Stability analysis and control for composite tape winding process

Xiao-dong He, Hua-lian Li, shi-xin Yang and Hai-qing Li

1 Lecturer, College of Mechanical Engineering, Inner Mongolia University of Technology, Hohehot, China

2 Engineer, College of Mechanical Engineering, Inner Mongolia University of Technology, Hohehot, China

3 Postgraduate, College of Mechanical Engineering, Inner Mongolia University of Technology, Hohehot, China

E-mail:hualianlihzhe@126.com

Abstract. In the composite winding process of thermal protection materials, the thickness errors of prepreg tape will result in an unstable winding process. In order to alleviate this problem, a control system is required. Therefore, a winding control system had been designed to control the stability by eliminate the winding error based on the analysis of stability winding process. The control system consists a speed controlled rotational roller. The thickness errors of the tape can be detected, and the rotational roller can be controlled to eliminate the errors and maintain the stability of winding process. Experimental results illustrate that the winding speed is converged in 30 second with a 30% initial thickness error, and winding control system could maintain the stability of winding process.

1. Introduction

Tape winding process is a mainly used method to manufacture the composite thermal protection system for aerospace engineering [1]. The incoming tape sticks the laminate of winded tape by the compaction roller, which widely used in composite winding and placement [2,3], and the compaction force direct is always fixed. A pneumatic compaction roller was designed by Rudd for fiber placement process [4], a pneumatic driven compaction roller was used to winding a composites gun tube by Littlefield [5], Hassan analyzed heat transfer for composite placement with a steel compaction roller [6], a robot with a compaction roller was designed to finish the fiber placement process optimization by Tauseef [7]. However, the resin prepreg tape can be deformed by the compaction in the winding process. Thus, some pores or gaps in winding layers could be inevitable, and the poor dispersion of materials and stability of winding process could be influenced. In order to reduce the pores in the composite Costa researched the influence of the porosity in carbon fiber resin composites, and how the porosity influence the material performance [8], Madsen designed a theory for the effect of pore in unidirectional fiber reinforced composite [9]; Koushyar analyzed the phenomenon of pore growing in carbon fiber/epoxy reinforced material under hot pressing and vacuum environment [10].
The researches above show that there would be some errors in winding process. The stability of winding process would be influenced by the errors. In order to maintain a stable winding process, a winding control system using speed controlled rotational roller is presented, which could control the winding angle to maintain the stability of winding process.

2. Tape winding process
There are several elements in the winding process including winding speed control, tension control, compaction force control and temperature control. By the tension control, compaction force control and temperature control, the thermal protection material could be formed by the combination of tape layers surrounded on the mandrel, and the tape-layers are compacted tightly in the process. By the speed control, the tape is guided along the mandrel to form the shape of the product. Winding process for the thermal protection system is shown in figure 1.

![Figure 1. Winding process for thermal protection system](image)

During the winding process, the tape is winded tightly by the compaction force and the tape tension, and the wrapped layers are formed at a certain winding angle to enhance the ability of thermal protection. The schematic of winding process is shown in figure 2 [11].

![Figure 2. Composite tape winding process](image)

The tape is guided to wrapped layers on the mandrel by a moving compaction roller, and the winding point is represented a position where the roller compacts the wrapped layer on the mandrel. The moving speed of the roller is calculated by equation (1). According to the equation, the roller speed is related to the tape thickness.

\[
B = \frac{\delta}{\sin \theta}
\]
Where, $B$ represents the moving speed of the roller, $\delta$ represents the tape thickness, and $\theta$ represents the winding angle.

Due to the compaction force and the tensile force in winding process, the tape thickness can be deformed, and a tape thickness error can be resulted. The tape thickness error will lead to the error of moving speed of the roller, and the speed error will result in an unstable winding process.

3. Stability analysis for the winding process

According to equation (2), when the tape which is thinner than designed is used in winding process, the moving speed of roller will be higher than the accumulation of wrapped tape. On the contrary, when the tape which is thicker than designed is used, the roller moving speed will be lower than the accumulation. Both the phenomena can lead to an unstable winding process.

When the thinner tape used, the inner edge of winding tape can be guided over the wrapped layer. The outer edge will be fitted to the wrapped layer by tension. Thus, there would be a gap between winding tape and wrapped layer, and the winding angle would be decreased, as shown in figure 3.

Fig.3.  Winding angle decreased in thinner tape winding process
The winding angle decrease model in thinner tape winding process is shown as equation (2).

\[
\begin{align*}
\varepsilon_a(n) &= \theta - \theta_n = \sum \varepsilon_n \\
\varepsilon_n &= \arcsin \left[ \frac{B}{W} \sin \theta_{n-1} - \frac{\delta - \varepsilon_{th}}{W} \right]
\end{align*}
\]

Where, $\varepsilon_a(n)$ represents the winding angle error at the $n^{th}$ layer, $\theta_n$ represents the decreased winding angle at $n^{th}$ layer, $\varepsilon_n$ represents the decrimental angle element between $n^{th}$ layer and $n-1^{th}$ layer, $W$ represents the tape width, and $\varepsilon_{th}$ represents the tape thickness error.

According to the equation (2), when the thinner tape used in winding process, a continuous decreased winding angle will be emerged, and the winding process is tended to be failed.

When the thicker tape used, the roller speed would be lower the accumulation of wrapped layers. The slower roller will be lag to the wrapped tape layer. Thus, the winding point can be pushed away from the mandrel, and the tape will be guided higher and higher, as shown in figure 4.
Figure 4. Winding position pushed away in thicker tape winding process

The error between mandrel and winding position which is pushed away can be described as equation (3), the error is the integration of thickness error $e_{th}$ and winding speed $B$.

$$
\begin{align*}
\epsilon_p(n) &= \sum r_n \\
\tau_n &= \frac{\delta + e_{th}}{\cos \theta_n} - B \tan \theta_n
\end{align*}
$$

(3)

Where, $\epsilon_p(n)$ represents error between the mandrel and the winding position at $n^{th}$ layer, and $\tau_n$ represent the error increment between $n^{th}$ layer and $n-1^{th}$ layer.

According to the equation (3), when the thicker tape used in winding process, a continuous increase of winding position will be emerged, and the wrapped layer of the tape can be accumulated away from the mandrel. That result in a gap between mandrel and the wrapped layer, and fail the winding process.

The gap between mandrel and the wrapped layer can lead an unstable structure of the wrapped layer, because there is no support like mandrel in the inner edge of wrapped layer. When the bonding strength of wrapped layer is lower than the compaction force, the wrapped layer would be slipped, and the winding angle would be increased. Thus, the winding process is failed, as shown in figure 5.

Figure 5. Winding angle error in thicker tape
As noted above, a winding angle error and a position error during winding process can be resulted by the error of tape thickness. Both the errors could influence the stability of winding process. These errors should be controlled and eliminated to maintain a stable winding process.

4. Winding control system for stability winding process

4.1 Rotational roller system

According to the error analysis, a control system should be designed to acquire and eliminate the errors. In order to acquire the winding angle error, a rotational roller has been used in the control system. The rotational roller system is shown in figure 6.

![Figure 6. Rotation roller for winding angle control](image)

The rotational roller system consists a primary cylinder, a feeding axis, a secondary cylinder and a roller. The roller could be rotated by the pushing of secondary cylinder to fit the winding angle of the wrapped layer of winding tape. The winding angle could be measured by an angle sensor on the rotation axis of the roller. Both the rotation roller and secondary cylinder are driven by the feeding motor among the feeding axis to control the roller moving speed and the winding position. The structures noted above are driven by the primary cylinder, which provides main compaction force for winding process. The winding position error is measured by a linear grating assembled on the primary cylinder. The schematic of rotational roller system is shown in figure 7.

![Figure 7. Schematic of rotational roller system](image)
accumulated by the tape in the winding process, and the tape thickness error will result in an error between accumulation speed of wrapped tape layer and moving speed of roller. In order to detect the error, the roller is driven to be rotated around the winding point to acquire the winding angle in real time. Compare the acquired winding angle and the designed winding angle, a winding error can be calculated. Based on the winding error, the moving speed of the roller will be adjusted by the feeding motor along the feeding direction (Z-axis) to fit the accumulation speed of wrapped tape.

In order to converse the rotation point from the pivot of the roller to the winding point, a coordinate transformation system is designed. The system consists the \{M\} coordinate system (represent the mandrel), \{W\} coordinate system (represent the wrapped layer), \{B\} coordinate system (represent the roller rotation), and \{R\} coordinate system (represent the roller). The coordinate transformation system is shown as figure 8.

![Coordinate transformation system of the rotation roller](image)

The winding point on the \{W\} coordinate system can be transformed to the \{M\} coordinate system with several offset values. The offset values represent the linear offsets \(W_z, W_x\) of \{M\} coordinate system on \{W\}, the linear offsets \(x_M, z_M\) of \{B\} coordinate system on the \{M\}, the rotation offset \(\theta\) of \{R\} coordinate system on the \{B\} and the linear offsets \(B_x, B_z\) of \{R\} on \{B\}. Therefore, the roller could be used to rotate around the winding point to measure the winding angle by using the rotational roller control system with the offset values. In the system, the position of the winding point in the \{W\} coordinate system is transformed to the position of the feeding motor and rotation of the roller around the pivot in the \{M\} coordinate system [12]. The transformation could be calculated by equation (4).

\[
\begin{align*}
M \cdot P_{BORG} & = ^w_T \cdot ^w_T \cdot ^w P_{BORG} \\
& = \begin{bmatrix} 1 & 0 & W_x & \cos \theta & -\sin \theta & x_w \\ 0 & 1 & W_z & \sin \theta & \cos \theta & z_w \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_M \\ z_M \end{bmatrix}
\end{align*}
\]

(4)

Where, \(^w T \) represents the transformation from \{M\} to \{W\}, \(^w T \) represents the transformation from \{W\} to \{R\}, \(^w P_{BORG}\) represents the offset of the winding point in \{R\} and \(M \cdot P_{BORG}\) represents the offset of \{B\} to \{M\}.

Equation (8) can be transformed to equation (5).

\[
R \cdot B + ^w P_b + W = ^M P_b
\]

(5)
Where $R$ represents the rotation transform, $B$ represents the offset between $\{R\}$ and $\{B\}$, $W$ represents the offset between $\{M\}$ and $\{W\}$, $w_P$ represents the linear offset of winding point in $\{W\}$ and $w_P$ represents the offset of $\{B\}$ in $\{M\}$.

When the $w_P$ in equation (5) is differentiated, there is:

$$d^M P_B = \frac{\partial R \cdot B}{\partial \theta} d\theta + d^W P_R$$

(6)

According to equation (6), the change of $w_P$ is consistent with the change of $w_P$ and the change of winding angular detected by the rotational roller. The change of $w_P$ represent the moving speed on Z and X direction for the roller driven by feeding motor and primary cylinder. The change of $w_P$ represent the moving speed of the winding point.

According to the principal analysis of rotational roller control system, an interpolate controller is presented using the change of winding angle to adjust the moving speed of roller. The adjustment could eliminate the winding angle error and maintain the stability of the winding process.

The interpolation controller is designed with equation (6). The change of $w_P$ which represent the speed of roller is discretized using first-order difference to equation (6), as shown in equation (7).

$$\Delta^M P_B = R(B(\theta) - R(\theta - \Delta\theta)) + \Delta^W P_R$$

(7)

In equation (7), the increment of $w_P$ represents the increment of feeding motor and the increment of the cylinder. As a compacting element, the position of cylinder is fitted to the mandrel and wrapped layer. Thus, the design of interpolate controller is focused on the adjustment of feeding axis speed on the Z axis direction. The increment of feeding axis in the $n^{th}$ sampling time is shown in equation (8).

$$\Delta z_{Mn} = B_x C_1 - B_x C_2 + \Delta z_{w0}$$

(8)

Where, $C_1=\sin\theta_n - \sin\theta_{n-1}$, $C_2=\cos\theta_n - \cos\theta_{n-1}$ and $\Delta z_{Mn}$ represents the increment of the feeding axis in the $n^{th}$ sampling time.

During the winding process, the winding angle can be changed by accumulation of the tape thickness error, and the stability of winding process would be influenced. The increment $\Delta z_{Mn}$ calculated by the interpolate controller using equation (8) with the change of the detected winding angle is inputted to feeding motor controller. The moving speed of the roller on Z axis is adjusted by the feeding motor, and the rotation of the roller is transformed from the pivot to winding point. Therefore, the winding angle could be measured by the roller rotation around the winding point.

4.2. Design of the stable winding control system

According to the analyzed above, the tape thickness error will lead to error of winding angle and error of winding position. Both the errors can lead to gaps between the wrapped layer and mandrel. Thus, the stability of the winding process can be influenced.

Shown as equation (2), both the winding angle error is nonlinear and related to the winding speed. According to equation (3), the winding position error can be seen as a linear with the winding speed when the thicker tape used in winding process. Therefore, a stability controller is designed with a combination of a fuzzy controller for winding angle error and a proportional controller for winding position error [13].

The fuzzy controller for winding angle error is designed as a double-input-single-output system. The winding angle error and differential of the error are represented as the inputs of the system, and the increment of winding speed is represented as the output of the system. The range of the inputs and output is normalized as [0,1].
Because the linear correlation between small range of tape thickness error and winding angle error, the input and output variables are designed to triangular membership function. The variables are separated to \{MB, MS, Z, S, B\}, which is represented \{minus big, minus small, zero, small, big\}. The degree of membership is shown in figure 9.

![Figure 9. Degree of membership in stable controller for winding angle error](image)

The control rules surface of the winding angle error, differential of winding angle error and winding speed increment for the winding angle error stable controller is shown as figure 10.

![Figure 10. Control rules surface of the stable controller for winding angle error](image)

With the analyzed above, a control system is designed for stable winding process is shown in figure 11.
By using the rotational roller system, the changing of the winding angle can be achieved by the roller which could be rotated around the winding point. And the changing of winding point position could be measured by the linear grating assembled on the primary cylinder. The winding speed can be adjusted with the measurements to fit the real thickness of the tape, and the winding errors could be eliminated. The fuzzy controller is used to eliminate the winding angle error and the proportional controller is used to eliminate the winding position error. Thus, the stability of winding process could be maintained. A controller switcher is triggered by a winding position error threshold in the stable winding system, and the switcher is used to switch the fuzzy controller and the proportional controller.

5. Experiments and results
The stable winding experiment has been finished using some pieces of glass fiber tape on a cylinder mandrel. The stable winding experiment is shown in figure 12, 13.

Figure 11. Stable winding control system

Figure 12. Rotational roller system

Figure 13. Stable winding system

The threshold of the switch is set to 0.5mm, the initial winding angle is designed as 12°, the width of winding tape is 40mm, the range of tape thickness is 0.2 to 0.24mm, and the rotation speed
The speed is about 30% higher than the designed winding speed to test the winding stability control system. The winding speed was convergence to the designed speed (1 mm/r) in 30 second, and the stability of winding process is ensured. The winding speed of the stable winding experiment is shown in figure 14.

Figure 14. Winding speed of stable winding experiment

6. Conclusions
A stability of winding system has been analyzed in this paper. A rotational roller system has been designed to acquire the winding angle error and winding position error during the winding process, and a stable winding control system has been developed to adjust the errors.

According to the experiment result, the tape thickness error can be acquired by detecting the winding angle error and winding position error. The system could adjust the winding speed to fit the thickness error to maintain the stability of winding process. A 30% thickness error can be converged in 30 second.

7. Acknowledgments
This study was supported by the Natural Science Foundation of Inner Mongolia (No. 2018BS05012). The authors would like to extend sincere thanks to all those who have helped to make this thesis possible and better.

8. Appendices

\[ B \] represents the winding speed.
\[ \delta \] represents the prepreg tape thickness.
\[ \theta \] represents the winding angle.
\[ W \] represents the tape width.
\[ e_{th} \] represents the tape thickness.
\[ e_{\theta} \] represents the increment of winding angle between nth layer and n-1th layer.
\[ \theta_{th} \] represents the winding angle at nth layer.
\[ e_{\alpha} \] represents the winding angle error at the nth layer.
\[ e_{p}(n) \] represents the winding position error at nth layer.
\[ \tau_{th} \] represents the increment of winding position between nth layer and n-1th layer.
\[ ^{m}\mathbf{T} \] represents the transformation from \{M\} to \{W\}.
\[ ^{w}\mathbf{R} \] represents the transformation from \{W\} to \{R\}.
$p_{R \text{ORG}}$ represents the roller position in \{R\}.

$\mu p_{M \text{ORG}}$ represents the roller position in \{M\}.

$\Delta z_{Mn}$ represents the increment on the feeding axis.

$B_{n+1}$ represents the winding speed fit to the tape thickness.

$B_n$ represents the actual winding speed.

9. References

[1] Funck R, Neitzel M. 1995 Improved thermoplastic tape winding using laser or direct-flame heating. *Composites Manufacturing* 6 189.

[2] Mazumdar S K, Hoa SV. 1996 Determination of manufacturing conditions for hot-gas-aided thermoplastic tape winding. *Journal of Thermoplastic Composite Materials* 9 35.

[3] Kim H J, Kim SK, Lee WI. 1996 A study on heat transfer during thermoplastic composite tape lay-up process. *Experimental thermal and fluid science* 13 408.

[4] Littlefield A, Hyland E, Andalora A, et al. 2006 Carbon fiber/thermoplastic overwrapped gun tube. *Journal of pressure vessel technology* 128 257.

[5] Rudd CD, Turner MR, Long AC, et al. 1999 Tow placement studies for liquid composite moulding. *Composites Part A: Applied Science and Manufacturing* 30 1105.

[6] Hassan N, Thompson JE, Batra RC, et al. 2005 A heat transfer analysis of the fiber placement composite manufacturing process. *Journal of reinforced plastics and composites* 24 869.

[7] Aized T, Shirinzadeh B. 2011 Robotic fiber placement process analysis and optimization using response surface method. *The International Journal of Advanced Manufacturing Technology* 55 393.

[8] Costa ML, De Almeida SM, Rezende MC. 2001 The influence of porosity on the interlaminar shear strength of carbon/epoxy and carbon/bismaleimide fabric laminates. *Composites Science and Technology* 61 2101.

[9] Madsen B, Lilholt H. 2003 Physical and mechanical properties of unidirectional plant fibre composites—an evaluation of the influence of porosity. *Composites Science and Technology* 63 1265.

[10] Koushyar H, Alavi-Soltani S, Minaie B, et al. 2012 Effects of variation in autoclave pressure, temperature, and vacuum-application time on porosity and mechanical properties of a carbon fiber/epoxy composite. *Journal of Composite Materials* 46 1985.

[11] Yaoyao S, Hong T, Qiang Y. 2008 Key Technology of the NC Tape-winding Machine. Acta Aeronautica et Astronautica Sinica 29 233 [in Chinese].

[12] Niku, SB. 2001 *Introduction to robotics: analysis, systems, applications* (New Jersey: Prentice Hall) p 56.

[13] Karasakal O, Guzelkaya M, Eksin I, et al. 2011 An error-based on-line rule weight adjustment method for fuzzy PID controllers. *Expert Systems with Applications* 38 10124.