CORRELATION PROPERTIES OF SPREAD SPECTRUM SIGNALS WITH MULTIBAND LOSSES

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Abstract

The probing signals with multiband losses correlation properties were analyzed. We raise the idea that it is not necessary to have a complete signal spectrum for operation: "rake" type signal covering wide bandwidth could perform better than single band of the "rake".

Linear frequency modulated (chirp) type signals were chosen for investigation. The choice of chirp signals was justified by the need for easy controllable frequency response spectrum shape and content. Performance of simple linear-frequency-modulated chirp signals was investigated. Signals were passed thorough the various rake type filters and correlation function performance investigated.

We present the variation of these correlation function parameters: RF and envelope mainlobe beam width and sidelobes level in time domain, equivalent bandwidth, envelope equivalent bandwidth, envelope bandwidth and central weight frequency.

1. INTRODUCTION

The time domain processing is essential in SONAR, RADAR and non destructive testing (NDT) systems. Positioning and navigation systems find its use in a variety of applications. Location estimation is also essential in imaging systems used for NDT [1]. This can be simplified to time-of-flight (ToF) value estimation. The frequency response of the probing signal is defining the correlation properties of the signal received [2,3]. But electrical impedance of the transmission channel [4], losses in propagation media [5] alter the frequency content received: the output of matched filter (correlation function) will change accordingly [6,7]. Numerous publications present the spectral response for such case [2-7]. Especially in telecommunications such signal types prevail: those are addressed as "rake" or "comb" filter or spectrum. But usually, especially in NDT, operation is chosen to avoid the high attenuation areas and concentrate the operation in one complete frequency band. We suggest using a complete signal spectrum. The aim of investigation was to investigate whether operation of "rake" type signal covering wide bandwidth can perform better than single band of the "rake" and what is the performance compared with complete, lossless spectrum signal.

2. THE ToF ESTIMATION

We have located three ToF estimation techniques [8,9,10]: the direct correlation maximization (DCM), the L2 norm minimization (L2M) and the L1 norm minimization (L1M). The DCM technique is using the position of peak value of cross-correlation function R_{DC} for signal arrival position (so the ToF) estimate:

$$ToF_{DC} = \arg\left[\max R_{DC}(\tau)\right], \qquad (1)$$

where R_{DC} is:

$$R_{DC}(\tau) = \int_{-\infty}^{\infty} s_T(t) \cdot s_R(t-\tau)dt \,. \qquad (2)$$

The L2M is using the minima of position of L2-norm of received signal and reference signal subtraction:

$$ToF_{L2} = \arg\{\min[L2(\tau)]\}, \qquad (3)$$

where $L2$ is:

$$L2(\tau) = \int_{-\infty}^{\infty} [s_R(t) - s_T(t-\tau)]^2 dt \,. \qquad (4)$$

The L1M uses the average magnitude difference function of received signal and reference signal:

$$ToF_{L1} = \arg\{\min[L1(\tau)]\}, \qquad (5)$$

where $L1$ is:

$$L1(\tau) = \int_{-\infty}^{\infty} |s_R(t) - s_T(t-\tau)| dt \,. \qquad (6)$$

The direct correlation technique theoretical analysis on ToF estimation variance is broad [2,3,8-14]. Therefore it has been chosen for this analysis.

As suggested in [11] and [12] the ToF estimation can be done by the direct correlation maximization to find and estimate of the true position of signal arrival. The variance of ToF standard deviation is [7]:

$$std_{CRLB}(TOF) \geq \frac{1}{2\pi F_e \sqrt{\frac{2E}{N_0}}}, \quad (7)$$

where E is signal $s_T(t)$ energy, F_e is effective bandwidth of the signal. The effective signal bandwidth can be calculated as:

$$F_e^2 = \beta^2 + f_0^2, \quad (8)$$

where β is the envelope bandwidth and f_0 is the center frequency:

$$\beta^2 = \frac{\int_{-\infty}^{\infty}(f - f_0)^2 |S(f)|^2 df}{E}, \quad f_0^2 = \frac{\left[\int_{-\infty}^{\infty} f |S(f)|^2 df\right]^2}{E^2}. \quad (9)$$

The envelope bandwidth β is also defining the resolution because it is directly related to the signal duration after its compression in matched filter.

3. SPECTRUM SPREAD

As (7) suggests, the reduction of random errors is possible by maximizing the signal energy, reducing the noise level and increasing the effective signal bandwidth. Once noise level has some physical limit it is more feasible to increase the energy and the bandwidth. If spread spectrum signals are used, both long duration and wide bandwidth are achieved.

But use of wideband excitation signals is limited by multi-band losses, usually occurring in imaging or navigation systems. The ultra-wideband (UWB) radar should avoid certain bands; also there is a particle absorption in the propagation media (ground penetrating radar) or atmosphere. This creates multi-band losses. Similar losses exist in ultrasonic NDT: when layered ultrasound composites are inspected, those posses certain multiple positive and negative resonances due to wave interaction between the layers. Same can be addressed to fiber composite materials [18,19]. Also, in case of multi-transducer measurements some frequency regions might not be covered.

Multi-band losses in radar, sonar or ultrasonic NDT can create "rake" type signal. Instead of avoiding of wideband signal use, we want to exploit its advantages and apply on channel with multi-band losses. First, possible spectral spread techniques have to be investigated.

Several techniques can be applied to spread the signal spectrum: phase manipulated pseudo-noise sequences [6,7,15], chirp [4,16] and arbitrary waveform excitation [17].

Phase manipulated sequences (Figure 1) make the excitation task easer since square waves can be used for signal generation: the hardware is less complex because power amplifier is replaced with high speed switch.

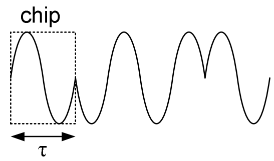

Fig. 1. Phase manipulated sequence

Application of the orthogonal coded sequences allows to easy separate the probing channels [15] so simultaneous surrounding area scanning with several ranging channels can be done.

The problem is that the resulting signal bandwidth is predicted by the smallest chip (Figure 1) duration. If integer number of half-periods must be used for chip this is a disadvantage since then the bandwidth adjustment step is discrete. Another disadvantage is that it's impossible to shape the signal spectrum in the arbitrary way.

Application of the arbitrary waveform produces any shape of amplitude and phasing spectrum and correlation function [15]. But this technique requires complicated excitation hardware. There are attempts to use some approximation using only limited number or excitation levels: in [7] a quinary excitation method is reported for linear frequency modulation windowing implementation.

A frequency spreading using a carrier frequency modulation [4,16] frequently is addressed as chirp signal (Figure 2).

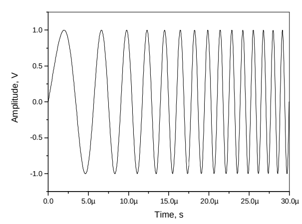

Fig. 2. Chirp signal

We suggest using chirp signals for excitation. Chirp signal excitation offers any spectral shape and easy excitation circuit and looks an attractive solution: in [2] the combination of chirp signals and wideband micromachined capacitance (CMUT) transducers application in air-coupled ultrasound is reported; in [4] a nonlinear frequency modulation of square wave signal is used in order to match the signal spectrum to ultrasonic transducer spectral response shape; in [16] chirp spectrum is wider than transducer bandwidth.

If nonlinear chirp signals are used, this would allow skipping the loss-bands and still using wideband inspection.

4. NUMERICAL EXPERIMENT

Here we aimed to investigate correlation properties of signals with multi-band losses. Linear frequency modulation chirp was produced and signal passed through rake filter (Figure 3). Rake filter was constructed by using serially connected elliptical notch filters. Resulting signal with multi-band losses we assume to use for excitation. Therefore this signal was used for analysis.

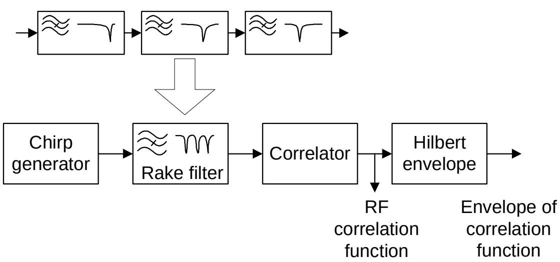

Fig. 3. Experiment diagram

The effective bandwidth F_e, envelope bandwidth β and the center frequency f_0 were calculated using discrete case of the equations (7), (8) and (9) presented in [3]. Signal with multi-band losses was used for autocorrelation function calculation. This function was treated as RF correlation function. The RF (before envelope extraction) autocorrelation function central lobe width at zero crossing level was measured and noted as τ_0. It should correspond to $2/f_0$. The autocorrelation function envelope was calculated using Hilbert transform and central lobe width at -6dB level was obtained. If should correspond to envelope bandwidth as $1/\beta$.

Four types of investigations have been carried out: i) when total stopband width was held constant, minimum and maximum frequencies were kept constant, but number of rake tooth varied; ii) when stopband width was varied, minimum and maximum frequencies and rake tooth number were kept constant; iii) same as above, but with single tooth; iv) when stopband was constant, but stopband tooth position in frequency domain varied.

4.1. Constant total bandwidth but variable tooth number

The aim of this investigation was to decide how the shape of the frequency response affects the correlation function. Number of notch tooth was varied, start and stop frequencies remained the same (Figure 4) in such way that and the center frequency f_0 was not affected.

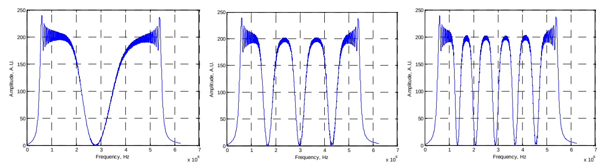

Fig. 4. Spectrum for variable tooth number, const. f_0

As expected, since f_0 was fixed there was no variation in RF correlation function central lobe width (Figure 5). There was a variation in sidelobes level: for tooth number above one in rake filter sidelobes were at acceptable level.

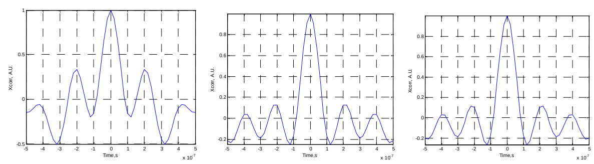

Fig. 5. RF correlation function for variable tooth number, const. f_0

Almost the same result was noted on envelope: for the case of single tooth envelope's mainlobe width was narrower than for multiple tooth. This can be explained by larger amount of energy being deviated from f_0 so the resulting increase of β (Fig. 6).

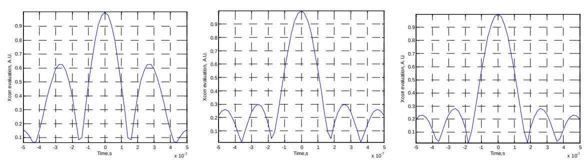

Fig. 6. Correlation function envelope for variable tooth number, const. f_0

4.2. Constant start and stop frequencies, center frequency and tooth number but variable bandwidth

The aim of this investigation was to check whether larger amount of energy being deviated from f_0 is resulting in increase of envelope bandwidth β. There was only one notch tooth but bandwidth was varied, start and stop frequencies remained the same (Figure 7) in such way that and the center frequency f_0 was not affected.

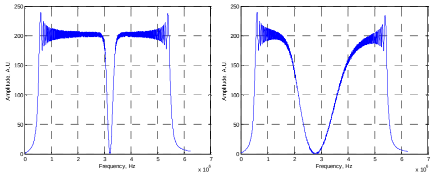

Fig. 7. Spectrum for variable bandwidth, const. f_0 and tooth number

Results confirmed the assumption: despite increase of stopband, envelope bandwidth was increasing (bottom grey line in Figure 8)

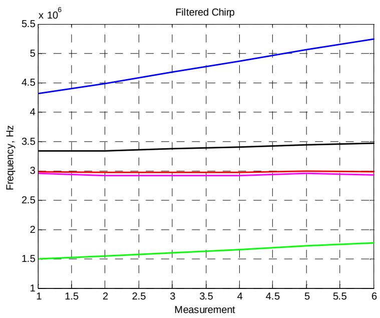

Fig. 8. Envelope bandwidth β , effective bandwidth F_e, and center f_0

4.3. Constant start and stop frequencies and tooth number but variable bandwidth

The aim of this investigation was to decide how the amount of stopband affects the correlation function. Number of notch tooth was kept constant but stopband increased, start and stop frequencies remained the same so that center frequency f_0 was not affected (Figure 9).

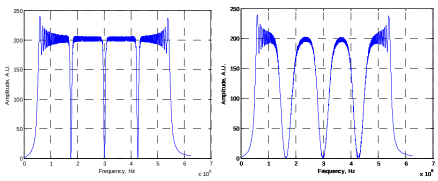

Fig. 9. Spectrum for variable stopband, const. f_0 and tooth number

As expected, since f_0 was fixed there was no variation in RF correlation function central lobe width (Figure 10). Odd result was noted on envelope: envelope's mainlobe width was narrower for larger stopband (Figure 11).

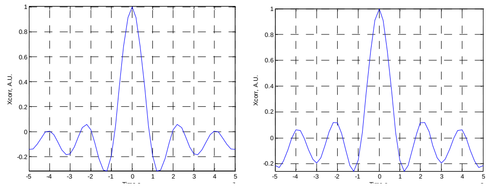

Fig. 10. RF correlation function for variable stopband, const. f_0 and tooth

This can be explained by shorter signal in time, resulting in shorter effective duration, since after passing the chirp through rake filter the corresponding positions in time are attenuated.

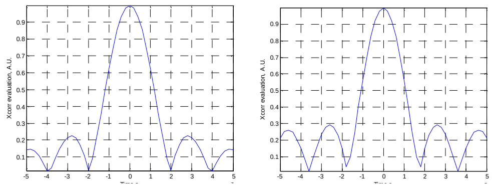

Fig. 11. Correlation function envelope vs. stopband, const. f_0

4.4. Constant start and stop frequencies and tooth number but variable tooth position

The aim of this investigation was to decide how the center frequency f_0 variation affects the correlation function. Number of notch tooth, envelope bandwidth β and stopband was kept constant, start and stop frequencies remained the same but tooth position was varied in such way that and the center frequency f_0 was affected (Figure 12).

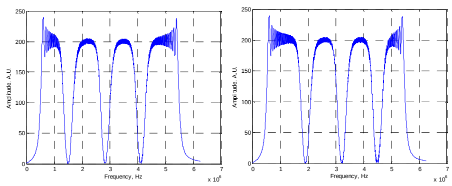

Fig. 12. Spectrum for variable f_0, const. stopband, β and tooth number

As expected, since f_0 was varied, there was similar variation in RF correlation function central lobe width. The rest of function remained unaffected: envelope mainlobe, sidelobes varied very slightly.

6. CONCLUSIONS

Multi-band losses in radar, sonar or ultrasonic NDT create "rake" type media filter. Chirp signal posses the ability to easily modify the excitation signals spectrum and energy. Application of such signals would allow skipping the lossy bands and still using wideband inspection in order to get high resolution.

ToF measurement and resolution related properties have been investigated. Experiments show that even significant losses within "rake" allow maintaining essential wideband properties of the signal. A multi-band loss ("rake") is affecting the sidelobes, but mainlobe performance remains and in some cases is even improved.

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