ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2010. No. 5(101)
ELEKTRONIKA IR ELEKTROTECHNIKA

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SIGNALŲ TECHNOLOGIJA

Probe Signals with Nonrectangular Envelope

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Introduction

Traditionally radar probe signals are considered to be square pulses, pulse trains or pulses with inner phase modulation. Advantages of rectangular signal envelope are insensitivity to nonlinearities of radar tract, ease of pulse generation and signal processing. In practice, real probe signals are never exactly rectangular. Producing pulse, which is absolutely rectangular, is impossible in both analog and digital technology. Raise and fall of signal voltage takes always some amount of time, therefore pulses are usually exponential near the edges. Also ideal square pulse would have infinite spectrum thus limited bandwidth in transmitter and receiver components would cause distortion in pulse shape anyway. Biggest disadvantage of square pulse is it‘s poor spectral efficiency. About 10% of rectangular pulse energy is spread into spectral sidelobes. Additionally ambiguity function of square pulse has high Doppler sidelobes and it causes Doppler-range ambiguity.

Recent advances in low-noise, high-power linear amplifiers and high-speed, digitally programmable arbitrary waveform generators, has allowed radar designers to consider the use of sophisticated pulse shaping techniques instead of simple square pulses [3]. Pulses with different shape can have different Doppler sensitivity. Pulse shaping can be used to compensate distortions in radar tract. But most important feature is possibility to adaptively change pulse shape for best detection and classification of current targets. Radar with such capability is called cognitive radar as it uses knowledge about it surroundings in order to change its output signal and internal processing for best fit to surrounding environment and targets.

At following we show that even simple nonrectangular envelope of probe signal can significantly increase performance of software radar system.

Envelope selection

Digital probe signal synthesizer has no problem to generate signals with almost any shape and duration. Thus our main consideration is selection of proper envelope for probe signal. To demonstrate main idea most clearly isosceles trapezoid shape [6] was selected because even this simple shape already shows many advantages compared to square pulse.

Lets define pulse $p_t(t)$ with shape of isosceles trapezoid (Fig. 1) as convolution of two rectangular pulses $p_1(t)$ and $p_2(t)$

$$p_t(t) = p_1(t) * p_2(t)\,. \tag{1}$$

Durations of those pulses are τ_1 and τ_2 where $\tau_1 \le \tau_2$. Duration of trapezoidal pulse $T_p = \tau_1 + \tau_2$, amplitude is A and shape can be determined by shape parameter k_s

$$k_s = \frac{\tau_1}{\tau_2}\,. \tag{2}$$

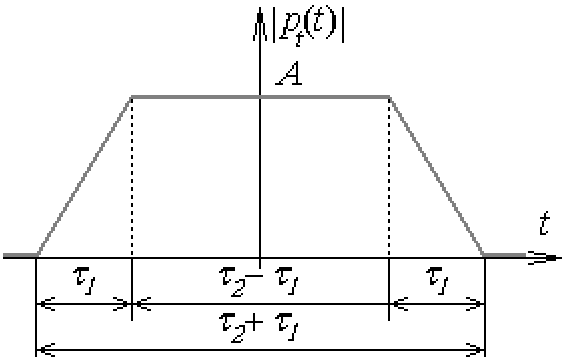

Fig. 1. Shape and parameters of trapezoidal pulse envelope

Now we have fully defined trapezoidal pulse $p_t(t)$ trough three parameters τ_1, τ_2 and A. When shape parameter $k_s = 0$ we get rectangular pulse with duration τ_2. At other extreme $k_s = 1$ we have triangular pulse with duration $2\tau_1$. Between those two values lie isosceles trapezoids with different shapes.

Spectral efficiency

Our aim was to find value of shape parameter k_s in such way that maximum amount of signal energy is concentrated into main lobe of spectrum.

Firstly a spectrum of trapezoidal pulse must be calculated. Representation of trapezoidal pulse as convolution of two rectangular pulses (1) becomes useful at this point. Convolution theorem for Fourier transform states that convolution in time domain equals point-wise multiplication in frequency domain:

$$F\{p_1(t) * p_2(t)\} = F\{p_1(t)\} \cdot F\{p_2(t)\}. \qquad (3)$$

Spectral density of square pulse is described as sinc function

$$F\{p(t)\} = \frac{\sin(\pi f \tau_p)}{\pi f}, \qquad (4)$$

where τ_p is duration of pulse. Using theorem (3) on equation (1) we obtain spectral density of trapezoidal pulse

$$P_t(f) = \frac{\sin(\pi f \tau_1)\sin(\pi f \tau_2)}{(\pi f)^2} = \\ = \frac{\sin(\pi f k_s \tau_2)\sin(\pi f \tau_2)}{(\pi f)^2}. \qquad (5)$$

Result is product of two sinc functions with different periods. Width of main lobe is determined by parameter τ_2.

To compare different pulse shapes we define spectral efficiency coefficient k_{se} that shows how much of signal energy E_t is concentrated into main lobe of specter within bandwidth $2/\tau_2$

$$k_{se} = \frac{\int_{-\frac{1}{\tau_2}}^{\frac{1}{\tau_2}} P_t^2(f)df}{E_t}. \qquad (6)$$

Numerical simulation was carried out to find spectral efficiency coefficient k_{se} for different shape factor values. Highest efficiency is achieved with shape factor $k_s = 0.74$. In such case 99.7% of signal energy is concentrated into main lobe of pulse spectrum. From now on trapezoidal pulse with shape factor $k_s = 0.74$ is referred as optimal trapezoidal pulse

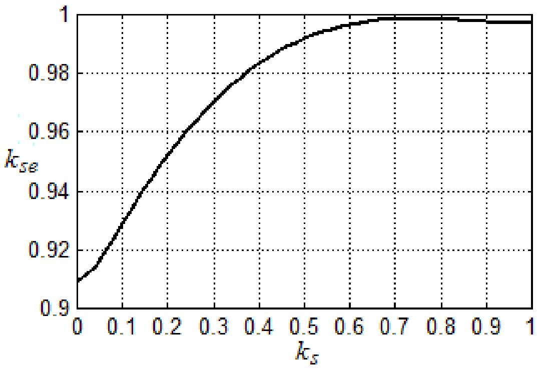

Fig. 2. Spectral efficiency k_{se} of trapezoidal pulse as function of shape parameter k_s

Main lobe of trapezoidal pulse spectrum is $1 + k_s$ times wider than in case of square pulse. By cost of increased main lobe bandwidth it is possible to concentrate practically all signal energy into spectral main lobe of probe signal.

Doppler and range resolution

Ambiguity function of radar pulse $\chi(\tau, f)$ is used for estimation of range- and Doppler resolution of radar [1]. It also allows estimating range-Doppler ambiguity of given probe signal.

Fig. 3 compares Doppler sensitivity of optimal trapezoidal pulse ($k_s = 0.74$) with one of square pulse. Both pulses have same duration. As it can be seen trapezoidal pulse has much lower sidelobes in Doppler range. This is desirable property, because high sidelobes can cause false alarms and masking of weaker targets. Central lobe is twice wider at case of trapezoidal pulse. This means that trapezoidal pulse has only a half of Doppler resolution of square pulse. When targets with similar radial velocities must be separated then square pulse should be preferred.

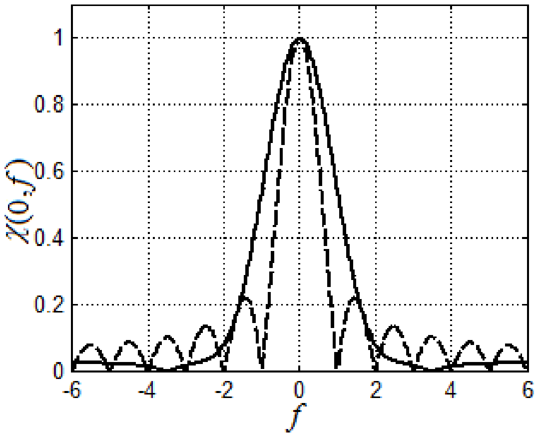

Fig. 3. Doppler sensitivity of square (dashed) and trapezoidal pulse (solid line)

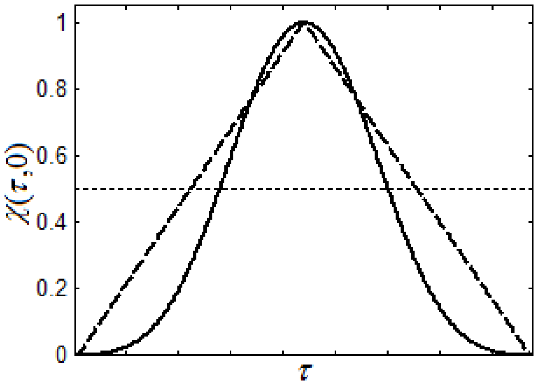

Fig. 4. Range resolution of square (dashed) and trapezoidal pulse (solid line)

On Fig. 4 is visualized output of optimal filter both for square and optimal trapezoidal pulse. Width of autocorrelation function at level 0.5 determines theoretical limit for range resolution of given signal. Range resolution of trapezoidal signal is 0.73 times smaller than square pulse has. This means that with trapezoidal pulse closer targets can be distinguished than with square pulse.

Linearization

Nonrectangular envelope of probe signal makes linearity of power amplifier an important issue. Any nonlinearity of amplifier causes distortions in signal shape and creates unwanted spectral side lobes.

There are two methods to achieve linear amplification. Backing - off A class amplifier is one solution, but this reduces power efficiency and increases heat dissipation. Second way to achieve power amplifier linearity is using linearization techniques [7]. As we dealing with software radar then digital predistortion technique is most suitable on given situation. Let the gain *G* of power amplifier be modeled as function of instantaneous magnitude of amplifier input voltage v_i. For simplification let assume that function G is memoriless. To compensate nonlinearities of power amplifier predistortion must be introduced to probe signal. Predistortion function F is function of the magnitude of input signal v_i in such way that

$$\mathrm{G}(\mathrm{F}(|v_i|)) = kv_i\,, \qquad (7)$$

where *k* is constant [7]. In telecommunication applications predistorter must be realized as separate block of communication equipment. In case of radar it is advisable to synthesize probe signals already with predistortion. Predistorted pulse shape can be written as

$$p^*(t) = \mathrm{F}(|p(t)|)\,. \qquad (8)$$

In real situations gain function G of power amplifier depends on environmental parameters such as ambient temperature, aging of equipment and others. Adaptive predistortion must introduce in such case. Additional sensors could be used to measure environmental parameters such as temperature and then chose appropriate predistortion function F for given set of parameters.

Instead of installing additional components to system one can use leakage of output signal to estimate linearity of power amplifier. No matter how good is isolation between output of power amplifier and input on LNA some amount of radiated power still leaks into radars input stage when probe signal is radiated. This leakage signal can be used to measure linearity of power amplifier and generate feedback signal to increase performance.

Third option is to leave distortions uncompensated and construct at receiver end optimal filter for distorted probe signal. Still it is more easy and efficient to use predistorted probe signals. Firstly then signal shape and spectrum is determined and limited since power amplifier, and trough whole receiver tract. Secondly it is simper to construct optimal filter for relatively simple signal than to its distorted version.

Probe signal synthesizing

Example of normalized trapezoidal probe signal at intermediate frequency is pictured at Fig. 5. Signal shape or instructions for construction it is stored in internal memory of probe signal synthesizer. In ideal, distortionles situation the signal is loaded into fast shift register for probe signal generation. In case of known stationary distortions predistortion can be calculated in advance and modified pulse can be stored in memory in similar way as in distortionles case. When adaptive linearization is applied then stored pulse shape is modified by predistortion function F (8). Values of F are calculated using leakage signal as feedback information.

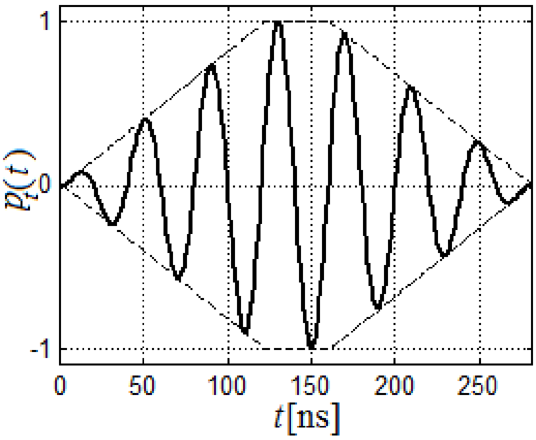

Fig. 5. Probe signal with trapezoidal envelope (at IF)

Cognitivity

Important feature of future radars is capability to sense its surroundings and adapt to it. Pulse shape, duration, repetition frequency and other parameters should be changed in ways that makes target detection tracking and identification maximally efficient [2]. Modifying envelope of probe signal widens greatly possibilities here [3].

As revealed earlier trapezoidal pulse has better range resolution. For example if cognitive radar has reason to believe that some objects at its range is separated very closely it changes pulse shape from rectangular to trapezoidal and thus increases own ability to separate targets. In other hand when measuring speed of targets has higher priority than rectangular envelope signal has advantage, and should be used.

Both signals can be used alternately to achieve both good range and Doppler resolution on same time. In general digital probe signal synthesizer with linearized power amplifier allows use probe signals with almost any desirable shape.

Future work

At present work advantages of nonrectangular pulse was demonstrated on example of trapezoidal pulse. It is clear that there must be much better shapes for probe signal than simple trapezoid. Raised cosine, Gaussian pulse and different wavelets seem promising candidates. As single pulses have low energy then next step is study of different pulse compression codes where code element is nonrectangular pulse [5].

Conclusions

Digital probe signal synthesize allows use of probe signals with nonrectangular envelope. Introduction of digital predistortion technique enables diminish influence of power amplifier nonlinearity to such signals. Simple isosceles trapezoid shaped pulse was chose to demonstrate advantages of pulse envelope shaping.

Trapezoidal pulse with shape factor $k_s = 0.74$ had spectral efficiency $k_{se} = 99.7$ % against rectangular pulse with $k_{se} = 90.6$ %. As minor disadvantage, trapezoidal pulses spectral main lobe is wider than one of rectangular pulse, but as mentioned only 0.3 % of its energy lies outside that main lobe.

Trapezoidal pulse has better range resolution and lower Doppler sidelobes than square pulse with same duration. Doppler resolution of trapezoidal pulse is only half of what we got with rectangular pulse. This can be desirable property in some radar designs where Doppler shift is not measured and low distortion to pulse shape by this phenomenon is demanded.

Target matched illumination demands capability of synthesizing pulses with complex envelope [3, 4]. Cognitive radar must be capable of changing shape of probe signal according to changes on environment and target situation. Also noise radar can be viewed as using pulse modulated by random noise. Those mentioned are only some examples of radar applications where probe signals with nonrectangular envelope could find use.

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Received 2010 02 15

I. Müürsepp, J. Berdnikova, T. Ruuben, U. Madar. Probe Signals with Nonrectangular Envelope // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 5(101). – P. 99–102.

Software radar technology allows use of probe signals with nonrectangular envelope. Even simple waveforms can achieve much better performance than traditional square pulse. Pulse with optimal trapezoidal envelope introduced in current article has higher spectral efficiency, lower Doppler side lobes and better range resolution than square pulse with same duration. Probe signals with variable envelope sets higher demands to linearity of power amplifier. Linearization techniques are discussed and digital predistortion method is found to be most suitable solution for software radar. Possible uses of probe signals with nonrectangular envelope are discussed. Ill. 5, bibl. 7 (in English; abstracts in English, Russian and Lithuanian).

И. Мююрсепп, Ю. Бердникова, Т. Рубен, У. Мадар. Зондирующие сигналы с непрямоугольной огибающей // Электроника и электротехника. – Каунас: Технология, 2010. – № 5(101). – С. 99–102.

Программируемые радары позволяют использовать в качестве зондирующих сигналы с непрямоугольной огибающей.Даже самые простые из них позволяют достичь намного лучших результатов, чем обычные прямоугольные импульсы. Импульс с оптимальной трапециодальной огибающей, имеет повышенную спектральную эффективность, пониженный уровень боковых лепестков и лучшее разрешение по сравнению с прямоугольным импульсом такой же длительности. Поскольку зондирующие сигналы с непрямоугольной огибающей предъявляют повышенные требования к линейности используемых усилителей мощности, рассматриваются методы линеаризации и предлагается метод цифровых предискажений как наиболее подходящий для программируемого радара. Обсуждаются также и иные вопросы использования зондирующих сигналов с непрямоугольной огибающей. Ил. 5, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

I. Müürsepp, J. Berdnikova, T. Ruuben, U. Madar. Nekvadratinės gaubiamosios siunčiami signalai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 5(101). – P. 99–102.

Aprašomi nekvadratinės gaubiamosios siunčiami signalai, kurie pasižymi paprastumu ir užtikrina optimalius radarų parametrus. Įrodyta, kad trapecinės formos gaubiamosios signalams būdingas didesnis spektrinis efektyvumas, mažesnė parazitinė laukų sklaida ir geresnė radarų priimamos informacijos kokybė. Įvertinta netiesinių iškraipymų įtaka projektuojant galios stiprintuvus. Pasiūlyta programuojamam radarui panaudoti skaitmeninį prognozių metodą, kuris gerokai sumažina nekvadratinės gaubiamosios siunčiamų signalų netiesiškumą. Il. 5, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).