Coded Excitation of Guided Ultrasonic Waves in Long Bone for Assessment of Fracture Depth

Hang Lu, Feng Xu, Chengcheng Liu, Huilin Zhang, and Dean Ta

Abstract

Single pulse (SP) excitation is the conventional method in long bone assessment which uses ultrasonic guided waves (GWs). However, the SP excitation will result in a small amplitude and low signal-to-noise ratio (SNR) of received signals due to the high attenuation during propagation. To solve the problem, this paper used coded excitation instead, which could help to improve the SNR of received signals. In simulations and in vitro experiments, the GWs were excited by 13 bits Barker code (BC) and 17 bits optimal binary code (OBC), then the received signals were decoded with weighted match filter (WMF) and finite impulse response least squares inverse filter (FIR-LSIF), respectively. The results showed good consistency between simulations and in vitro experiments. Besides ensuring the accuracy and authenticity of signals, the 13-bits BC and 17-bits OBC both got a larger amplitude and a better SNR than single pulse excitation. In the case of strong noise (SNR = 0 dB), the correlation coefficient between received signals and reference signals dropped to 0.70 when using single pulse excitation, while the correlation coefficient still remained above 0.95 for coded excitation. Furthermore, coded excitation modulated by 0.2 MHz sine wave had produced only two modes, L(0,1) and L(0,3), in received signals. When the depth of fracture varying from 0 to 0.5 mm, the energy mainly concentrated in L (0,3) mode. However, the energy mainly concentrated in L(0,1) mode when the depth of fracture varying from 0.5 to 5.0 mm. Therefore, the depth of fracture in long bone could be estimated based on energy transmission percentages.

Keywords

Coded excitation • Pulse compression • SNR improvement • Guided waves • Long bone fracture assessment

1 Introduction

Ultrasonic guided waves (GWs) is gradually becoming an important method for long bone assessment [1]. Due to the multiple reflection and scattering during propagation in long bone, GWs could be more sensitive to the mechanical and geometrical properties of bone than first arriving signal (FAS) velocity measurement. GWs might get more information than FAS method, but the large attenuation resulted from soft tissue and long-distance propagation would make received signals almost buried in random noise, which could raise the error of assessment [2].

GWs method usually uses single pulse as excitation. To improve the SNR of received signals, increasing the voltage amplitude of excitation might be an effective way, but operation at higher peak intensity will also raise the risk of uncontrollable effects, such as local temperature elevation

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and cavitation event [3]. To solve this problem, coded excitation proposed in radar field was introduced into medical ultrasound [4]. It could help to improve the SNR of received signals.

This paper chose 3D pipe-like model rather than 2D plate-like model to do the simulation and in vitro experiment. Lefebvre et al. [5] made simulation experiment which use 3D pipe-like model to simulate long bone structure. The result showed that 3D pipe-like model has distinct differences than 2D plate-like model when detection frequency becomes lower. The dispersion curve of 3D pipe-like model and 2D plate-like model begins to present differences when internal diameter to wall thickness ratio reached to 10 and the product of the guided wave frequency and wall thickness drop to 0.5 MHz mm. What's more, bone marrow and soft tissue is a considerable impact factor in in vivo assessment but it's not take into consideration in 2D plate-like model.

Simulations were carried out to investigate the advantages of coded excitation in long bone assessment. Besides, in vitro experiment was conducted to investigate the relationship between fracture depth and energy transformation percentage of predominant GW modes.

2 Methods

2.1 Coding Scheme

For Barker code (BC) with length N, the peak of its autocorrelation function is N, and the side lobe levels fall between +1 and −1. So the proportion of main lobe amplitude to side lobe amplitude reaches up to N, which is the highest among all binary sequences of same length. But there are only nine BCs have been found, of which the longest BC is 13 bits [6].

Therefore, it's reasonable to find longer length codes based on some different criteria. This paper introduced a criterion that is widely used in the evaluation of coded excitation system performance named peak side lobe level (PSL) [7]. In each length, code sequences were decoded by least square inverse filter (LSIF), and the sequence that has the minimum PSL was chosen as the optimal binary code (OBC).

2.2 Decoding Method

Matched filter is widely used in radar, sonar and communication systems. Because it not only improves the SNR of received signal, but also plays an important role of pulse compression, which will improve the range solution and measurement accuracy.

However, the results decoded by matched filter still have some side lobes, which symmetrically distribute on both sides of main lobe. Thus, it is acceptable to use the weighted network to eliminate the influence of side lobes, and we called this improved filter as the weighted matched filter (WMF).

The result decoded by WMF has smaller PSL than result decoded by matched filter. For 13 bits BC, the PSL of matched filter decoded result is approximately −11 dB, and the PSL of WMF decoded result decreases to −26 dB.

Though easy to implement, matched filter has a poor side lobe suppression effect. So some researchers proposed non-matched filter whose purpose of decoding is to compress coded sequences into Kronecker delta function.

The inverse filter could be calculated in time domain that omits the process of Fourier transformation and Fourier inverse transformation. However, there is no analytic solution for the results, so LSIF chose the filter with the minimum module of error sequence.

3 Experiments

3.1 Simulation

Cortical bone is a pipe-like bone with bone marrow filled inside, and covered by soft tissue. Correspondingly, the established model is a 3D pipe-like model, and divided into three layers along the transverse direction: the outermost layer is soft tissue, the interlayer is cortical bone, and the innermost layer is bone marrow. Table 1 listed the material parameters of soft tissue, cortical bone and bone marrow used in the simulations. Simulation diagram was shown in Fig. 1.

Simulation and in vitro experiment used three different excitations: sine pulse (SP, 0.2 MHz), modulated BC (13 bits, modulated by 0.2 MHz sine sequence) and modulated OBC (17 bits, modulated by 0.2 MHz sine sequence). Each code element corresponds to two periodic sine waves.

3.2 In vitro experiments

The in vitro experiment was performed on a cortical bone from bovine tibia. The experiment used water to simulate soft tissue and marrow. Bone fracture was made artificially.

Table 1 Simulation parameters

Parameters	Soft tissue layer	Cortical bone layer	Marrow layer
Thickness (mm)	2	5	5
Density (kg/m^3)	920	1500	1020
First Lame constants (MPa)	1937	14,539	1500
Second Lame constants (MPa)	0	5111	0
longitudinal wave velocity (m/s)	–	4063	–
Transverse wave velocity (m/s)	–	1846	–
Attenuation parameter (Pa s)	–	110	–

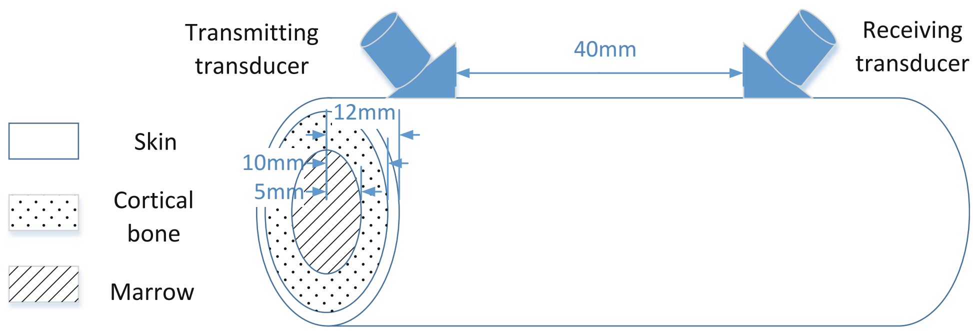


Fig. 1 Simulation setup diagram

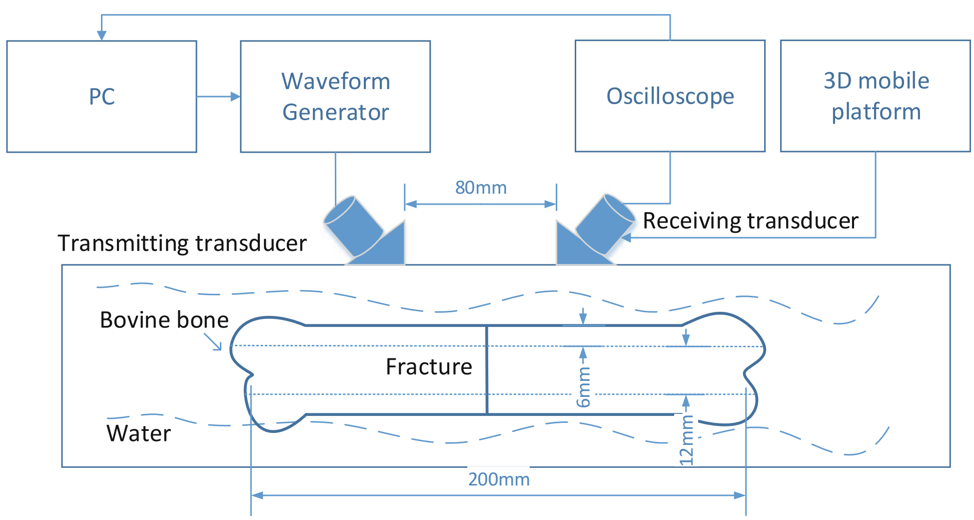


Fig. 2 Experimental setup diagram

The fracture width was constant as 1 mm and the fracture depth was varied from 0 to 5.5 mm with an interval of 0.5 mm. The in vitro experimental setup was shown in Fig. 2.

4 Result and Discussion

4.1 Simulation

When using coded excitations, received signals were decoded by WMF and LSIF, respectively. Results were shown in Figs. 3 and 4. Comparing the two different coded excitations, OBC has a better performance on maximum amplitude when decoded by WMF. Besides, WMF decoded signals excited by BC and OBC had a larger amplitude than SP received signals.

It is easy to compare three different excitations when normalized two decoded signals and SP received signals. For better visualization, waveforms from 20 to 120 µs were magnified. It is clear to see that the three waveforms were perfectly coincided.

The simulation results suggested that both BC and OBC were able to generate a larger amplitude received signals than single pulse. Meanwhile, the correlation coefficients between decoded signals and SP received signals were all

Fig. 3 BC decoded signals and comparison with SP received signals

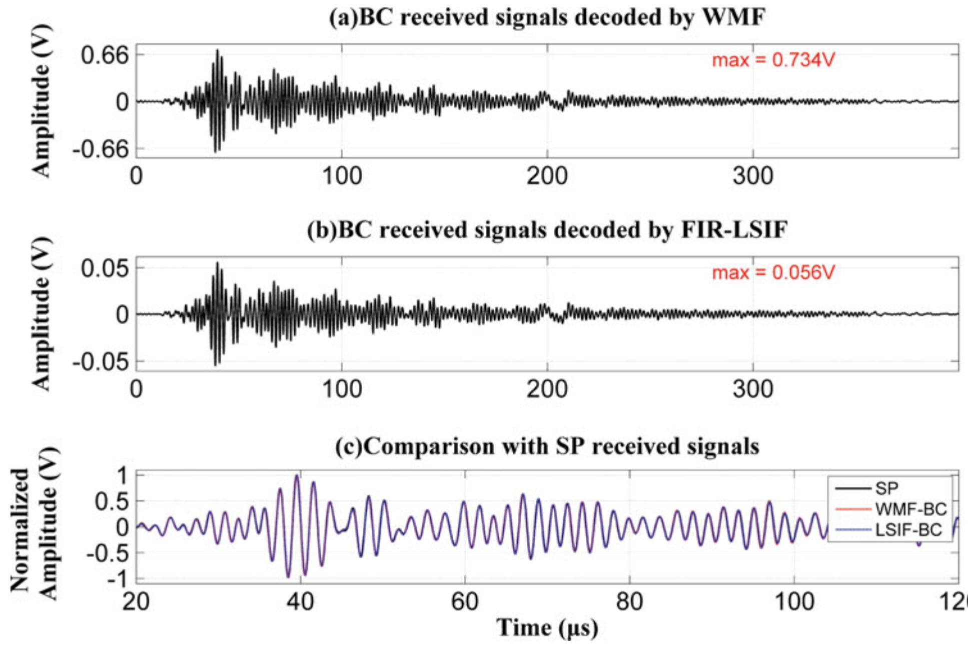
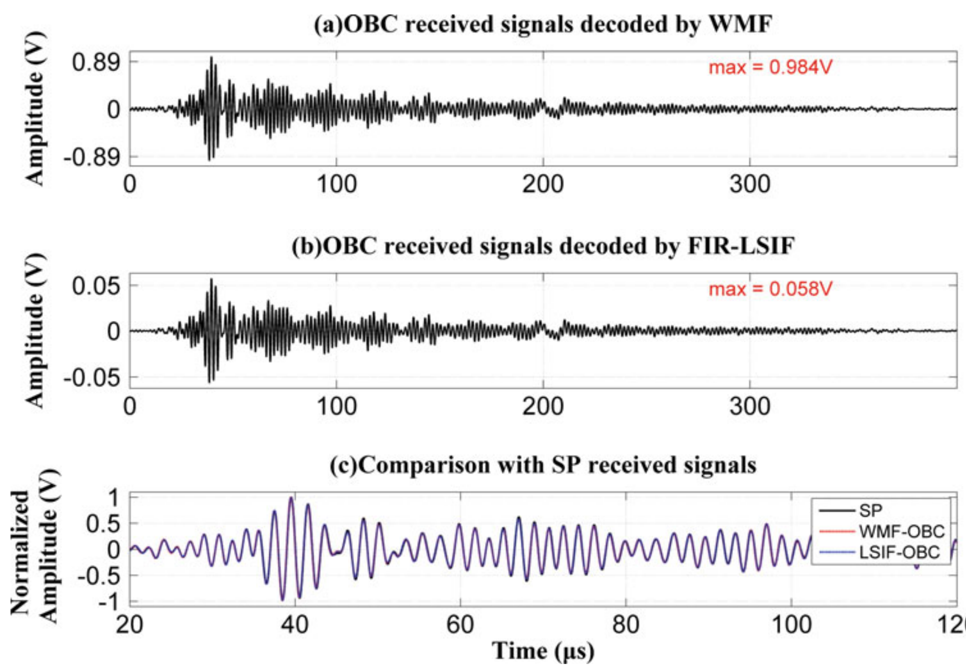


Fig. 4 OBC decoded signals and comparison with SP received signals



above 98%, which means coded excitation has few information loss during detection process.

In order to analyze the advantage of BC and OBC in terms of noise suppression, the random white noise generated by MATLAB (The Mathworks Inc, USA) was artificially added to three received signals for simulating noise environment. Noise power gradually increased, which resulted in SNR decreased from ∞ dB (∞ dB means noise-free) to 0 dB. The results were shown in Fig. 5.

With increasing noise power, the correlation coefficients between decoded signal and original signal declined. When *SNR* was down to 0 dB, the correlation coefficient between SP received signal and original signal dropped to 70.5%. However, the correlation coefficients between decoded signal (excited by BC or OBC) and original signal still remain above 95%, which indicated that coded excitations (BC and OBC excitations) have a better noise suppression effect than SP excitation in strong noise environment.

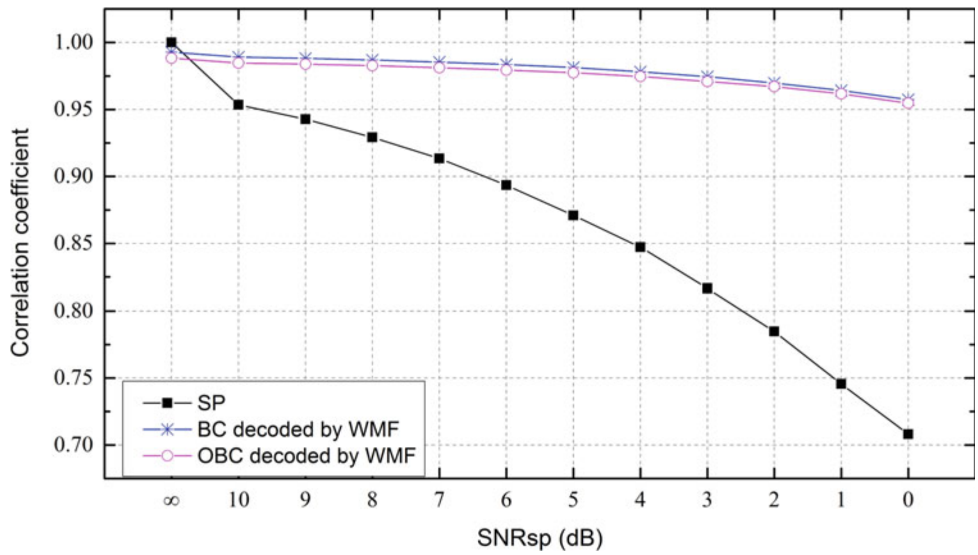


Fig. 5 Noise resistance comparison between SP and coded excitation

4.2 In Vitro Experiment

In vitro experiment used time-frequency representation (TFR) method to analyze three different excitations. Firstly, we applied short-time Fourier transform (STFT) method to obtain energy distribution of decoded signals in time-frequency domain, where signals were all decoded by FIR-LSIF. Then, crazy-climber algorithm was used to separate TFR ridges of individual modes [8], and the results were shown in Fig. 6. 0.2-MHz sine waveform was chosen to modulate transmitting signals for simplifying GW modes, because the difference between group velocities of different

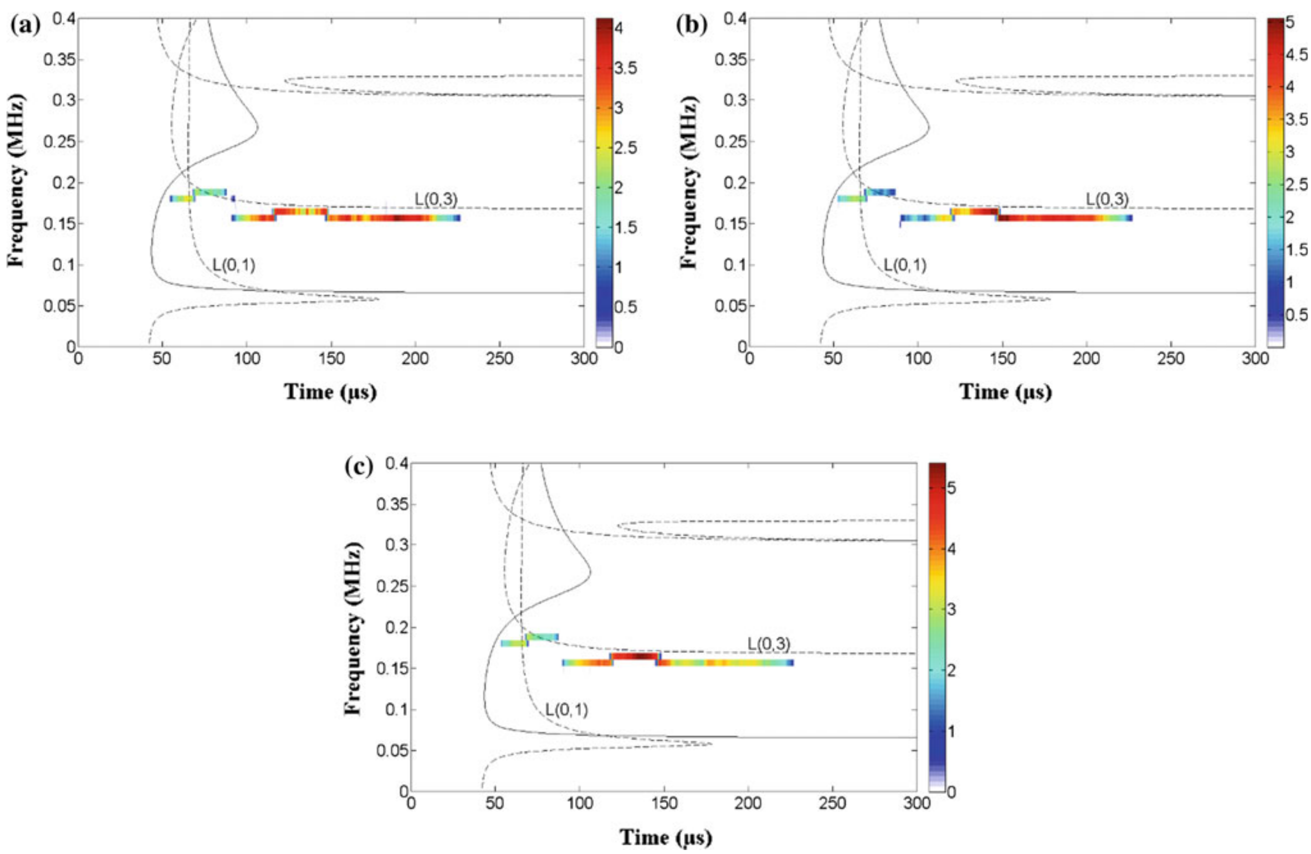


Fig. 6 The TFR ridges of the SP received signals (**a**), BC decoded signals (**b**) and OBC decoded signals (**c**)

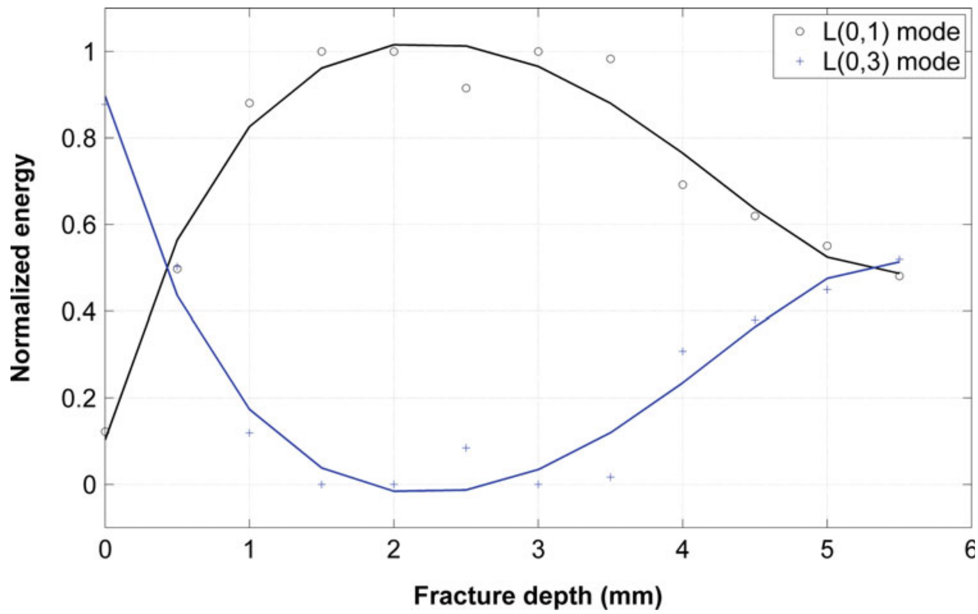


Fig. 7 Energy transformation of GW modes with fracture depth changes

GW modes will be narrowed if using high transmitting frequency, which could result in a poor model resolution.

Varying the fracture depth from 0 to 5.5 mm at the step of 0.5 mm, we could get a set of decoded signals. Using STFT and crazy-climber algorithm to separate GW modes of these decoded signals. Then, the corresponding time domain signals of L(0,3) and L(0,1) could be reconstructed from their TFR ridges. Figure 7 showed the normalized energies of L (0,3) mode and L(0,1) mode.

With fracture depth increasing, the energy transformed between L(0,1) and L(0,3) mode. When fracture depth closed to 0 mm, the energy of L(0,3) mode was greater than L(0,1) mode. When fracture depth changed between 0.5 and 5.0 mm, signals' energy mainly concentrated on L(0,1) mode.

5 Conclusions

This paper introduced coded excitation into 3D pipe-like long bone model. Simulation showed the advantages of BC and OBC excitations in terms of their amplitude improvements and SNR improvements. Besides, decoded signals could also ensure signal authenticity. In in vitro experiment, we could calculate different GWs' energy using STFT and crazy-climber algorithm. The energy transformation percentage of predominant GW modes could be an effective parameter to estimate fracture depth of long bone.

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