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Study of Various Excitation and Reference Signals for Pulsed Correlation-based Ultrasound Signal Processing

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Introduction

Ultrasound lamb-waves (generated and received for example, by piezo-transducers -PZTs) can be efficiently used for health monitoring of composite structures (SHM) [1], including (among other applications) monitoring of the wind turbine blades, which is based on changes in wave attenuations, time-frequency analysis, wave reflections and “time of flight” (TOF) information. Pulse-echo and pitch-echo methods are main alternatives of implementation of the pulsed Lamb-waves based diagnostics [2]. Also beam-forming (ultrasonic radar) can be a useful approach [2–5].

Typically excitation signal is 3-5 periods (“burst”) of windowed sinewave of ultrasound frequency and received signal is found by cross-correlation processing [1-5] (by convolution or dot-product calculation in digital case, as a function of the time delay) of the received signal, by using of the reference (expected) waveform (generated signal itself, in a most typical case). Further more, reconstruction of the envelope of the received burst from the correlation signal, for example by using of the Hilbert transfer [3,4,5,7] for imaginary part of the correlation function and taking module of the received (real) and calculated imaginary part can give better understanding about the received pulse, being a smooth function with a single peak- while correlation function itself has many local maximums.

In the patent information additionaly to ideas of using of the Hilbert transform for signal envelope generation [7], also a pair of quadrature reference signal has been suggested [6,7] or delaying the input waveform by a peak-to-zero delay (PZD) interval [8], that means by 90 degrees.

For improving of the time resolution or signal-to-noise ratio so called ”pulse compression” can be used, by modulating the excitation burst signal in the frequency or phase domain. Probably using of the linear chirp is a simple alternative. Simplification of the used waveforms, eg using of the rectangular (binary) signals instead of sinewaves can allow to relax the requirements to the hardware and software of the embedded structural health monitoring solutions [9].

Measurement setup

Generation of the excitation waveform (“bursts” of sine-wave or binary pulses), as well as data acquisition and processing has been carried out by PC-based setup. PZTs (of Noliac - www.noliac.dk) – 3 pieces (of which two pieces were used in the described experiments)- are fixed to a glass fiber composite material 500x500x4 mm) by special glue (Fig. 1).

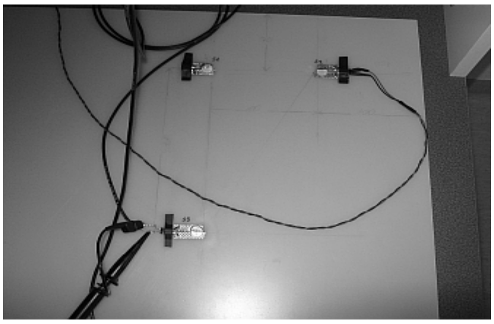

Fig. 1. Placement of PZTs (a photo)

For described experiments a following setup has been used. Measurement system is PC-based (with Matlab tools and interfaces) with using of National Instruments' USB-6259, a USB high-speed M-series multifunction data acquisition (DAQ) module optimized for good accuracy at fast sampling. This unit contains multiplexed analog-to-digital converter (ADC) and digital-to-analog converter (DAC), both with maximum 1.25Ms/s speed (actually 1Ms/S was used in described experiments) and 16-bit resolution. A signal conditioning analog front end is containing a power driver with Ku=3 voltage amplification and a voltage divider (1:3) to measure excitation voltage Uexc (to ±30V) is on the PZT1 circuit and a response voltage from another PZT2 (Fig. 2).

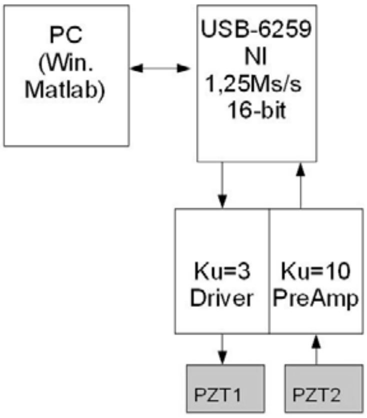

Fig. 2. Measurement setup (block diagram)

Algorithms and measurement results

In current study a burst of the sine-wave of 5 periods of 200 kHz has been generated. The following cases has been studied:

1) In one case the excitation signal has been windowed by Gaussian windows;
2) In another case no windowing (that means “rectangular window“) has been used;
3) In third case a binary sequence instead of sine-wave has been for excitation and instead of fixed frequency a linear chirp (from 180 kHz to 220 kHz) has been used.

In all cases the absolute value of the *cross-correlation* with excitation signal (as expected response) has been found as a function of a time delay (or lag, in other words, in ms units). Furthermore, a *correlation with “quadrature”* version of the excitation (cosine wave, identical to used sine-wave) has been calculated and combined, in one case *as sum of absolute values*, in another case as *sum of squared values of these two (“inphase and quadrature”) correlations.* Using of “quadrature correlation” component, calculated from the cosine reference wave is calculation-efficient, compared with using of Hilbert transform in general form (over received input signal, for example).

So, the following experiments has been carried out (with measured and calculated results showed on Fig. 3 till Fig. 17.

Windowed burst of 5 sine-periods (200kHz).

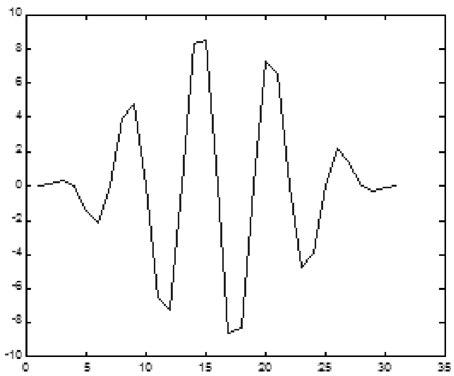

Fig. 3. Windowed burst of excitation *(relative amplitud vs indexes of samples)*

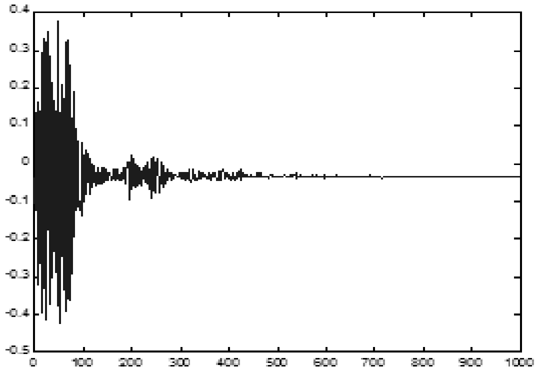

Fig. 4. Windowed burst of excitation- response signal *(voltage vs time in ms)*

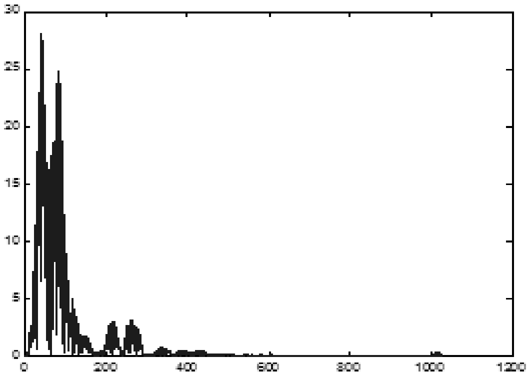

Fig. 5. Windowed burst of excitation- cross-correlation (absolute value) with response *signal (accumulated dotproduct vs time in ms)*

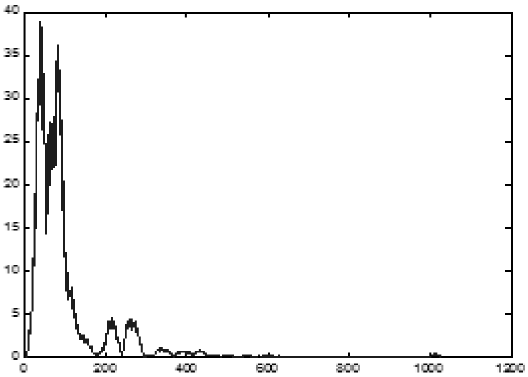

Fig. 6. Windowed burst of excitation- sum of cross-correlations (absolute values) with response signal *and its quadrature component*

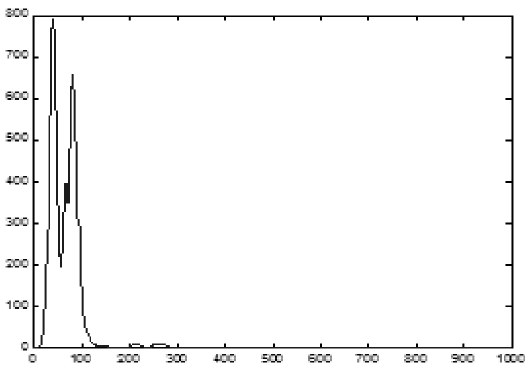

Fig. 7. Windowed burst of excitation- sum of squares of cross-correlation with response signal and **its quadrature component** (*time in ms)*

Burst of 5 binary periods of 200kHz.

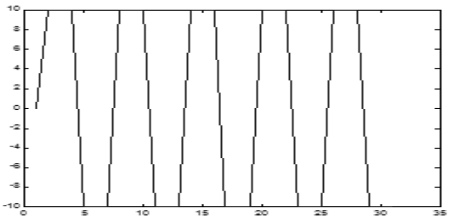

Fig. 8. Binary burst of excitation excitation *(relative amplitud vs indexes of samples)*

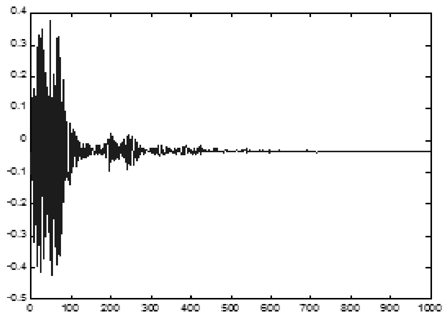

Fig. 9. Binary burst of excitation- response signal*(voltage vs time in ms)*

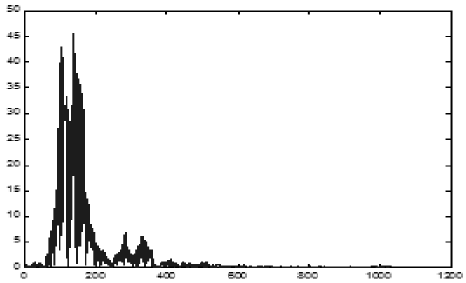

Fig. 10. Binary burst of excitation- cross-correlation (absolute value) with response signal *(accumulated dotproduct vs time in ms)*

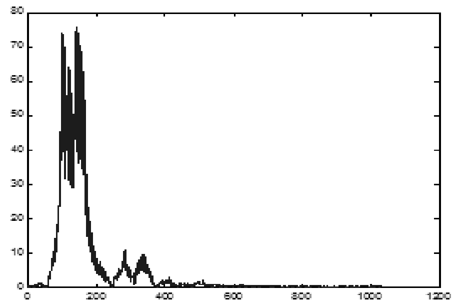

Fig. 11. Binary burst of excitation- sum of cross-correlations (absolute values) with response signal *and its quadrature component*

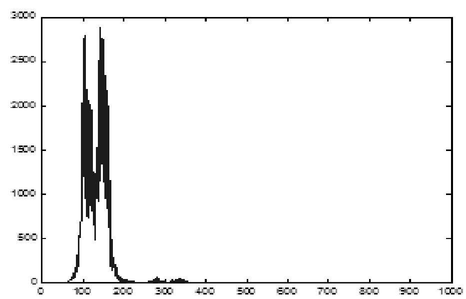

Fig. 12. Windowed burst of excitation- *sum of squares* of cross-correlation with response signal and *its quadrature component* (*time in ms)*

Burst of 5 binary periods of chirp (180-220kHz).

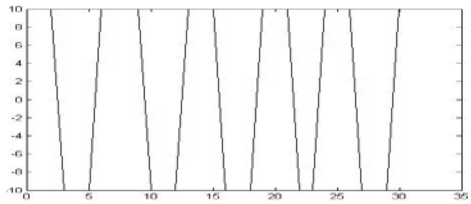

Fig .13. Binary burst of excitation (Chirp) *(relative amplitud vs indexes of samples)*

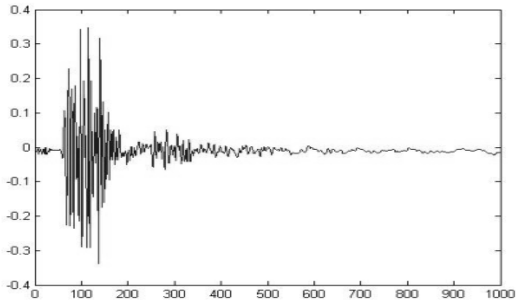

Fig. 14. Binary burst of excitation (chirp)- response signal *(voltage vs time in ms)*

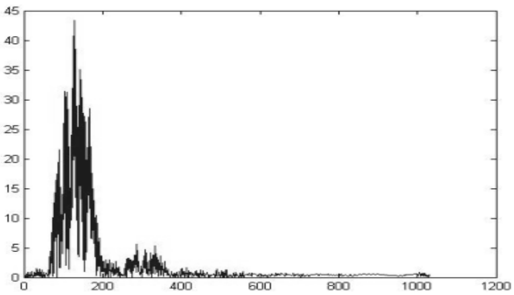

Fig. 15. Binary burst of excitation- cross-correlation (absolute value) with response signal *(accumulated dotproduct vs time in ms)*

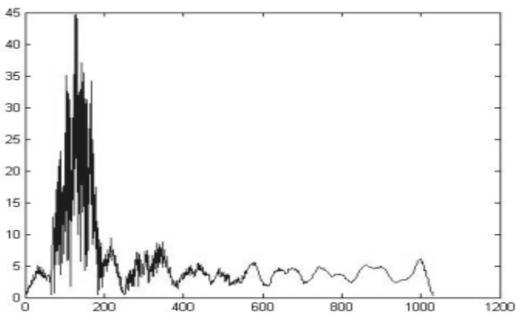

Fig. 16. Binary burst of excitation- sum of cross-correlations (absolute values) with response signal *and its quadrature component*

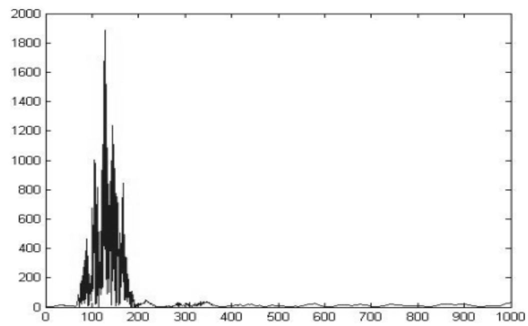

Fig. 17. Windowed burst of excitation – *sum of squares* of cross-correlation with response signal *and its quadrature component*

Conclusions

While using of correlation calculation for finding of time-of-flight and parameters of the received pulse (burst), using of additional "quadrature correlation" component improve the envelope shape and is computationally more efficient, compared with widely used Hilbert transform. Alternatively to summing of in-phase and quadrature correlation components as squared *values a linear sum of absolute values of correlations can much improve the envelope,* with lower cost of algorithm realization complexity and still with good results, *especially for binary signals.* Also experiments show the efficiency of using of binary and chirp signals for excitation and as reference signals for correlation calculation.

Acknowledgements

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O. Märtens, T. Saar, M. Reidla. Study of Various Excitation and Reference Signals for Pulsed Correlation-based Ultrasound Signal Processing // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 9(105). – P. 89–92.

Ultrasound Lamb waves are used for health monitoring of composite structures. Received signals are correlated by windowed bursts of excitation signal to find time-of-flight and parameters of the received waveforms. In current paper modifications of excitations signals and reference signals are studied, emulations with using a PC-based measurement experimental setup with a composite plate and piezo-sensors are carried out. The study shows the ways of improvement of correlation-based signal processing accuracy, for finding the signal envelopes more precisely, from one side, and possible simplifications of the signal waveforms and signal processing from other side, to make the solutions more practical for implementations. Ill. 17, bibl. 11 (in English; abstracts in English and Lithuanian).

O. Märtens, T. Saar, M. Reidla. Ultragarsinių signalų apdorojimas taikant impulsinę koreliaciją įvairaus žadinimo ir šaltinių signalams // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 9(105). – P. 89–92.

Sveikatos stebėsenai sudėtinėse sistemose taikomos ultragarsinės Lamb‘o bangos. Gautieji signalai koreliuoja su žadinimo signalais. Apžvelgiami žadinimo ir pirminiai šaltinių signalai. Atlikti eksperimentiniai matavimai su kompozicine plokštele ir pjezojutikliais. Iš gautų rezultatų matyti koreliacijos sąlygotų signalų tikslumo didinimo bei signalų apdorojimo supaprastinimo būdai. Il. 17, bibl. 11 (anglų kalba; santraukos anglų ir lietuvių k.).

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