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Comparison between time and frequency domain ToF estimators for signals in close proximity

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Abstract

Case is when two reflections are in close proximity is analysed. Such proximity introduces bias errors in ToF estimators for all interfering signals. Purpose of the investigation was the comparison of the time and frequency domain estimation algorithms with the aim to establish the insight into possible algorithms which are capable to reduce those errors. Evaluation is based on simulation using the pre-recorded real single reflection. Simulation is supported by additional experimental results.

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Keywords: Time-of-flight; digital signal processing; sparse reflections; bias error; thickness measurement.

1. Introduction

Case considered is dealing with ultrasonic thickness measurement. Measurement involves probing pulses delay or time of flight (ToF) estimation. Time domain and spectroscopy techniques were considered for ToF estimation. Svilainis and Aleksandrovas (2013) have indicated that bias errors are introduced in ToF estimators when two reflections are in close proximity. The closer are the signals, the larger is the error which also depends on to the amplitudes of the interfering signals. Spectroscopy technique proposed by Gomez (2003) should be free of such bias errors and offers improved resolution for overlapping reflections. Aim of the research was to compare the performance of these techniques both by simulation and by real experiments.

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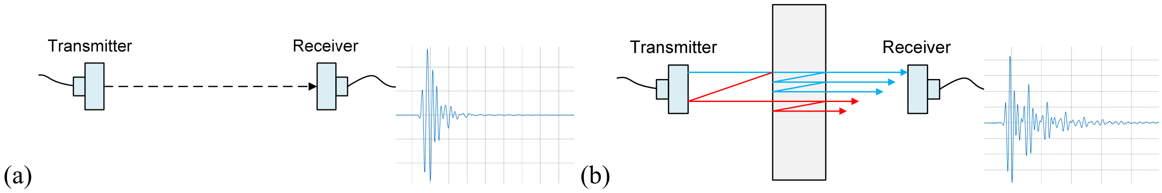

Fig. 1. Setup used to (a) record the reference signal and (b) measurement signal when test sample is inserted into ultrasound path.

2. Investigation techniques

Thickness of the plate thickness can be measured if velocity of the material is known. Case considered involves simultaneous velocity and thickness estimation, using setup (see Fig. 1) described by Hsu and Hughes (1992) and by Gomez (2010). Taking the reference signal without the test sample inserted obtained in setup Fig.2a and the measurement signal propagated through the sample (Fig.2b) the difference in propagation delay between reference and the first pulse can be established ΔToF_{R1}. It should be noted, that only first pulse of the measurement signal has to be used. Taking ToFs of succeeding pulses of the measurement signal (Fig.2b) differences between first and second echo, ΔToF_{12}, between second and third echo, ΔToF_{23}, and so on can be obtained. According to Hsu and Hughes (1992) ΔToF_{R1} and ΔToF_{12} can be combined to obtain ultrasound velocity in plate material c_m and plate thickness h:

$$c_m = c_{air}\frac{\left(\Delta ToF_{R1} + \Delta ToF_{12}\right)}{\Delta ToF_{12}},\ h = c_{air}\left(\Delta ToF + ToF_{12}\right), \tag{1}$$

where c_{air} is the ultrasound velocity of the coupling media around the tested plate, in our case it was air. Errors in c_{air}, ΔToF_{R1} and ΔToF_{12} estimation will increase the uncertainty of equations (1) and (2) application result. Of course, there are other sources of error like plate surface roughness, plate orthogonality to beam and others but in current research we consider only uncertainty components present in equations (1) and (2). Temperature variation within (17-22) C^o will cause deviation of c_{air} by -1.59 m/s to +1.33 m/s from 343.21 m/s nominal value. Sensitivity analysis indicates that this will cause thickness h estimation error of -0.46 % to +0.38 % if plate with h=3.124 mm and c_m=1639.867 m/s is measured. Deviation by 100ns in ΔToF_{12} estimation will cause 0.6 %error of plate thickness h estimation. Same deviation in ΔToF_{R1} estimation will cause 1.1 %error of thickness estimation. Temperature influence can be compensated by careful temperature stabilization of additional temperature measurement. But if ToF estimation technique produces errors these can not be compensated so easily.

2.1. ToF estimation using iterative deconvolution

The idea of iterative deconvolution is based on subsequent removal of reflections from the signal (Barrodale (1984)): 1) remainder is assigned to the measurement signal; 2) candidate for removal is found using correlation between measurement signal and the reference peak or remainder minimum (Crilly (1991)), ToF_i is the position of the peak which is additionally interpolated using cosine function (see Svilainis and Lukoseviciute (2013)); 3) scaling A_i of the reference is found using correlation coefficient for candidate position (Kazys (1997)); scaling; 4) ToF_i and A_i are stored to the output spike train; 5) reference signal is shifted into ToF_i position, scaled and subtracted from measurement signal. Next iteration continues from point 2 using the new remainder. Process is stopped once the predetermined number of reflections is extracted.

Obtained ToF were used to calculate ΔToF_{R1} and ΔToF_{12} estimates and material thickness and velocity. In case of simulated signals actual ΔToF_{12} value was known. Therefore estimate of the ΔToF_{12} was additionally checked for bias errors produced by interference with neighboring reflections. Same was for all three techniques considered.

2.2. ToF estimation using reiterative deconvolution

Reiterative deconvolution reiterates all the iterative deconvolution steps. First reiteration acts exactly as iterative deconvolution. But iterative deconvolution suffers ToF (and the scaling) bias errors if reflections are close (see Svilainis and Aleksandrovas et al. (2013)). Reiterative deconvolution is aimed to reduce these errors. Next reiterations are different from iterative deconvolution: 1) remainder is produced from the measurement signal; candidate for removal is already known from previous steps but it needs temporal and scaling adjustment, therefore all the latest information on reflections positions and scaling is used to subtract the interfering reflections so only reflection of the interest remains in the remainder; 2) ToF_i position is found using correlation and subsample interpolation; 3) scaling of the reference is found using correlation coefficient; 4) ToF_i and A_i are stored to the output spike train, replacing the previously stored values. Note that remainder signal is always produced from the measurement signal, but removing all but candidate reflections. Number of reiterations is always the same as for the first reiteration. Number of reiterations was predetermined.

2.3. ToF estimation using spectroscopy

Spectroscopy can directly estimate $\Delta \mathrm{ToF}_{12}$ value by measuring the thickness resonance of the sample. Analysis is improved by taking the ratio of the measurement and reference signals spectra (see Gomez (2003)). To counter the noise problem theoretical model of the plate is fit on measured ratio spectra. It has to be done for the frequency range where one or several resonances of the membrane appear. It has been noted in Gomez (2009) that at resonance conditions spectra corresponds to measurements taken without interference and ΔToF_{R1} can be established too.

3. Results and discussion

Simulation has been carried out to evaluate the errors occurring. Two reflections (reflection from step reflector) were placed at variable, known spacing and measured spacing was compared for errors. Results are presented in Fig.2a. It can be seen that two reflections produce large errors in case of iterative deconvolution. Reiterative deconvolution reduces bias errors significantly. Another case simulated was analyzing the setup of Fig.1b: multiple reflections in plate. It can be noted that errors are lower here thanks to symmetry of neighboring reflections placement. Both deconvolution techniques exhibit processing errors yet reiterative deconvolution behaves better. Errors for spectroscopy were not included in graphs because they were negligible. This is natural to expect because plate propagation model used in spectroscopy was used for simulation.

Real experiments included several materials placed between two wideband 0.6 MHz center frequency air-coupled transducers designed and manufactured by CSIC (see Gomez (2013)).

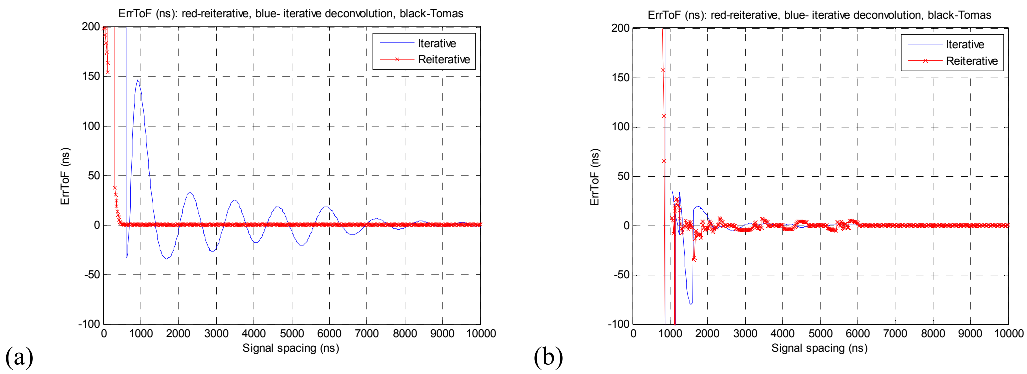

Fig. 2. Bias errors obtained from simulation when (a) two reflections are in signal and (b) seven reflections are in signal.

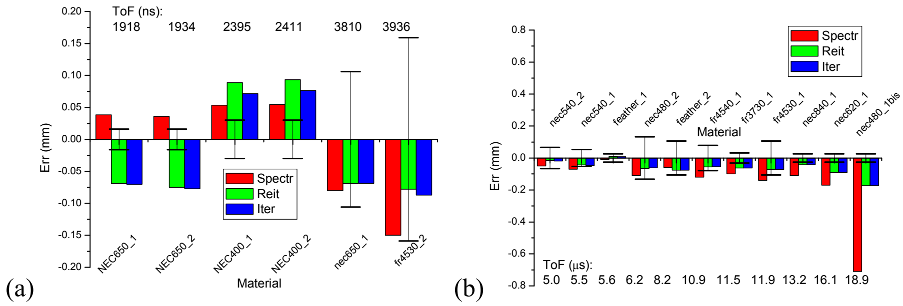

Fig. 3. Errors of real experiment results when thickness was measured for (a) < 4µs spacing; (b) > 5µs spacing between multiple reflections.

Multiple micrometer measurements were done on the test plates. Basing the obtained average values estimation errors for air-coupled thickness measurement were obtained. Results are summarized in Fig. 3. Same micrometer measurements were used to calculate the thickness variation which was plotted on error graphs as limiting scatter. It can be seen that spectroscopy produced lower errors for close proximity between multiple reflections (Fig. 3a). Iterative techniques were able to produce lower errors when spacing between reflections was larger than 4 µs (refer ToF values indicated in Fig. 3).

4. Conclusion

It was noted that iterative deconvolution is more stable and applicable for automated measurements. Yet, it requires suitable reference signal. Therefore subtraction quality is good only for first reflections. Removal of succeeding reflections is problematic if reference signal is not adaptive. Spectroscopy combined with plate propagation model is capable to handle frequency domain losses. Furthermore, material density, porosity can be extracted from spectral information. All techniques can be combined together to produce better parameters estimate.

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