

APPLICATION OF PULSE COMPRESSION TECHNIQUE IN AIR-COUPLED ULTRASONIC NON-DESTRUCTIVE TESTING ON COMPOSITE MATERIAL

ZHOU Zhenggan, ZHANG Hongyu, WEI Dong
Institute for Nondestructive Testing and Mechatronic Engineering,
Beihang University □ Beijing 100191, P. R China

Abstract

There is severe attenuation and a low signal to noise ratio (SNR) in the process of composite component non-destructive testing. The system SNR and the precision of defect position measurement can be greatly improving by application of pulse compression method in the ultrasonic transducers excitation and receiving. The composite which usually used in aerospace and defense industries were tested using liner frequency modulation (LFM) pulse compression method. A carbon fiber reinforced plastic (CFRP) component was taken for instance. Firstly, the theory of pulse compression method including the matched filter calculation and the key parameters selection were briefly introduced. Secondly, the pulse/echo mode and the through mode were compared then CFRP component was scan by modified C-scan system using two transducers with different frequency and the results were evaluated. Theory analysis and the experiment results show that the efficiency of transducer and the testing resolution can be greatly improved by pulse compression method, which is suitable for air-coupled ultrasonic composite testing applications. Pulse compression is considered as a potential signal processing method.

Introduction

Application of air-coupled ultrasonic nondestructive testing in composite material overcomes the coupling medium restriction of the conventional ultrasonic testing and has distinctive advantage. But difficulties are brought in by this advantage, such as the huge acoustic impedance difference between air and material, the low transmission coefficient and the inefficient transducer. Air-coupled transducers usually have low frequency and narrow bandwidth which cause the long duration aftershock that can superimpose with defect echo. The current solutions include high performance transducer matching layer materials, ultra-low-noise preamplifier and advanced signal processing method^[1]. Signal processing method is received increasing attention by less hardware modification.

Pulse compression is a signal processing method using modulation signal to excite the transmit transducer and a matched filter after the receiving transducer at the same time. Correlation process is taken between echo and reference signal. If the reference signal is chosen appropriately, it gets short time duration but high amplitude signal after the matched filter. The signal has the shape like $\text{sinc}(x)$ waveform. This method first applied to radar system and ultrasonic medical imaging obtained good results. The low SNR and the testing resolution of composite material air-coupled ultrasonic nondestructive testing can be compensated by the characteristics of this method.

A pulse compression system is made up of modulation excitation signal generator, transducers and the matched filter. The modulation signal generator and the matched filter are the most important parts of the system. Their parameter chosen impacts the compressed results significantly. A sample example of pulse compression system is shown in Fig. 1.

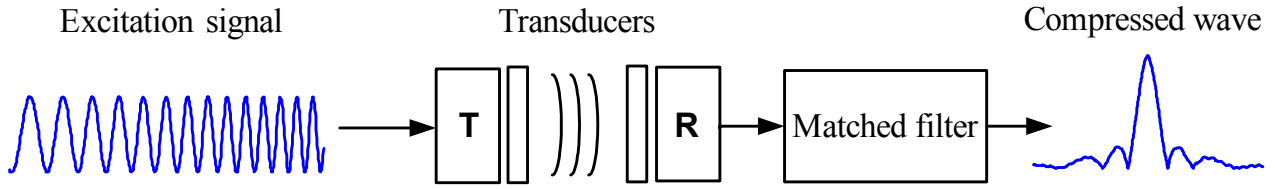


Fig. 1 Example of pulse compression system

Theory

Liner frequency modulation signal is mostly used in pulse compression system. LFM, also known as chirp signal, can be compressed after matched filter. It is easy to achieve and has the waveform of formula 1.

$$p(t) = A \cdot \exp \left[j \cdot 2\pi \left(f_0 t + \frac{B}{2T} t^2 \right) \right] \quad (1)$$

Where $p(t)$ is the LFM signal, A is the amplitude of signal, f_0 is the center frequency of transducer, T is the duration of excitation signal called time width, B is the modulation frequency band width of excitation signal called bandwidth, $K = B/T$ is called frequency modulation slope.

Ideally, the echo signal without any attenuation is still the same as the excitation signal. According to the signal processing theory^[2], the echo signal passed the matched filter gets highest SNR when the matched filter transfer function is the conjugate of the echo frequency domain expression. So the transfer function of matched filter is formula 2.

$$H(f) = G \cdot R_i^*(f) \quad (2)$$

Where G is a constant value, usually $1 \square R_i^*(f)$ is the conjugate of echo frequency domain expression, $H(f)$ is matched filter frequency transfer function.

(a) Preferences chosen

The compressed results are impacted significantly by the most important preferences, time width T and the modulation frequency bandwidth B . Time-bandwidth product $B \cdot T$ of single without modulation tends to be 1. The bigger time-bandwidth product gets better compressed results. The impact of parameters on the matched filter output is shown in Fig. 2 and Fig. 3.

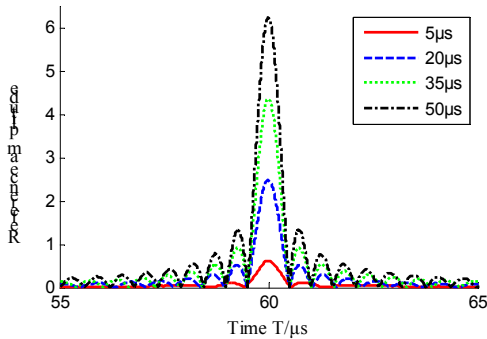


Fig. 2 Time width effect on filter output
Fixed parameters: $f_0=2.5\text{MHz}$ $B=2\text{MHz}$

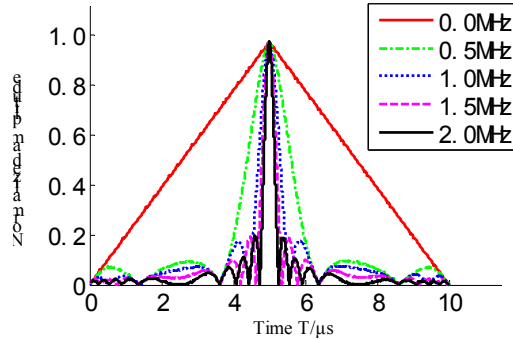


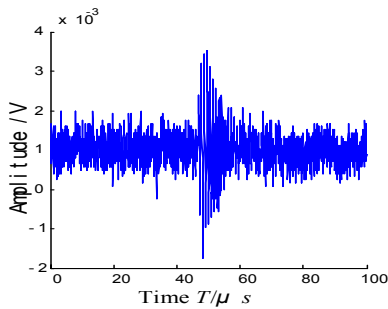
Fig. 3 Bandwidth effect on filter output
Fixed parameters: $f_0=2.5\text{MHz}$ $T=10\mu\text{s}$

The transmit power of transducer by a single excitation is decided by time width of excitation signal. When other parameters of LFM are fixed, longer time width causes higher output main lobe

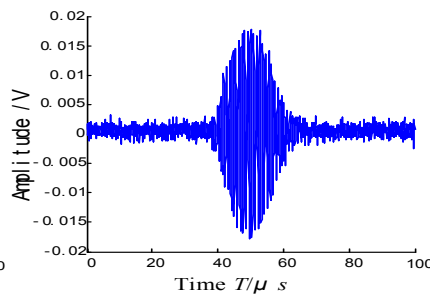
amplitude but does not have effect on the main lobe width. As bandwidth B , greater bandwidth gets a narrower main lobe when other parameters are fixed. Bandwidth B does not have effect on the amplitude. It can be sum up as bigger time-bandwidth product gets better compressed result.

(b) Using Hanning window

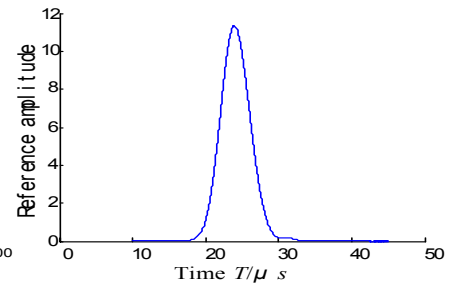
Ultrasonic transducers have limited bandwidth. Negative pulse excitation is usually used in ultrasonic nondestructive testing. Efficiency can be greatly increased by using the continuous wave excitation signal which has the same spectrum with transducer's frequency response [3]. Other frequency components are not introduced at the start point and the end point of excitation signal by using hanning window. Application of hanning window is benefit for pulse compression method and air-coupled ultrasonic testing. The first echo through 1mm thickness CFRP by through mode with 1.1MHz air-coupled transducers is shown in Fig. 4-6.



$T=1\mu s$



$T=30\mu s$ $B=0\text{MHz}$ hanning window



$T=30\mu s$ $B=0.4\text{MHz}$

Fig. 4 200V negative pulse excitation echo

Fig. 5 200V LFM CW excitation echo

Fig. 6 Compressed result

Experiment system

Pulse compression method can be added to normal C-scan system with little hardware modification. The hardware of experiment system includes Ritec RAM-5000 high power ultrasonic testing system, Ultrason Group point focus air-coupled ultrasonic transducers, AFG3102 arbitrary wave/function generator, TDS5034B digital oscilloscope. The software has the capability of full-waveform, real-time processing and storage which greatly facilitates the signal processing development of C-scan. System hardware and software diagram is shown in fig 7 and key parameters in table 1.

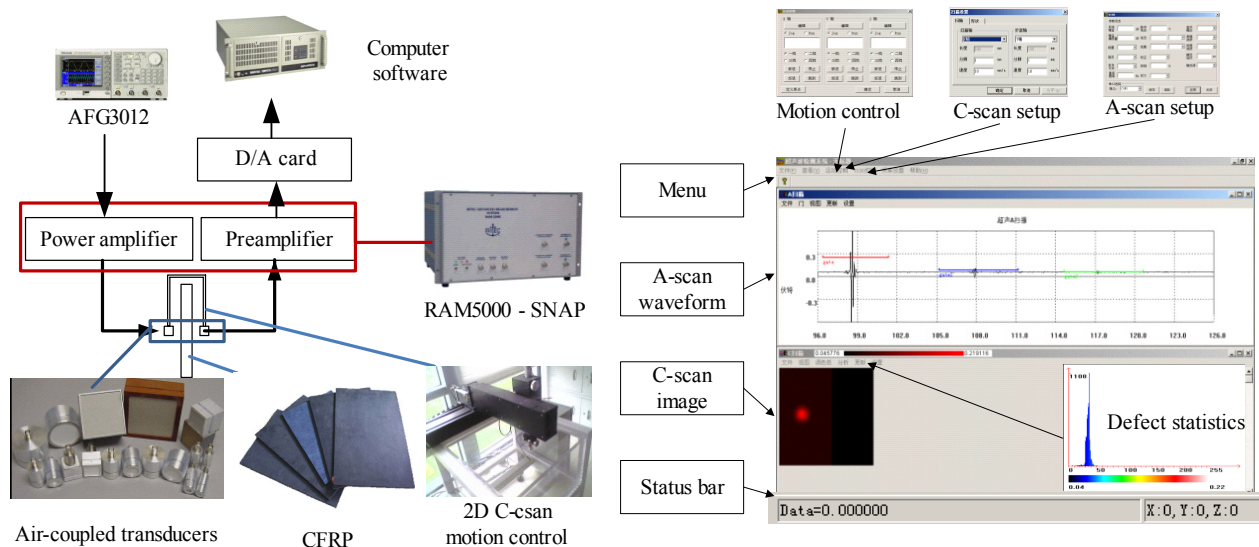


Fig. 7 Hardware and software of ultrasonic C-scan system

Scanning rate:	35mm/s at 0.2 mm accuracy
Scan accuracy:	0.1mm
Sample frequency:	120MHz, 60MHz, 30MHz, 20MHz, 1MHz
Excitation mode:	Negative pulse 400V, Continuous wave(CW) , Arbitrary waveform
Signal view:	RF, Positive, negative and bi-directional detection, Envelope detector, LFM pulse compression
Data visualization:	A-scan, B-scan, C-scan, Spectrum
Data Interface:	Full-waveform, real-time processing and storage

Table. 1 System key parameters

Experiment results

(a) Testing mode selection

Air-coupled ultrasonic testing has long duration aftershocks which can overlap with other defect echoes. Without considering the aftershock and the surface reflection wave, better results can be got easily by through mode. So through mode is generally used in air-coupled ultrasonic testing. Experimental result of 4mm CFRP board by through mode with air-coupled transducers is shown in Fig 8. Parameters $f_0 = 0.4\text{MHz}$, $B = 0.4\text{MHz}$ and $T = 30\mu\text{s}$ were used in the experiment.

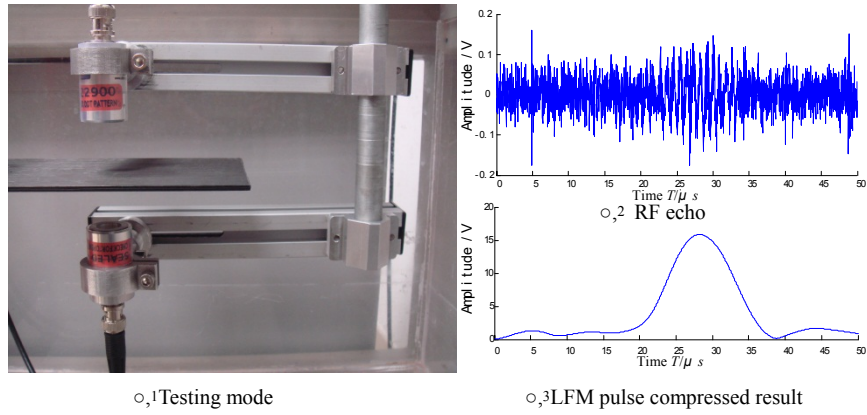


Fig. 8 Experimental result of CFRP using through mode

As shown in Fig 8, SNR of RF echo was 3.065dB. After pulse compression, SNR of the result was 21.77dB. SNR was increased 18.71 dB by pulse compression method using through mode.

When echoes are too close, they may affect each other. So the peak judgments and flight time determination are affected. The echo through 1mm CFRP board by 0.4MHz air-coupled transducers is shown in Fig. 9(a). Because the first wave was not absorbed completely by the absorbing layer, there were several echoes following the main one. After pulse compression, as shown in Fig.9 (b), near echoes can be separated. Wave reflection in the transducer can be seen clearly. So SNR and testing resolution can be greatly increased by application of pulse compression in air-coupled ultrasonic testing. According to the radar system range resolution formula [4]

$$\Delta R = c / 2B \quad (3)$$

Where ΔR is minimum distinguished distance, c is velocity, B is modulation bandwidth.

So if transducer bandwidth is known, minimum defects distinguished distance of pulse compression

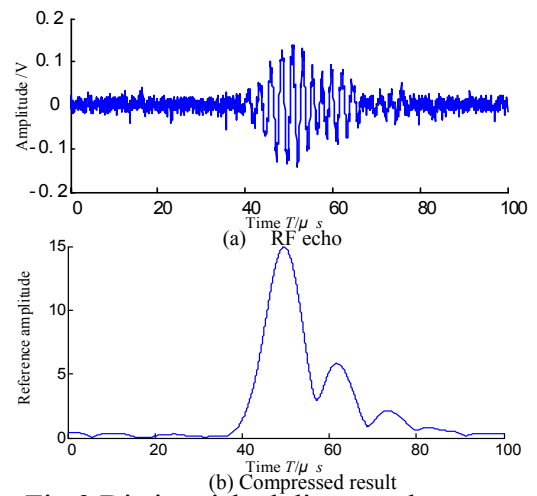


Fig.9 Distinguished distance demo

or the minimum thickness of the specimen can be calculated. The modulation bandwidth B can be chosen according to the concerned accuracy and the transducer bandwidth.

C-scan results

Two pairs of air-coupled transducers with different frequency were used to test the artificial defects in CFRP board. Experiment was made by through mode. Experimental results are shown in Fig.10 and table 2.

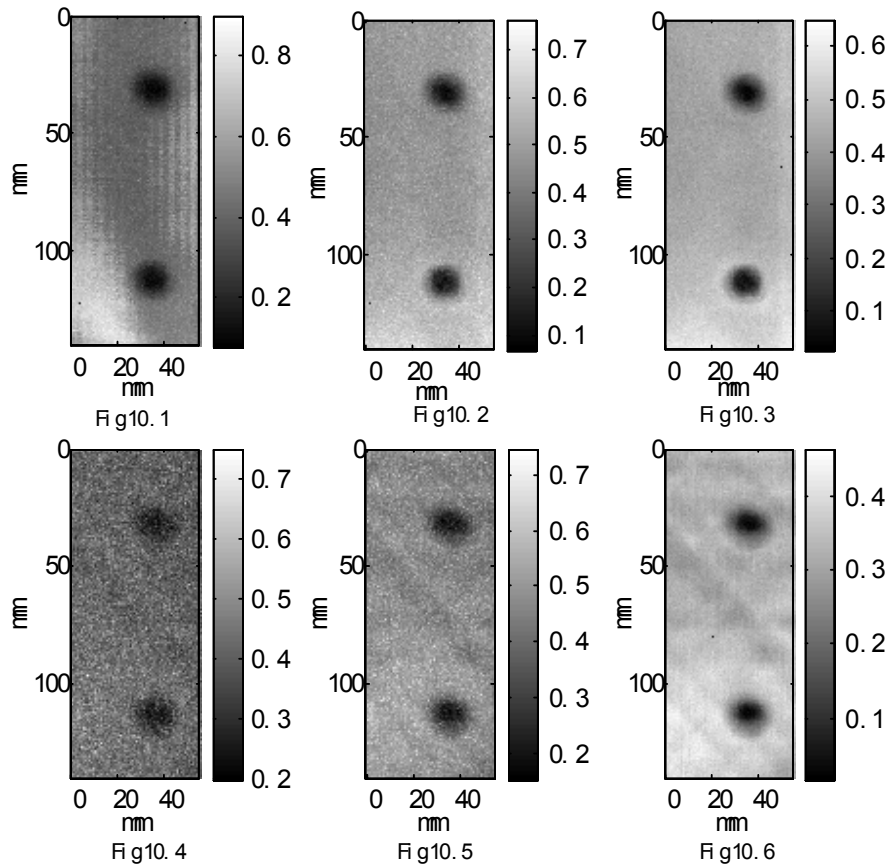


Fig. 10 Experimental results of ultrasonic C-scan

	Fig 10.1	Fig 10.2	Fig 10.3	Fig 10.4	Fig 10.5	Fig 10.6
Extraction method	1 cycle	CW	LFMPC	1 cycle	CW	LFMPC
f_0 /MHz	0.44	0.44	0.44	1.1	1.1	1.1
T /cycle	1	15	15	1	15	15
B /MHz	0	0.2	0.2	0	0.4	0.4
Power/ V_{pp}	200	200	200	200	200	200
Amplified /dB	70	70	70	90	70	70
SNR /dB	17.76	18.25	22.07	9.627	12.79	21.07

* Continues Wave (CW), Linear Frequency Modulation Pulse Compression (LFMPC)

Table.2 Experimental results comparison

SNR was calculated according to reference [5]. After compression, SNR of 0.4MHz transducer was increased 3.82dB, but SNR of 1.1MHz transducer was increased 8.28dB. It shows that a broad band transducer has better compression ability and is more suitable for pulse compression. The advantage of this method is more obviously in low SNR application.

Conclusion

- (1) Pulse compression method can be used in air-coupled ultrasonic composite material nondestructive testing. The SNR and minimum distinguished distance can be greatly increased.
- (2) The compressed result was significantly impacted by the key parameters, modulation bandwidth and time width. Parameters should be chosen carefully according to the transducer and the sample.
- (3) Under the same circumstances, a better compressed result can be got by using broad band transducers. Pulse compression is a potential signal processing method on composite material ultrasonic NDT.

Acknowledgements

- 1 . Project 50675012 supported by National Natural Science Foundation of China.
2. Project HK2008003 supported by Open Fund of Aeronautical Science and Technology Key Lab. of Aeronautical Test and Evaluation, Nanchang Hangkong University.

REFERENCES

- [1] ZHOU Zhenggan, WEI Dong. Progress of Air-coupled Ultrasonic Non-destructive Testing Technology [J]. Journal of Mechanical Engineering. 06 2008
- [2] T.H. Gan, D.A. Hutchins, D.R. Billson, D.W. Schindel. The use of broadband acoustic transducers and pulse-compression techniques for air-coupled ultrasonic imaging [J]. Ultrasonics 39 2001
- [3] Bassem R. Mahafza. Radar System Analysis and Design Using MATLAB [M]. Beijing: Electronics Industry Press. Second Edition, 2008:214-233
- [4] PENG Hu. Introduction to ultrasound imaging algorithm [M]. Hefei: China Science and Technology University Press, 2008:143-152
- [5] ZOU Mouyan. Deconvlution and signal recovery [M]. Beijing: National Defense Industry Press, 2000: 185-189