Study of the Stress Relaxation Property of Vortex Spun Yarn in Comparison with Air-jet Spun Yarn and Ring Spun Yarn

Abstract

The structure of vortex spun yarn made by the Murata vortex spinning machine is different from that of other yarns, such as ring spun yarn, air-jet spun yarn and so on. The stress relaxation model is constructed by a generalized Maxwell model connected in a row to a Hook’s spring in order to predict and analyse the stress relaxation property of vortex spun yarn. Based on the stress relaxation model, the stress relaxation properties of vortex spun yarn, ring spun yarn and air-jet spun yarn are compared and analysed. The factors influencing the stress relaxation property of vortex spun yarn, such as the tensile strain, tensile rate and yarn count are discussed. The research results show that the stress relaxation model can be used for describing the stress relaxation mechanism of vortex spun yarn. The elasticity of vortex spun yarn is better than that of air-jet spun yarn, but worse than that of ring spun yarn. When the tensile strain is lower and the tensile rate is larger, vortex spun yarn has a more obvious stress relaxation phenomenon. The stress relaxation phenomenon of finer yarn is more obvious than that of coarser yarn.

Key words: Murata vortex spinning, vortex spun yarn, stress relaxation.

Table 1. Fibre properties.

<table>
<thead>
<tr>
<th>Fiber properties</th>
<th>Colored cotton</th>
<th>White cotton</th>
<th>Bamboo pulp fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper quartile length, mm</td>
<td>26.8</td>
<td>29.3</td>
<td>-</td>
</tr>
<tr>
<td>Fibre length, mm</td>
<td>-</td>
<td>-</td>
<td>40.1</td>
</tr>
<tr>
<td>Fineness, dtex</td>
<td>1.46</td>
<td>1.74</td>
<td>1.56</td>
</tr>
<tr>
<td>Micronaire, micronaire</td>
<td>3.14</td>
<td>4.81</td>
<td>-</td>
</tr>
<tr>
<td>Tenacity, cN/dtex</td>
<td>1.9</td>
<td>2.83</td>
<td>2.21</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>5.7</td>
<td>7.6</td>
<td>19.3</td>
</tr>
</tbody>
</table>

Table 2. Yarn formation process parameters

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Vortex spun yarn</th>
<th>Air-jet spun yarn</th>
<th>Ring spun yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Spinning Machine</td>
<td>Murata vortex spinning</td>
<td>Air-jet spinning</td>
<td>Ring spinning</td>
</tr>
<tr>
<td>Delivery speed, m/min</td>
<td>320</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Total draft</td>
<td>129</td>
<td>218</td>
<td>128</td>
</tr>
<tr>
<td>Main draft</td>
<td>40</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Nozzle type</td>
<td>75, Holder 130d, 9.3</td>
<td>75, Holder 130d, 8.8</td>
<td>75, Holder 130d, 8.8</td>
</tr>
<tr>
<td>Condenser/</td>
<td>Hollow spindle, mm</td>
<td>Hollow spindle 1.4</td>
<td>Condenser 4</td>
</tr>
<tr>
<td>Spindle speed, r.p.m.</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ring diameter, mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feed ratio</td>
<td>1</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Take up ratio</td>
<td>0.99</td>
<td>1.013</td>
<td>1.013</td>
</tr>
<tr>
<td>Air pressure, MPa</td>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Distance between front roller and spindle/N2 nozzle, mm</td>
<td>19</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Yarn count, tex</td>
<td>18.2</td>
<td>18.2</td>
<td>32.4</td>
</tr>
</tbody>
</table>

by the fibre spatial trajectory in vortex spun yarn based on the yarn formation process [15]. Compared with ring and open-end rotor spun yarns, vortex spun yarns have lower hairiness and better pilling resistance [14, 16 - 18]. Basal et al. found that vortex spun yarns have tenacity advantages over air jet yarns, particularly at high cotton contents [13].

4. Investigation of the fabric characteristics produced by vortex spun yarn in comparison with ring and rotor spun yarn knitted fabrics [18 - 20]. These investigations found that fabrics made from MVS yarn had a more even appearance and lower pilling tendency.

This paper will further discuss the properties of vortex spun yarn. As we all know, the properties of fabric are greatly affected by the yarn properties, such as tenacity, hairiness, evenness, viscoelastic property and so on. The viscoelastic behavior, such as stress relaxation under constant deformation and creep elongation at constant stress, which is also one of the most important yarn properties, will affect the dimensional stability of a fabric. The viscoelastic behavior of yarns with the same fibre components are affected by the yarn type, yarn count, different tensile strains and rates. The creep elongation property of vortex spun yarn has already been investigated by Zou [21]. Therefore this paper will focus on the stress relaxation property of vortex spun yarn.

## Stress relaxation model

The internal stress of a yarn under a fixed tensile strain is a function of the relaxation time, which can be described by constructing a stress relaxation model with Hook’s springs and Newton’s dashpots. The stress relaxation model with more Hook’s springs and Newton’s dashpots can more accurately describe the stress relaxation phenomenon of a yarn. This paper will adopt the modified generalised Maxwell model in Figure 1, used to describe the viscoelastic behaviour of Agave Americana L. fibres by Oudiani et al. [22], to analyse the relaxation property of the vortex spun yarn. The mechanical behaviour of this model is expressed by Equation 1 as follows:

\[
\text{Equation 1:} \quad \frac{\mu_2}{E_2} \varepsilon + \left( \frac{E_1}{E_2} + \frac{\mu_2}{\mu_1} \right) \varepsilon = \frac{E_2}{E_1} \varepsilon + \left( \frac{E_1}{E_2} + \frac{1}{\mu_1} \right) \varepsilon + \left( \frac{E_1}{E_2} - \frac{1}{\mu_1} \right) \varepsilon = 0
\]

where

\[
\text{Equation 2:} \quad \varepsilon = \frac{E_2}{E_1} \varepsilon + \left( \frac{E_1}{E_2} + \frac{1}{\mu_1} \right) \varepsilon + \left( \frac{E_1}{E_2} - \frac{1}{\mu_1} \right) \varepsilon = 0
\]

The stress relaxation test

Stress relaxation tests were carried out on test samples in cases 1 - 5, which were subjected to relaxation for 300 seconds at different test conditions. The stress relaxation properties of the yarns were measured by a YG061 electronic single-yarn tensile tester. Tests were conducted in a conditioned atmosphere of 20 ± 2 °C and 65 ± 2% relative humidity. 10 tests per sample were performed and their mean values were used to describe the stress relaxation behaviour of vortex spun yarn. For all tests, an ample gauge length of 500 mm was chosen. The pre-tension for measuring creep elongation was 0.5 cN/tex.

### Equation 3

\[
\text{Equation 3:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

where

\[
\text{Equation 4:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

### Equation 5

\[
\text{Equation 5:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

### Equation 6

\[
\text{Equation 6:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

Therefore, the simplified form of Equation 4 is described by the following equation

\[
\text{Equation 4:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

where

\[
\text{Equation 7:} \quad \sigma(t) = \frac{E_2}{E_1} \varepsilon_c + c_1 \varepsilon_c^c + \frac{E_3}{E_1} \varepsilon_c^c + \frac{1}{\mu_1} \varepsilon_c^c + \frac{\mu_2}{\mu_1} \varepsilon_c^c
\]

### Materials

Table 1 shows the properties of the coloured cotton, white cotton and bamboo pulp fibres used in this study. The cotton and bamboo pulp fibres were provided by Dezhou Huayuan Eco-Technology Co., Ltd, and Henan Xinye Textile Co., Ltd. in China, respectively. The process parameters used to produce different experimental samples are shown in Table 2. The 18.2 tex white cotton/coloured cotton blend yarns with an 85% white cotton ratio, in cases 1, 4 and 5 of Table 2, were spun by Murata vortex spinning, air-jet spinning and ring spinning. The vortex spun yarns of 18.2 tex and 32.4 tex in cases 2 and 3 of Table 2, respectively, were spun from a bamboo pulp fibre/white cotton blend with a 70% bamboo pulp fibre ratio on Murata vortex spinner.

![Figure 1. Modified generalised Maxwell model [22]; E1, E2, and E3 - elastic coefficients of Hook’s springs, µ1 and µ2 - viscosity coefficients of Newton’s dashpots.](image-url)
and \( \tau_1 \) and \( \tau_2 \) are the stress relaxation time.

### Results and discussion

**Stress relaxation property of vortex spun yarn compared with other yarn types**

Different yarns made by different spinning machines have different yarn structures, which result in discrepancies in their stress relaxation properties. The vortex spun yarn in case 1 has the same yarn counts and same material composition as the air-jet and ring spun yarns in cases 4 and 5, respectively. The stress relaxation properties of these yarns are tested under a 200 mm/min tensile rate and 4% tensile strain. The stress relaxation properties of the vortex spun yarn in case 1 compared with the air-jet spun and ring spun yarns in cases 4 and 5 is shown in Figure 2. Based on test data of the yarns’ stress relaxation behaviour, theoretical curves of the stress relaxation behaviour for cases 1, 4 and 5 are fitted using Equation 7 by means of Origin 8.0 software. The stress relaxation curves are characterised by parameters presented in Table 3 together with correlation coefficients. The high correlation coefficient validates the effectiveness of the stress relaxation model. The parameters of the stress relaxation model for every yarn type are also shown in Table 3.

For Figure 2, when the vortex, air-jet and ring yarns are all at a 4% tensile strain, the internal stress action on the vortex spun yarn is greater than that on the air-jet spun yarn and less than that on the ring spun yarn. For every yarn type the stress relaxation phenomenon taking place in approximately 10 seconds is very significant, which then gradually weakens with time until it reaches a plateau. As shown in Table 3, values of the stress relaxation time \( \tau_1 \) and \( \tau_2 \) of vortex spun yarn are larger than those of air-jet spun yarn and less than those of ring spun yarn, which is caused by their different structure; this can be used to illustrate the elasticity of ring spun yarn being greater than that of vortex spun yarn, followed by air-jet spun yarn. The stress relaxation of a yarn under fixed tensile strain reaches a balance earlier for a loose yarn structure, like that of air-jet spun yarn. Compared with air-jet spun yarn, vortex spun yarn has more wrapper fibres, which restricts the slippage of core fibres. Therefore the stress relaxation time of vortex spun yarn is longer than that of air-jet spun yarn under fixed tensile strain.

<table>
<thead>
<tr>
<th>Yarn types</th>
<th>Parameters of stress relaxation model</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex spun yarn</td>
<td>(92.98, 16.74, 15.43, 78.09, 4.05)</td>
<td>0.9959</td>
</tr>
<tr>
<td>Air-jet spun yarn</td>
<td>(80.53, 17.19, 18.27, 56.96, 4.34)</td>
<td>0.9963</td>
</tr>
<tr>
<td>Ring spun yarn</td>
<td>(129.51, 23.46, 23.12, 86.69, 4.88)</td>
<td>0.9955</td>
</tr>
</tbody>
</table>

**Table 3. Parameters of the stress relaxation model for different yarn according to Equation 7 for curves presented in Figure 2 and correlation coefficient \( R^2 \).**

**Table 4. Parameters of the stress relaxation models under different tensile strain levels for vortex spun yarn in case 1 according to Equation 7 for curves presented in Figure 3 and correlation coefficient \( R^2 \).**

<table>
<thead>
<tr>
<th>Tensile strain, %</th>
<th>Parameters of stress relaxation model</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>(64.48, 13.38, 18.71, 56.46, 0.95)</td>
<td>0.9933</td>
</tr>
<tr>
<td>4</td>
<td>(97.31, 19.36, 27.89, 60.82, 0.92)</td>
<td>0.9942</td>
</tr>
<tr>
<td>5</td>
<td>(114.89, 21.28, 32.53, 61.31, 1.01)</td>
<td>0.9906</td>
</tr>
</tbody>
</table>
The internal stress of vortex spun yarn sharply decreases initially in approximate 10 seconds, and then slowly falls with the stress relaxation test time approaching constant stress, as can be shown in Figure 4. Figure 4 also shows that the internal stress of vortex spun yarn becomes high when the tensile rate increases from 50 mm/min to 350 mm/min. Values of the stress relaxation time \( \tau_1 \) and \( \tau_2 \) are lower at a higher tensile rate, as shown in Table 5. Therefore the stress relaxation phenomenon for vortex spun yarn is more obvious at a higher tensile rate.

**Effect of yarn count on the stress relaxation property of vortex spun yarn**

Stress relaxation tests of yarns with counts of 18.2 tex and 32.4 tex for cases 2 and 3 were done after the yarns had been drawn up to a 4% tensile strain at a rate of 200 mm/min. According to the stress relaxation test results, stress relaxation curves for different yarn counts (counts 18.2 tex and 32.4 tex) were drawn based on Equation 7 using Origin 8.0 software, as shown in Figure 5 (see page 32). The stress relaxation curves are characterised by parameters presented in Table 6 together with correlation coefficients. The high correlation coefficient shows that the stress relaxation model can effectively describe the stress relaxation behaviour of vortex spun yarns with different yarn counts.

The internal stress attenuates rapidly at first and then slowly decreases with an increase in the stress relaxation test time until tending towards a stable condition. The internal tension is high when the vortex spun yarn becomes fine, which may be caused by the difference in the proportions of wrapper fibres for cases 2 and 3. It shows that the fine count yarn of vortex spun yarn has more wrapper fibres than coarse count yarn, validated by Tyagi et al. [8], resulting in less slippage between fibres for vortex spun yarn with a 4% tensile strain. However, the stress relaxation times \( \tau_1 \) and \( \tau_2 \) are bigger for coarse count yarn in Table 6 (see page 32), which shows its relaxation phenomenon is not obvious.

![Figure 4. Stress relaxation curves under different tensile rates for vortex spun yarn in case 1. Parameters of curves of the stress relaxation model according to Equation 7 are given in Table 5 together with correlation coefficient R².](image-url)
sile rate and is finer, the relaxation time is at a lower tensile strain level, higher tensile rate thereon is high. When vortex spun yarn is and finer count, the internal stress action on air-jet spun yarn and those for vortex spun yarn is better than that of ring spun yarn. Moreover the elasticity of internal stress for all test conditions decreases sharply initially and slowly attenuates with prolongation of the relaxation period. The research shows that the stress relaxation behaviour of yarn is influenced significantly by the yarn type, tensile strain level, the tensile rate and yarn count. The internal stress for all test conditions decreases sharply initially and slowly attenuates with prolongation of the relaxation test time until approaching a constant stress. At the same tensile strain, as compared with air-jet and ring spun yarns, the internal stress action on vortex spun yarn is between the values of the internal stress action on air-jet spun yarn and those for ring spun yarn. Moreover the elasticity of vortex spun yarn is better than that of air-jet spun yarn, but worse than that of ring spun yarn. For vortex spun yarn at a larger tensile strain level, higher tensile rate and finer count, the internal stress action thereon is high. When vortex spun yarn is at a lower tensile strain level, higher tensile rate and is finer, the relaxation time is shorter, as shown by the fact that vortex spun yarn has a more obvious stress relaxation phenomenon.

Table 6. Parameters of the stress relaxation models under different yarn counts for vortex spun yarns in cases 2 and 3 according to Equation 7 for curves presented in Figure 5 and correlation coefficient $R^2$

<table>
<thead>
<tr>
<th>Yarn Count, tex</th>
<th>Parameters of stress relaxation model</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.2</td>
<td>$c_0 = 3.87$, $c_1 = 0.91$, $c_2 = 0.93$, $r_1 = 85.35$, $r_2 = 4.15$</td>
<td>0.9974</td>
</tr>
<tr>
<td>32.4</td>
<td>$c_0 = 3.28$, $c_1 = 0.75$, $c_2 = 0.81$, $r_1 = 90.24$, $r_2 = 4.61$</td>
<td>0.9969</td>
</tr>
</tbody>
</table>

Conclusions

In this study, a stress relaxation model was developed to describe the relaxation behaviour of vortex spun yarns at different external conditions which best simulated the tension and relaxation behaviour of the vortex spun yarn.

The research shows that the stress relaxation behaviour of yarn is influenced significantly by the yarn type, tensile strain level, the tensile rate and yarn count. The internal stress for all test conditions decreases sharply initially and slowly attenuates with prolongation of the relaxation test time until approaching a constant stress. At the same tensile strain, as compared with air-jet and ring spun yarns, the internal stress action on vortex spun yarn is between the values of the internal stress action on air-jet spun yarn and those for ring spun yarn. Moreover the elasticity of vortex spun yarn is better than that of air-jet spun yarn, but worse than that of ring spun yarn. For vortex spun yarn at a larger tensile strain level, higher tensile rate and finer count, the internal stress action thereon is high. When vortex spun yarn is at a lower tensile strain level, higher tensile rate and is finer, the relaxation time is shorter, as shown by the fact that vortex spun yarn has a more obvious stress relaxation phenomenon.

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References


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