Systematic Investigation of Twist Generation and Propagation in A Modified Ring Spinning System

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Abstract:

Twisting is an important process to form a continuous yarn from short fibers and to determine the structure and properties of the resultant yarn. This paper systematically examined yarn twisting process in a modified ring spinning process based on a theoretical model proposed recently. In order to reduce the number of experiments, response surface methodology (RSM) involving a central composite design (CCD) in three factors of twist multiplier, speed ratio and wrap angle was successfully employed for the study and analysis. The significant terms of the models were studied, and it was discovered that the speed ratio and wrap angle are statistically significant for the responses of twist efficiency, propagation coefficients of twist trapping and congestion. And more importantly, linear relationships were found among the three responses.

Keywords: yarn motion, twist generation, twist propagation, ring spinning

Introduction

Spinning is a fundamental method to produce long strands from staple raw fibers of cotton, wool, flax, or other material.[1] Twisting is a vital process to determine the staple yarn structure and performances like strength (tenacity), elongation, evenness and hairiness.[2] Till now, ring spinning continues to predominate in yarn manufacturing industry due to its high yarn quality and flexibility in materials and yarn counts.[3-5] According to the latest statistics, the total number of spindles around world was astonishing 244 million.[6] With the increasing demand of novel features or improving qualities, many modifications have been developed, such as Compact[7, 8], Siro [9, 10] and Solo[11-14]. In recent years, a novel spinning technology, named Nu-Torque[15-17], has been developed by introducing a false-twisting unit into the conventional ring frame for producing low twist and soft handle single yarns. The modified cotton yarns and fabrics have significant advantages in terms of soft handle, higher yarn strength at lower twist factor, lower residual torque and low knitted fabric spirality after washing and tumble-dry cycles. [18-24] Among over ten mills using the technology, 18 to 40% increment in production rate has been achieved for cotton ring yarns with various versions of the technology. In addition, a significant average energy saving of 337KWh/ton was reported by a mill producing Ne 30 and 1100 KWh/ton for another mill for spinning Ne 80 yarns.

Despite achieved low twist and soft handle single yarns, fundamental mechanism in terms of false twisting process needs to be addressed. Twist generation and propagation[25, 26], which are key issues leading to the essence of spinning, including the amount of false-twist generated by the false-twister, false-twisting efficiency and blockage rate, as well as the relationships between false-twisting efficiency and system parameters. The false-twisting unit employed in this study is single friction-belt with circular cross-section. It has been identified that the friction-belt generates the false-twists into yarn, meanwhile traps the upward propagation of the real twist as well as congests the downward propagation of the false twists. In our recent published paper [27], a steady-state model of yarn dynamics in the modified ring spinning system has been proposed, which deals with two important phenomena simultaneously, that is, twist generation and twist propagation. Based on the proposed model, in this paper a systematic evaluation of twist generation and propagation in the modified ring spinning system has been carried out to assess effects of system parameters on the false-twisting efficiency as well as propagation coefficients. In order to minimize the number of experiments, response surface methodology involving a central composite design in three factors of twist multiplier, speed ratio and wrap angle has been successfully employed for the study and analysis. The significant terms of the models were studied and relationships among three responses were investigated.

Twist generation and propagation

As shown in Figure 1, a simplified system is composed of front rollers at point A, a friction-belt false-twister, which contacts with the yarn in zone BC and a real-twister at point D. Hence, there are two twist units in the system: one is the real-twister at point D; another is the false-twister which generates the frictional moment at zone BC.

Three concepts are introduced to describe the roles played by friction, correspondingly, three coefficients are defined. The first parameter is the twisting efficiency of the false-twister. To determine it, let R_0 be the radius of the yarn, $n_c = T_c v$ be the rotational speed of the yarn, T_c be the total twist generated by the moving belt, v be the delivery speed of the yarn, and v_b be the moving speed of the belt, the twist efficiency of the moving belt is expressed as

$$\lambda = \frac{2\pi R_0 T_c v}{v_b} \tag{1}$$

The second effect is the twist trapping in the up-ward propagation of the real twist inserted by D. To quantify this effect, let T_t be the total twist lost in zone BC, and T_{CD} be the twist in zone CD, then the propagation coefficient of twist trapping is defined as

$$k = 1 - \frac{T_t}{T_{CD}} \tag{2}$$

The last effect of friction is the twist congestion, which occurs in the downward propagation of twist in zone AB. Let T_h be the total twist increment in zone AB, then the propagation coefficient of the twist congestion is defined as

$$\eta = \frac{T_c}{T_c + T_h} \tag{3}$$

From the kinematic point of view, the twist in zone AB in Figure 1 can be expressed as

$$T_{AB} = kT_{\mathrm{CD}} + \frac{\lambda T_{BC}}{\eta} \tag{4}$$

where $T_{BC} = \frac{v_b}{2\pi R_0 v}$ is the theoretical twist generated by the false-twister, and all three coefficients range from 0 to 1.

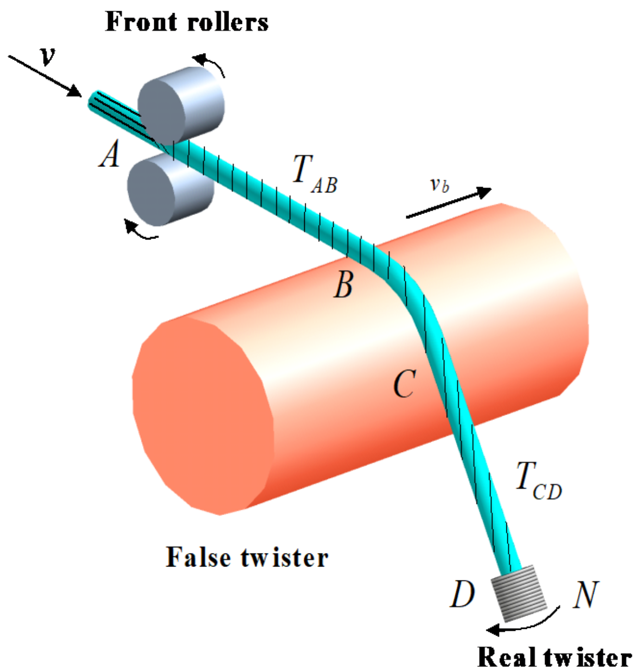


Figure 1 A simplified spinning system

Experimental design

The experiments were conducted on a ring spinning frame (Zinser 351) by installing a moving friction-belt with diameter of 6mm between the front rollers and the yarn guide. A cotton yarn with linear density of Ne 32 and diameter of 0.16 mm was adopted for the experiments. Three important parameters, twist factor (X_1), speed ratio (X_2), and wrap angle (X_3) were chosen as the potential influencing, and twist efficiency (Y_1), propagation coefficients of twist trapping (Y_2) and congestion (Y_3) were the dependent variables calculated by our proposed model[27]. Although yarn tension may have a large impact on twist generation and propagation, it was not considered here for further investigation not only because its value cannot be arbitrarily changed at such a wide range for industry production, but also the fact that it is not a continuously adjustable parameter for the experiment.

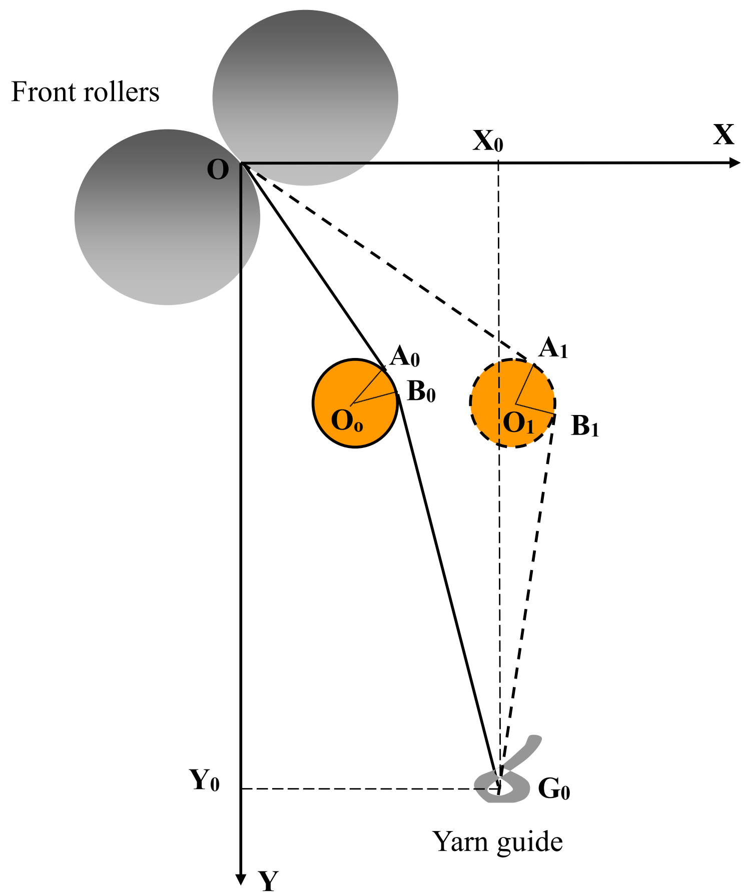


Figure 2 Schematic view of belt position in a ring spinning frame

In order to reduce the number of experiments needed, response surface methodology (RSM) involving a central composite design (CCD) was employed to exam the relationships between several input parameters and one or more response variables. The range and levels of the independent variables investigated as listed in Table 1. Speed ratio is defined as the ratio of belt moving speed to the yarn delivery speed. Wrap angle is defined as the angle formed by the yarn and belt, ∠AOB as shown in Figure 2. The change of wrap angle can be achieved by adjusting belt position in the spinning frame. The independent variables were tested in an orthogonal 2^3 CCD with six center points and six-star points. Each of the independent variables was conducted at five different levels as per CCD in three variables with a total of 20 experiments [28]. The plan of CCD in coded levels of three independent variables is shown in Table 2. The statistical significance level (p value) was set at 0.05. The coded and actual values of the design were generated in a randomized run order using Minitab 16 software. Based on the RSM, quadratic polynomial regression equations are developed to fit the experimental data, as show in the following equation,

$$Y = C_0 + \sum_{i=1}^{K} C_i X_i + \sum_{j=1}^{K} C_{ii} X_i^2 + \sum_{i=1}^{K-1} \sum_{j=2}^{K} C_{ij} X_i X_j + \varepsilon \ (i < j) \quad (5)$$

where Y is the response, C_0 is constant, C_i, C_{ii} and C_{ij} are regression coefficients and X_i are the coded factors, ε is the error and K is the number of independent variables.

Table 1 Coded and actual level for each variables of the CCD

Variables	Code	Variation levels				
		-1.682	-1	0	+1	+1.682
Twist factor	X_1	2.51	2.91	3.50	4.09	4.49
Speed ratio	X_2	1.01	1.41	2.00	2.59	2.99
Wrap angle (°)	X_3	30.00	42.16	60.00	77.84	90.00

Table 2 Coded and actual levels in experimental design by CCD method

Run order	Coded levels			Independent variables			Responses		
	X_1	X_2	X_3	Twist factor	Speed ratio	Wrap angle	Twist efficiency (Y_1)	Trapping coefficient (Y_2)	Congestion coefficient (Y_3)
1	0	-1.682	0	3.50	1.01	60.00	0.126	0.873	0.892
2	-1	-1	+1	2.91	1.41	77.84	0.166	0.829	0.860
3	0	0	0	3.50	2.00	60.00	0.124	0.874	0.895
4	-1	+1	-1	2.91	2.59	42.16	0.073	0.926	0.939
5	0	+1.682	0	3.50	2.99	60.00	0.098	0.900	0.916
6	+1	-1	+1	4.09	1.41	77.84	0.143	0.853	0.877
7	+1.682	0	0	4.49	2.00	60.00	0.130	0.867	0.889
8	+1	+1	-1	4.09	2.59	42.16	0.070	0.929	0.941
9	0	0	-1.682	3.50	2.00	30.00	0.043	0.956	0.966
10	-1.682	0	0	2.51	2.00	60.00	0.152	0.844	0.872
11	0	0	0	3.50	2.00	60.00	0.133	0.864	0.887
12	0	0	0	3.50	2.00	60.00	0.131	0.866	0.889
13	+1	-1	-1	4.09	1.41	42.16	0.103	0.896	0.912
14	0	0	+1.682	3.50	2.00	90.00	0.171	0.821	0.854
15	0	0	0	3.50	2.00	60.00	0.131	0.866	0.889
16	0	0	0	3.50	2.00	60.00	0.144	0.853	0.878
17	-1	-1	-1	2.91	1.41	42.16	0.101	0.898	0.915
18	-1	+1	+1	2.91	2.59	77.84	0.124	0.870	0.893
19	+1	+1	+1	4.09	2.59	77.84	0.109	0.886	0.905
20	0	0	0	3.50	2.00	60.00	0.107	0.890	0.908

Results and discussions

Analysis of variance (ANOVA)

ANOVA is a statistical technique to analyze the differences among group means and their associated procedures, which is accomplished by subdividing the total variation in a dataset into component parts allied with sources of variation for testing hypotheses on the variables of the model [29, 30]. Precision of a parameter estimation depends on the degree of freedom (DF), which equals to the number of experiments subtract the number of additional parameters estimated for that calculation [31]. Followed by Fisher's statistical test (*F* test), ANOVA was employed to study the importance of each independent variable [32]. *F* value is calculated by the regression mean square divided by the real error mean, which implies the influence of each controlled parameter on the model [33, 34]. The ANOVA data in Table A1 lists *F* value for twist efficiency, propagation coefficient of twist trapping and congestion as 10.36, 11.16 and 11.33 respectively, suggesting that the regression equation is highly significant. Generally, the large Fisher value denotes that the variation in the responses can be interpreted by the model. The associated *p* value is an important parameter to estimate if *F* value is large enough to display statistical significance [35, 36]. The *p* values is the index of the significance of the test, whose value below 0.05 indicates that the model and the associated terms are statistically significant at 95% confidence level [37-39]. The significance of each coefficient is also determined by the *F* and *p* values [40, 41]. ANOVA indicated that the highest significant level was shown by the wrap angle (X_3), followed by the speed ratio (X_2) and lastly, the quadratic wrap angle (X_3*X_3), while the interaction terms ($X_1* X_2$, $X_1* X_3$, $X_2* X_3$), the linear and quadratic twist factors (X_1, $X_1* X_1$) were less significant.

Table A1 also shows multiple correlation coefficient (R^2) and adjusted R^2. The R^2 implies the variation of the response in the model [42]. The higher the R^2, the better the model fits the data. The values of R^2 were calculated to be 90.31%, 90.95% and 91.07% for twist efficiency, propagation coefficients of twist trapping and congestion, respectively, implying that the experimental data was well-fitted. The adjusted R^2 explains the number of predictors in the model and is useful for comparing models with different numbers of predictors [43]. The high value of adjusted R^2 supports a high correlation between the experimental and the predicted data [30]. In this study, the values of adjusted R^2 for twist efficiency, propagation coefficients of twist trapping and congestion were 81.59%, 82.80% and 83.03%, respectively, which means the regression models were statistically significant. The lack-of-fit *p* value of the model for twist efficiency, propagation coefficients of twist trapping and congestion were 0.334, 0.332 and 0.312, respectively, which were higher than 0.05, indicating that the models fitted all the design points well.

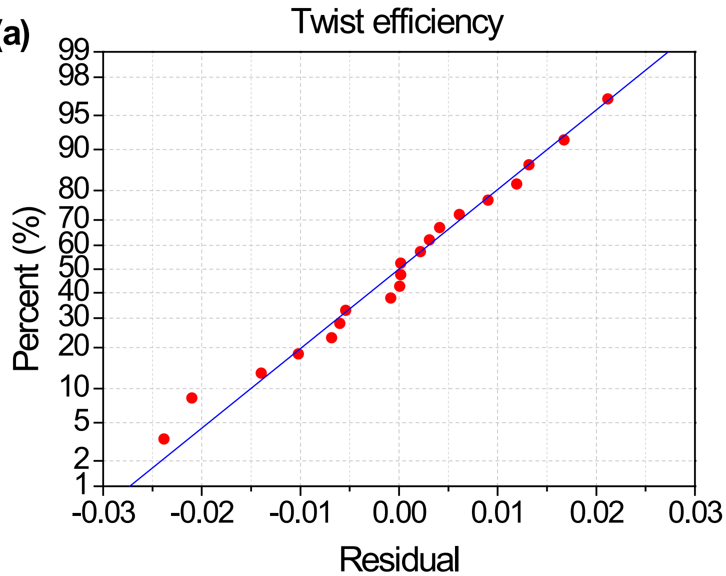
Since there were some insignificant terms existing in the regression models, it was necessary to simply them by eliminating insignificant terms. Decreasing the number of terms can make the model manageable, meanwhile increase the precision of the predictors. By examining the *F* and *p* values of each coefficient, it was found that all terms containing twist factor (X_1) over the range of 2.51 to 4.49 has little impact on the responses, thus should be removed from the models. Moreover, the interaction terms should also be removed as they are not significant for the models. The significant terms for the models were wrap angle (X_3), speed ratio (X_2) and quadratic wrap angle (X_3*X_3). The quadratic wrap angle (X_2*X_2) was reserved as it is significant at 10% level. Therefore, these four terms were employed to reconstruct the regression formulas. The results of simplified model and ANOVA are listed in Table A2, from which we can concluded that the reduced model was superior to the complete quadratic equations because the reduced models have higher F values and lower p values than those of previous ones. Moreover, all the four terms were statistically significant for the three responses and the adjusted R^2 were better than the previous ones, implying that the reduced regression models were significant and adequate to depict the actual relationship between the responses and inputs.

Model validation

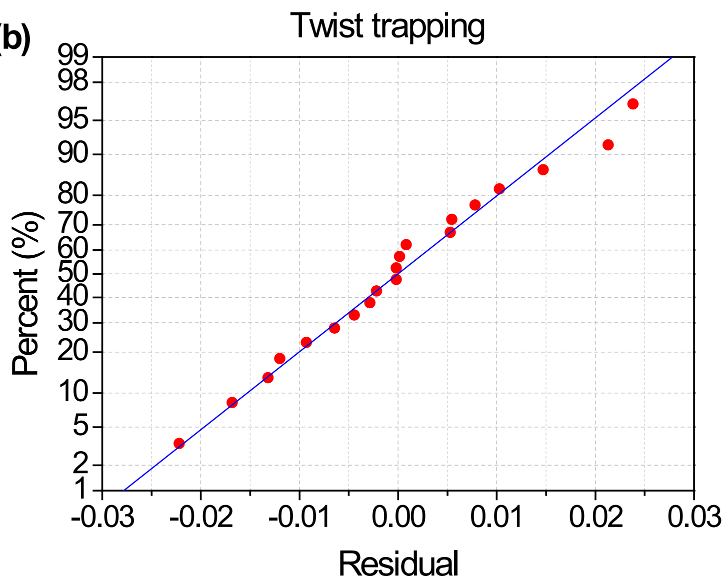
It is necessary to check the regression model to guarantee that adequate prediction to the actual data is obtained [44]. Diagnostic plots such as normal probability plots shown in Figure 3 enable to judge the normal distribution of the residuals. The residual is the error between the experimental data and the simulated value by the theoretical model. A small residual value represents a high accuracy of the prediction by the model. In Figure 3, the data points on the figure were close to the straight line, implying that the data was normally distributed.

The regression models were also investigated by nine sets of randomly selected data. As shown in Table 3, the estimated results generally agreed well with the experimental data, particularly for trapping and congestion coefficients. Errors between the estimated and experimental values for three responses were generally less than 10%. All the above results implied that the reduced regression equations provided sufficient accuracy for predicting the responses. Based on the analysis above, the reduced regression models were capable of estimating and explaining the actual relationships between twist efficiency, propagation coefficients and the various system parameters of twist factor, speed ratio and wrap angle.

(a)


Twist efficiency
Percent (%)
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
Residual

(b)


Twist trapping
Percent (%)
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
-0.03
-0.02
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Residual

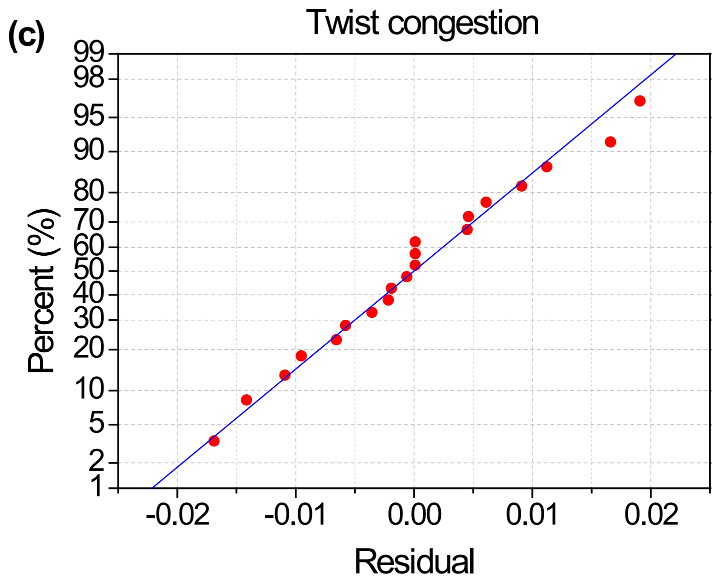


Figure 3 Normal probability plots of residuals for responses

Table 3 Model verifications for 9 cases

Order		1	2	3	4	5	6	7	8	9
Twist factor		2.5	2.8	3.3	3.7	4.2	2.7	3	4.3	4.1
Speed ratio		2.5	1.5	2.2	1.8	2.5	3	2	2.8	1.8
Wrap angle		30	40	50	65	50	60	45	75	85
Twist efficiency	A	0.039	0.098	0.110	0.143	0.095	0.085	0.102	0.109	0.163
	P	0.036	0.091	0.106	0.142	0.094	0.086	0.099	0.117	0.158
	E (%)	**7.69**	**7.14**	**3.64**	**0.70**	**1.05**	**1.18**	**2.94**	**7.34**	**3.07**
Trapping coefficient	A	0.957	0.901	0.888	0.854	0.904	0.913	0.897	0.892	0.830
	P	0.963	0.908	0.892	0.854	0.904	0.912	0.900	0.879	0.836
	E (%)	**0.63**	**0.78**	**0.45**	**0.00**	**0.00**	**0.11**	**0.33**	**1.46**	**0.72**
Congestion coefficient	A	0.967	0.917	0.906	0.879	0.919	0.928	0.914	0.910	0.860
	P	0.971	0.924	0.911	0.879	0.920	0.926	0.917	0.899	0.865
	E (%)	**0.41**	**0.76**	**0.55**	**0.00**	**0.11**	**0.22**	**0.33**	**1.21**	**0.58**

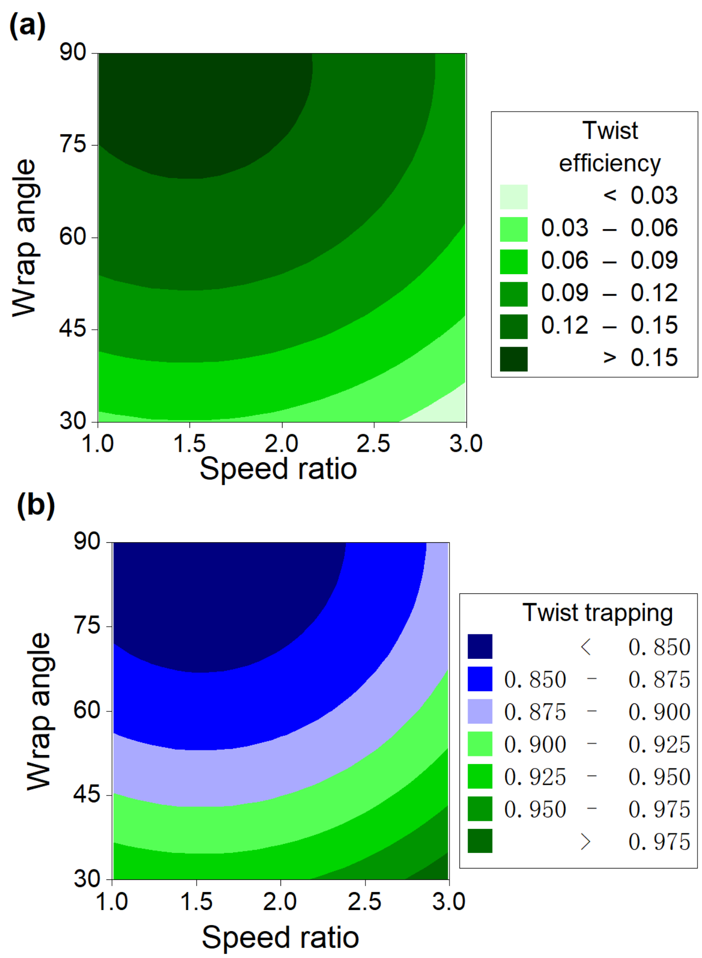
A: actual value P: predicted value E: error

Effect of control variables on the responses

Equation 6 is the empirical equations for the twist efficiency (Y_1), propagation coefficients of twist trapping (Y_2) and congestion (Y_3) as a function of the independent variables of speed ratio (X_2) and wrap angle (X_3) in coded units. It was found that the twist efficiency was increased with the decrease of X_2 and the increase of X_3. Besides, the trapping and congestion coefficients were increased with the increment of X_2 and the decrement of X_3. Moreover, the sign of the coefficients except constant for Y_1 was opposite to that of Y_2 and Y_3, while the coefficients of Y_2 and Y_3 had the same sign and similar value.

$$Y_1 = 0.131 - 0.013X_2 + 0.030X_3 - 0.008X_2^2 - 0.010X_3^2$$
$$Y_2 = 0.866 + 0.013X_2 - 0.032X_3 + 0.008X_2^2 + 0.009X_3^2 \quad (6)$$
$$Y_3 = 0.889 + 0.011X_2 - 0.026X_3 + 0.006X_2^2 + 0.008X_3^2$$

The contour plot of control parameters on twist efficiency is shown in Figure 4a, where it could be seen intuitively that the twist efficiency was reduced as the wrap angle decreased and speed ratio increased. The wrap angle has a more significant effect than the speed ratio. Figure 4b shows that as the wrap angle went up, the trapping coefficient dropped sharply. Meanwhile, the trapping coefficient was reduced as the speed ratio decreased. A similar trend was noted in the congestion coefficient in the contour plot of Figure 4c.



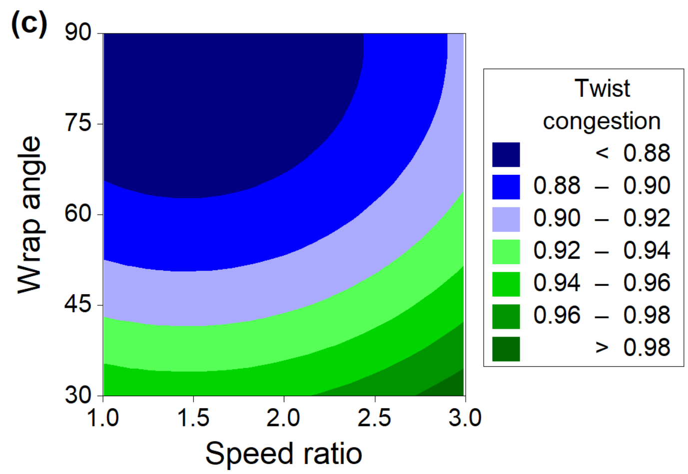


Figure 4 Response surface plots for (a) twist efficiency, (b) twist trapping, and (c) twist congestion

Relationships among three responses

Based on the analysis of the reduced regression equations, it was interesting to unveil whether the three responses were related with each other. Thus, a fitting scheme was carried out in order to check their relationships. Figure 5a displays the experimental data of the twist efficiency and trapping coefficient. Results showed an approximately linear relationship between Y_1 and Y_2 with a high correlation coefficient of 0.998 and could be well explained by the following linear regression equation.

$$Y_2 = 1.002 - 1.042Y_1 \tag{7}$$

Moreover, the relationship between Y_1 and Y_3 are shown in Figure 5b and a linear regression equation with a high correlation coefficient of 0.998 was indicated to explain the relationship as below,

$$Y_3 = 1.001 - 0.860Y_1 \tag{8}$$

In addition, Figure 5c depicts the experimental data of propagation coefficients of twist trapping and congestion, from which a linear relationship could be obtained with the same high correlation coefficient. The relationship was expressed by the following linear regression formula.

$$Y_3 = 0.175 + 0.825Y_2 \tag{9}$$

Finally, it was concluded that the three responses have linear relationships.

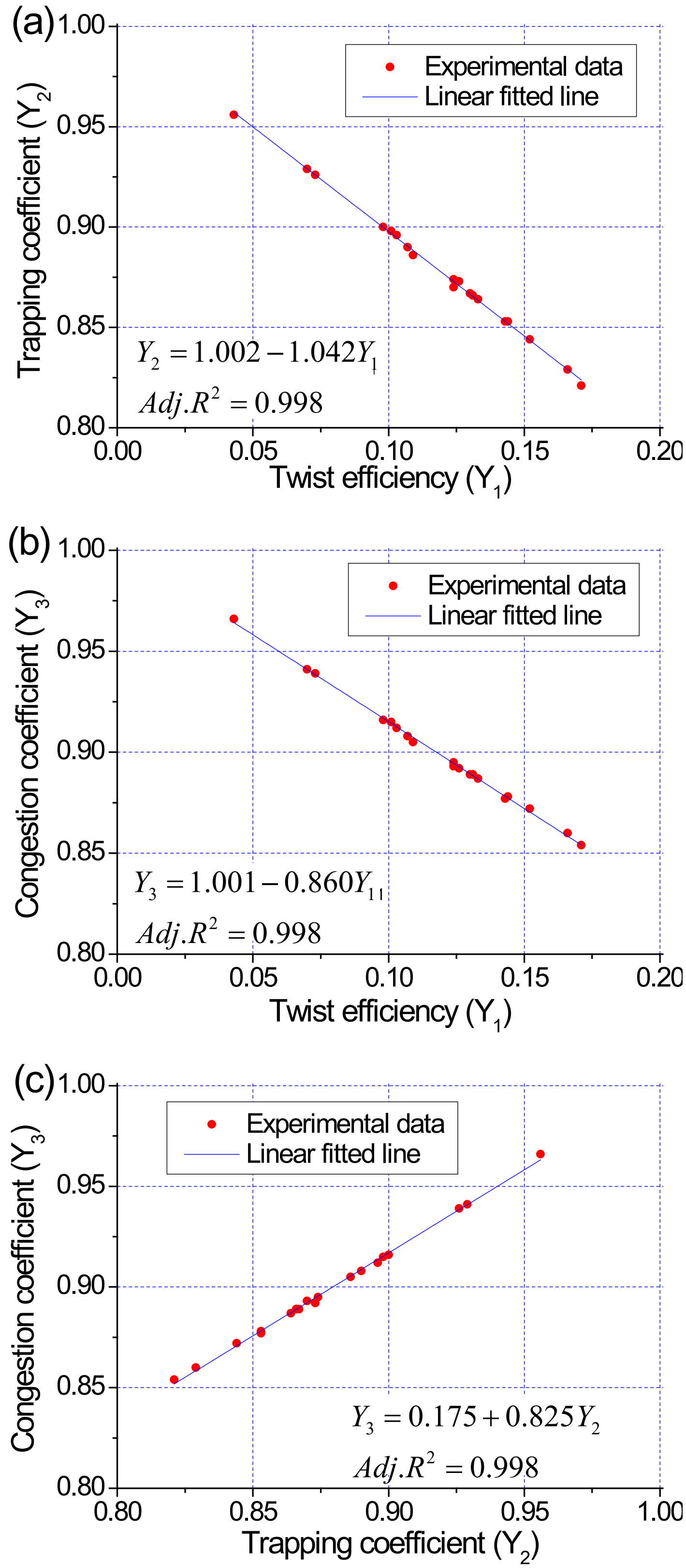


Figure 5 Linear relationships among three responses

Conclusions

In this paper, a systematic investigation was carried out to study yarn twisting process in a modified ring spinning system using central composite response surface design. It was found that the speed ratio and wrap angle are statistically significant for the twist efficiency, propagation coefficients of twist trapping and congestion at 5% significant level, while the twist factor has little effect on the responses. Then, the complete quadratic regression models were further simplified by eliminating insignificant terms, which were validated by normal probability analysis and another nine randomly selected experiments. Finally, it was important to discover that relationships among three responses can be expressed by linear regression equations with a high correlation coefficient of 0.998. The findings can be used to predict yarn twist in the spinning zone under given operation parameters and facilitate further research in improving spinning technology as well as reforming machine design.

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Appendix

Table A1 Analysis of variance for responses

Term	DF	Seq. SS	Adj. MS	*F*	*p*
		Twist efficiency			
Regression	9	0.017579	0.001953	10.36	0.001
X_1	1	0.000423	0.000423	2.24	0.165
X_2	1	0.002481	0.002481	13.16	0.005
X_3	1	0.012325	0.012325	65.35	0.000
$X_1 * X_1$	1	0.000106	0.000106	0.56	0.471
$X_2 * X_2$	1	0.000819	0.000819	4.34	0.064
$X_3 * X_3$	1	0.001249	0.001249	6.62	0.028
$X_1 * X_2$	1	0.000001	0.000001	0.01	0.940
$X_1 * X_3$	1	0.000171	0.000171	0.91	0.363
$X_2 * X_3$	1	0.000028	0.000028	0.15	0.707
Residual error	10	0.001886	0.000189		
Lack-of-fit	5	0.001131	0.000226	1.50	0.334
Pure error	5	0.000755	0.000151		
Total	19	0.019465			
		R^2=90.31%	R^2(adj.)=81.59%		
		Trapping coefficient			
Regression	9	0.019255	0.002139	11.16	0.000
X_1	1	0.000465	0.000465	2.43	0.150
X_2	1	0.002383	0.002383	12.44	0.005
X_3	1	0.014050	0.014050	73.32	0.000
$X_1 * X_1$	1	0.000122	0.000122	0.64	0.444
$X_2 * X_2$	1	0.000934	0.000934	4.88	0.052
$X_3 * X_3$	1	0.001106	0.001106	5.77	0.037
$X_1 * X_2$	1	0.000001	0.000001	0.01	0.940
$X_1 * X_3$	1	0.000190	0.000190	0.99	0.343
$X_2 * X_3$	1	0.000021	0.000021	0.11	0.747
Residual error	10	0.001916	0.000192		
Lack-of-fit	5	0.001152	0.000230	1.51	0.332
Pure error	5	0.000765	0.000153		
Total	19	0.021171			
		R^2=90.95%	R^2(adj.)=82.80%		
		Congestion coefficient			
Regression	9	0.013140	0.001460	11.33	0.000

X_1	1	0.000234	0.000234	1.82	0.207
X_2	1	0.001745	0.001745	13.54	0.004
X_3	1	0.009509	0.009509	73.79	0.000
$X_1 * X_1$	1	0.000077	0.000077	0.60	0.458
$X_2 * X_2$	1	0.000519	0.000519	4.02	0.073
$X_3 * X_3$	1	0.000950	0.000950	7.37	0.022
$X_1 * X_2$	1	0.000000	0.000000	0.00	1.000
$X_1 * X_3$	1	0.000113	0.000113	0.87	0.372
$X_2 * X_3$	1	0.000008	0.000008	0.06	0.808
Residual error	10	0.001289	0.000129		
Lack-of-fit	5	0.000791	0.000158	1.59	0.312
Pure error	5	0.000498	0.000100		
Total	19	0.014429			
		R^2=91.07%	R^2(adj.)=83.03%		

Seq. SS: sequential sum of squares, Adj. MS: adjusted mean squares

Table A2 Analysis of the reduced regression model

Term	DF	Seq. SS	Adj. MS	F	p
Twist efficiency					
Regression	4	0.016850	0.004212	24.16	0.000
X_2	1	0.002481	0.002481	14.23	0.002
X_3	1	0.012325	0.012325	70.69	0.000
$X_2 * X_2$	1	0.000888	0.000888	5.09	0.039
$X_3 * X_3$	1	0.001335	0.001335	7.66	0.014
Residual error	15	0.002615	0.000174		
Lack-of-fit	4	0.000994	0.000248	1.69	0.223
Pure error	11	0.001621	0.000147		
Total	19	0.019465			
R^2=86.56% R^2(adj.)=82.98%					
Trapping coefficient					
Regression	4	0.018455	0.004614	25.49	0.000
X_2	1	0.002383	0.002383	13.16	0.002
X_3	1	0.014050	0.014050	77.61	0.000
$X_2 * X_2$	1	0.001012	0.001012	5.59	0.032
$X_3 * X_3$	1	0.001191	0.001191	6.58	0.022
Residual error	15	0.002716	0.000181		
Lack-of-fit	4	0.000997	0.000249	1.60	0.244
Pure error	11	0.001719	0.000156		
Total	19	0.021171			
R^2=87.17% R^2(adj.)=83.75%					
Congestion coefficient					
Regression	4	0.012708	0.003177	27.70	0.000
X_2	1	0.001745	0.001745	15.21	0.001
X_3	1	0.009509	0.009509	82.90	0.000
$X_2 * X_2$	1	0.000565	0.000565	4.92	0.042
$X_3 * X_3$	1	0.001015	0.001015	8.85	0.009
Residual error	15	0.001720	0.000115		
Lack-of-fit	4	0.000690	0.000172	1.84	0.192
Pure error	11	0.001031	0.000094		
Total	19	0.014429			
R^2=88.08% R^2(adj.)=84.90%					