Investigation of the Ultrasonic Transducer Suitability for Spread Spectrum Systems

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Abstract—Investigation of the ultrasonic transducer properties with aim for spread spectrum (SS) signals application is presented. Structure and parameters of dedicated ultrasonic data acquisition system are presented. Transducer impedance was measured and interaction with excitation generator was evaluated for attainable power delivery efficiency and bandwidth. For transducers planned to be used in imaging, the directivity of the transducer was evaluated in reflection mode. Steel ball of 5 mm diameter was used as reflector. X-Y scan was performed using fixed step, while Z step was adapted to on-axis pressure variation. Data processing flow for automated directivity calculation is outlined. Obtained X-Z, Y-Z, X-Y directivity plots are presented for 20 MHz focused transducer. Investigation of the spectral content versus off-axis coordinate is presented. Pressure field produced by transducer was measured using the needle hydrophone at several Z-planes for wideband 5 MHz transducer.

Keywords— signals acquisition system; ultrasonic transducer evaluation; style; styling (key words)

I. INTRODUCTION

Conventional ultrasonic systems are using pulse signals. Reasoning for such choice is that pulse signals exhibit wide spectrum, generation of such signals is simple so the size of equipment is small [1]. Another important property is that such signals possess low correlation sidelobes and occupy short duration which contributes the temporal resolution [2]. But pulse signals have several essential drawbacks [3]: i) low energy; ii) limited spectral content control; iii) presence of spectral zeros; iv) processing gain of resolution is small. Spectral content can be varied only by adjusting the duration. Duration must be short when aiming the bandwidth but in such case signal energy is reduced [4]. Energy can be improved by increasing the amplitude of the pulse but there are certain limits in transducer and electronics capabilities.

Increasing popularity of composite materials demands for some kind of non-destructive testing (NDT) of the composite goods. Ultrasonic techniques offer simple and portable testing equipment [5,6] but due to the material attenuation and scattering suffer the attainable results. In the case of the air-coupled ultrasound applications signal transmission losses are high so high energy signals are required [7]. The energy and the bandwidth of the signal are important in ultrasonic measurements: signal-to-noise ratio and effective bandwidth define the attainable precision [8,9]. All the aforementioned applications require both wideband and high energy probing. Therefore complex, compressible signals are used which usually are addressed as spread spectrum (SS) signals [10-12].

We are planning to explore SS signals capabilities1. But essential part of the ultrasonic system that limits the SS performance is the ultrasonic transducer: transducer must match the bandwidth of the excitation signal [13,14]. Therefore investigation of transducer performance under complex excitation signal is needed [15,16]. Transducer impedance interaction with excitation generator was evaluated for attainable efficiency and bandwidth. If transducer suppose to be used in imaging, the directivity of the transducer is important. Directivity was evaluated noting the spectral content changes.

II. INVESTIGATION SETUP

A. Acquisition System

Data acquisition system, dedicated for spread spectrum signals, has been designed (Fig.1). System includes: high voltage pulse trains generator, capable of conventional and spread spectrum signals excitation; signal reception, filtering and digitization equipment; digital processing and data transfer module; 3D scanner and the corresponding controller.

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Excitation signals amplitude can be varied from 1 V to 300 V. Excitation signal’s rise/fall times of 10 ns ensure 30 MHz system bandwidth. Pulse train duration step is 10 ns. Reception channel’s gain can be varied in 0-45 dB range. Analog-to-digit conversion frequency is 100 MHz and uses 10 bit resolution. Minimum scanning step along x and y axes is 10 μm, and 7.5 μm along z. System had to be developed since the commercial products with required functionality do not exist [17].

System is unique also in that sense, that it is capable to use several types of signals for experiment simultaneously. This ensures that data obtained several signals can be reliably compared. Software has been prepared for experiment results collection and processing.

B. Signals Used

Few types of excitation signals were used: i) chirp, as spread spectrum signal; ii) continuous wave (CW) burst and narrowband signal; iii) single pulse and iv) step as low energy wideband signals. Refer Fig.2 for spectrograms of example signals.

![Spectrograms of example signals](image1)

Signals represent three possible combinations: energy, bandwidth and duration in time. For pulse and step spectrum is significantly wide but all the energy of the spectral components is concentrated in single temporal position. For CW burst it is the opposite: energy is concentrated in one spectral component but spread over time. And chirp represents both wide spectral content and both spread of the components in time.

III. ANALYSIS RESULTS

A. Transducer Impedance Analysis

The transducer impedance is an important parameter characterizing the ability of the load to accept the energy from the exciting circuit.

Results of 20 MHz, wideband, focused ultrasonic transducer IRY220 (from NDT transducers LLC), impedance measurements carried out using the precision impedance analyzer 65120B from Wayne Kerr Electronics are presented in Fig.3.

![Measured impedance of the ultrasonic transducer](image2)

Ultrasound transducer impedance can be used to estimate the transducer excitation efficiency or to calculate the electrical matching circuits [18]. Power delivery efficiency:

$$\eta = \frac{4R_g \text{Re}(S_T)}{e_g^2} \times 100\% = \frac{4R_g Z_m}{(R_g + Z_m)(R_g + Z_m)} \times 100\% \tag{1}$$

where $e_g$ is the generator’s intrinsic voltage; $Z_m$ is the transducer input impedance and $R_g$ is generator’s intrinsic resistance. It was assumed that real part $P_T$ of the complex power $S_T$ is equal to the power delivered.

Refer Fig.4 for exciting generator’s output impedance influence on power delivery efficiency for the same transducer IRY220.

![Influence of the pulser output impedance on power delivery efficiency for 20 MHz transducer IRY220](image3)

It can be seen that power delivery to load is maximized when pulser output impedance is around 20 Ω. With the measured transducer impedance available, transducer performance can be estimated without the need for model derivation. Impedance measurement allows to predict that moderate output impedance (20 Ω for investigated case) is needed in order to assure wideband SS signal match.

B. Ultrasound Transmission Measurement Technique

The frequency response of the transducer was determined by recording the probing signal on transducer clamps and the signal received from reflector. Taking the
Fourier transforms of the two and dividing the received signal \( u_{\text{env}}(f) \) by transmitted spectrum \( u_{\text{in}}(f) \) transmission frequency response can be obtained:

\[
G(f) = \frac{u_{\text{env}}(f)}{u_{\text{in}}(f)}.
\]

(2)

Results for transmitted (left) and received (right) signals spectrum obtained for wideband air-coupled 1 MHz ultrasonic transducer are presented in Fig.5.

Transducer was excited by SS signal (linear chirp, 30 \( \mu \)s duration, with frequencies ranging from 0.5 MHz to 3 MHz). Excitation signal amplitude was +/-300 V. It can be seen that despite out of band attenuation transducer response follows the excitation bandwidth: signal-to-noise (SNR) is high (10 dB above the noise floor) where excitation signal is present.

Same investigation was carried out on wideband, 5 MHz transducer IRY405 (from NDT transducers LLC). Transducer was excited by +/- 20 V(40 Vpp) chirp ranging from 1 MHz to 10 MHz, 1 \( \mu \)s duration, reflection from 4.75 mm steel ball was taken. Transmission function obtained by Eq.(2) is presented in Fig.6 left. Same investigation for 15 MHz transducer IBHG152 (from NDT Systems) was carried out using 60 Vpp chirp excitation ranging from 8 MHz to 22 MHz and 1 \( \mu \)s duration. Transmission function frequency response obtained by Eq.(2) is presented in Fig.6 right. -20dB bandwidth obtained for Fig.6 corresponds to manufacturer specifications.

It can be seen that transducer response obtained by excitation with spread spectrum signals produces the signal with the bandwidth corresponding to transducer spectral response, but signal obtained still has significant SNR (20 dB above the noise floor) so all the range used for excitation is usable. E.g. for IBHG152 transducer the manufacturer specified bandwidth at -20 dB level is (2-9) MHz and so is the response obtained (Fig.6), but SNR is so high that response is obtained even at signal harmonics (square wave is used for excitation). Total usable frequency range for 15 MHz transducer is from 6 MHz up to 30 MHz.

C. Transducer Directivity Estimation

The reflection mode directivity of the transducer was investigated using 5 mm steel ball as point target (Fig.7, left). Scan was done along x axis first, then y coordinate was stepped. Same step was used along x and y axes.

Axis z had variable step to adjust z-slice positions to beam variation intensity (Fig.7, right).

Recorder A-scans were stored for further processing. Application of long SS signals created additional problem: reflection from the steel ball backwall was too close to the front reflection’s tail. Therefore, accurate signal gating was needed. Generator waveform length is obtained from computer file used for excitation signal description. Signals acquired at focal point (at distance \( L_0 \) from transducer) are taken and location where rms value of the A-scan has a peak established along x and y axes. Peak location \( x_0 \) and \( y_0 \) coordinates were stored for further processing and A-scan signal taken was processed to locate the temporal position for envelope. Envelope was taken using Hilbert transform:

\[
s_{\text{env}}(t) = |\mathcal{F}^{-1}(\mathcal{F}[s(t)]_{0 \leq f \leq 0})|
\]

(3)

where \( s(t) \) is signal in time domain; \( s_{\text{env}}(t) \) is the signal envelope obtained; and \( \mathcal{F} \) and \( \mathcal{F}^{-1} \) are inverse and forward Fourier transforms respectively. Envelope peak position together with excitation signal length was used for automated signal gating.

Same procedure was iterated for another measurement plane, obtained at distance \( L_{FF} \) from transducer (further than focal point, in far field). Peak coordinates \( x_{FF} \) and \( y_{FF} \) were stored for further processing.
Then, gated signals at focal point and the further position were cross correlated to establish the time of flight (ToF) difference between the two:

$$ToF = \arg[\max(x_m)],$$

(4)

where $x_m$ is:

$$x_m = \sum_{k=1}^{K} s_{k-m} \cdot s_k$$

(5)

Thanks to high SNR, accuracy below the sampling period is achieved. The estimated subsample shift is obtained using cosine interpolation:

$$\Delta ToF_{\text{cos}} = -\frac{\theta}{f_s \omega_0},$$

(6)

where $f_s$ is the sampling frequency and

$$\omega_0 = \arccos\left(\frac{x_{m-1} + x_{m+1}}{2x_m}\right).$$

(7)

$$\theta = \arctan\left(\frac{x_{m-1} - x_{m+1}}{2x_m \sin \omega_0}\right).$$

(8)

Since scanner positioning accuracy is high, and plane positions were known, then ToF was used to obtain the velocity in water:

$$c_w = \left(\frac{L_{\text{FF}} - L_0}{2 \cdot ToF}\right).$$

(9)

Obtained velocity was used for gating position calculation for entire scan field.

Another problem that had to be solved was associated with transducer’s inclination: even accurate alignment of the one scan, to position the beam inside the scan, did not ensure that succeeding planes were centered. Offset of peak location from center was obtained (Fig.8).

Offset values were used for developing the equation for beam inclination compensation for every z-slice offset:

$$x_{\text{offset}} = x_{01} + \beta_{zx} L_i - x_{\text{center}},$$

$$y_{\text{offset}} = y_{01} + \beta_{zy} L_i - y_{\text{center}},$$

(10)

where $x_{01}$ and $y_{01}$ are x and y bias values; $\beta_{zx}$ and $\beta_{zy}$ are inclination coefficients, obtained from $\Delta x_0$, $\Delta y_0$, $\Delta x_{\text{FF}}$, $\Delta y_{\text{FF}}$ values (Fig.8); $L_i$ is the z-slice distance and $x_{\text{center}}$ and $y_{\text{center}}$ are desired x and y center locations after beam alignment.

In order to evaluate the beam profile, signal reduction with depth was removed and every z-slice analyzed for -3 dB and -6 dB rms signal drop to evaluate the beam width variation along z-axis. Beam profile analysis results for focused transducer IRY220 are presented in Fig.10.

Signal peak value variation along z axis was presented separately (Fig.11).

Signal rms level at specific z-axis location was analyzed. Fig.12 is presenting results for beam profile measurement at focal point for transducer IRY220.
Results above were presented for chirp signal, and directivity performance is the best for this SS signal. Refer Fig.13 for directivity comparison.

Data in Fig. 13 represents beam size measured at -3 dB, -6 dB and -14 dB. It is evident, that in case of the pulse excitation, beam width is larger than in case of SS signal: 0.8 mm for SS vs. 1.5 mm for pulse. Beam size for CW burst is 1 mm.

Better explanation of spectral content influence can be found in Fig. 14: beam width for the every spectral component is calculated separately here (at -3 dB, -6 dB).

Here one can see that SNR at high frequencies is advantageous for SS and SNR for low frequencies is better for pulse. Meanwhile, the CW burst signal has acceptable SNR only around 10 MHz.
Beam profiles obtained for different excitation signals indicate the SS signal has narrower beam, similar to CW burst. Pulse beam is the widest.

Pressure field directivity study was done for wideband composite transducer TF5C6N-E supplied by Doppler inc. Transducer was placed at the bottom wall of the water tank (Fig.17). Excitation was done using 4.96 MHz (peak response) CW burst signal of 3 μs duration and bipolar, +/30 V (60 Vpp) amplitude.

It can be seen that directivity diagram is almost flat at small distances (Fig.18 left) and converges to Gaussian form at far field (Fig.18 right).

IV. CONCLUSIONS

Investigation presented above, was dedicated for the performance of the ultrasonic transducers evaluation under excitation by spread spectrum signals. Comparison of several excitation signals revealed that SS signals are able to deliver more energy into high frequency range. Therefore, directivity when SS signals are used is better than in case of pulse or CW burst excitation. Signal is useful even beyond the passband: SNR is high therefore components below 30 dB of the peak sensitivity are clearly resolved.

REFERENCES