

Deviation-Rectifying Control of Carbon Fiber Prepreg Slitting and Winding Machine

Wen Liwei^{1*}, Zhu Tengfei¹, Qin Lihua², Wang Xianfeng¹, Pan Jie¹, Feng Qiaoqiao¹

1. College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China; 2. Beijing Institute of Space Long March Vehicle, Beijing 100076, P. R. China

(Received 30 November 2016; revised 20 February 2017; accepted 23 May 2017)

Abstract: With the growing needs of prepreg tapes for the automated fiber placement (AFP), the deviation-rectifying of prepreg in slitting process was investigated on a self-developed 16-tow prepreg slitting and winding machine. The process of slitting and rewinding of prepreg tape was introduced, and the reason of prepreg tape deviation in slitting process was analyzed. In order to ensure the quality of the narrow prepreg slits, the application of the fuzzy PID algorithm in a closed-loop control system was discussed. A fuzzy PID algorithm was designed by combining fuzzy rules and PID controller. By applying it to precise deviation-rectifying control strategy, the automatic control of rectification could be achieved with accuracy of 0.1 mm, which satisfies the requirement of the prepreg tape both in slitting quality and layup quality for AFP.

Key words: automated fiber placement; prepreg tape; slitting and winding; fuzzy PID; deviation rectifying

CLC number: TB332

Document code: A

Article ID:1005-1120(2018)03-0547-09

0 Introduction

Automated fiber placement (AFP) technology has become a heated research topic in the field of composite materials. The related researches include equipment study, manufacturing process study, and path planning and material study^[1-3], etc. AFP employs narrow (3.18 mm, 6.35 mm, 12.7 mm in width) unidirectional pre-impregnated fiber as raw materials, with a specific combination of tow forming prepreg with variable width, which is placed onto the mold surface^[4]. It is a key technology of forming complex surface (such as fuselage, blended wing body, inlet, etc.), with a wide range of application, high molding efficiency and reliable part quality^[5]. The high quality, precision and reliability of AFP enable its application in the manufacture of structural components of large aircraft, launch vehicles and other types of aerospace vehicles in the developed countries^[6-8].

At present, the preparation methods of prepreg used in AFP can be divided into two categories; Direct hot-melt method and slitting method. Direct hot-melt prepreg has lower efficiency, lower resin content and difficulty in width control, making it only suitable for small batch production for space grade prepreg. Slitting method slits prepreg directly with high efficiency and high precision, and it suits mass production, which is main method for AFP prepreg tapes^[9]. The principle of slitting mechanism is shown in Fig. 1. AFP technology has high demands on the width and edge quality of prepreg slits, which can seriously affect the final fiber placement efficiency and product performance. This requires high slitting precision and quality of the slitting machines. Factors such as mechanical vibration and unsteady tension in the slitting process can lead to deviation of the prepreg, which affects the slitting precision and quality. Most of the traditional deviation-rectifying controllers use switch sensor,

* Corresponding author, E-mail address: wenliwei@nuaa.edu.cn.

and its control method is applied to the traditional PID control^[10-11]. Traditional deviation-rectifying controller needs more sensors installed to ensure high rectification accuracy, and the PID control method has high precision, while the system has larger overshoot and overshoot time. In order to improve the slitting precision and meet the process requirements of prepreg, we propose a self-developed photoelectric deviation-rectifying control system based on fuzzy control algorithm, which can eventually realize the automatic rectification in the process of slitting^[12-13].

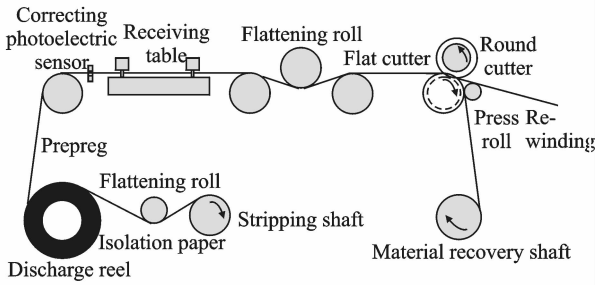


Fig. 1 Principle of slitting mechanism

1 Influence of Prepreg Tape Deviation on Slitting Quality

Due to the viscosity of prepreg, fiber residue and resin tend to stick on the blade, which will be detrimental to the quality of prepreg tows. As the prepreg is highly anisotropic, it is easy to be slit in the longitudinal direction but likely to crack in the transverse direction. The traditional slitting method without deviation control is unable to ensure the precision of tows.

Slitting method mainly contains three steps: unwinding, slitting, rewinding. In the slitting process for wide prepreg tapes, deviation often occurs, resulting in width change of the slit prepreg and material scrap. The width deviation of narrow prepreg tapes should be controlled within 0.1 mm after the slitting process, in order to meet the requirements of AFP. The so-called deviation refers to the non-straight movement of prepreg tape, where its centerline deviates away from the reference centerline, during slitting right after unwinding.

The wide prepreg is divided into 16 prepreg

tapes by a circular cutter and is rewound by 16 groups of rewinding units, respectively. If the tensions on the 16 prepreg are not uniform, prepreg offset and significant separation will occur, resulting in uneven width of the prepreg taps. There are many reasons for prepreg tape deviation, such as the imperfect processed roller, installation inaccuracy, tension instability, irregular width and stretching of raw prepreg material and machine vibration. Prepreg tape cannot be slit with clear and precise borderline in the case of position deviation.

2 Construction of Automatic Deviation-Rectifying Control System

The self-developed photoelectric automatic deviation-rectifying control system is shown in Fig. 2. The photoelectric sensor collects the position of the prepreg tape and feeds it back to the PLC controller. After fuzzy PID operation, pulses are sent to the driver to drive the stepper motor screw mechanism, controlling the movement of releasing roller and implementing rectification function.

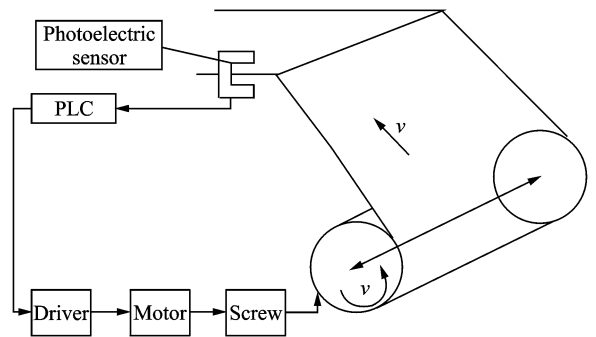


Fig. 2 Deviation-rectifying control system

The sensor is a U-shaped opposite-type photoelectric sensor with the analog voltage output, whose detection accuracy is up to 0.01 mm. The edge of the tape passes through the sensor, and the principle is shown in Fig. 3.

When there is no obstruction between the lens, the prepreg is completely out of the sensor. At this time, the power value of received light is P . Within a certain emission circuit, P is a constant value. The power received by the receiver is

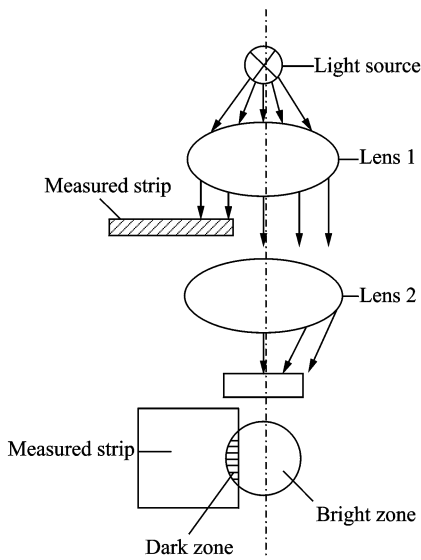


Fig. 3 Principle of photoelectric detection

$P_1 = P/2$ (half of the light flux), when the prepreg is in normal position (Prepreg edge is located on the centerline of the lens). Therefore, an offset value of r can produce a unique output voltage value.

By experiment, the output voltage can be measured when the tape in Fig. 3 is moving from left to right, and its relationship is shown in Fig. 4.

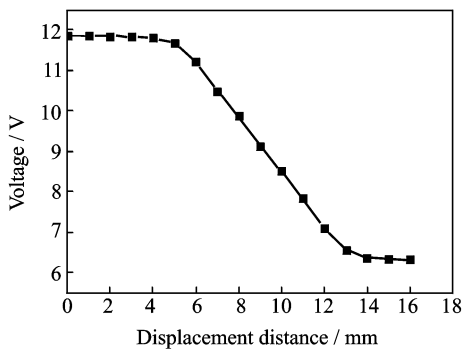


Fig. 4 Output voltage linearity of photoelectric sensor

3 Automatic Deviation-Rectifying Control Scheme

The actual model of rectification system has many influencing factors and many variables which need to be compensated. Its construction parameter is not very clear, and it is a non-linear, time-varying and lagging system. A controller is required for good self-adaptation, which can auto-

matically adjust the controlling parameters. By using an experience and knowledge based fuzzy PID control system, the mathematical model is object independent. It has some other advantages as well, for example, it overcomes the adverse effects to system performance, which are brought by the uncertainties of AC speed control system.

The fuzzy self-adaptive PID control system can detect and analyze the uncertain conditions, parameters, delay and interference in the control process. The on-the-fly self-tuning of PID parameters— K_P , K_I and K_D can be achieved by fuzzy reasoning. It is more advanced control system, which not only remains the simple principle, easiness and robustness of traditional PID control system, but also has better flexibility, adaptability and control precision.

In this paper, fuzzy PID control algorithm output linguistic variables are K_P , K_I and K_D after clarification by fuzzy control rules. And the input linguistic variable is the deviation of converted digital value from input voltage in photoelectric sensor after fuzzification, as shown in Fig. 5.

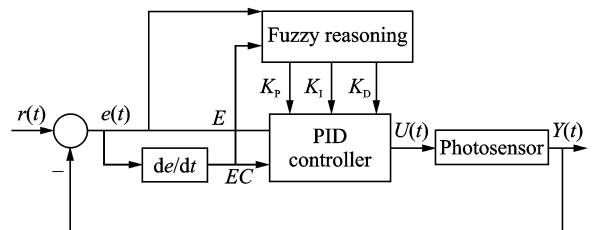


Fig. 5 Fuzzy PID control diagram

3.1 Fuzzy PID control scheme

3.1.1 Fuzzification of deviation, deviation change and output value

The inputs of the fuzzy controller are mainly measured. First of all, they need to be scale-converted to the values in discrete domains. This is actually a conversion of a domain of discourse into a certain number of small segments, which is quantifying each segment with a specific term, resulting in the formation of a discrete domain. After scaling, fuzzy sets are defined by assigning degree of membership to each specific term in the new discrete domain. In this example, the abso-

lute deviation value $|E|$ and the deviation changing rate $|EC|$ are considered as input linguistic variables. Each linguistic variable takes three linguistic values: big (B), medium (M) and small (S), whose membership functions are selected as triangle functions^[14], as shown in Figs. 6, 7.

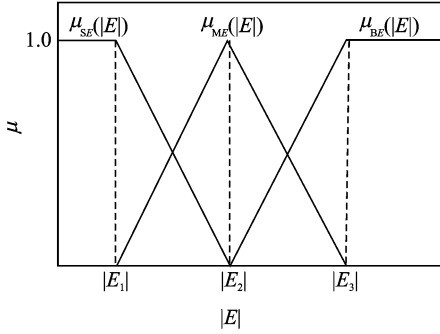


Fig. 6 Membership functions of deviation $|E|$

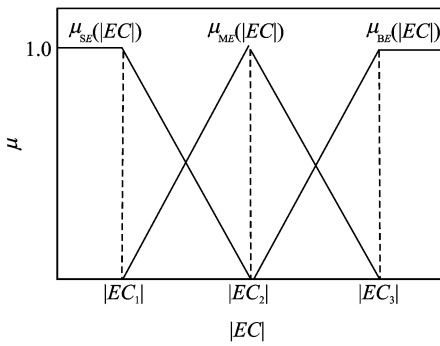


Fig. 7 Membership functions of deviation changing rate $|EC|$

Among them, the degree of membership μ can be adjusted according to the actual situation of different turning points $|E_1|$, $|E_2|$, $|E_3|$, $|EC_1|$, $|EC_2|$ and $|EC_3|$. By defining the membership function, numeric variables $|E|$ and $|EC|$ could be classified as “big medium or small”. In this example, the receiving end of the photoelectric sensor is a circle with a diameter of 15 mm. The detected analog voltage through the A/D module is converted into a digital value with resolution of 6 000. According to the experimental results, the relationship between digital value and deviation is shown in Fig. 8.

From Fig. 7, it can be seen that when the distance is over 3.55 mm, the tape is located in the edge area of the sensor, or has been off the

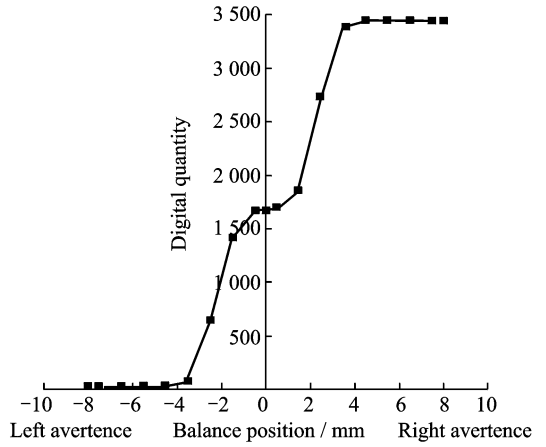


Fig. 8 Relationship between the number and the deviation

sensor, while the received digital variation range is very small. When the deviation is between 1.70 mm and 3.55 mm, the change of received digital value is very large. When the deviation is within 1.70 mm, the change of the received digital quantity tends to be moderate.

From the above analysis, $|E_1|$ is set as 0.15 mm, $|E_2|$ as 1.70 mm, and $|E_3|$ as 3.55 mm. In this example, an OMRON PLC type CP1H- XA is selected as the processor, the program scan cycle is set as 100 millisecond, and the sampling period is also set to 0.1 s as well. In addition, $|EC_1|$, $|EC_2|$ and $|EC_3|$ are set as 30, 75, and 150, respectively.

Similarly, the required PID parameter values can be sorted out for different states by conventional method and fuzzification. And the membership functions are shown in Fig. 9.

Degree of membership can be set by adjusting different turning points of the value— K_{P1} , K_{P2} , K_{I1} , K_{I2} and K_{D1} , K_{D2} , according to the actual situation. In this example, K_{P2} , K_{P1} are set to 0.5 and 1.5, respectively; K_{I1} , K_{I2} to 0.12 and 0.18, respectively; and K_{D1} , K_{D2} to 0.18 and 1, respectively.

3.1.2 Determination of fuzzy control rules

The setting of PID parameters must take into account the role of the three parameters at different stages and the relationship between them. From the traditional experience, it is known that the requirement of the parameters in the control

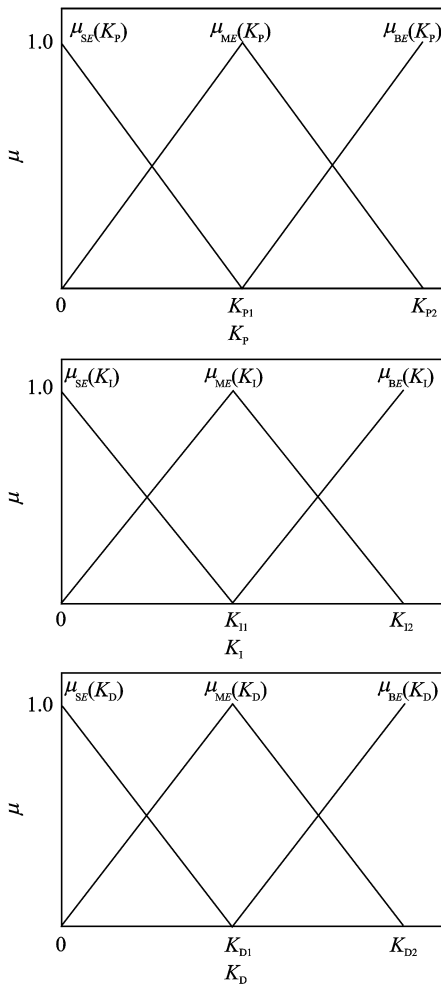


Fig. 9 Membership functions of K_P , K_I , K_D

process is as follows [15]:

When the deviation $|E|$ is large, larger K_P and smaller K_D should be taken for better fast-tracking performance of the system. At the same time, in order to avoid system response to a large overshoot, the integral action should be limited, and usually set as $K_I=0$.

When the deviation $|E|$ is in normal range, K_P should be set to small value, for system response to smaller overshoot. And in this case, the value of K_I and K_D should be moderate, so as to ensure the system responding speed. And the value of K_D has a greater influence on the system response.

When the deviation $|E|$ is small, K_P and K_I should be larger, for better system stability. At the same time, to avoid the oscillation of the system around the setting value, and for the anti-

interference performance of the system, when $|EC|$ is small, the K_D value should be large, and usually taken as medium value; when $|EC|$ is large, K_D should be small.

According to the above rules, the fuzzy control rules are set as shown in Tables 1—3.

Table 1 K_P fuzzy control rules

$ E $	$ EC $		
	S	M	B
S	B	M	B
M	B	M	B
B	B	S	M

Table 2 K_I fuzzy control rules

$ E $	$ EC $		
	S	M	B
S	B	S	S
M	B	S	S
B	M	S	S

Table 3 K_D fuzzy control rules

$ E $	$ EC $		
	S	M	B
S	B	S	S
M	B	S	S
B	M	S	S

3. 1. 3 Fuzzy reasoning and clarification (defuzzification)

According to Eq. (1), the weighted average method (gravity center method) is used to calculate the product of the elements, their degrees of membership and the ratio of the elements for each state. That is, the fuzzy output of each state should be clarified [16].

$$K_{Pj} = \frac{\sum_{i=1}^n \mu(K_{Pi}) K_{Pi}}{\sum_{i=1}^n \mu K_{Pi}} \quad (1)$$

where j can be small “S”, medium “M” and big “B”, in the three states. According to the membership function of K_P and the equation, K_P value for each state can be obtained

$$K_{PS} = \frac{0 \times 1 + 0.1 \times 0.8 + 0.2 \times 0.6 + 0.3 \times 0.4 + 0.4 \times 0.2 + 0.5 \times 0}{1 + 0.8 + 0.6 + 0.4 + 0.2 + 0} = 0.13$$

$$K_{PM} = \frac{0 \times 0 + 0.3 \times 0.6 + 0.5 \times 1 + 0.5 \times 1 + 0.75 \times 0.75 + 1 \times 0.5 + 1.25 \times 0.25 + 1.5 \times 0}{0 + 0.6 + 1 + 10.75 + 0.5 + 0.25 + 0} = 1.18$$

$$K_{PB} = \frac{0.5 \times 0 + 0.75 \times 0.25 + 1 \times 0.5 + 1.25 \times 0.75 + 1.5 \times 1}{0 + 0.25 + 0.5 + 0.75 + 1} = 1.25$$

According to the aforementioned fuzzy rules, input deviation $|E|$ and deviation change rate $|EC|$ can be obtained by inference corresponding to the output. Firstly, the membership degree of the corresponding output is obtained, for example, when both input variables $|E|$ and $|EC|$ belong to category “S”, according to fuzzy reasoning algorithm, output K_P will belong to “B”. And the corresponding membership degree is

$$\mu(K_{PB}) = \mu_S(|E|) \wedge \mu_S(|EC|)$$

where the operator “ \wedge ” takes the minimum value of both of the corresponding values, namely

$$\mu(K_{PB}) = \min\{\mu_S |E|, \mu_S |EC|\}$$

In this case, obtained is the membership degree of output K_P adjusted according to fuzzy rule, under different $|E|$ and $|EC|$ variables. A numerical example to validate the fuzzy rule is given as follows: $|E|$ is assumed as 1.5 mm and $|EC|$ as 40. Then, the membership degree of $|E|$ is 0.13 at “S” state, 0.88 at “M” state and 0

$$K_P = \frac{0.13 \times 1.25 + 0.8 \times 1.25 + 0 \times 1.25 + 0.13 \times 1.18 + 0.2 \times 1.18 + 0 \times 0.13 + 0 \times 1.25 + 0 \times 1.25 + 0 \times 1.18}{0.13 + 0.8 + 0 + 0.13 + 0.2 + 0 + 0 + 0 + 0} =$$

1.23

One can know that when the deviation is 1.5 mm and the variation rate of deviation is 40, the output K_P is 1.23, following the fuzzy control rule.

Similarly, PID parameters K_P , K_I , K_D obtained by fuzzy reasoning, can be transferred directly into the PID instruction of PLC and the output control u can be calculated according to the following equation

$$u(n) = K_P E(n) + K_I \sum E(n) + K_D [E(n) - E(n-1)]$$

3.2 Output control scheme

The drive system employs a stepper motor to drive the screw movement, with a controller of

at “B” state according to Fig. 5. And the membership degree of $|EC|$ is 0.8 at “S” state, 0.2 at “M” state, 0 at “B” state. According to Table 1, it can be known that there are nine kinds of output states, respectively

$$\mu_1 = \mu(K_{PB}) = \mu_S(|E|) \wedge \mu_S(|EC|) = 0.13$$

$$\mu_2 = \mu(K_{PB}) = \mu_M(|E|) \wedge \mu_S(|EC|) = 0.8$$

$$\mu_3 = \mu(K_{PB}) = \mu_B(|E|) \wedge \mu_S(|EC|) = 0$$

$$\mu_4 = \mu(K_{PM}) = \mu_S(|E|) \wedge \mu_M(|EC|) = 0.13$$

$$\mu_5 = \mu(K_{PM}) = \mu_M(|E|) \wedge \mu_M(|EC|) = 0.2$$

$$\mu_6 = \mu(K_{PS}) = \mu_B(|E|) \wedge \mu_M(|EC|) = 0$$

$$\mu_7 = \mu(K_{PB}) = \mu_S(|E|) \wedge \mu_B(|EC|) = 0$$

$$\mu_8 = \mu(K_{PB}) = \mu_M(|E|) \wedge \mu_B(|EC|) = 0$$

$$\mu_9 = \mu(K_{PM}) = \mu_B(|E|) \wedge \mu_B(|EC|) = 0$$

According to Eq. (2), the weighted average of these states can be calculated by the corresponding P, I, D parameter values

$$K_P = \frac{\sum_{i=1}^9 \mu_i [(|E|, |EC|) \times K_{Pj}]}{\sum_{i=1}^9 \mu_i (|E|, |EC|)} \quad (2)$$

OMRON CP1H-XA PLC. For the photoelectric sensor voltage signal reading, input analog range is 0—10 V, and A/D resolution is set to 6 000. For stepper motor control, “pulse + direction” mode is used, and the independent mode is applied for motor control.

4 Experimental Results

In this case, the deviation-rectifying device is mounted on the unwinding roller and the deviation-rectifying takes place before slitting. Since a set of circular blades are fixed, the widths of prepreg tape between each two blades remain constant. Therefore, first of all, the deviation-rectif-

ying should be turn on to slit at a speed of 16 m/min, after the centerline is aligned, as shown in Fig. 10. Large width of the remaining material will affect the measurement. Therefore, a scrap strip of prepreg at the edge is selected as a research object. Measured at 10 s interval, the width variation is studied, comparing with the scrap strip of prepreg after slitting without the rectifying device. And the rectifying effect is characterized according to the straightness of prepreg. Wide prepreg tape slitting experiment is shown as Fig. 11.

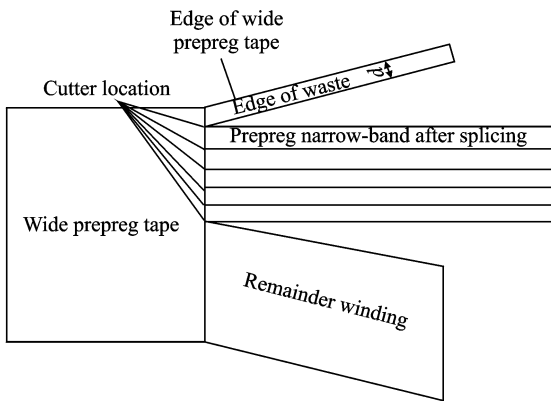


Fig. 10 Slitting process of wide prepreg tape



Fig. 11 Wide prepreg tape slitting

The relationship between the width of edge scrap strip at the rear edge and the slitting time with installation of rectifying device is shown in Fig. 12. The relationship between the width of edge scrap strip at the rear edge and the slitting time with isolation of rectifying device is shown in Fig. 13.

As can be seen from Fig. 12, although the centerline is aligned before slitting, prepreg tape deviation occurs at the beginning stage, due to rotation of the slitting roller axis, machine vibration, inconsistencies of uncut prepreg tape width

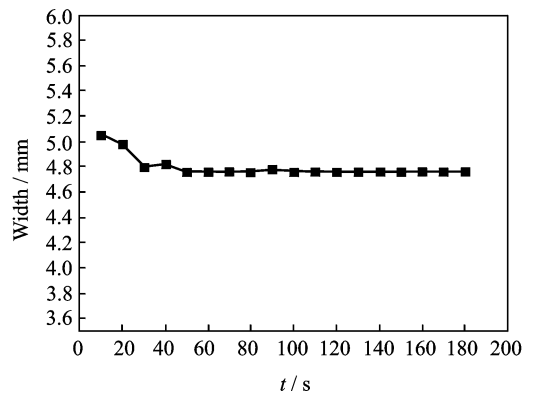


Fig. 12 Results of the post deviation

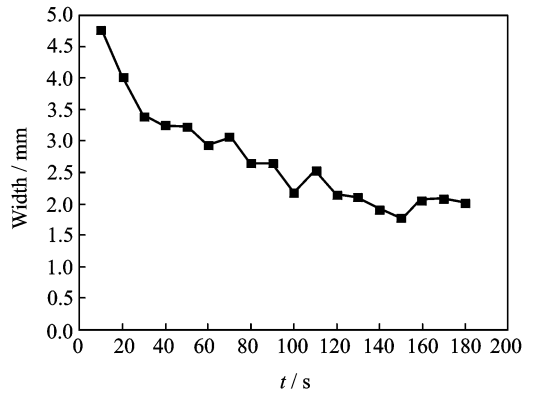


Fig. 13 Results of separation of the isolated deviation-rectifying device

and other reasons. The width deviation of the edge scrap strip prepreg tends to be stable after 30 s, and maintains at the vicinity of 4.76 mm.

As can be seen from Fig. 13, the width of the edge scrap deviated drastically after 20 s with isolation of the rectifying device. During the period of measuring, the width is not stable and deviates largely. This results in unexpected inconsistency of tape width, which has negative impact on the next subsequent slitting process.

5 Conclusions

(1) The slitting technology of prepreg narrow tapes for the AFP is discussed. Reasons of prepreg tape deviation in slitting process is analyzed, automatic deviation control system is set up for better precision.

(2) A self-developed carbon fiber prepreg slitting-winding machine is integrated with photo-

electric rectifying control system. Unlike the traditional rectification control, fuzzy PID control algorithm is applied to the rectifying control of prepreg slitting-winding machine, achieving a good rectification effect. Deviation-rectifying accuracy reaches 0.1 mm.

Acknowledgements

This work was financially supported by the National Basic Research Program of China (973 Program), the Priority Academic Program Development of Jiangsu Higher Education Institutions, and the Fundamental Research Funds for the Central Universities (No. 3082615NS2015056).

References:

- [1] WEN Liwei, XIAO Jun, WANG Xianfeng. Progress of automated placement technology for composites in China[J]. *Journal of Nanjing University of Aeronautics & Astronautics*, 2015,47(5):637-649. (in Chinese)
- [2] XIAO Jun, LI Yong, WEN Liwei, et al. Progress of automated for polymer placement technology for polymer composites[J]. *Materials China*, 2009,28(6):28-32. (in Chinese)
- [3] BECKWITH S W. Filament winding vs. fiber placement manufacturing technologies[J]. *SAMPE Journal*, 2008,44(2):54-55.
- [4] ZHOU Xiaoqin, CAO Zhenghua. Development and application of automated placement technology for composites[J]. *Aeronautical Manufacturing Technology*, 2009(S1):1-3. (in Chinese)
- [5] ZHAO Cong, LU Nannan, YAN Xitao. Research on the process of preparation of prepreg tow applied in automatic fiber placement[J]. *Journal of Solid Rocket Technology*, 2014(5):718-723. (in Chinese)
- [6] KHALIULIN V, WANG Z J, GERSHTEIN E. Development of composite cellular cores for sandwich panels based on folded polar quadra-structures[J]. *Transaction of Nanjing University of Aeronautics and Astronautics*, 2016,33(5):519-528.
- [7] HE Nan, YANG Jiabin, GAO Feng. Application tendency of advanced composite materials for military unmanned aerial vehicles[J]. *Fiber Reinforced Plastics/Composites*, 2013(2):94-97. (in Chinese)
- [8] LUO Yifeng. The newest developments of advanced composite materials in high-end and general industrial field[J]. *Hi-Tech Fiber & Application*, 2012,37(4):41-48. (in Chinese)
- [9] OUYANG Santai, OUYANG Xi. Automatic control system of photoelectricity rectified deviation based on PLC-fuzzy controller[J]. *Light Industry Machinery*, 2004(4):112-114. (in Chinese)
- [10] YANG Kaiping, SHI Yaoyao, HE Xiaodong. Controlling technology of intelligent position correcting in winding process of composites[J]. *Acta Aeronautica et Astronautica Sinica*, 2011,32(7):1318-1325. (in Chinese)
- [11] HE Xiaodong, SHI Yaoyao, QIN Xiansheng. Research on technology of lateral position control in composites tape winding[J]. *Journal of Northwestern Polytechnical University*, 2014,32(3):464-469. (in Chinese)
- [12] SUN G, ZHU Z H. Fractional order tension control for stable and fast tethered satellite retrieval[J]. *Acta Astronautica*, 2014,104(1):304-312.
- [13] SUN Tianfeng, WEN Liwei, XIAO Jun. Design and research on automatic slitting and rewinding mechanism of carbon fiber prepreg[J]. *Aeronautical Manufacturing Technology*, 2015(16):66-70. (in Chinese)
- [14] YANG Guohua, WU Yanqiang, YANG Bo, et al. Several problems about strain calculation and analysis and correction of related deviation[J]. *Geodesy and Geodynamics*, 2011,2(1):29-35. (in Chinese)
- [15] RAO K A G, REDDY B A, BHAVANI P D. Fuzzy PI and integrating type fuzzy PID controllers of linear, nonlinear and time-delay systems[J]. *International Journal of Computer Applications*, 2010,1(6):41-47.
- [16] EL-BARDINI M, EL-NAGAR A M. Interval type-2 fuzzy PID controller for uncertain nonlinear inverted pendulum system[J]. *ISA Transactions*, 2014,53(3):732-743.

Dr. **Wen Liwei** received the B. S. and Ph. D. degree in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2000 and 2005, respectively. He joined the China Composite Materials Society and the Jiangsu Composite Materials Society as a director in 2007. From 2005 to present, he has been with College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA), where he is currently an associate professor. His research has focused on technology and software of advanced composite material automation.

Mr. **Zhu Tengfei** received the M. S. degree in Materials Engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2016. From 2016 to present, he has been with Aviation Industry Corporation of China. His research is focused on the technology of prepreg tape splicing and rewinding machine.

Dr. **Qin Lihua** received the M. S. and Ph. D. degrees in Electrical Engineering from Harbin Institute of Technology, Harbin, China, in 2000 and 2005, respectively. He joined Beijing Institute of Space Long March Vehicle in May 2005, where he is a senior mechanical design engineer. His research is focused on application of aeronautical materials.

Dr. **Wang Xianfeng** received the M. S. and Ph. D. degrees in Electrical Engineering from Harbin Institute of Technology, Harbin, China, in 2004 and 2008, respectively. From 2008 to 2010, he was director of China Composite Material Equipment Committee. From 2008 to present, he has been

with College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA). His research is focused on automated fiber placement, automated tape laying and relevant fields.

Mr. **Pan Jie** received the B. S. and M. S. degrees in Materials Engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2014 and 2017, respectively. In May 2017, he joined the China COMAC Shanghai Aircraft Design and Resea. His main research direction is three-dimensional reinforced composite of one-sided stitching technology.

Mr. **Feng Qiaoqiao** received the Bachelor of Engineering degree from Anhui Polytechnic University, Wuhu, China, in 2016. Currently, he is a graduate student in Materials Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA). His main research direction is three-dimensional reinforced composite of one-sided stitching technology.

(Production Editor: Xu Chengting)

