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Spectral Content Improvement by Spread Spectrum Excitation for Air-Coupled Ultrasound

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Abstract: Analysis how spectral content of the air-coupled signals can be improved, by using the spread spectrum (SS) signals is presented. Three air-coupled transducers were used to compare the obtained bandwidth, SNR and spectral flatness, when excited using conventional signals and programmable spectrum signals.

Keywords: air-coupled ultrasound, spread spectrum signals, losses compensation.

Introduction

Air-coupled ultrasound is offering the advantage of non-contact measurements. However, the impedance mismatch between the piezoelement and the air objects efficient transduction. Using quarter wavelength matching layers improve transduction but transmission is still relatively narrowband [1]. Other transduction techniques, like capacitive are able of broader bandwidth, but suffer sensitivity [2]. Use of higher excitation amplitude voltage can increase the signal SNR, but there is a limit (breakdown voltage, electronics capabilities [3]). Also, if narrower pulse is used aiming the bandwidth, excitation energy is lower. Spread spectrum (SS) signals offer bandwidth which does not depend on signal duration. It was already demonstrated that SS signals, like nonlinear frequency modulation (NLFM), arbitrary position, and width pulses sequences (APWP) enable to control the spectral content [4]. Then spectral losses in transduction can be compensated, broadening the transmitted bandwidth [5], [6]. This investigation analyses how spectral content of the air-coupled signals can be improved, by using the SS signals.

Methods

Three pairs of air-coupled transducers were used in investigation: i) quarter-wavelength layers-matched PZT with center frequency 650 kHz, ii) quarter wavelength layers-matched PZT with center frequency 1 MHz and iii) capacitive (electrostatic) transducer. The quarter-wavelength layers-matched PZT transducers (designed and manufactured by the Spanish National Research Council, CSIC) had a 20 mm diameter piezoelement [7]. Capacitive transducer was made by placing a 12 µm metalized (300 nm Al) PET film on FR4 PCB with 20 mm diameter copper electrode on it. A pair of same transducers, one transmitting, other receiving was used. Transducers were placed at 20 mm distance, were excited by a half bridge topology pulser (SE-TX01-02) [3], using bipolar, rectangular chirps (linear frequency modulation, LFM, 0.1-1.5 MHz 100 µs long). The $\lambda/4$ matched PZT 650 kHz and 1 MHz center frequency transducers were excited by 10 V amplitude, capacitive transducer was excited by 50 V. The capacitive transducer had 300 V bias. Receiving transducer signal was amplified by a programmable gain preamplifier SE-RX02-00 (0.1-3 MHz bandwidth, 1kΩ input impedance) [8]. A dedicated ultrasonic signal acquisition system [8] was used. Signals acquired were used to derive the 100 µs long bipolar APWP signals using technique described in [5]. Optimization of APWP signals aimed to get a flat spectrum within same frequency range. Tukey window with 0.1 transition rate was used with flat portion of the window corresponding to the desired frequency range. This type of signals is useful is application requiring flat and broad spectrum: non-contact resonant spectroscopy, imaging, ranging applications requiring axial resolution. Narrow correlation peak is obtained after pulse compression thanks to wider bandwidth. As an intermediate results NLFM signals were derived. Additionally, preamplifier output noise was measured when loaded by transducer and was converted to input-referenced noise using technique [9].

All signals used for excitation were rectangular, bipolar counterparts of the respective versions of the signals used. These signals then were used to excite the same transducer pairs and results stored for further processing. Signals, received using LFM and APWP signals were transferred into frequency domain and results were compared in a sense of obtained bandwidth, SNR and spectral flatness.

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Results

The transmission response of the whole system can be obtained by taking the ratio of the received signal spectrum to the spectrum of code transmitted. Transmission response of the $\lambda/4$ matched PZT 650 kHz center frequency transducer is presented in Fig. 1.

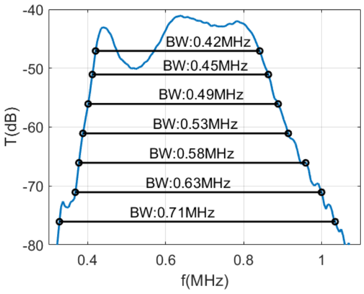

Fig. 1: System transmission when $\lambda/4$ matched PZT 650 kHz center frequency transducers.

Note the transmission bandwidth of the system at -6, -10, -15, -20, -25, -30 and -35 dB. Same for 1 MHz center frequency $\lambda/4$ matched PZT transducer is presented in Fig. 2.

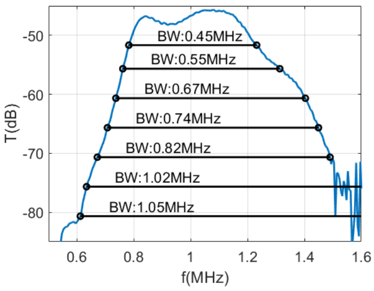

Fig. 2: System transmission response in case $\lambda/4$ matched PZT 1 MHz frequency transducers.

It can be noted that bandwidth is broader than 650 kHz case: at -20 dB bandwidth is 0.74 MHz vs. 0.53 MHz. Sensitivity is slightly lower therefore -30 dB and -35 dB bandwidth estimation is unreliable due to noise presence. Estimated passband frequencies were used as a range for NLFM and APWP derivation. Results for capacitive transducers pair are presented in Fig. 3. Despite lower resonance frequency, -20 dB bandwidth is 1.32 MHz, almost twice compared to PZT transducers. Capacitive transducers had lower sensitivity, therefore bandwidth estimation below -20 dB is not reliable. Capacitive transducers had lower sensitivity (compare -80 dB transmission at peak vs. -40 dB and -45 dB for PZT), therefore bandwidth estimation below -20 dB is not reliable.

Spectra of received signal for 650 kHz transducer

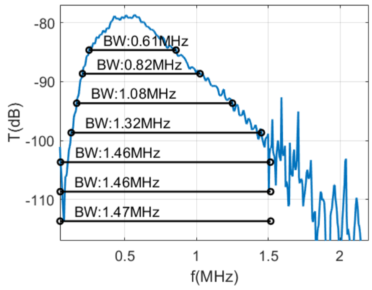

Fig. 3: System transmission of capacitive transducers.

pair when spectral losses are compensated are presented in Fig. 4 (-20 dB). Results are normalized to excitation voltage, i.e. excitation using +/-1 V.

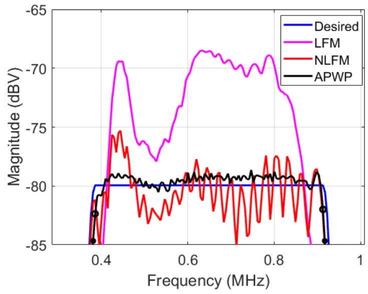

Fig. 4: Received optimized signals spectra for -20 dB (Fig. 1) bandwidth for PZT 650 kHz transducers.

Flat spectrum within the optimization range (circles) was achieved in both cases. More nonuniformity can be noted in NLFM signals when more compensation is required.

Two essential differences can be noted: i) broader compensation bandwidth requires more passband losses (compare -72 dBV vs. -85 dBV in passband, a 13 dB drop in signal level) and ii) spectrum is less uniform when more compensation is required. Results for 1 MHz transducers pair is presented in Fig. 5 (-30 dB).

Same can be concluded: broader bandwidth requires more passband losses (-75 dBV vs. -95 dBV in passband, a 20 dB drop), spectrum is less uniform when more compensation is required. Results for capacitive transducers pair is presented in Fig. 6 (-20 dB).

One more important aspect should be accounted: usually noise spectral density is nonuniform, see Fig. 7 for 1 MHz transducer.

Resulting SNR for 650 kHz transducer is presented in Fig. 8 and Fig. 9. It must be noted that results are for +/-1 V excitation voltage. Therefore, SNR reported has to be scaled by actual excitation voltage. Since excitation voltage in air-coupled measurements

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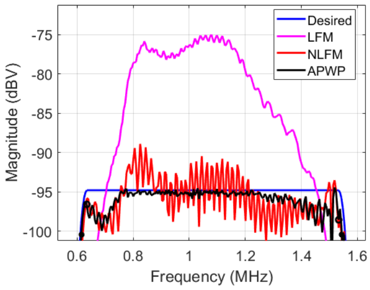

Fig. 5: Received optimized signals spectra for -30 dB (Fig. 2) bandwidth for PZT 1 MHz transducers.

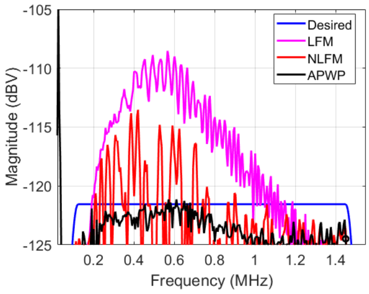

Fig. 6: Received optimized signals spectra for -20 dB (Fig. 3) bandwidth for capacitive transducers.

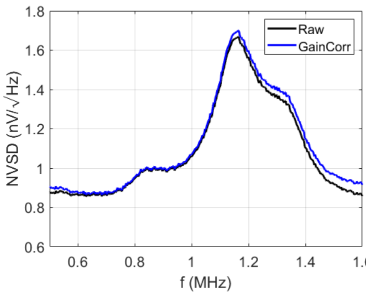

Fig. 7: Input-referenced noise of PZT 1 MHz.

usually is hundreds or even thousands of volts, much larger SNR can be expected in actual measurements.

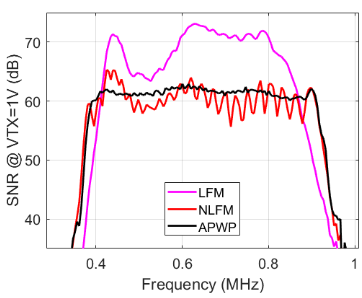

Fig. 8: SNR of PZT 650 kHz at -20 dB comp.

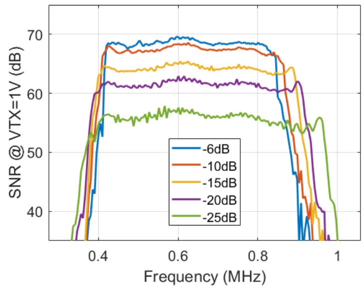

Fig. 9: All cases SNR of PZT 650 kHz transducers.

It can be noted that SNR spectrum is not as uniform as signal received, though smoother than in case of LFM or NLFM signals. The resulting SNR for 1 MHz transducers pair is presented in Fig. 10 and Fig. 11.

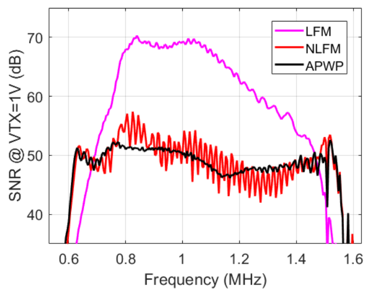

Fig. 10: SNR of PZT 1 MHz at -30 dB compensation.

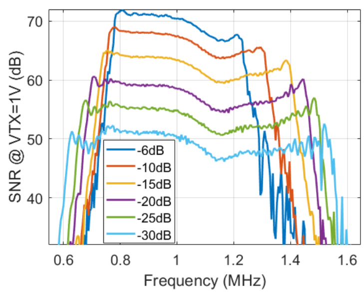

Fig. 11: All cases SNR of PZT 1 MHz transducers.

SNR for the capacitive transducers pair is presented in Fig. 12 and Fig. 13, in -6, -10, -15, -20 dB cases. Note: SNR evaluation results are for +/-1 V excitation voltage. Therefore, actual SNR, if higher excitation voltage is used, will be higher.

If normalized to the same excitation voltage, PZT-based $\lambda/4$-matched transducers deliver much higher SNR than capacitive transducers. Yet, capacitive transducers have more uniform AC response, therefore broader bandwidth can be obtained after compensation (Fig. 14).

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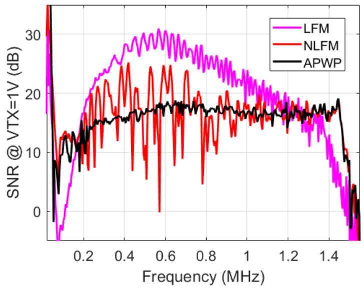

Fig. 12: Capacitive transducer SNR, -20 dB comp.

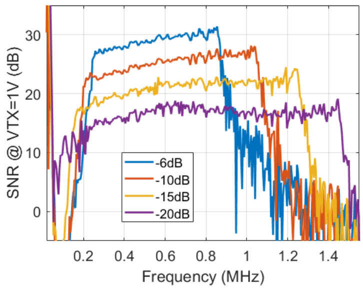

Fig. 13: All cases SNR of capacitive transducers.

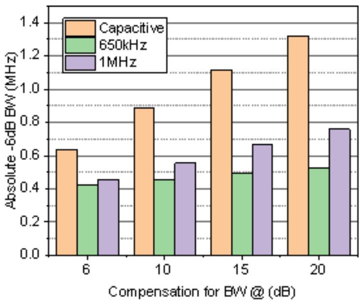

Fig. 14: Attainable -6 dB bandwidth.

It can be concluded that efficiency of the bandwidth improvement depends on transition band roll-off rate: the less steep is the transition band roll-off the better results can be obtained after spectral losses compensation.

Conclusions

APWP signals can be used to broaden the bandwidth of the received signal if excitation signal spectrum is programmed to compensate the spectral losses. Compensation is achieved by pushing the energy of the excitation signal into transition band. As a consequence, SNR is reduced. For instance, 650 kHz PZT-based transducer bandwidth can be improved from 420 kHz to 570 kHz at the expense of SNR reduction from 72 dB to 62 dB (at 1 V excitation). Bandwidth of 1 MHz PZT-based transducer can be widened from 450 kHz to 760 kHz but SNR is reduced from 72 dB to 62 dB. Capacitive transducer bandwidth can be improved from 570 kHz to 1320 kHz at the expense of SNR reduction from 30 dB to 18 dB.

Acknowledgements

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