithms based on the CFAR technique is depicted in Figure 3.

The idea of the GOSGO method rests on the need to determine whether for the spectrum components, analysed consecutively, the amplitude of a particular index exceeds the background value in the vicinity of that index by a specified factor. In order to estimate the clutter power level Z, two reference windows are constructed on both sides of the index, placed within a specified number of guard cells away from it (at the Institute of Aviation one guard cell and a 16 cell window have been applied). Amplitude values are ranked from the lowest to the highest in every window and the cell the position of which is ¾ of the length of the window is used as a reference level, hence in this particular case the spectrum amplitude of the 12th cell is used. The greatest value chosen from the left and the right window is taken into account and it is multiplied by selected factor T. If the spectrum amplitude of the examined index is larger than the established value TZ, it is considered that the peak of that index has been detected (Mende *et al.* 2005; Rouveure *et al.* 2005; Jankiraman 2007; Panzhi, Chendong 2010).

The main advantage of the algorithm with ordered elements is its behaviour in the case of ambiguous and multitarget situations. It does not detect clutter edges, but only peaks that contain the information about targets. On the other hand, its huge disadvantage is a longer time of data processing due to the use of sort algorithms in reference windows.

In the second solution of the radar the simplified algorithm the CFAR was used, which, in order to calculate the reference level, uses a mere averaging of samples in the windows instead of sorting (Rohling 1983; You 1994; Di Cenzo 1990).

3. Selected practical problems

3.1. The leakage of signal from the transmitting antenna to the receiving antenna

Signal leakage between the antennas is inevitable to some extent, but it could be limited by the use of a proper shield between them; in the antenna head used at the Institute of Aviation there was no shield. The leakage signal is equivalent to an echo from a closely situated fixed target and, theoretically, it has a form of a fragment of a cosinusoid (the radar head that is applied at the Institute of Aviation has quadrature outputs I and Q, and the latter is created by mixing the received signal with the transmitted one shifted additionally by 90°, hence on it the signal has a form of a fragment of a sinusoid). The sinusoid or cosinusoid can be shifted due to the possible delay of the leaking signal. A similar effect is caused by the transmitted signal reflected (or dispersed) from the radar windshield/dome.

The adverse influence of this phenomenon is always due to a certain "blinding" of the radar at the peak with the index number 1 (the echo with this index should be many times stronger than the leakage signal itself in order to be taken into account). Furthermore, due to the large amplitude of the leakage signal it predominates over the useful echo signal, increasing the

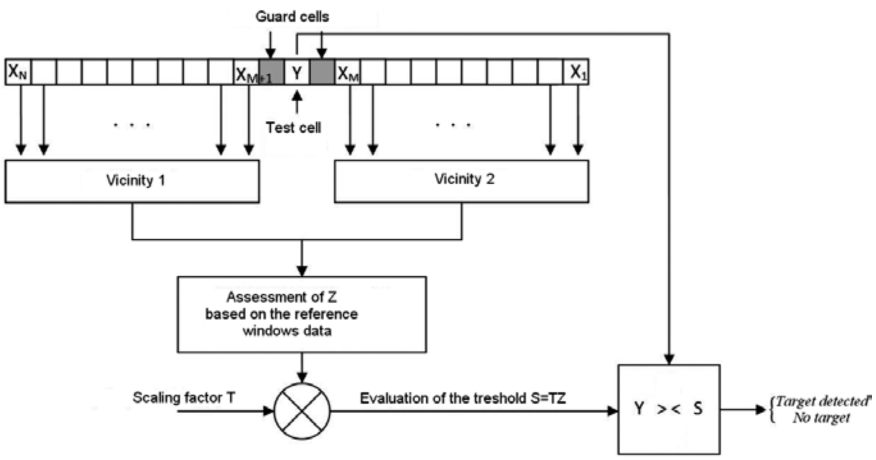
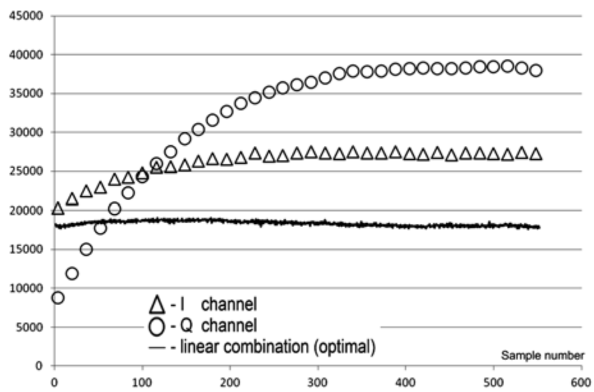


Fig. 3. The principle of the CFAR technique

dynamic scope of the total signal, so either the resolution of the ADC must be increased or weak echo signals disappear in the noise, which decreases the practical range of radar.

At the Institute of Aviation, in order to reduce the leakage signal dynamics, the normal use of the quadrature output function was abandoned. The I and Q signals were added together in such a proportion that the effective scope of the leakage signal was the smallest (this solution could be called a kind of compensation method). It is assumed that they are the sine and cosine of a certain angle. This operation, done on the theoretical cosinusoidal and sinusoidal I and Q signals, in general, causes only a phase shift of the resultant sinusoidal signal, leaving its overall amplitude unchanged. However, the period of the sinusoid in the presence of a leakage signal is so long that the single scan covers only a section of it. Thus, a phase shift can be selected so that the section contains a symmetrically located vertex, when the effective span of such a section is the smallest. For a practical establishment of addition factors, the waveforms of the I and Q signals were registered separately using the same amplification factor of receiver, while the antennas were aimed at the sky. The angle α at which the sum Icosα + Qsinα had the

a)



b)

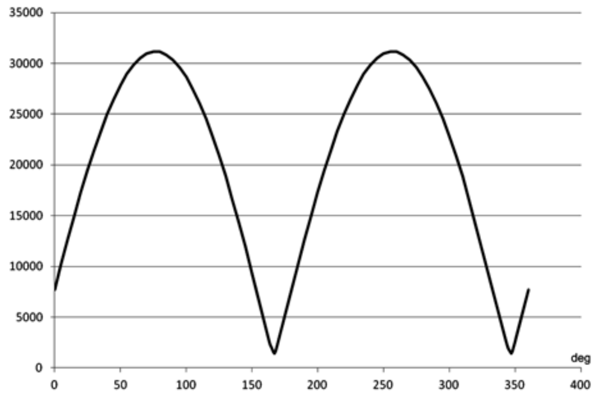


Fig. 4. a) – the leakage signal in I and Q channels together with their optimal linear combination; b) – dynamic range of I·cos(α) + Q·sin(α) combination versus α parameter

smallest dynamic range over the whole scan period was established. The graphs of I and Q signals together with their optimal combination and also dynamic range versus α are shown in Figure 4, respectively.

During the first trials of the radar after equipping it with a windshield a strong increase of false detections was observed, which completely prevented the normal functioning of radar. This was caused by the leakage signal reflected from the laminate windshield. The laminate had to be replaced with a foam material, and this change reduced the false detections to an acceptable level.

3.2. The influence of the transmittance of the receiver channel

The echo signal from a single target could be treated as a superposition of the sinusoid with the frequency equivalent to the spectrum peak of the echo and the signal with the frequency of switching between A and B samples. If the frequency response of the receiver channel is not flat, it could cause a change of proportion between both components and, eventually, alter the difference between the phases of peeks in the spectra of A and B samples. Due to a synchronous sampling of the received signal every phase shift resulting from a non-flat phase response could also be threatening for difference measured between A and B samples, which results in a false difference between the phases of A and B peaks.

Both occurrences lead to the situation, when with an ideal receiver a single sample (for example A) should occur, for a real receiver channel this A sample is accompanied by a series of trailing samples, alternately B and A, with diminishing amplitudes. The effect can be measured without the need to interfere with the structure of the radar head (it would be difficult to do when the amplitude-to-phase characteristic of the receiving line must not be changed). The leakage signal from the transmitting antenna to the receiving antenna that was described earlier could be used in this case: at least one of the two outputs (I or Q) contains a voltage step for the transition from the last B segment to the first A segment. In Figure 5, the received signal waveform for antennas directed to the sky, registered for five initial modulation cycles, has been shown.

In the vicinity of the selected step, the linear approximation of A and B samples has been determined based on over a dozen samples before and after the step (in the latter case by omitting a couple of initial samples, because they have an adverse influence of non-ideal transmittance). Afterwards, the theoretical values of the samples have been calculated, which are a result of approximation equations. Also, the deviation of current values of individual samples from the approximated values in the vicinity of the step has been determined. The result for a selected step of the leakage signal is shown in Figure 6a.

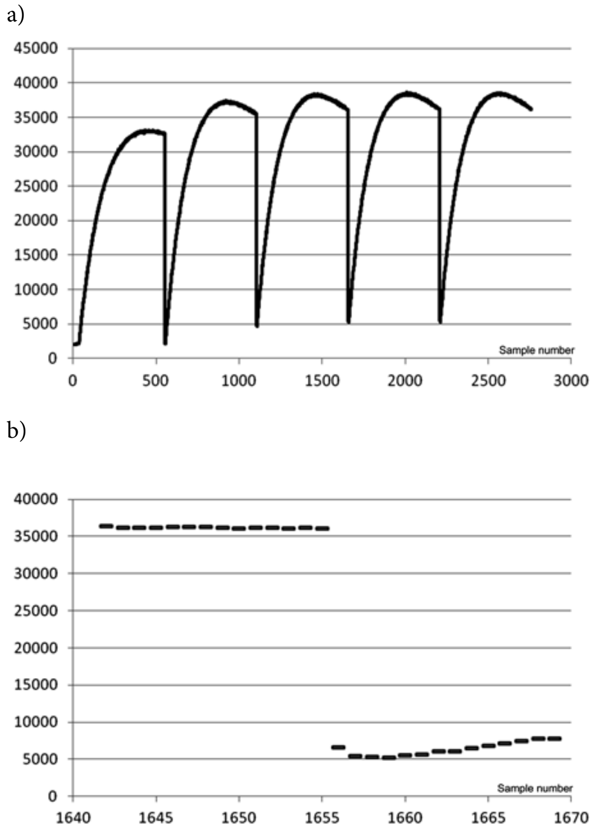


Fig. 5. a) – the leakage signal waveform; b) – an enlarged fragment of one of the steps

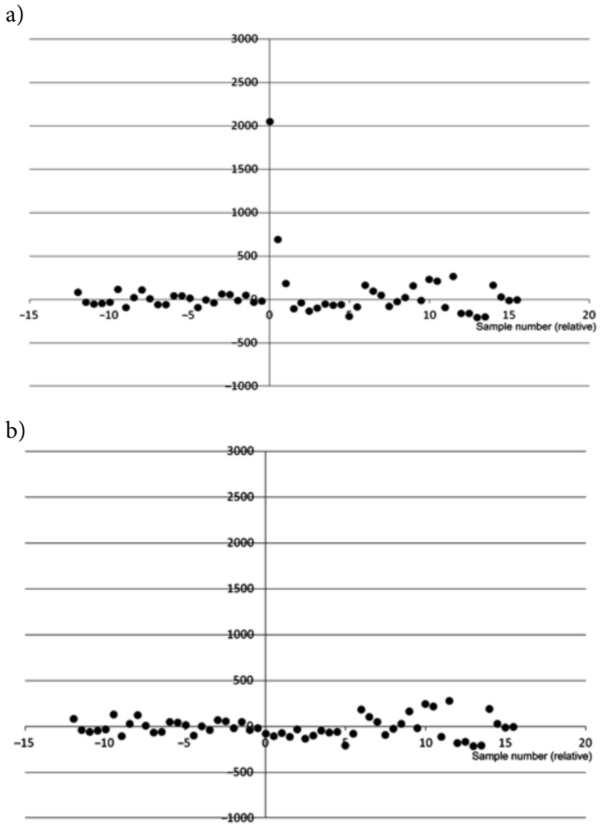


Fig. 6. a) – the approximated error of the radar receiver channel response for the selected step of the leakage signal; b) – the error for the same situation after an addition of a pre-compensation digital filter

Based on the error signal and the height of the step resulting from the approximated values of samples on the left and right side of the step, the response of the receiver channel to the unit step could be determined and the transmittance of a digital filter, designed for recovering the undistorted values of samples, could be calculated. The calculation for the correcting filter has been made for an averaged error signal with all registered steps of the penetrating signal. The result of passing the registered samples through this filter is shown in Figure 6b as a waveform of the error signal of the selected step.

The effectiveness of corrective filtering has been proven by practical trials. The first trial of measurement of the echo from the wall of the neighboring building situated 20.5 meters away from the point in which the radar head was located gave the result of distance equal to 17.5 m and of velocity equal 0.5 m/s. After the implementation of corrective filtration into the radar software (in practice, it was simplified to a non-recursive structure of the first order, which reduced the calculations to a minimum), the measurement results became equal to 20.3 m and –0.1 m/s respectively. The design resolutions ΔL and Δv of this radar were equal to 2.95 m for distance and 0.627 m/s for velocity, so the errors were not high, but it is be beneficial to be able to get rid of those errors without putting too much effort.

4. Conclusions

The projects realized at the Institute of Aviation, connected with detection and avoidance of obstacles during the flight of an unmanned aerial vehicle, are only an example of the vast application of radar techniques in aviation. Besides the detection and ranging of objects in the air it includes, for example, measurement of aircraft velocity with the Doppler radar, detection and imaging of storms with the weather radar, and many others (e.g. numerous military applications). Improving the accuracy and the sensitivity is an important issue in the design phase of the radar system.

The methods of processing a radar signal with the LFM-FSK modulation, whether during the procedure of measurement in order to improve its accuracy or during the development phase while optimizing the parameters of the electronic circuit, proved its effectiveness. They were especially beneficial in the latter case, allowing for greater reduction of the leakage signal and the increase of the amplification and sensitivity of the receiver channel. There are no doubts that the best choice is to fight the leakage at its source by the use of the radar head of a higher class and the use of proper material for the windshield of the head (what was in fact done). However, the possibilities offered by the compensational method were shown as well.

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