# ON-LINE TECHNIQUE FOR MEASURING THICKNESS FOR THREE-DIMENSIONAL BRAIDED COMPOSITE MATERIAL PREFORMS

**Zhenkai Wan, Jialu Li**

Tianjin Polytechnic University
Tianjin 300160, THE PEOPLE'S REPUBLIC OF CHINA
E-MAIL: wanzhenkai@tjpu.edu.cn

## *Abstract*

*This paper presents an automatic method that can measure the thickness of three-dimensional (3-D) braided composite preforms. The thickness of 3-D braided composite material preform is an important parameter of 3-D braided composites. With the development of 3-D braided composite technology, an automated measurement technology for thickness of braided composite preform has become an importantgoal. The objective of this paper is to present an automatic measuring system. The system we devised consisted of a computer, a proximity sensor, a pressure sensor, an analog-to-digital converter and pulse motor, etc. The measuring principle and results are discussed in the paper. The system was tested on both carbon and glass fibre preforms. We obtained very encouraging results. Experiments showed the pressure and eddy current resistance value are important parameters for measuring the thickness of 3-D braided composite material preforms. The measuring precision is higher when the pressure value ranges from 0.6kg/cm$^2$ to 0.8kg/cm$^2$ and the eddy current resistance is 2k$\Omega$ for preforms made of carbon-fibre than of other substances.*

## *Key words:*

*thickness measurement,* three-dimensional braided, preform composite material, eddy current resistance, critical distance*,* power spectrum

## INTRODUCTION

Three-dimensional (3-D) braided composite material preforms for structural applications are the subject of rapidly increasing interest. The huge potential of 3-D braided composites is becoming more and more obvious with the recent developments of automated, computer controlled machines capable of manipulating hundreds, even thousands of yarn ends in the 3-D braiding processes, and thus satisfying the in-plane size and thickness requirements [1]. Importantly, while increasing the machine operation speed, these technologies become competitive from the viewpoint of productivity. It was well understood for a while that 3-D braided preforms provide unique structural features and performance characteristics. Among those are the full suppression of delamination, improved damage tolerance and impact resistance, better fatigue properties, higher strength near holes and openings, near bolts and fasteners, higher stiffener/skin attachment strength, etc.

3-D braiding can be classified into two-step, four-step, and multistep processes. The number of steps refers to the number of movements required for the yarn carriers to return to their original positions. The 4-step process is a general term for processes that include Omniweave, Magnaweave, Scodid, and Cartesian braiding. Multistep braiding is a generalisation of the four-step procedure which involves individual control over columns and rows. 3-D braiding machines use a beater to control compaction as the yarns interlace. The degree of compaction is a process variable which affects the resulting fabric's geometry [2].

A diagram of a typical 4-step 3-D braiding machine is shown in Figure 1.

The biggest automatic braiding machine (600 × 400) in China based on 4-step was made by the Tianjin

Polytechnic University in 1993. It has produced variable preforms of 3-D braided composites material. Some are shown in Figure 2.

In recent years much work about 3-D braided composites material has been analysed. Based on early research, much of the work has focused on the use of mechanical analysis [3]. The thickness of braided preform is closely related to material mechanical performance after the braided preform had been reinforced. This is very important research, using a computer to analyse the thickness of the 3-D braided material preform.

Many test instruments offer the operator the ability to use either magnetic induction or eddy current test methods for measuring coating thickness. Coating thickness measurement is made on both steel and on non-ferrous metals. However, their measurement range is small (less than 1 mm) [4]. They cannot be used for measuring the thickness of 3-D braided composite material preforms.

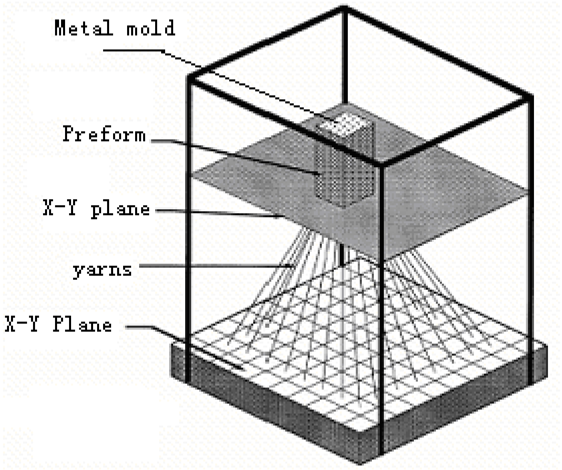

**Figure 1.** Diagram of a typical 4-step 3-D braiding machine

The ultrasonic test method is very useful for taking accurate thickness measurements. It has been employed to detect the depth of cracks for composite material [5]. However, the technology cannot be used for measuring the thickness of composite material preforms. This is because the ultrasonic energy will be absorbed during the measuring process.

So far, no measuring method or test standard have been reported for the thickness of 3-D braided composite preforms in scientific literature. Our research has led to a new development for measuring 3-D braided composite material preforms. It will provide perfect data for improving artifact technology for 3-D braided composite material preforms.

This paper is organised as follows; the system design is described in Section 2, and experimental results are given in Section 3. Finally, a conclusion is provided in Section 4.

**Figure 2.** Some samples of 3-D braided perform

## A MEASURING SYSTEM FOR THE THICKNESS OF 3-D BRAIDED COMPOSITE MATERIAL PREFORMS

Because no standard of thickness for 3-D composite material preforms has been established in the People's Republic of China, we will institute a standard recently based on the method which will be described in this paper. This value of thickness for 3-D composite material preforms was measured according to the GB / T 3820-1997 standards, which specifies the thickness of textiles and textile products to be measured in China [6]. The measuring principle is shown schematically in Figure 3. The system consists of a computer (PC), a proximity switch (model 3RG46), a pressure sensor (model BLR-10), an A/D converter, a motor driver (model ZETA4) and a step motor (model ZETA 57-83).

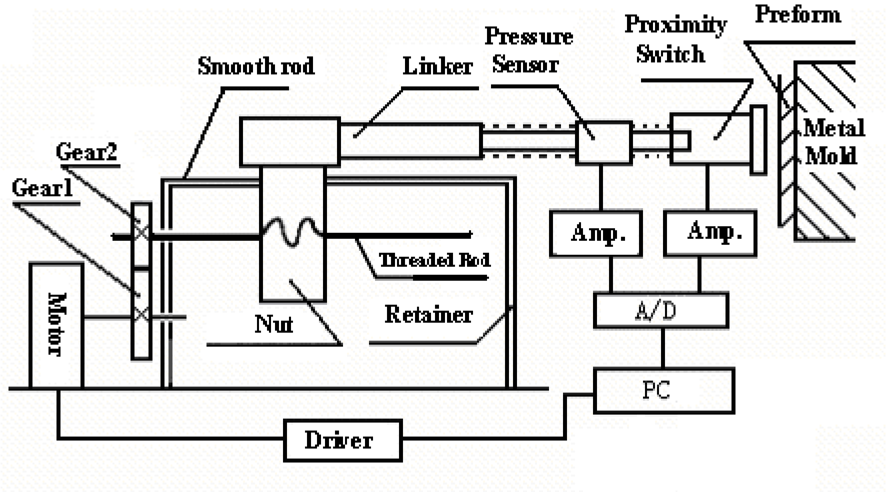

**Figure 3.** Diagram of measuring principle

The measuring principle is based on the very sensitive proximity switch and pressure sensor. A proximity switch (3RG46) with an operating distance of 80 mm was used in the system. A hard plastic cover, round in shape with an area of 10cm$^2$, was installed in front.

When the system operates, the step motor runs forward under I/O card controlling, and the drive threaded rod rotates. The proximity switch moves forward. With the motor running, the proximity switch will sense the metal mould and change its state. This position is the critical point of the proximity sensor for metal mould. The distance between the critical point and the metal mould is called the *critical distance*. The computer will record and measure the pressure value as long as the proximity switch's statecontinues to change. When the pressure value is come to setting pressure value, the motor stops and computer calculates the thickness of the preform.

The thickness of the composite material preform is given by:

$$H = L - M \cdot P \tag{1}$$

where $L$ is the critical distance, $M$ is the sum of the pulses which were recorded by PC from the critical point position to the step motor stop position, *P* is the moving distance of the threaded rod for one pulse.

$$P = \theta \cdot t \tag{2}$$

where $\theta$ is the step angle of the step motor, and $\theta$=0.018 degree; $t$ is the screw-pitch of the threaded rod, and $t$=1.5mm.

The pressure sensor (model BLR-10) is described as follows:

- pressure range: 0 to10 kg,
- full scale output: 147mV,
- total maximum error: better than 2% full scale,

- power supply +12 V DC, 30 mA.

Table 1 shows the data on the measured and reported weight in ??[[grams of 18]]. Denoting the measured weight by *Y* and the reported weight by *X*, a line relating the two variables has the following regression equation:

$$Y = A + BX \tag{3}$$

**Table 1.** The data of measured and reported weight for the pressure sensor

| Measured Reported | | Measured Reported | | Measured Reported | |
|---|---|---|---|---|---|
| weight x(g) | weight y(g) | weight x(g) | weight y(g) | weight x(g) | weight y(g) |
| 0.00 | 0.00 | 600 | 605.9 | 1400 | 1410.0 |
| 100 | 103.25 | 700 | 707.2 | 1600 | 1609.3 |
| 200 | 205.0 | 800 | 809.2 | 1800 | 1819.7 |
| 300 | 302.7 | 900 | 909.8 | 2000 | 2010.8 |
| 400 | 401.6 | 1000 | 1010.3 | 2400 | 2410.2 |
| 500 | 502.3 | 1200 | 1220.1 | 2500 | 2521.4 |

$$B = \frac{n \cdot \sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \quad A = \overline{Y} - B\overline{X} \tag{4}$$

The correlation coefficient is:

$$R = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{\left[n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]}} \tag{5}$$

From Table 1, the regression equation is:

$$Y=0.075+1.012X$$

The correlation coefficient is:

$$R=0.999996$$

This shows that the pressure sensor has a favourable linear performance.

According to GB / T 3820-1997, the thickness value of the preform will be calculated considering the pressure value and pressure value ranges from $0 kg/cm^2$ to $1kg/cm^2$. Therefore, the maximum pressure value is 10kg in the system. The minimum differential output voltage from the pressure sensor will be 0 mV (0kg), and the maximum sensor voltage will be 147 mV (10kg). In a five-volt system where VDD = 5V, the maximum amplifier output is equal to 4.9 V. The minimum output of the sensor is 0 *mV*.

The value of pressure had been obtained by using a pressure sensor and an operational amplifier (MCP602). The gain is calculated by dividing the maximum output voltage by the maximum input voltage. The signal processing circuit is shown in Figure 4. The appropriate gain for the system is 33.33.

$$G_G = \frac{2R_1}{Gain - 1 - \frac{R_1}{R_2}} \tag{6}$$

if $R_1 = 30k\Omega$ and $R_2 = 10k\Omega$ ,then

$$R_G = \frac{60k\Omega}{33.33-4} = 2.04k\Omega \text{ ( closest 1\% value)}$$

The inductive proximity sensor circuit is shown in Figure 5. In this figure, the eddy current resistance R2 is different for the different material preforms.

For the purpose of process control, a PCI-1710 card was used. The PCI-1710 is a multi-function data acquisition card for the computer's PCI bus. This card provides multiple measurement and control functions. It offers sixteen 12-bit single-ended channels of A/D input, 16 channels of digital inputs, 16 channels of digital outputs, two 12-bit channels of analogue output, etc.

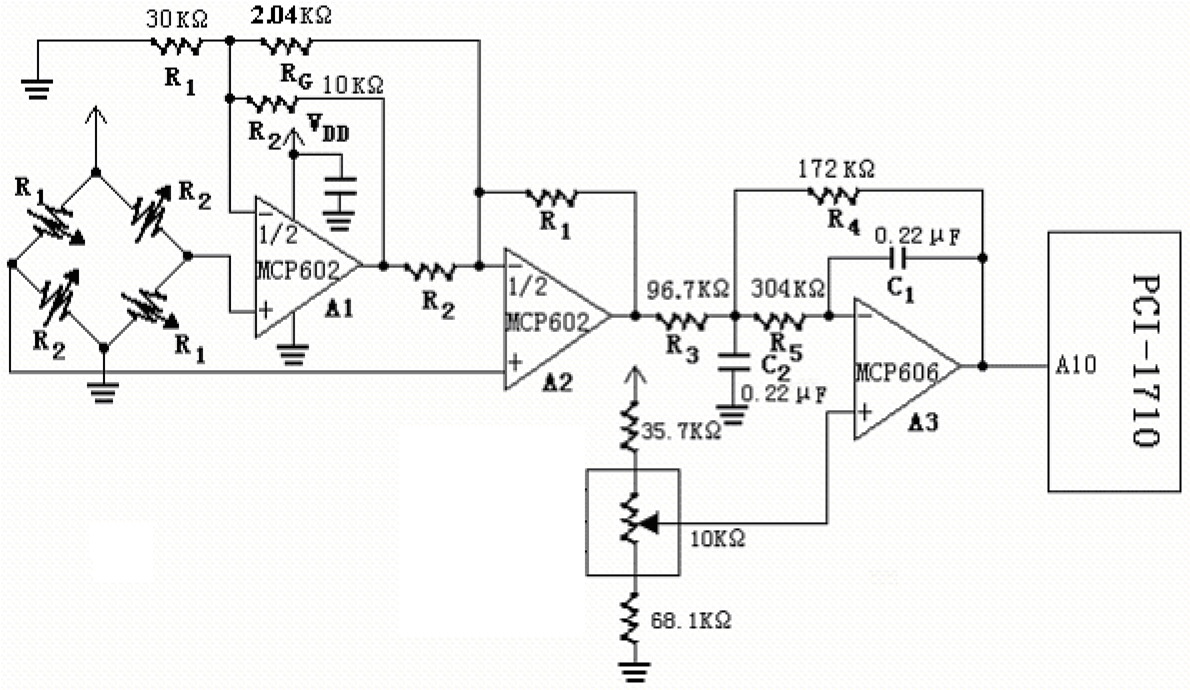

**Figure 4.** The circuit for signal processing

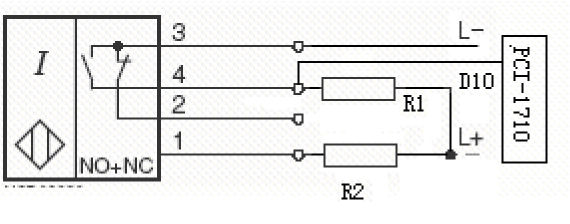

**Figure 5 .** The interface circuit of the inductive proximity sensor

The flow chart of thickness to be measured for 3-D braided preforms is shown in Figure 6.

## EXPERIMENTAL RESULTS

In the system, we will describe the results by means of the sample mean, sample standard deviation and the power spectrum. The sample mean is an estimator available for estimating the population mean. It is a measure of location, commonly called the average. Standard deviation is a measure of the spread or dispersion of a set of data [7]. They are:

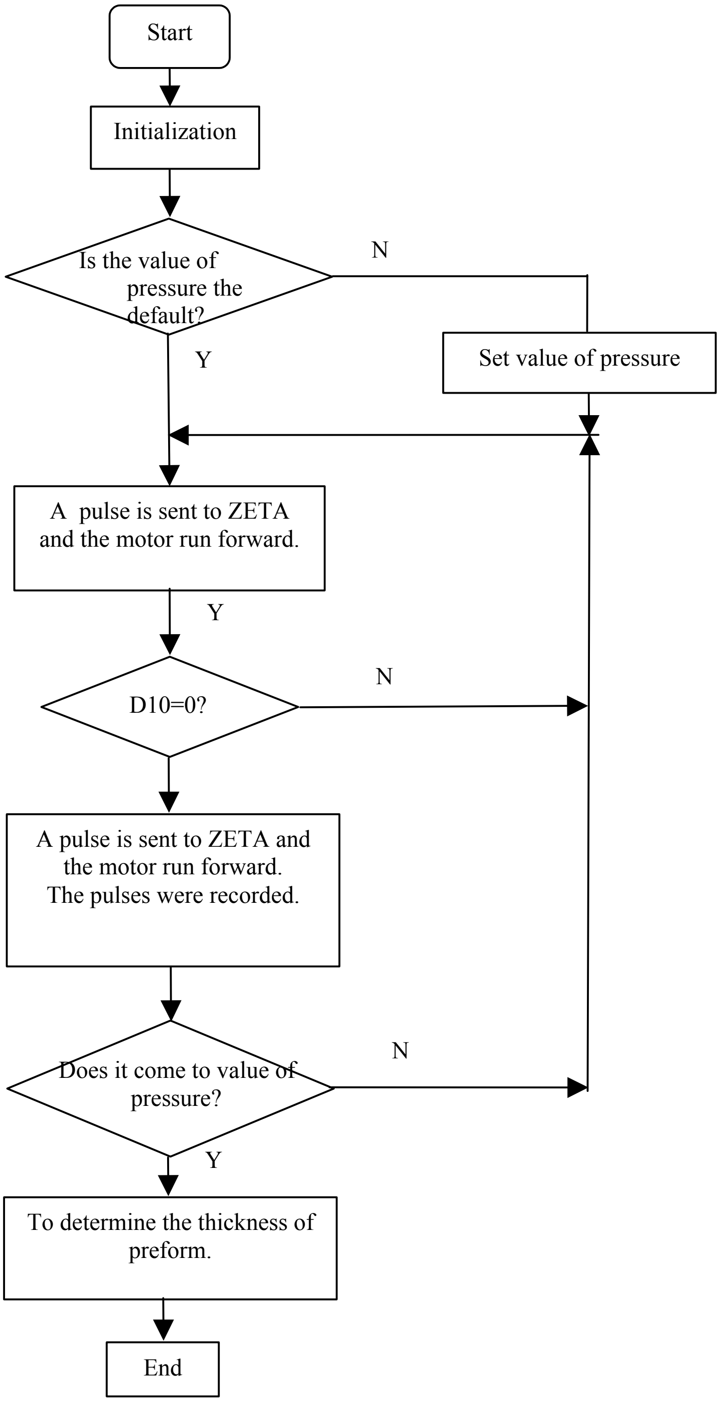

**Figure 6.** The flow chart of thickness to be measured for 3-D braided preforms

$$\overline{X} = \frac{\left(\sum_{i=1}^{n} x_i\right)}{n} \tag{7}$$

$$S_{n-1} = \sqrt{\frac{\left(\sum_{i=1}^{n} x^2 - n\overline{X}\right)}{n-1}} \tag{8}$$

$\overline{X}$ = sample mean (average).

$n =$ number of specimens.

$x_i =$ measured or derived property.

$S_{n-1}$ = sample standard deviation.

## Experiment 1. Thickness to be measured for glass-fibre preform

Test parameter: R2=0Ω, Pressure value=0.6 $kg/cm^2$, L=25 mm

The measuring result for 20 times is listed in Table 2. The scatter diagram is shown in Figure 7.

**Table 2.** The measuring result for glass-fibre preform

| *i* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Thickness | 6.625 | 7.563 | 7.600 | 6.563 | 7.413 | 6.175 | 7.338 | 7.788 | 8.388 | 8.538 |
| *i* | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Thickness | 6.363 | 6.663 | 6.663 | 8.275 | 7.338 | 8.463 | 8.500 | 8.013 | 8.575 | 8.05 |

$\overline{X}$ =7.54 *mm*, $S_{n-1}$ = 0.81 *mm*, $X_H$ = 7.49*mm*, $|\overline{X} - X_H|$=0.05 *mm*.

$X_H$ denotes the average value of thickness which was measured by hand. The manual measuring was used for the piercing method. The fibre will be mangled manually.

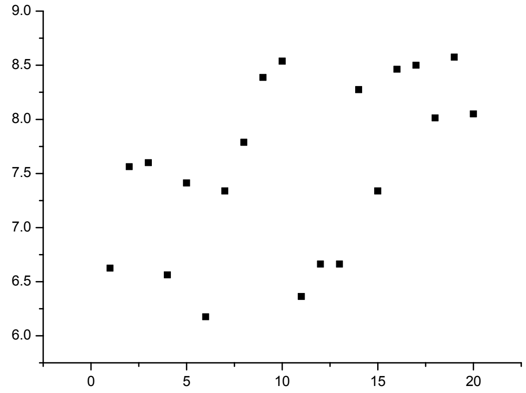

**Figure 7.** The scatter diagram of thickness for glass-fibre preform

## Experiment 2. Thickness of preform for carbon-fibre to be measured

Test parameter: R2=500Ω, Pressure value=0.6 $kg/cm^2$, L=22 mm

The measuring result after 20 times is listed in Table 3. The scatter diagram is shown in Figure 8.

**Table 3.** The measuring result for carbon-fibre preform

| *i* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Thickness | 6.475 | 6.550 | 6.325 | 6.625 | 6.963 | 6.138 | 6.663 | 6.925 | 6.663 | 7.488 |
| *i* | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Thickness | 6.700 | 5.838 | 6.363 | 6.963 | 6.700 | 6.100 | 6.813 | 6.400 | 6.363 | 5.538 |

$\overline{X} = 6.53\,mm$, $S_{n-1} = 0.44\,mm$, $X_H = 7.58mm$, $\left|\overline{X} - X_H\right| = 1.05\,mm$

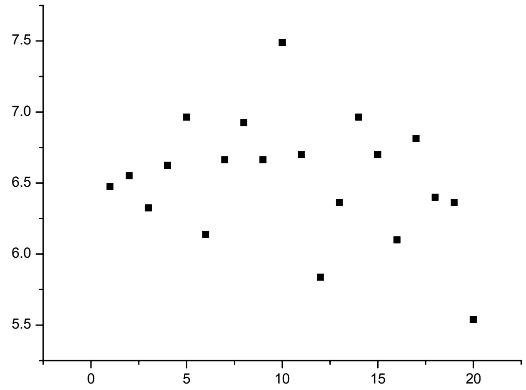

**Figure 8.** The scatter diagram of thickness for carbon-fibre preform

## Experiment 3. Thickness of preform for carbon-fibre to be measured

Test parameter: R2=1$k\Omega$, Pressure value=0.6 kg/cm$^2$, L=22 mm.
The measuring result for 20 times is listed in Table 4. The scatter diagram is shown in Figure 9.

**Table 4.** The measuring result for carbon-fibre preform

| *i* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Thickness | 5.313 | 5.388 | 6.288 | 5.613 | 6.950 | 5.538 | 5.725 | 5.650 | 5.838 | 5.500 |
| *i* | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Thickness | 5.200 | 5.275 | 5.350 | 5.125 | 5.463 | 5.013 | 5.388 | 5.500 | 5.575 | 5.500 |

$\overline{X} = 5.56$ mm, $S_{n-1} = 0.43$ mm, $X_H = 5.64$ mm, $\left|\overline{X} - X_H\right| = 0.08$ mm.

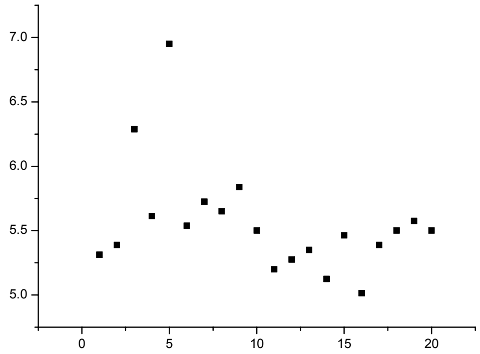

**Figure 9.** The scatter diagram of thickness for carbon-fibre preform

## Experiment 4. Thickness of preform for carbon-fibre to be measured

Test parameter: R2=2k$\Omega$, Pressure value=0.6 kg/cm$^2$, L=22 mm.
The measuring result for 20 times is listed in Table 5. The scatter diagram is shown in Figure 10.

**Table 5.** The measuring result for carbon-fibre preform

| *i* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Thickness | 5.463 | 5.463 | 5.463 | 5.725 | 5.725 | 5.763 | 5.500 | 5.430 | 5.688 | 5.238 |
| *i* | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Thickness | 5.275 | 5.050 | 5.238 | 5.688 | 5.725 | 5.463 | 5.763 | 5.5 | 5.6125 | 5.275 |

$\overline{X} = 5.50$ *mm*, $S_{n-1} = 0.21$ *mm*, $X_H = 5.52$*mm*, $\left|\overline{X} - X_H\right|$ =0.02 *mm.*

From Figures 8-10, the measurement precision when R2=2kΩ is higher than for (R2=500Ω, R2=1kΩ). The results imply that the conductivity of carbon-fibre preform should be taken into account in the measuring process. Furthermore, the eddy current resistance value of 2 *k*Ω was adopted is reasonable within this system.

## Experiment 5. Thickness of preform for carbon-fibre to be measured on a point under different pressure value

Test parameter: *R2*=2*k*Ω, *L*=22 mm.

The measuring result for 20 times is listed in Table 6. The scatter diagram is shown in Figure 11.

**Table 6.** The measuring result for carbon-fibre preform

| Value of pressure( $kg/cm^2$ ) | 0.3 | 0.5 | 0.6 | 0.8 | 1.0 |
|---|---|---|---|---|---|
| Average value of thickness for 20 times on a point | 5.73 | 5.68 | 5.50 | 5.26 | 5.11 |
| $\overline{X}$ | 5.60 | 5.56 | 5.48 | 5.24 | 5.05 |
| $\left\|\overline{X} - X_H\right\|$ | 0.13 | 0.12 | 0.02 | 0.02 | 0.06 |

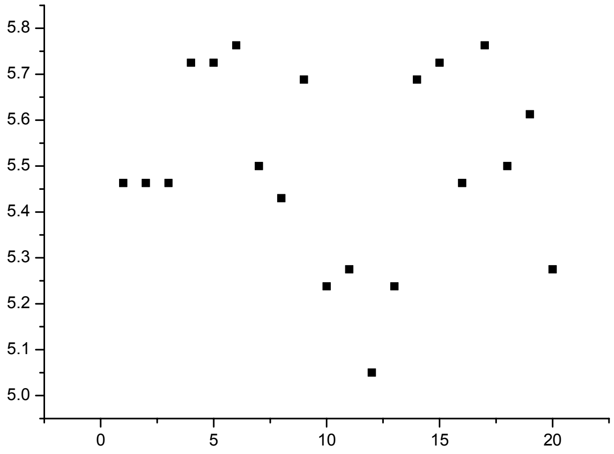

**Figure 11.** The scatter diagram of thickness for carbon-fibre preform

From Table 5, the measurement precision is higher when the value of pressure ranges from 0.6 kg/cm$^2$ to 0.8 kg/cm$^2$ than in other situations. The pressure value is the main parameter for the thickness to be measured for 3-D braided preforms.

**Experiment 6. Thickness of preform for carbon-fibre to be automatically measured**

The power spectrum indicates the power of each frequency component of the source time domain waveform. The power spectrum can be used to analyse a variety of thicknesses for braided preform. In a signal analyser, the time record length is adjustable, but it must be selected from a set of predefined values. Since thickness signals are not periodic within the predefined data block time periods, a window must be applied to correct for leakage. In the system, a Fast Fourier Transform (FFT) using the Harming Window Function was performed on each group of 64 data points.

We use 64 readings for thicknesses that are automatically measured from the preforms of carbon-fibre. The test parameters are $R2=2k\Omega$ *and* $L=22$ mm. The power spectrum is shown in Figure 12, and the scatter diagram is shown in Figure 13.

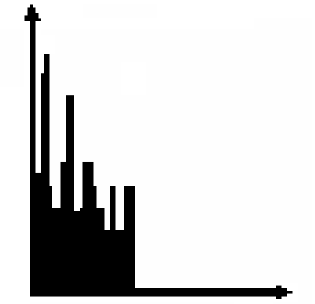

**Figure 12.** The power spectrum for 64 readings of thickness

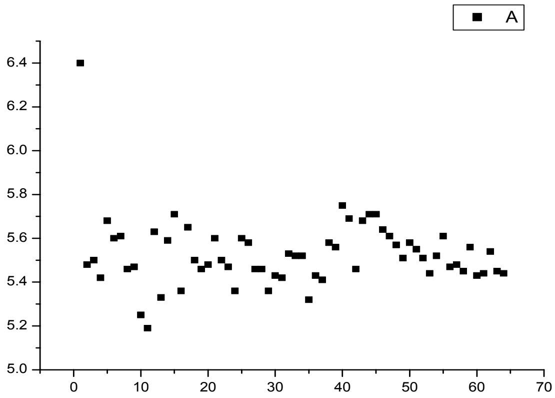

**Figure 13.** The scatter diagram of thickness for carbon-fibre preform

The power spectrum shows the uneven structure of frequency for thickness. An increase in amplitude of a frequency peak may indicate a potential problem or deterioration in quality. The power spectra can characterise the unevenness of thickness.

## CONCLUSION

In the present study we have carried out the thickness measurement for 3-D braided composite material preforms. This method can be used to rapidly measure the thickness of complex composite preforms which are made of both glass-fibre as well as carbon-fibre.

The eddy current resistance and pressure value are important factors for controlling measuring precision.

The work will provide the foundation for establishing a test standard for 3-D braided composite material in the People's Republic of China.

The findings of this research work will help our country's composite manufacturing companies to diversify into civilian applications.

## *References*

1. *M.H. Mohamed, A.E. Bogdanovich, L.C. Dickinson, J.N. Singletary, and R.B. Lienhart, "A New Generation of 3D Woven Fabric Preforms and Composites," SAMPE J., 37(2001), pp. 8-17.*
2. *Gowayed, Yasser; Hwang, Jhy-Cherng; Chapman, Daryl, "Thermal conductivity of textile composites with arbitrary preform structures" J. of Composites Technology & Research,17(1995),pp.56-62.*
3. *Degrieck, J and Van Paepegem W, "Fatigue Damage Modelling of Fibre-Reinforced Composite Materials: Review", Applied Mechanies Reviews,54 (2001),pp. 279-300.*
4. *http://www.helmut-fischer.com/Product_Group_overview_1.asp?PSG=0130&wg=11&CountryID=91&LanguageID=2, Hand-Held Instruments - DUALSCOPE® for magnetic induction and eddy current test methods.*
5. *Brian J. Tucker, Donald A. Bender, David G. Pollock, and Michael P. Wolcott, "Ultrasonic Plate Wave Evaluation Of Natural Fibre Composite Panels", Wood and Fibre Science, 35( 2003) ,pp. 266–281.*
6. *http://www.cnaec.com.cn/guifan/02/W00-09.htm*
7. *John E. Masters and Marc A. Portanova, Standard Test Methods for Textile Composites, Lockheed Martin Engineering & Sciences Company,1996*

∇∆