Selection of Excitation Signals and Acoustic Pressure Measurement for In-Vivo Studies with Ultrasound Array Research Platform II

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Abstract. In recent years, the Ultrasound Group at the University of Leeds has developed an open platform (OP) known as Ultrasound Array Research Platform II (UARP II). The OP serves as a main component for researchers to test and implement new algorithms which is not feasible with the commercially available clinical scanners. In this paper, three types of excitation signals, the square pulse, 2-cycle sinusoid and linear frequency modulated chirps which are commonly employed in ultrasound imaging, were investigated for \textit{in-vivo} experiments with the UARP II OP. The USA food and drug administration (FDA) provides strict guidelines that need to be followed when working with \textit{in-vivo} medium. This is to ensure that the acoustic beam intensities do not cause any types of thermal damage and cavitation. The acoustic pressures produced by those excitation signals were measured with a needle hydrophone. The main three parameters of the excitation signals measured and calculated are the mechanical index (MI), spatial peak pulse average intensity (SPPA) and spatial peak temporal average intensity (SPTA). By considering advantages and disadvantages of all investigated excitation signals, the 2-cycle sinusoidal signal has been selected for all simulations and experiments with the \textit{in-vivo} medium.

1. Introduction

Acquiring commercially available ultrasound scanning equipment can be impracticable for research groups due to its limitation. Many properties such as the excitation signals, transmit and receive sampling frequencies, apodization, beamforming and many other properties have been fixed in those ultrasound machines. With those limitations, it will be nearly impossible for the researchers to study, explore and implement any new techniques that can enhance the capabilities of ultrasound for new diagnostic methods. Due to the huge demand from many research groups, few ultrasound scanner manufacturers have added some interfaces on their machines \cite{1}. This allows the researchers to access the post delay-and-sum (DAS) beamforming signals. This very limited access to the commercial ultrasound machines provided by the manufacturers still could not fulfil the researchers’ needs. Thus, many ultrasound research groups have developed their own open platform (OP) ultrasound scanners that can be manipulated and configured \cite{2, 3}. In Leeds, UK, the Ultrasound Group developed their own ultrasound machine known as ultrasound array research platform (UARP). The first version of UARP was...
developed in 2012 by Smith et al. [4]. Later on, David et al. continuously upgraded the UARP machine capabilities by increasing the channel number, imaging depth, sampling frequencies and data transfer capabilities to allow for real-time applications [5]. With that UARP II was born. Many new imaging techniques such as synthetic aperture (SA) imaging, compound plane wave imaging, shear wave elastography, and vector flow imaging, have been implemented on the UARP II [6–10]. The UARP II also has been used for harmonic imaging, contrast agent studies and non-destructive-test (NDT) applications [9,11].

Although the UARP II has been used for many ultrasonic applications, no in depth studies have been conducted on the type of excitation signals and the acoustic pressure that are suitable for in-vivo experiments. Thus in this paper, three excitation signals, the square pulse, 2-cycle sinusoidal and linear frequency modulated chirps have been investigated. As an outcome, an excitation signal was selected to be employed for in-vivo experiments.

2. Materials and Methods

2.1. Ultrasound array Research Platform II

The UARP II is a custom ultrasound imaging system developed by the Ultrasound Group at the University of Leeds [4,5]. It contains a 8-field programmable gate array (FPGA) backplane which connects to a computer running any 64 bit version of the Windows operating system (OS) via a 16-channel peripheral component interconnect express (PCIe) link each equipped with 1-GB DDR3, Stratix V FPGA. Each FPGA card consists of 16 channels and there are totally 128 channels in the current UARP II. However, this system is highly flexible, and it can be easily scaled to have more channels. All excitation signals except the square pulse are designed in the Matlab software package (The MathWorks Inc., Natick, MA, USA) by using a harmonic reduction pulse width modulation (HRPWM) method [12]. The sampling rate for Tx is 160 MHz. Those signals are then uploaded to the UARP II which excites the connected probe by using a five level switched mode excitation scheme [13]. The received radio frequency (RF) data are acquired at a 80 MHz sampling rate and processed off line using MATLAB. The maximum sampling depth for a single firing can be more than 32768 samples per channel, which equates to a round trip in water of approximately 61 cm with the speed of sound of 1482 m/s at 22°C.

2.2. Excitation Signals

Three different excitation signals have been explored in order to find the most suitable one for in-vivo imaging. Each of the excitation signals except the square pulse was uploaded to the UARP II utilizing a five level switching mode with the driving voltages of ±100, ±50 and 0 Volts. The maximum amplitude for all excitation signals was fixed to ±100 volts in order to generate maximum pressure values at the elevation focus. The first excitation was a broadband square pulse signal \( e_{s1}(t) \) with a 50 ns duration and can be expressed in the analytical form as

\[
e_{s1}(t) = \begin{cases} 
1, & 0 \leq t \leq T \\
0, & \text{otherwise}
\end{cases}
\]

where \( T \) is the time duration. The Tukey window was applied to the excitation with a weightage of 0.5. Figure 1 shows the square pulse in the time and frequency domain. The output of the transducer is known as the result of convolution between the excitation signal and the transducer impulse response. While the echo is a convolution result between the acoustic response and the transducer’s impulse response.

Next the 2-cycle sinusoidal signal \( e_{s2}(t) \) tapered in the time domain using a Tukey window \( a(t) \) with a factor of 0.5 was applied. The signal can be expressed as follows:
Figure 1. Square pulse signal properties shown in the a) time domain and b) frequency domain.

\[ e_{s2}(t) = \begin{cases} 
  a(t)\sin(2\pi f_o t), & 0 \leq t \leq 2/f_o \\
  0, & \text{otherwise} 
\end{cases} \] (2)

Figure 2 shows the 2-cycle sinusoidal signal in the time and frequency domain. Finally, the linear frequency modulated (LFM) chirp excitation signal \( e_{s3}(t) \) with a 10 \( \mu \)s duration, 57% bandwidth and tapered with a Tukey window \( a(t) (\alpha = 0.50) \) was employed in the experiments. The signal can be expressed as follows:

\[ e_{s3}(t) = \begin{cases} 
  a(t)\sin(2\pi t(f_o + kt/2)), & 0 \leq t \leq T \\
  0, & \text{otherwise} 
\end{cases} \] (3)

where \( T \) is the signal duration, \( f_o \) is the centre frequency and \( k \) is the rate of the frequency change as given by

\[ k = \frac{f_2 - f_1}{T} \] (4)

where \( f_1 \) is the starting frequency of the sweep and \( f_2 \) is the frequency at the end of the time duration \( T \). The chirp signal can be pulse compressed to produce a short pulse by applying matched or mismatched filtering techniques [14]. The output of the matched filter has a narrow main lobe with side lobes [13]. In the matched filtering technique, the received signal is cross correlated with the same excitation signal as shown in figure 3(a). The frequency domain of the matched filtering output is shown in figure 3(c).

The summary of all the excitation signals is given in Table 1. It should be noted that the convolution model used to form B-mode images is only an approximation of the real excitation signal-tissue interaction [15]. Real models can be more complex when considering the hard surface condition which can produce strong reflections. However, considering the fact that the regions occupied by strong reflectors are not common in regular ultrasound images, the convolution model is known to approximate very closely the real image formation process. The
Figure 2. Tukey windowed ($\alpha = 0.5$) 2-cycle sinusoidal signal shown in the a) time domain and b) frequency domain.

Figure 3. Tukey windowed ($\alpha = 0.5$) linear frequency modulated chirp signal shown a) in the time domain b) produced with HRPWM and c) in the frequency domain.
approximation convolution model has been widely used in numerous methods for ultrasound image reconstructions as shown in [16].

| Excitation Signals | Duration | Fractional Bandwidth | Windowing      |
|--------------------|----------|----------------------|----------------|
| Square Pulse       | 50 ns    | 57%                  | None           |
| Sinusoid           | 0.4 µs   | 57%                  | Tukey, α = 0.5 |
| LFM Chirp          | 10 µs    | 57%                  | Tukey, α = 0.5 |

Table 1. Excitation signals.

2.3. Pressure Measurement

Before conducting in-vivo experiments, the acoustic pressures need to be measured. The measured parameters need to be within the limits set by the food and drug administrations (FDA) [17]. This is to ensure that the acoustic beam intensities do not cause any thermal damage and cavitation. The most important three parameters that need to be monitored according to the FDA are the mechanical index \( MI \leq 1.9 \), the spatial peak pulse average intensity \( ISPPA \leq 190W/cm^2 \) and the spatial peak temporal average intensity \( ISPTA \leq 720mW/cm^2 \) [18, 19]. The \( MI \) is a metric used to avoid cavitation and it is unit-less. It is defined as:

\[
MI = \frac{p_m}{\sqrt{f_o}} \leq 1.9
\]  

(5)

where \( p_m \) is the peak negative pressure (PNP). \( ISPPA \) is the maximum intensity in the beam averaged divided by the pulse duration.

\[
ISPPA = \frac{p_m^2}{2\rho c} \leq 190W/cm^2
\]  

(6)

where \( \rho \) is the density and \( c \) is the speed of sound in the propagating medium. As the measurements were performed inside the degassed and deinonized water, \( \rho \) is set to 1000 kg/m³. The speed of sound \( c \) inside water measured at room temperature 22° C was 1482 m/s [20]. \( ISPTA \) is the maximum intensity divided by the pulse repetition period. It indicates the thermal deposition and is related to the likelihood of cavitation due to the rise of the tissue temperature.

\[
ISPTA = ISPPA \frac{T}{TPRP} \leq 720mW/cm^2
\]  

(7)

The pressure reading of all the three excitation signals with the signal properties as shown in Table 1 have been recorded at the centre of the transducer along the elevation direction. The pressure waveform emitted by the transducer was measured by using a 0.2-mm needle hydrophone (Model 1574, Precision Acoustic, Dorchester, UK). The needle hydrophone was attached to the submersible preamplifier (Model PA07093, Precision Acoustic, Dorchester, UK). The submersible preamplifier was connected to a DC coupler (Model 692, Precision Acoustic, Dorchester, UK) and the signal output was displayed and recorded with an oscilloscope (Model MSO-S 104A, Agilent Technologies, California, United States) with the sampling rate of 10 GS/s. The complete setup for the pressure measurements is shown in figure 4.

The measurement was performed at the 20 mm depth where the maximum PNP occurs at the elevation focus. The raw data recorded from the hydrophone in voltage formats were converted into acoustic pressures by using the following equation:
6

\[ p_m = \frac{V}{m(f)} \]  

(8)

where \( V \) is the measured voltage in mV, and \( m(f) \) is the sensitivity of the hydrophone as a function of frequency in mV/MPa. The uncertainty of this 0.2-mm needle hydrophone was 14%. The water attenuation coefficient value is far smaller than any other tissue or material which falls into a range from 0.15 to 20 dB cm\(^{-1}\) MHz\(^{-1}\) [21]. The in-situ pressures were then estimated with a derating factor of 0.3 dB cm\(^{-1}\) MHz\(^{-1}\), corresponding to a linear factor as given by [19,22]:

\[ p_d = \exp(-0.069 f_c z f) p_m \]  

(9)

3. Results and Discussion

In this paper, three different types of excitation signals, a square pulse, a 2-cycle sinusoid and a LFM chirp have been investigated, as shown in figure 5. Each of the excitation signals has their own advantages and disadvantages. A square pulse with shortest duration is able to produce high axial resolution but the pressure is relatively low compared to the sinusoid and chirp. The sinusoid on the other hand has a higher energy than the square pulse and is able to penetrate deeper in the scanning medium with a compressed axial resolution [23]. Chirp excitation signals are well known for its ability to improve the image SNR and penetration depth whilst retaining the axial resolution [11]. The biggest challenge in chirp coded imaging is to design its matching filter. This is because the non-linearity in the imaging medium causes shifts in frequency on the echoes which will directly affect the design of the matched filter [11]. Chirps also produce the highest amount of MI, SPPA and SPTA intensities among all investigated signals. Those values can be lowered by reducing the transmitted voltage, frame rate and pulse duration.

The MI measured for all the three excitation signals are below the limitation of 1.9 set by the FDA. The highest MI value is 0.55 for the 10 \( \mu \)s chirp signals while the lowest is 0.22 for the square pulse signal. The \( I_{SPTA} \) value for the 10 \( \mu \)s chirp signal is 3778 mW/cm\(^2\), which is far
Figure 5. Peak negative pressures at 20 mm depth measured at the maximum elevation focusing point for a square pulse, a 2-cycle sinusoid and a linear frequency modulated chirp.

more than the maximum value of 720 mW/cm$^2$. There are two reasons for this high value. The first reason is the longer pulse duration of 10 µs within a single pulse repetition interval and the second reason is the high frame rate of 37 kHz (at 20 mm depth, c = 1480 m/s). In order to comply with the FDA requirements, either the pulse duration or the FR shall be reduced if the pressure has been fixed. Other FDA limits are given in Table 2.
Table 2. Acoustic Parameters for Safety Consideration

| Metrics          | \(p_m\), MPa | \(p_d\), MPa | MI | \(I_{SPPA}\), W/cm\(^2\) | \(I_{SPTA}\), mW/cm\(^2\) |
|------------------|---------------|---------------|----|--------------------------|--------------------------|
| Square Pulse     | 0.98          | 0.49          | 0.22 | 1.63                     | 3                        |
| 2-Cycle Sinusoid | 1.55          | 0.78          | 0.35 | 4.13                     | 61.1                     |
| 10 \(\mu\)s LFM Chirp | 2.43        | 1.22          | 0.55 | 10.2                     | 3778                     |
| FDA Limits       | -             | -             | 1.9  | 190                      | 720                      |

4. Conclusion

It is found that the excitation signal duration affects the pressure measurements and SPPA. The frame rate affects the SPTA. A high PNP can be hazardous because it can produce cavitation and thermal heating. Thus, by considering advantages and disadvantages of all investigated excitation signals on the UARP II, the 2-cycle sinusoidal signal has been selected for future in-vivo investigations.

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