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Arbitrary Position and Width Pulses Sequences Excitation for Ultrasound Spectroscopy

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Abstract: Application of spectral losses compensation in thickness resonance ultrasound spectroscopy (TRUS) was investigated. The arbitrary position, and width pulses (APWP) sequences were used to deliver higher energy and bandwidth and results compared to single pulse and chirp excitation in air-coupled and immersion setup.

Keywords: thickness resonance ultrasound spectroscopy, spread spectrum signals, losses compensation.

Introduction

Thickness resonance ultrasound spectroscopy (TRUS) is a tool to simultaneously estimate the sample thickness, density, ultrasound velocity and attenuation [1]. This technique requires wide bandwidth signals. Ultrasonic transducers are not able to provide broadband transduction. Furthermore, usually pulse signals are used for measurements. Pulse duration has to be reduced in order to obtain broadband spectrum. But then energy is reduced leading to SNR reduction. SNR can be improved by using higher excitation amplitude, but there is a limit. Spread spectrum (SS) signals can provide both energy (by increasing the signal duration) and bandwidth. Nonlinear frequency modulation (NLFM) and arbitrary position, and width pulses sequences (APWP) can also provide a programmable spectral content [2]. Then, by pushing the energy of the excitation signal into frequencies where transduction losses are high received signal bandwidth can be improved [3],[4]. This investigation analyses positive effects of spectral losses compensation on TRUS measurements.

Methods

TRUS [1] is exploiting the thickness resonance of the sample and temporal shift when sample is inserted. Its main advantages are that: i) completely overlapping internal reflections and ii) thickness and velocity of the sample are estimated simultaneously along with attenuation and density. When air-coupled ultrasound is used it becomes a non-contact resonant ultrasound spectroscopy (NC-RUS). Yet, it can be used in immersion setup too.

Two transducers (one acting as transmitter and other as receiver) are mounted at some distance, ensuring operation in the near field (flat wavefront). Two measurements (Fig. 1) are taken: i) calibration measurement, when path between transducers is free from obstacles and ii) sample measurement, when sample is inserted between transducers.

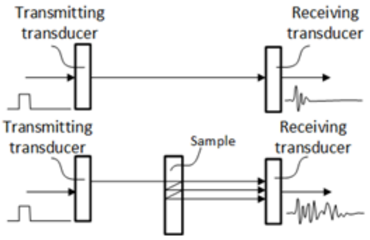

Fig. 1: TRUS measurement: Calibration (top), Reference (bottom) setup.

Calibration measurement is used to simulate the Sample signal by using the transmission model for layered media [5]. Model parameters (sample thickness, density, ultrasound velocity and attenuation) are adjusted until best fit to measured Sample signal is obtained. More details on the algorithm are in [6].

The 2 mm (resonance expected at 560 kHz) polycarbonate (PC) sample was investigated. Measurements were carried out in air-coupled and immersion setup.

Air-coupled setup used a pair of 20 mm diameter wideband 650 kHz center frequency transducers (designed and manufactured by the Spanish National Research Council, CSIC) [7]. Transducers were placed at 32 mm distance. Excitation used a half bridge topology pulser, 10 V bipolar, rectangular chirps (linear frequency modulation, LFM) and APWP [2] sequences. Sensitivity of these transducers is very high, up to 12 Pa/V in transmission, therefore, in order to avoid nonlinearity in air and exaggerate noise effects, low excitation voltage was used. Signal from receiving transducer was amplified by a programmable gain preamplifier (0.1-3 MHz bandwidth, 5 kΩ input impedance) [8]. A dedicated ultrasonic signal acquisition system [8] was used to collect data.

The APWP signals were optimised to achieve flat received signal spectrum within predefined frequency range. The 50 μs long bipolar APWP signals were derived using [6], based on 100 kHz-1.5 MHz 100 μs LFM excitation. Two ranges were used: 385 kHz-910 kHz (corresponding to -20 dB-deep losses compensation) and 240 kHz-860 kHz (-6 dB compensation). Additionally, LFM signals of same range were generated for comparison. LFM, APWP and single 100 ns pulse were used in NC-RUS measurements (Fig. 1).

Immersion setup used a pair of 6 mm diameter wideband composite 2 MHz center frequency transducers, placed at 10 mm distance (near field condition is satisfied only beyond 1.5 MHz). No diffraction correction was used. Acqusition used same equipment [2] as in air-coupled setup.

The APWP signals were optimised [3] to achieve flat received signal spectrum witin 740 kHz-3.43 MHz (corresponding to -20 dB-deep losses compensation) and 1.12 MHz-2.34 MHz (-6 dB compensation), basing on 300 kHz-3.9 MHz 50 μs long LFM excitation. Derived 40 μs APWP signals along with same range LFM and 100 ns pulse were used in TRUS [6] immersion measurements.

Results

Spectra of received signals in air-coupled setup for 650 kHz transducer pair are presented in Fig. 2 (compensated for -6 dB bandwidth), and Fig. 3 (-20 dB bandwidth). Results are normalized to excitation voltage, i.e. correspond to excitation using +/-1 V.

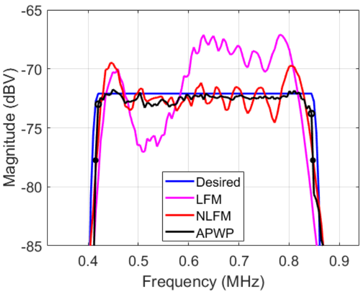

Fig. 2: Received signals spectra for 418 kHz-840 kHz bandwidth in air-coupled setup.

Flat APWP signal spectrum within the optimization range (circles) was achieved in both cases. It must be noted that bandwidth improvement comes at the expense of energy loss at center frequency. LFM signal has its excitation spectrum uniformly distributed over desired bandwidth. Therefore, received signal contains losses at the bandpass edges. NLFM signal has broader spectral coverage, comparable to APWP, but its spectrum is nonuniform.

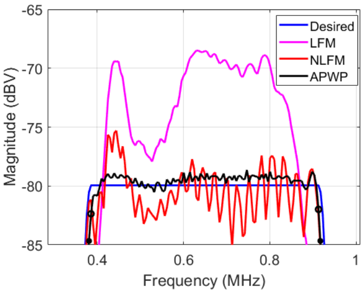

Fig. 3: Received signals spectra for 385 kHz-910 kHz bandwidth in air-coupled setup.

Results of NC-RUS, obtained using signals above are presented in Fig. 4. Frequency range covered by wideband excitation is sufficient to locate one resonant peak and one valley. NC-RUS inverse solution is close to expected values: thickness *h* is 2028 μm (caliper-measured value is 2050 μm), velocity *v* is 2172 m/s (expected 2222 m/s) density ρ is 1484 kg/m^3 (expected 1193.6 kg/m^3) attenuation α_0 is 29 Np/m at 560kHz (expected 43.5 Np/m) and estimated power law *n* is 0.3 (expected 1). The last two have large deviation form expected, but reason is that wide frequency range is required for these measurements to converge to correct values. Next experiment had much better frequency range coverage.

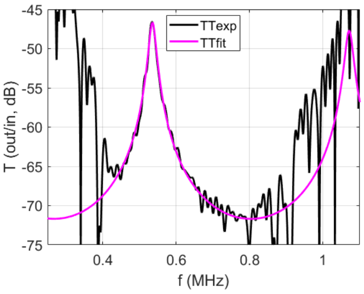

Fig. 4: NC-RUS magnitude for wideband APWP in air-coupled setup.

Results for 2 MHz transducers pair immersion setup when optimization was carried out within transducer -6 dB passband (1.12 MHz-2.34 MHz) are presented in Fig. 5. Results for broader (740 kHz-3.43 MHz), -20 dB passband optimization are presented in Fig. 6. Both have 40 μs length. It must be noted, that reception preamplifier bandwidth was 3 MHz, so compen-

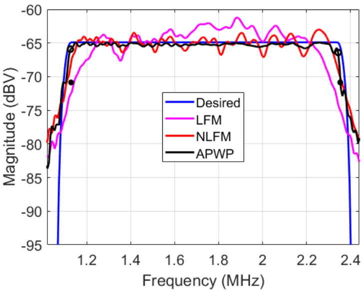

Fig. 5: Received signals at 1.12 MHz-2.34 MHz bandwidth for 2 MHz transducers immersion setup.

sation for preamplifier losses was required in order to attain 3.43 MHz passband. This was done intentionally, to demonstrate the compensation capabilities. Same can be concluded: broader bandwidth requires more passband losses, NLFM spectrum is less uniform when more compensation is required. Results of immersion mode TRUS, obtained using signals above are presented in Fig. 7.

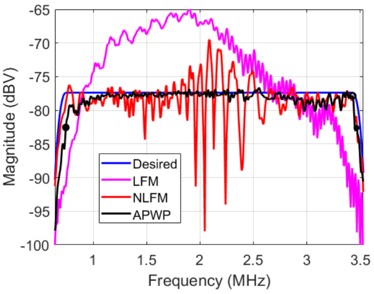

Fig. 6: Received signals at 740 kHz-3.43 MHz bandwidth for 2 MHz transducers immersion setup.

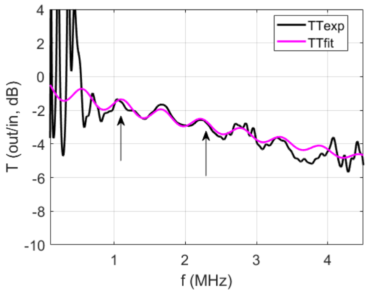

Fig. 7: TRUS magnitude for narrowband APWP signal.

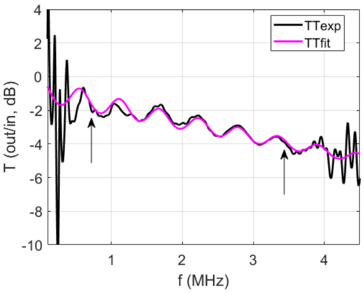

Fig. 8: TRUS magnitude for wideband APWP signal.

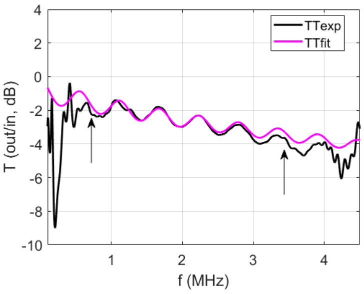

Fig. 9: TRUS magnitude for wideband LFM signal.

Few conclusions can be drawn: PC impedance is much closer to water than air, therefore signal passing through contains more energy. Also, transduction to water produces much higher pressure. Therefore, SNR is much higher than in previous experiment. Narrowband excitation concentrates more energy into passband, but SNR in the stopband is lower, therefore transmission response beyond the excitation range (indicated by arrows) is distorted. Less energy at high frequencies also means less accuracy in frequency-dependent attenuation estimation (α_0 and n). Wideband LFM signal does not provide enough energy at high frequencies, therefore fitting deviates (compare Fig. 8 and Fig. 9 results).

TRUS results are summarized in Fig. 10.

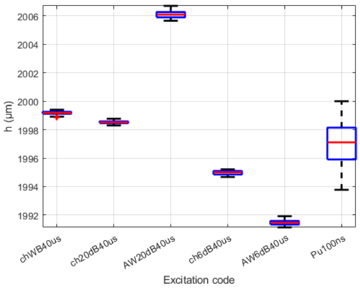

Fig. 10: TRUS results for sample thickness.

It can be noted that only wideband APWP signal (AW20dB40us) is closest to expected thickness h value (2045 μm), yet bias errors for other signals are not large, maximum 0.6 %. Higher bias errors are obtained for narrowband signals. Even pulse bias error is lower than for narrowband signals. Yet, pulse has low energy therefore random errors are largest here. Same can be found for velocity (Fig. 11).

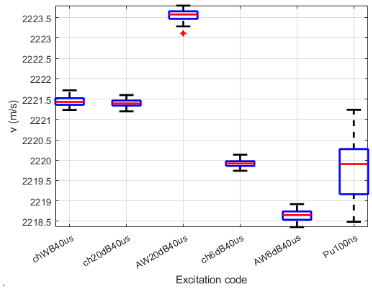

Fig. 11: TRUS results for sample velocity.

Wideband APWP signal is giving 2223 m/s (expected 2222 m/s), lowest bias error. Narrowband (ch6dB40us and AW6dB40us) or even wideband LFM (chWB40us) produce larger errors, yet maximum bias error is 0.2 %. Again, pulse has largest random errors. Similar situation is with density (Fig. 12).

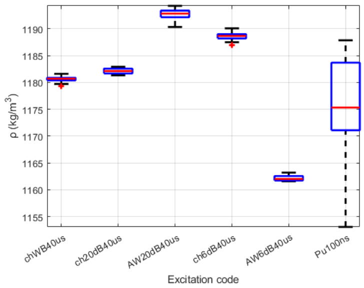

Fig. 12: TRUS results for sample density.

Attenuation was not estimated correctly (expected α_0 is 638 dB/m/MHz, (Fig. 13)), but this can be the case, because transducer diameter was small, for low frequencies wavefront deviates from flat, energy leaks away from beam. This results in artificially reduced attenuation at high frequencies.

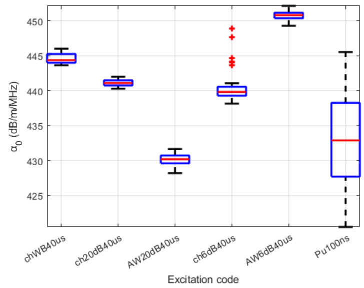

Fig. 13: TRUS results for sample attenuation.

It can be seen that random errors, though extremely small, are higher for APWP signal than its LFM counterpart (refer Fig. 2, Fig. 3, and Fig. 5, Fig. 6 for spectra comparison). This is the toll to be paid for improved bandwidth and reduced bias errors.

Conclusions

APWP signals can be used to broaden the bandwidth. This results in lower bias errors of TRUS if bandwidth is flat. Wideband SS signals, like LFM do not result in flat bandwidth therefore bias errors obtained are higher than for APWP. TRUS random errors are quite small, indicating it as an accurate tool for sample parameters measurement.

Acknowledgment

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