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COMPARISON OF CONVENTIONAL AND SPREAD SPECTRUM SIGNALS TIME OF FLIGHT ERROR CAUSED BY NEIGHBORING REFLECTIONS

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Abstract: Performance comparison of conventional and spread spectrum signals in Time of Flight estimation is given. Ultrasonic measurement under multiple reflections condition is analyzed. It was indicated that if two reflections are in close proximity the neighboring signal induces energy leak into its opponent signal. Due to such situation ToF estimate is obtained with bias error. Narrow signals like single rectangular pulse, should suffer less from the aforementioned phenomena. But use of spread spectrum signals is preferred thanks to their compressibility. It was hypothesized that such long signals will have worse bias error due to neighbor reflection. Goal of the investigation was to compare the performance in multiple reflections environment in Time of Flight estimation for classical signals and spread spectrum signals. Investigation revealed that spread spectrum signals have better performance in a sense of bias error caused by neighboring reflection.

Keywords: time of flight; time delay estimation; ultrasonic measurements; multiple reflections.

1. INTRODUCTION

Ultrasonic imaging and measurement offers direct interaction of the probing signal with the mechanical properties of the test object. Many measurement systems explore the ultrasound delay time: temperature [7], load measurement [9], food product quality monitoring [3]; thickness [4], non-destructive imaging [6] or biomedical applications [8]; flow rate measurement [5]. Essential procedure carried out in such measurements is the estimation of signal delay or time-of-flight (ToF) [1, 2].

Usually, pulse signals are used because easy to generate [10]. Yet these signals are not able to deliver sufficient energy if measurement precision is needed. Toneburst signals are used when high signal energy is needed [4]. But if pulse signals have good temporal resolution, tonebursts do not have this property. Spread spectrum (SS) signals [11-14] offer both: high energy and high resolution. Most widely used signals are chirp, linear frequency modulation and coded sequences [12]. New class of SS signals was suggested recently [15]: trains of pulses of arbitrary pulse width and position (APWP). For single reflection the SS signals have clear advantage: both sharp main correlation lobe and high energy increase the estimation accuracy. Estimation of signal arrival time gets complicated when multiple reflections are in close proximity: in [26] it was shown that additional error occurs.

Investigation presented was aimed to compare the ToF estimation performance of conventional and SS signals in multiple reflections case.

2. MULTIPLE REFLECTIONS PROBLEM

Thin plate thickness measurement creates a challenge: front face and back wall reflections are close in time. If short pulse signals are used, close reflections can be resolved (Fig. 1).

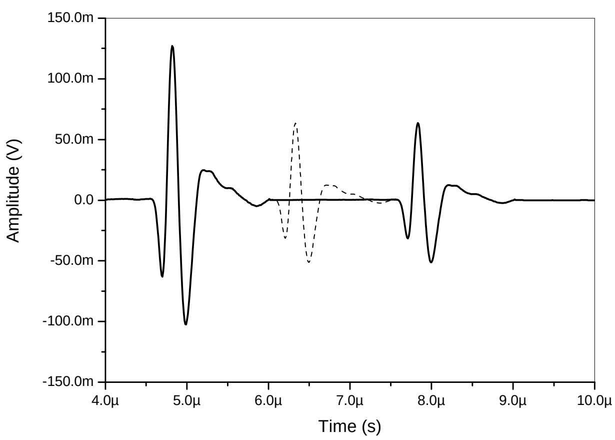

Fig. 1 – Multilayer reflections example when short pulse is used for probing.

But the shorter is the pulse the less energy it has and the lower is the attainable accuracy. In such case SS signals can be considered (Fig. 2).

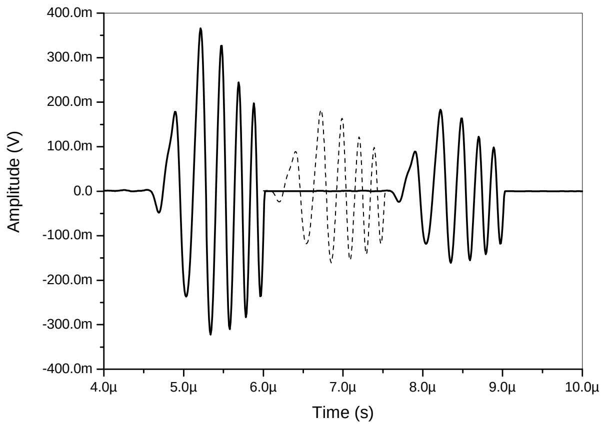

Fig. 2 – Multilayer reflections example when spread spectrum (chirp) signal is used for probing.

Application of SS signals is offering high energy yet it seems that resolution could be worse since operation in closer proximity (Fig. 2 dashed curves) could be complicated. Yet application of correlation processing compresses the signal and temporal resolution should not be jeopardized (Fig. 3).

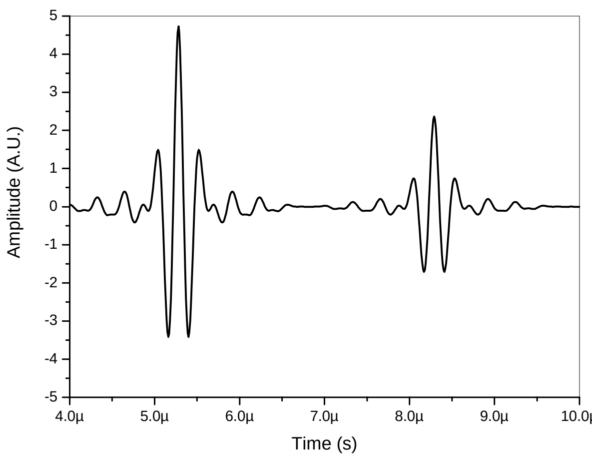

Fig. 3 – Signal compression result for chirp.

But in case of SS signal correlation sidelobes are higher (Fig. 3) than for pulse signal (Fig. 4).

Research presented in [26] was aimed to investigate the neighboring reflection influence on ToF estimation bias errors. Real signals were recorded using wideband transducer TF5C6N-E with delay line attached. Signals were averaged to produce noise-free reference signal ref_k. Here k=1…K represents the sample number. This reference signal later was used to construct a signal representing two reflections: front face, ff_k, with unity amplitude and backwall, bw_k with 0.7 amplitude. One signal was placed at original position which was not altered. Another signal was artificially shifted by introducing the Δt_n (n=1..N) delay via the phase alteration in frequency domain:

$$bw_{1..k}(t-\Delta t_n) = IFFT\left(FFT(ref_{1..k})\cdot e^{j\omega_{1..k}\Delta t_n}\right) \quad (1)$$

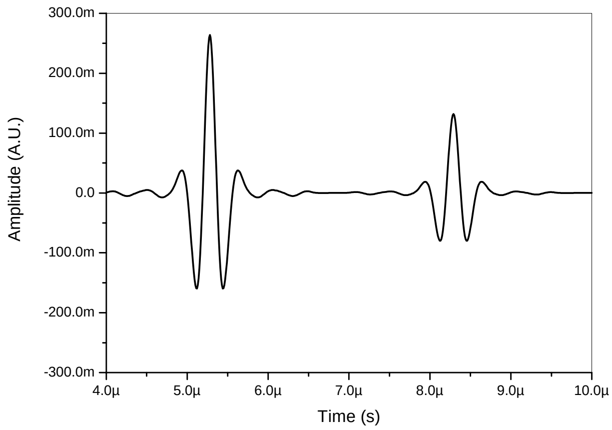

Fig. 4 – Signal compression result for pulse.

Then received signal is the sum of ff_k and bw_k:

$$sig_{1..k} = ff_{1..k} + bw_{1..k} \quad (2)$$

Several TOF estimation techniques exist [18, 27, 28]. If cross-correlation function x of reference and received signal is:

$$x(\tau) = \int_{-\infty}^{\infty} ref(t)\cdot bw(t-\tau)dt \quad (3)$$

Then the peak position of the cross-correlation function is the ToF estimate:

$$ToF_{DC} = \arg[\max(x(\tau))] \quad (4)$$

But it is more practical to produce the cross-correlation function in digital space. Therefore signals analyzed are discrete.

$$x_m = \sum_{k=1}^{K} ref_{k-m}\cdot bw_k \quad (5)$$

If ToF errors below the sampling period are expected then interpolation is used to estimate the ToF between the samples. In ideal case, *sinc* function should be used for this purpose. But usually speed is required, so several truncated interpolation techniques exist [21-23]. Cosine interpolation was suggested as the best candidate in [26]. If CCF peak for a relatively narrowband signal was assumed to be harmonic function, then cosine interpolation can use samples x_{m-1}, x_m and x_{m+1} around the peak:

$$\Delta ToF_{\cos} = -\frac{\beta}{f_s \alpha}, \tag{6}$$

where

$$\alpha = \arccos\left(\frac{x_{m-1}+x_{m+1}}{2x_m}\right)\ \beta = \arctan\left(\frac{x_{m-1}-x_{m+1}}{2x_m \sin\alpha}\right) \tag{7}$$

Signals synthesized by (1) and (2) were used to obtain two ToF values, ToF_{ff} and ToF_{bw}: for ff_{k} and bw_{k} correspondingly. Peaks were located by gating the area of first and second reflection. Estimates were obtained using (4), (5), (6) and (7). Since there was N values for spacing Δt_{n} between the signal, every delay value was used to obtain the bias error $\varepsilon(ToF_e)$, by subtracting the introduced delay Δt_{n} (0 ns to 4000 ns for second reflection and 0 ns for first reflection):

$$\varepsilon(ToF_n) = ToF_n - \Delta t_n \tag{8}$$

ToF bias error is clearly seen in Fig. 5.

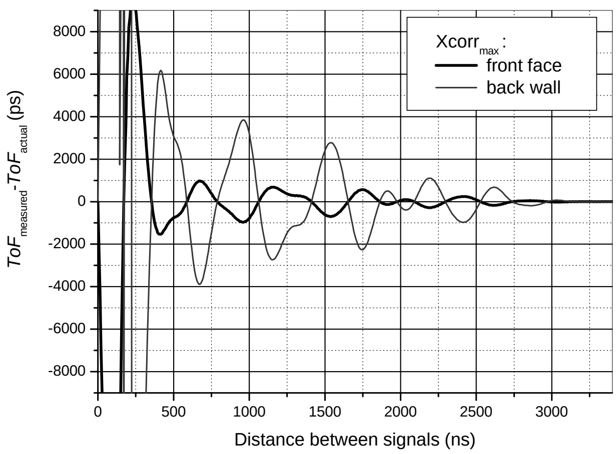

Fig. 5 – ToF bias error induced by neighboring signal.

It can be seen that presence of the neighboring reflection creates bias error. The influence is of opposite sign and depends on opposing signal amplitude: first reflection is larger so has less influence from second reflection and second reflection is smaller so has stronger influence from first reflection. The closer are the signals, the larger is the error. Situation can be expected from Fourier analysis point: pulse signal can be disassembled into several frequency components which exist beyond signal peak (Fig. 6).

But which type of signals will have lower errors? It was hypothesized that long SS signals which correlation lobes are larger should have worse bias error due to neighboring reflection.

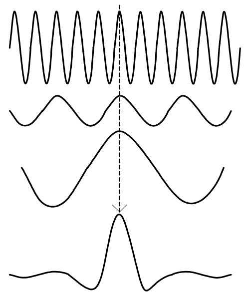

Fig. 6 – Pulse signal components exist beyond the peak.

3. EXPERIMENTAL RESULTS

In this investigation we aimed to compare the neighbor reflection influence on bias error for short single pulse and SS signals. Same transducer TF5C6N-E was used for real signals collection. Signals were collected from attached delay line, averaged to produce reference signal *ref*. Chirp signal with frequency 1-10 MHz and 2 μs duration was used as SS signal representative (Fig. 2). Conventional signal was represented by 100 ns rectangular pulse (Fig. 1).

Reference signals were artificially shifted as per equation (1). ToF values obtained using (4), (5), (6) and (7). Bias error due to neighbor reflection was obtained using (8).

At large spacing (Fig. 7, more than 3 μs) all signals had same performance bias error due to neighboring reflection is below few ps (ToF interpolation error).

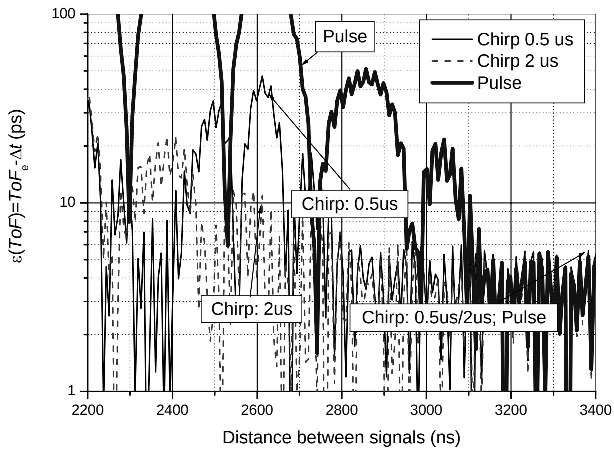

Fig. 7 – Bias error due to neighboring reflection vs. signal type at large spacing.

Performance degrades significantly if distance between reflections is reduced. Error for pulse signal is larger even in case of small spacing (Fig. 8). Such behavior of pulse signal is unexpected: being more concentrated in time it should be less sensitive to neighboring reflections.

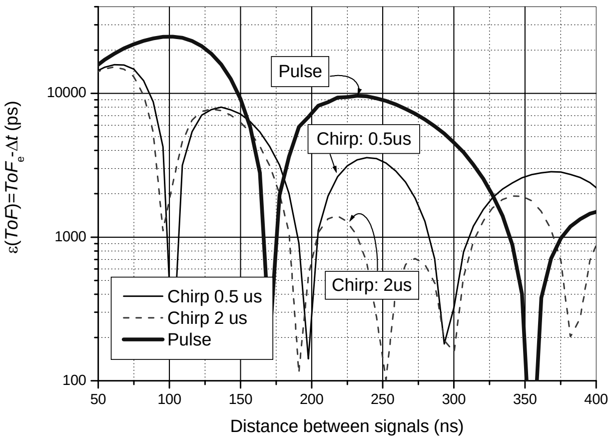

Fig. 8 – Bias error due to neighboring reflection vs. signal type at small spacing.

Obtained ToF error was normalised by the period of the transducer center frequency, f_0:

$$\delta(ToF)_{est} = \frac{\varepsilon(ToF)}{T_0} \cdot 100\% \qquad (9)$$

Results for relative ToF error obtained for 100 ns rectangular pulse (matched for for 5 MHz transducer center frequency) are presented in Fig. 9.

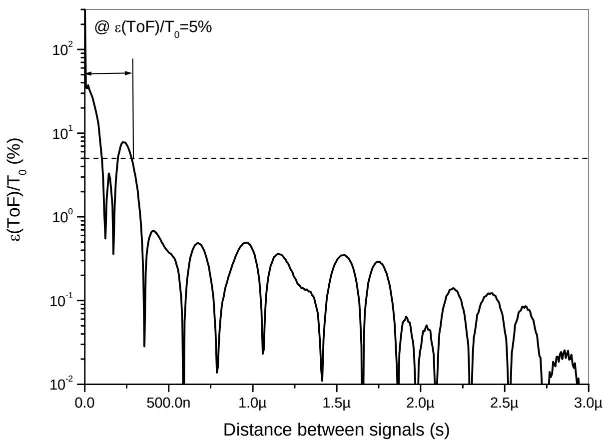

Fig. 9 – Relative time of flight estimation error for pulse signal.

Comparison of Fig. 9 results with errors for spread spectrum (2 μs chirp, Fig. 10) signal indicate the advantage of the last: errors are in the order of magnitude lower for spread spectrum excitation.

For instance, relative ToF estimation error is 5 % at 200 ns for spread spectrum signals and at 280 ns for pulse signal. For 0.1 % relative error signal spacing should be 1.25 μs for spread spectrum signals and 2.5 μs for pulse signal. Relative error is virtually zero if spacing is more than 1.3 μs for spread spectrum.

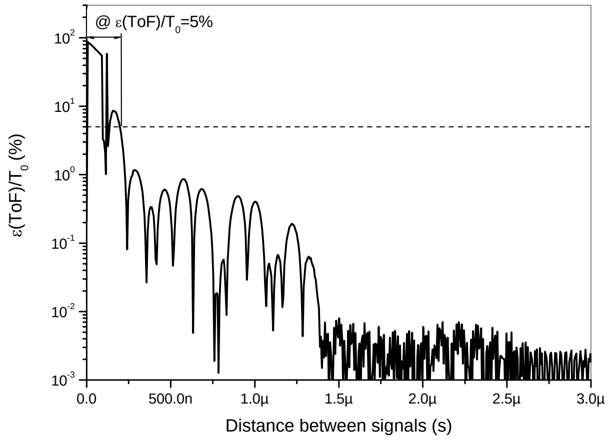

Fig. 10 – Relative time of flight estimation error for spread spectrum signal.

Amplitude reconstruction performance was studied. Once the position *ToF* is found then estimation A_{est} of the reflection amplitude in received signal s_k can be expressed via the reference signal ref_k:

$$A_{est} = \frac{\sum_{k=1}^{K} ref_k \cdot s_k}{K \sum_{k=1}^{K} (ref_k)^2 \cdot \sum_{k=1}^{K} (s_k)^2} \qquad (10)$$

Then, this estimated amplitude can be compared to actual amplitude A_{act} of used in experiment to obtain the amplitude estimation error:

$$\varepsilon_{est} = \frac{A_{est} - A_{act}}{A_{act}} \cdot 100\% \qquad (11)$$

Results for larger (first reflection in Fig. 1) pulse amplitude reconstruction are presented in Fig. 11.

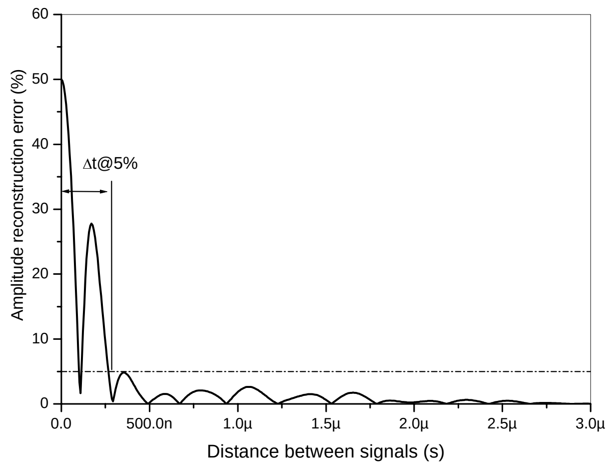

Fig. 11 – Amplitude estimation error due to neighboring reflection for pulse signal.

It can be seen that estimation error is reduced with distance and at 270 ns spacing is below 5 %. Amplitude estimation performance is slightly worse for spread spectrum (chirp) signal (Fig. 12): amplitude estimation error for chirp signal drops below 5 % at 300 ns distance.

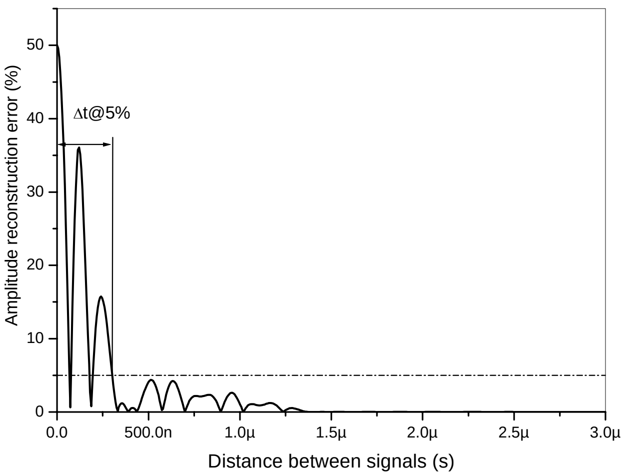

Fig. 12 – Amplitude estimation error due to neighboring reflection for chirp signal.

But it can be seen that amplitude estimation error for chirp signal is much better at large spacing: it is virtually zero at spacing above 1.3 μs. While for pulse signal such reduction is achieved only at more than twice the distance (3 μs).

5. CONCLUSIONS

It was demonstrated that presence of the neighboring reflection introduces time of flight estimation error. For separation larger than the duration of the reference signal, only interpolation errors prevail. In close proximity, additional time of flight estimation bias error is introduced which is of opposite sign for counteracting signals and depends on the amplitude of opposing signal. Situation can be explained from the signal theory: the neighboring signal produces the energy leak into its opponent. Narrow signals like single rectangular pulse, should suffer less from the aforementioned phenomena. But use of spread spectrum signals is preferred thanks to their energy and compressibility property. It was hypothesized that spread spectrum signals, being long signals will have worse bias error due to neighbor reflection. Comparison time of flight estimation error bias caused by neighbor reflection of pulse and chirp signal revealed that spread spectrum signals have better performance compared to short pulse signals.

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