THREE-DIMENSIONAL COMPUTER SIMULATION OF TWILL WOVEN FABRIC BY USING POLYNOMIAL MATHEMATICAL MODEL

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ABSTRACT. This study was carried out to obtain visual simulations of twill woven fabrics on a computer screen using certain fabric characteristic. Based on the Peirce model, the polynomial curve fitting method is utilized to simulate the buckling configuration of twill weave yarns. Polynomial mathematical model was never used in constructing twill weave woven fabric structure in the past studies. In polynomial model, each point on yarn buckling track is calculated through the curvature, the radius of the warp and weft yarn, the geometric density, and the buckling curve height. Moreover, the twill weave structure is displayed through the arrangement of the warp and weft yarns. The polynomial mathematical model method was applied to convert the yarn path to a smooth curve and will be provided for three-dimensional computer simulation of satin weave fabric. Different twill weave is displayed by changing fabric parameters. In the VC++6.0 development environment, according to polynomial mathematical model, the three-dimensional simulation of twill fabric structure was given in details through the OpenGL graphics technology.

1. Introduction. The models of fabric structure simulation mostly utilize round or oval to describe the shape of the cross section, and use the sine cosine function or B-spline curve to simulate the buckling state of yarns. In VC programming environment, the OpenGL graph function library is combined to draw graphs to realize the three dimensional (3D) simulation of fabric structure. Although B-spline curve surfaces can be very convenient to design free-form curves and surfaces, the design of interpolating curves and surfaces is relatively complex. Yamagushi [12] utilized iterative method to approximate the control point of interpolation B-spline. One disadvantage of this method is that the interpolation curve is not accurate, and the shape of the curve cannot be modified. Barsky [1,3] calculated the control vertex

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through the inverse calculation method. Although the method can accurately calculate the interpolation value points, it is time and labor consuming. Turan [9, 10] created a B-spline for 2/2 twill woven fabric 3D simulation. Ali [6, 7] studied structure and surface simulation of woven fabrics using fast Fourier transform techniques. Jiahua Zhang [2, 13] proposed an interlaced mass-spring system for real-time woven fabric simulation. The garment is simulated using a 3D quadrangular mesh based on a mass-spring system in Feng Ji’s paper [4]. And also 3D dynamic behaviors simulation of weft knitted fabric based on particle system [8,14,15]. Even if the improved B-spline interpolation curve can partly control the offset and modification of the curve, the poor control of the parameter can affect the continuity and smoothness of the curve. Moreover, the local modification of the buckling and weaving of the yarns may affect the overall appearance of the fabric [5, 11]. For this purpose, this research establishes the polynomial model to simulate the buckling state of the yarn according to the geometrical relationship between the fabric structure parameters. Finally, OpenGL graphic technology is utilized to realize the 3D simulation of fabric structure, and control the change of the simulation curve according to the variations of structural parameters.

2. Method of polynomial mathematical model.

2.1. Single weft yarn curve equation of twill woven fabric. The difference between twill weave and plain weave lies in the increase of yarn floating length. In this paper, the polynomial mathematical modeling considers the yarn floating length as a straight line segment. The warp and weft yarn equations with the floating length can utilize the plain weave and the straight line to establish the model with the different arrangements of warp and weft yarns. Due to the time constraints, this paper only lists the curve equation of warp and weft yarn when step number is ±1.

Plain weave is the most fundamental and simplest fabric weave. The study of the plain weave yarn curve equation laid the foundation for the research of twill weave yarn curve equation. Without considering the elasto-plasticity of warp and weft, the parameters of fabric geometry and their letter codes are as follows:

- Distance of warp ($\rho_j$), namely geometric density $l_j$
- Distance of weft ($\rho_w$)
- Radius of warp $r_j$, diameter $d_j$
- Radius of weft $r_w$, diameter $d_w$
- Wave height of warp buckling $h_w$
- Wave height of weft buckling $h_j$

According to Peirce model:

$$l_j \geq \sqrt{(d_j + d_w)^2 - h_w^2}, l_w \geq \sqrt{(d_j + d_w)^2 - h_j^2}$$

Take the combined twill weave as an example, the simple twill weave will be achieved easily. $S_1$ and $S_2$ are organization points of warp yarn; $W_1$ and $W_2$ weave points of weft yarn. When $S_2$ and $W_2$ is 0, it is the simple twill weave fabric. For instance, as for the left twill of $\frac{3}{2}$, $S_1 = 3$, $S_2 = 2$, $W_1 = 2$ and $W_2 = 3$ are weave diagram, which is shown in Fig. 1.

Take the combined twill weave as an example, the weft sectional drawing of a unit of the first weft yarn is observed. Each warp yarn is at the equal distance of $l_j$ as shown in Fig. 2. They are expanded to other left twill weave, and the sectional drawing is shown in Fig. 3. Each unit curve of the weft yarn is divided into 8
sections, as shown in Figs. 3, 1, 3, 5 and 7 are straight segment, while 2, 4, 6 and 8 are AB segment or BC segment of plain weave weft fundamental curve equation, as shown in Fig. 4 and Fig. 6, respectively. Therefore, on unit curve of the weft of non-plain weave is the straight segment added at the after separating a unit curve of plain weave weft at the Symmetrical position. Here, circle represents the warp yarns, and curve represents the weft yarns.

The weft curve equation of the plain weave fabric refers to the waft axis. A basic segment of the weft insertion of the fabric is cut out, as shown in Fig. 5.

The coordinate system is established, as be seen in Fig. 6. Y direction represents the warp direction. The equation of the weft under the established coordinate system is assumed to be $z = f(y)$, $y\in[-l_j, l_j]$.

$f(y) = f(-y)$, and $f(y)$ is even function. Only the equation at the $[0, l_j]$ segment needs to be calculated. There is a horizontal tangent line at these two points. The radius of curvature $\rho = r_j$ and $f(y)$ meets the following three conditions:
Due to condition (2), $f(y)$ is concave downward at $y = 0$, and concave upward at $y = l$. Meanwhile, $f(y)$ should also meet:

$$-f''(0) = f''(l_j) = \frac{1}{r_j}$$

Suppose $f(y) = a_5 y^5 + a_4 y^4 + a_3 y^3 + a_2 y^2 + a_1 y + a_0, y \in [0, l_j]$

then $f'(y) = 5a_5 y^4 + 4a_4 y^3 + 3a_3 y^2 + 2a_2 y + a_1$,

$f''(y) = 20a_5 y^3 + 12a_4 y^2 + 6a_3 y + 2a_2$,

$f(0) = r_w + r_j - h_j \Rightarrow a_0 = r_w + r_j - h_j$;

$f(l_j) = -(r_j + r_w) \Rightarrow a_5 l_j^5 + a_4 l_j^4 + a_3 l_j^3 + a_2 l_j^2 + a_1 l_j + a_0 = -(r_j + r_w)$;

$f'(0) = 0 \Rightarrow a_1 = 0;$
Three-dimensional computer simulation \textsuperscript{1171}

\[ f'(l_j) = 0 \Rightarrow 5a_5l_j^4 + 4a_4l_j^3 + 3a_3l_j^2 + 2a_2l_j = 0 \Rightarrow 6a_5l_j^3 + 4a_4l_j^2 + 3a_3l_j + 2a_2 = 0, \]

\[ -f''(0) = \frac{1}{r_j} \Rightarrow -2a_2 = \frac{1}{r_j}, \]

\[ f''(l_j) = \frac{1}{r_j} \Rightarrow 20a_5l_j^3 + 12a_4l_j^2 + 6a_3l_j + 2a_2 = \frac{1}{r_j}. \]

It can obtain \( a_0 = r_w + r_j - h_j, a_2 = -\frac{1}{r_j}, \) and equation set

\[
\begin{bmatrix}
  l_j^2 & l_j & 1 \\
  5l_j^2 & 4l_j & 3 \\
  10l_j^2 & 6l_j & 3
\end{bmatrix} \begin{bmatrix}
  a_5 \\
  a_4 \\
  a_3
\end{bmatrix} = \begin{bmatrix}
  A + B \\
  2A \\
  2A
\end{bmatrix},
\]

\[ A = \frac{1}{2f_jl_j}, B = \frac{h_j - 2(r_j + r_w)}{l_j^3} \]

It can be solved that \( a_3 = 2(5B + 2A), a_4 = -\frac{5}{l_j}(3B + A), a_5 = \frac{2}{l_j^2}(3B + A). \)

Therefore, the curve equation of the basic segment of weft yarn is:

\[
\begin{align*}
  z &= f(y) = \begin{cases}
    a_5y^5 + a_4y^4 + a_3y^3 + a_2y^2 + a_0, y \in [0, l_j] \\
    z = f(y) \Rightarrow -a_5y^5 + a_4y^4 - a_3y^3 + a_2y^2 + a_0, y \in [-l_j, 0]
  \end{cases} \\
  \text{The coefficients are} &\ a_0 = r_w + r_j - h_j, a_2 = -\frac{1}{2r}, a_3 = 2(5B + 2A), \\
  &\ a_4 = -\frac{5}{l_j}(3B + A), a_5 = \frac{2}{l_j^2}(3B + A) \\
  &\ A = \frac{1}{2r_jl_j}, B = \frac{h_j - 2(r_j + r_w)}{l_j^3}
\end{align*}
\]

Low degree polynomial model can not meet the accuracy requirements. However, high degree one normally requires a high computational cost, and the correction accuracy is not significantly improved. Therefore, five degree polynomial is generally a weigh between accuracy and speed. Point A, Point B and Point C are three characteristic points. When \( y \in [0, l_j], \) the curvatures of Point B and Point C are the same. When \( y \in [-l_j, 0], \) the curvatures of Point A and Point B are the same. Curvature is related to first-order and second-order derivatives. The coefficients of the five polynomials from \( a_0 \) to \( a_5 \) are determined by the set values of \( A \) and \( B. \)

The values of \( A \) and \( B \) are controlled by the radius of warp and weft yarn, height of the flexural wave, and the distance between the warp and the weft yarn. That is, different input parameters will generate different coefficients of the polynomial, which lead to different buckling of curves.

In the same coordinate system, the right twill weave can be obtained by summarizing the left twill weave at X axis. Therefore, the curve of either weft or warp yarn needs to be obtained. All the following equations take the left twill as the objects. For the convenience of calculation, the starting point for the first yarns is regarded as the origin, with \( x = 0. \) The segmentation method in Fig. 4 is utilized to obtain the equation \( z = f_1(Y) \) of the basic curve equation of the first weft, which is composed of eight sections of piecewise function.
Figure 7. A unit curve and the corresponding coordinate of the $\frac{3}{2}$ twill weave warp yarn

Figure 8. A unit curve of the twill weave warp yarn

(1) $f(0) \quad y \in [0, (w_2 - 1)l_j]

(2) $f[y - (w_2 - 1)l_j] \quad y \in [(w_2 - 1)l_j, w_2l_j]

(3) $f(-l_j) \quad y \in [w_2l_j, (w_2 + s_2 - 1)l_j]

(4) $f[(w_2 + s_2 - 1)l_j - y] \quad y \in [(w_2 + s_2 - 1)l_j, (w_2 + s_2)l_j]

(5) $f(0) \quad y \in [(w_2 + s_2)l_j, (w_2 + s_2 + w_1 - 1)l_j]

(6) $f[y - (w_2 + s_2 + w_1 - 1)l_j] \quad y \in [(w_2 + s_2 + w_1 - 1)l_j, (w_2 + s_2 + w_1)l_j]

(7) $f(l_j) \quad y \in [(w_2 + s_2 + w_1)l_j, (w_2 + s_2 + w_1 + s_1 - 1)l_j]

(8) $f[(w_2 + s_2 + w_1 + s_1 - 1)l_j - y] \quad y \in [(w_2 + s_2 + w_1 + s_1 - 1)l_j, (w_2 + s_2 + w_1 + s_1)l_j]

Where, $f(y)$ is the equation 1 of the plain weave weft yarn.

2.2. Single warp yarn curve equation of twill woven fabric. Similarly, according to sectional drawing of the first warp in the warp direction shown in Fig. 7, the basic curve equation of the first warp can be determined as Fig. 8, which can also be divided into eight segments as Fig. 9. (Generally speaking, the diameter of warp yarn is small, while the diameter of weft yarn is large.) In view of the clearness of the figure, the diameter of the yarn is magnified.

The warp yarn curve equation of the plain weave fabric refers to the warp axis. A basic segment of the warp insertion of the fabric is cut out, as shown in Fig. 10. Similarly, the diameter of warp is small, while the diameter of weft is large. At the same time, in view of the clearness of the figure, the diameter of the yarn is magnified, which is the same as discussed above.

The equation of the warp curve $A_1B_1C_1$ is considered under the same coordinate system as the derivation of the weft curve equation, as shown in Fig. 11. The
equation of the warp under the established coordinate system is assumed to be $z = g(x), x \in [-l_w, l_w]$.

$g(x)$ should meet the following three conditions:

1. $g(0) = -h_j$,
2. $g'(0) = 0, g''(0) = \frac{1}{r_w}$,
3. $g(l_w) = 0, g'(l_w) = 0, g''(l_w) = -\frac{1}{r_w}$

Similar to the derivation of the weft curve equation, the curve equation of the warp is:
\[ z = g(x) = \begin{cases} 
  b_0x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_0, & x \in [0, l_w] \\
  -b_0x^5 + b_4x^4 - b_3x^3 + b_2x^2 + b_0, & x \in [-l_w, 0] 
\end{cases} \]

The coefficients are \( b_0 = -h_j, b_2 = \frac{1}{2r_w}, b_3 = 2(5B + 2A), \) \( b_4 = -\frac{5}{l_w}(3B + A), b_5 = \frac{2}{l_w^2}(3B + A); \)

Therefore, the equation \( z = g_1(X) \) of the first twill warp yarn is also composed of eight piecewise functions.

1. \( g(0) \) \( x \in [0, (w_2 - 1)l_w] \)
2. \( g[x - (w_2 - 1)l_w] \) \( x \in [(w_2 - 1)l_w, w_2l_w] \)
3. \( g(l_w) \) \( x \in [w_2l_w, (w_2 + s_2 - 1)l_w] \)
4. \( g[(w_2 + s_2 - 1)l_w - x] \) \( x \in [(w_2 + s_2 - 1)l_w, (w_2 + s_2)l_w] \)
5. \( g(0) \) \( x \in [(w_2 + s_2)l_w, (w_2 + s_2 + w_1 - 1)l_w] \)
6. \( g[x - (w_2 + s_2 + w_1 - 1)l_w] \) \( x \in [(w_2 + s_2 + w_1 - 1)l_w, (w_2 + s_2 + w_1)l_w] \)
7. \( g(-l_w) \) \( x \in [(w_2 + s_2 + w_1)l_w, (w_2 + s_2 + w_1 + s_1 - 1)l_w] \)
8. \( g[(w_2 + s_2 + w_1 + s_1 - 1)l_w - x] \) \( x \in [(w_2 + s_2 + w_1 + s_1 - 1)l_w, (w_2 + s_2 + w_1 + s_1)l_w] \)

Where, \( g(x) \) is the plain weave warp equation 2.

2.3. Curve equations of multiple weft and warp yarns arrangement in twill woven fabric. The curve equation of the first weft yarn expanded along y axis with the cycle development of \((w_2 + s_2 + w_1 + s_1)l_j\). The curve equation of the second weft yarn is to translate the first weft yarn by \(2r_j\) along the negative direction of y axis and then translate by \(l_w\) along the positive direction of x axis with the cycle development of \((w_2 + s_2 + w_1 + s_1)l_j\). Moreover, the curve equation of the third weft is to translate the first weft yarn by \(4r_j\) along the negative direction of y axis and then translate by \(2l_w\) along the positive direction of x axis with the cycle development of \((w_2 + s_2 + w_1 + s_1)l_j\). Similarly, the curve equation of the \(w_2 + s_2 + w_1 + s_1\) weft yarn is to translate the first weft yarn by \(2(w_2 + s_2 + w_1 + s_1 - 1)r_j\) along the negative direction of y axis and then translate by \((w_2 + s_2 + w_1 + s_1 - 1)l_w\) along the positive direction of x axis with the cycle development of \((w_2 + s_2 + w_1 + s_1)l_j\). Therefore, the curve equation of the first weft yarn is the most crucial to multiple weft yarns arrangement. The loop curve equation of the first weft yarn is \(F_2(Y)\) at \(y \in [0, N(w_2 + s_2 + w_1 + s_1)l_j]N = 0, 1, \ldots, n\), which is composed of the following eight equations:

1. \( f(0) \) \( y \in [q(w_2 + s_2 + w_1 + s_1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 - 1)l_j] \)
2. \( f[y - (w_2 - 1)l_j] \) \( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 - 1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + w_2l_j] \)
3. \( f(-l_j) \) \( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + w_2l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 - 1)l_j] \)
4. \( f[(w_2 + s_2 - 1)l_j - y] \)
\( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 - 1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2)l_j] \)

(5) \( f(0) \)
\( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1 - 1)l_j] \)

(6) \( f[y - (w_2 + s_2 + w_1 - 1)l_j] \)
\( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1 - 1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1)l_j] \)

(7) \( f(l_j) \)
\( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1 + s_1 - 1)l_j] \)

(8) \( f[(w_2 + s_2 + w_1 + s_1 - 1)l_j - y] \)
\( y \in [q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1 + s_1 - 1)l_j, q(w_2 + s_2 + w_1 + s_1)l_j + (w_2 + s_2 + w_1 + s_1)l_j] \)

Note: \( q = 0, 1, 2, \ldots \) \( N \) Where, \( f(y) \) is the curve equation 1.

So, multiple circulation of weft yarns curve equations of twill woven fabric becomes

\[
\begin{align*}
Z &= F_p(Y) = F_2[y - 2Mr_w] \\
x &= Kl_w(K = 0, 1, 2, \ldots) \\
M &= (p - 1) - \left[ \frac{p - 1}{s_1 + w_1 + s_2 + w_2} \right] (s_1 + w_1 + s_2 + w_2)
\end{align*}
\]

(3)

Where, \( \left[ \frac{p - 1}{s_1 + w_1 + s_2 + w_2} \right] \) is round number. \( p = 0, 1, 2, \ldots \) \( N \) represent the number of the weft yarns.

Similarly, curve equation of the first warp yarn was also composed of eight equations. So, multiple circulation of warp yarns curve equations of twill woven fabric was,

\[
\begin{align*}
Z &= G_p(X) = G_2[x - 2Mr_j] \\
y &= Kl_j(K = 0, 1, 2, \ldots) \\
M &= (p - 1) - \left[ \frac{p - 1}{s_1 + w_1 + s_2 + w_2} \right] (s_1 + w_1 + s_2 + w_2)
\end{align*}
\]

(4)

Where, \( \left[ \frac{p - 1}{s_1 + w_1 + s_2 + w_2} \right] \) is round number. \( p = 0, 1, 2, \ldots \) \( N \) represent the number of the warp yarns.

2.4. Weft and warp yarn curved surface equations of twill woven fabric.
The weft yarn surface \( S_w \) is curved surface, which can be regarded as the enveloping surface of the circle system, as shown in Fig. 12. The circles are on the plane perpendicular to the axle wire of the weft yarn, and the center of the circle \( s \) on the axle wire of the weft yarn. The radius is \( r_w \).

Therefore, the \( S_w \) equation can be obtained:

\[
[z - F_p(Y)]^2 + x^2 = r_w^2, \quad y \in [0, N(w_2 + s_2 + w_1 + s_1)l_j] \quad N = 0, 1, \ldots n
\]

Where, \( F_p(y) \) has been given in equation (3). The shape of the basic segment is shown in Fig. 12. Similarly, the equation of the warp surface \( S_j \) is:

\[
[z - G_p(X)]^2 + y^2 = r_j^2, \quad x \in [(0, N(w_2 + s_2 + w_1 + s_1)l_w)], \quad N = 0, 1, \ldots n
\]

Where, \( G_p(x) \) has been given in equation (4). The shape of the basic segment is shown in Fig. 13.
3. **Results.** The paper takes the $\frac{2}{3}$ left twill woven fabric as an example. 3D graphic and the flow chart of the twill woven fabric are shown in Fig. 14. The warp yarn is blue and the weft yarn is red. In this study, a polynomial mathematical model was used to constitute the centerline curve of yarn path in order to develop the 3D geometrical model of $\frac{2}{3}$ twill weave fabric. The aim of the study was to form an approximate curve which followed the control polygon consisting of specific control points.

Through polynomial geometry model and OpenGL developing program, this research realizes the 3D simulation of fabric appearance of twill structure, manifests the interlacing state and weft in fabric, interweave rule of warp and weft yarn and the effect of diverse geometry parameters on the fabric outlook. The results prove the practicality of polynomial curve line fit in simulating the flexing state of yarns and provide a practical mathematical construction model in complex fabric outlook simulation in the future, as shown in Fig. 14.

4. **Conclusion.** The key to developing fabric 3D computer simulating is to establish the appropriate fabric structure model and accurately estimate the dimensional structure of yarns in fabric. Most of the present researches aiming at fabric 3D computer simulation both at home and abroad adopt B-spline to simulate the flexing state of yarn interlacing. This paper employs the polynomial curve fitting to simulate the flexing state of yarns instead of the bowing modality of using straight lines and curves in Peirce model. The method adopted in this paper, which chooses polynomial curve fitting that combines the bowing curvature of yarns, radius of warp and weft yarn, thread-spacing, crimp amplitude to calculate every spot in flexing trace of yarns as well as defining structure through the arrangement of multiple warp and weft yarns, better describes the practical structure of twill woven fabric. The method used in the paper was never used in the other paper which focused on 3D computer simulation of woven fabric structure. The fitting curve of yarns in the paper was smooth. Especially when flex wave height of weft or warp yarn was zero, the fitting curve was not straight, while was little flex wave. This is in agreement with the practical yarns interweaving in woven fabric.

Through polynomial structure model and OpenGL developing program, this research realizes the 3D computer simulation of twill woven fabric appearance, manifests the interweaving state in fabric, interweaving rules of warp and weft yarns and the effect of diverse geometry parameters on the woven fabric appearance. The results prove the practicality of polynomial curved line fit in simulating the flexing state of yarns and provide a practical mathematical construction model in complex fabric outlook simulation in the future.
Figure 13. The curved surface of twill weave warp yarn

Figure 14. Yarn model and 3D image of $\frac{3}{2}$ left twill fabric structure

woven fabric simulation in the future. Evaluation of the structural properties of twill fabric woven from various fibers using Peirce’s model [3, 5] can be combined with polynomial structure model in further research.

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