Research Article

Reducing the Collision Damage Done to the Tips of Steel Needles during Integrated Piercing by Using Shape Optimization with Feature Selection

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Abstract

Recent research has shown that, during integrated piercing, the yarn tension can displace the needles from the centers of the holes in the piercing template. To reduce the damage done to the needle tips when the needles and the hole walls collide when the needle displacement is too large, this paper proposes a method for optimizing the needle shape that satisfies the strength constraint while targeting minimum needle displacement. First, the optimal objective function and strength constraint conditions for the tip displacement of the integrated puncture needle are established, which are affected by many factors. Then, the feature selection method of machine learning is used to reduce the dimensionality of the objective function after data reduction, and the feasible region of key features is reduced to avoid falling into the local best point in the optimization iteration. Finally, machine vision is used to measure experimentally the tip displacement of a needle array. The results show that the average tip displacement is reduced by 18.16–31.42% and the collision risk is reduced from 43.14% to 5.54%. It shows that the optimization method of needle shape based on feature selection is effective for reducing needle tip impact damage during integrated piercing.

1. Introduction

Carbon/carbon (C/C) composite preforms have received much attention in recent years because of their excellent properties of high specific strength, high specific modulus, and good ablation resistance. Integrated piercing (IP) on 3D fabrics has good overall structure and fiber volume fraction; they are excellent substrates for high-performance and heat-insulating C/C composite materials and are used widely in aircraft brake pads and rocket nozzles after curing C/C composites [1–5]. The distance between the needle tip of the steel needle array and the hole center of the template is determined by the structure and geometric parameters of the steel needle array [6–11]. The distance directly affects the uniformity of fiber volume fraction and the distribution of the damage degree between the tip and the hole wall.

Truss structure optimization with application diversity is one of the most popular problems in civil engineering [12–19]. Truss optimization includes three types: section shape, geometry, and topology. The integrated piercing process of woven carbon cloth is affected by many factors, such as fabric structure, needle geometry parameters, array layout, and template parameters. As a special application form of truss optimization in the field of textile machinery, the shape optimization of steel needle array aiming at reducing the impact damage of needle tip is a highly nonlinear optimization problem.

Optimization methods can be generally divided into two categories: (1) gradient descent method represented by gradient derivation and (2) metaheuristic algorithm combining random method and local search. Gradient descent method is the most popular machine learning optimization algorithm in recent years. However, choosing the appropriate learning rate when using the gradient descent method to avoid falling into the local best point is a problem. Improvements made for the application of gradient descent...
include mini-batch gradient descent, annealing gradient descent, and accelerated stochastic gradient descent [20–22]. On the contrary, research studies based on natural heuristic technologies, such as simulated annealing, genetic algorithm, tabu search, ant colony optimization, particle swarm optimization, cuckoo search, leapfrog, flower pollination algorithm, fruit fly optimization algorithm, and ideal gas molecular movement, have made important progress. Researchers have applied and improved these algorithms in the field of truss structure optimization [12, 14, 19, 23]. However, there is currently no specific metaheuristic algorithm that can be applied to the optimal solution of all structures and geometric dimensions. Proper selection of algorithms and parameters for a specific optimization problem is a time-consuming process, and engineering applications need to combine experience and trial and error. Naderi et al. [23] proposed a multistage metaheuristic method called top-up technology, which can solve the problem that metaheuristic algorithm falls into local optimum. In this paper, a feature selection method is proposed to reduce the feasible region of optimization problems under constraints. It can avoid the metaheuristic algorithm falling into the local optimal solution range of nonkey factors in the iterative solution process.

Neither the gradient descent method nor the element heuristic algorithm can be used to solve the problem well. In this paper, a single-needle displacement model satisfying the strength requirement is proposed, which takes into account the fabric structure parameters, needle shape parameters, and punching template parameters. The paper then simplifies the model and retains the parameters that are highly correlated with the target feature parameters, and it optimizes the calculation examples given within the allowable range of process parameters. Finally, the results of this optimization are applied to an experiment, and data samples of the needle tip displacement of a steel needle array are obtained using machine vision. The mean and variance of the needle displacement in the needle array from the corresponding hole center of the piercing template are analyzed to test the accuracy and applicability of the theoretical model.

2. Displacement Modeling Method of Needle for Integrated Piercing

During the IP of woven carbon cloth, the displacement of the steel needles away from the hole centers of the piercing template should be reduced as much as possible under the condition of meeting the constraint of the needle material strength. First, in modeling the yarn tension, three factors are considered, namely, (i) the horizontal needle winding, (ii) the Z-direction slippage, and (iii) the compensation of yarn tension caused by the Z-direction bending in different fabric structures. Second, the constraint condition between the parameters of the steel needles and the tension is established on the premise that the influence of the number of carbon layers on the steel needles is ignored. Finally, the deflection model of a combined variable-section cantilever beam under concentrated load is used to simplify the calculation of the displacement of a single IP steel needle under the tension of the yarn.

2.1. Tension Modeling of Representative Unit-Cell Yarn for Integrated Piercing of Woven Carbon Cloth. During IP, the needle array disturbs the yarn pattern in the carbon cloth and squeezes into the fiber gaps, causing the fiber to stretch horizontally and vertically, as described by Zhu [4]. The fiber tension acts on the steel needles to cause horizontal displacement, and if that displacement is too large, then the needles will collide with the hole walls and damage the needle tips. To avoid that problem, it is very important to study the representative unit-cell (RPC) yarn tension model of the interaction between the equidistant and closely arranged steel needles and the yarn.

2.1.1. Analysis of Integrated Piercing of Woven Carbon Cloth. The IP process can be summarized as (i) arrangement of needle array, (ii) integral puncture, (iii) pressurization compaction, and (iv) needle replacement [24, 25]. The detailed process of IP preform is shown in Figure 1.

Each needle in the array corresponds to a pinhole in the piercing template. Then, when the piercing template moves downward, the equidistant dense steel needles touch the carbon cloth, as shown in Figure 2. The IP equipment has two sets of orthogonal direction carbon cloth conveying devices, which work alternately in sequence [26].

As shown in Figure 3, the IP process has four stages. Figure 3(a) shows the woven carbon cloth is placed on the top of the needle array; at this time, the carbon cloth experiences zero net force and remains stationary. Figure 3(b) shows the fiber straightening caused by the carbon cloth being pressed onto the needle tips when the piercing template is moved slowly downward to touch the static carbon cloth. Figure 3(c) shows that, as the piercing plate continues to move downward, the needle tips penetrate the carbon cloth and occupy the spaces therein. In short, the area of the carbon cloth in which the steel needles are inserted changes gradually from the smallest (the needle tips) to the largest (the steel needle rods) and then remains constant. The two processes described above are shown in Figures 3(c) and 3(d).

There are two reasons for the complex and irregular bending and elongation of most fibers when they enter the gaps of the needle array. First, in the ideal state, the fibers in the warp and weft directions are evenly distributed in the gaps of the steel needle array, but it is difficult to achieve in practice. Second, when the manipulator holds the woven carbon cloth, the consequent wrinkling and deformation prevent the warp and weft yarns from remaining absolutely orthogonal, which is determined by the loose structure of the woven carbon cloth.

The fiber displacements occur during IP include horizontal displacement (Figure 4(a)) and vertical displacement (Figure 4(b)). The horizontal displacement is caused by the needle tips squeezing the fiber, the vertical displacement is caused by the frictional force of the fiber, and Figure 4(c) shows a plan view of the simultaneous horizontal and Z-direction displacements. Although in some ways similar to [5], the present study refines the model and considers the fiber slip in the vertical direction.
2.1.2. Bending Model of Fiber around Needle considering Z-Direction Slip

(1) Maximum Elongation of Bending Fibers around Adjacent Steel Needles. In the second case of fiber winding around the needle, as shown in Figure 4(a), the fiber has the largest elongation. As shown in Figure 4, the yarn paths between the three steel needles $i_{21}$, $i_{22}$, and $i_{23}$ have symmetry; therefore, only the length of the fiber $B_1B_2$ between $i_{21}$ and $i_{22}$ is analyzed in Figure 5, and the dotted line between $C_2B_2'$ is the projection of $C_2B_2$ on the plane.

The fiber length $B_1B_2$ after bending and stretching between two adjacent needles can be obtained from Figure 5 as follows:

$$B_1B_2 = B_1A_1 + A_1D + DC_2 + C_2B_2.$$  \hfill (1)

The four-segment lengths that makeup $B_1B_2$ are described by equations (2)–(5), and these formulas are derived from the geometric relationship in Figure 5:

$$B_1A_1 = R_1\theta.$$  \hfill (2)

$$= R_1\arcsin \frac{O_1A_1}{O_1D},$$

$$= R_1\arcsin \frac{R_1 + R_2}{d_{ij}},$$
where $R_1$ is the tip radius of the contact point between the yarn and tip 1, $R_2$ is the same for tip 2, and $d_k$ is the distance between the two holes adjacent to the center of the piercing template.

$$A_1D = (O_1D^2 - O_1A_1^2)^{1/2},$$

$$= \left[ \left( \frac{d_k R_1}{R_1 + R_2} \right)^2 - R_1^2 \right]^{1/2}. \quad (3)$$

$$DC_2 = DA_2' - C_2A_2' = \left( \left( \frac{d_k R_2}{R_1 + R_2} \right)^2 - R_2^2 \right) - \sqrt{d_k^2 - R_2^2}, \quad (4)$$

where $d_k$ is the hole diameter.

$C_2B_2 = B_2A_2'^2 + C_2A_2' + A_2'B_2'^{1/2}$,

$$= \left[ h^2 + d_k^2 - R_2^2/2R_2^2 \arcsin \frac{R_1 + R_2^2}{d_k} \right]^{1/2}. \quad (5)$$

where $h$ is the distance from the yarn to the piercing template at any time.

(2) Compensation for Bending and Stretching of Adjacent Steel Needle Fibers around the Needle. The close contact of the needle array with the carbon cloth makes it impossible to obtain compensation from the fiber segment at a far distance when the fiber is bent and stretched. Therefore, fiber compensation is considered to occur only in an RPC of the fabric structure in this study. In theory, plain-weave, twill-weave, or satin-weave carbon cloth can be used as an IP
woven carbon cloth. However, considering the high modulus and brittleness of the carbon fiber, to reduce the fiber abrasion during weaving of the woven carbon cloth, it is preferable to use a satin-structured carbon cloth, as suggested in [4]. In the present paper, 8/3 satin fabrics are taken as an example, and their organizational structure is shown in Figure 6. The curve of the fabric structure phase is expressed by a sinusoidal curve with some adjustments in [27].

In Figure 6, the length \( s \) of the bent fiber can be obtained by integrating the fiber path curve at \((0, L_{xj})\):

\[
Z = C \sin \left( \frac{\pi}{2L_{xj}} X \right),
\]

\[
ds = \left(1 + \left( \frac{Z}{2} \right)^2 \right)^{1/2} dX,
\]

\[
s_{bu} = \int_0^{L_{xj}} \left(1 + \left( \frac{C \pi}{2L_{xj}} \right)^2 \left(\cos X\right)^2 \right)^{1/2} dX,
\]

where \( Z \) is the fiber path curve, \( C \) is the crimp height of the fabric structure phase, \( L_{xj} \) is the spacing of adjacent warp or weft yarns in the fabric, and \( \tau \) is the correction coefficient of the yarn spacing.

2.1.3. Fiber Tension between Adjacent Steel Needles. From fiber material science, we have

\[
F = E_c A_z \left( \frac{B_1B_2 - S_{bu} - d_{kj}}{S_{bu} + d_{kj}} \right),
\]

where \( E_c \) is the carbon cloth modulus of elasticity and \( A_z \) is the carbon cloth fiber-bundle cross-sectional area. Satin-weave carbon cloth is soft and deforms easily, and the crimp height during the orthogonal stacking process is affected by engineering factors, so the adjustment factor \( \tau \) should be considered. During the IP, the needle tip only directly contacts the adjacent fibers, so the adjustment coefficient \( \eta \) related to the yarn \( k \) number, the fabric structure, and the needlepoint diameter should be introduced. Therefore, from equations (1)–(9), the tension model during the IP process can be obtained as follows:

\[
F_{\text{max}} = 0.25E_c \eta \pi d_{\text{med}}^2 = \left\{ \frac{d_{\text{med}} \arcsin \left( 2d_{\text{med}}/d_{kj} \right) + 2 \left( 0.25d_{kj}^2 - d_{kj} \right)^{1/2} - \left( d_{kj}^2 - d_{\text{med}}^2 \right)^{1/2} + 0.25 + \left( d_{kj}^2 - d_{\text{med}}^2 \right)^{1/2} + d_{\text{med}} \arcsin \left( 2d_{\text{med}}/d_{kj} \right) \left( \frac{2d_{\text{med}}}{d_{kj}} \right)^{1/2} \} }{d_{kj} + \int_0^{L_{xj}} \left( 1 + \left( rC\pi/2L_{xj} \right)^2 \left(\cos X\right)^2 \right)^{1/2} dX} - 1 \right\}.
\]

(10)

where \( d_{\text{med}} \) is the needle diameter.

From the knowledge about fiber materials, it is known that the yarn elongation determines the yarn tension received by the needles. However, equations (1)–(9) show that a number of factors determine the tension of the yarn during IP. To ensure needle stability, the tension is calculated according to the maximum possible elongation. To simplify the calculation, \( R_1 \), \( R_2 \), and \( d_{\text{med}} \) are made equal herein, and thus, the value of \( h \) in equation (5) is actually a multivariable numerical value that is very difficult to calculate accurately because of the interaction between the piercing template and the needles in a certain range. Based on the engineering experience in [4], \( h = 0.5 \) mm can be obtained.

By substituting the parameters of Table 1 into Equation (10), the yarn tension \( F_{\text{max}} \) was found to be 14.69 N, from which the yarn strain \( \varepsilon \) was calculated easily as \( 1.67 \times 10^{-2} \) based on the values of the tension \( F_{\text{max}} \), the elastic modulus \( E_c \), and the cross-sectional area \( A_z \). It is known from engineering experience that yarn with a strain of less than 2 \( \times 10^{-2} \) is stretched safely.

2.2. Displacement Modeling of Steel Needle under Yarn Tension. To study how the yarn tension influences the needle displacement in IP, the deflection model of a composite variable cross-sectional cantilever beam under variable concentrated load was used to study how the needle displacement changes under the influence of the yarn resultant force. The displacement modeling of a single steel needle under the action of yarn tension is divided into three steps, namely, (i) force analysis of the needle, (ii) strength constraints, and (iii) displacement modeling.
2.2.1. Force Analysis of Steel Needle under Yarn Tension. For the convenience of analysis, the IP needle force model is rotated 90° to the right, as shown in Figure 7. The coordinate system is established with the needle tip O as the origin, horizontally left as the X direction, and vertically upward as the Y direction. Then, the cross-sectional radius \( r \) of the needle tip section changes with \( x \), and the curve of the needle tip is given an exponential form \([4]\), which considers the processing feasibility.

Figure 7(a) shows that the needle tip curve passes through point \( B' \) with coordinates \((L_1, d_{ned})\), from which we can derive
\[
y = d_{ned} \left( \frac{x}{L_1} \right)^{1/m},
\]
where \( L_1 \) is the length of the needle tip, \( d_{ned} \) is the radius of the needle rod, \( m \) is the exponent in the power function representing the tip shape curve, and \( x \) is the distance from any point to the apex of the tip.

For Figure 7(b), when the yarn acts at any point \( C' \) of the tip, the direction of \( F \) is the normal direction of the needle tip curve of the contact point, and \( F \) is decomposed into \( F_1 \) in the horizontal direction and \( F_2 \) in the vertical direction. As shown in Figure 7(c), the \( F_2 \) action point is translated to the intersection point \( C \), which is the intersection point of the neutral layer of the steel needle and \( F_2 \), and then, \( F_1 \) can be translated to the tip vertex \( F'_1 \). Next, a couple of \( M_1 \) must be added, which is determined by the translation theorem of the force, and the couple moment of component \( F_2 \) to point \( A \) is \( M_2 \).

The position of the contact between the fiber and the IP needle changes with the IP process, and the direction of the force \( F \) is always perpendicular to the tangent line of the contact point \( C' \). As shown in Figure 7(b), if the angle between \( F_1 \) and \( F_2 \) is \( \theta \), then
\[
\frac{\pi}{2} - \theta = \arctan \left( \frac{mL_1}{d_{ned} L_1} \right)^{(m-1)/m}.
\]

From Figure 7(b), the tension components \( F_1 \) and \( F_2 \) are calculated as
\[
F_1 = F_{max} \sin \left( \arctan \left( \frac{mL_1}{d_{ned} L_1} \right)^{(m-1)/m} \right),
\]
\[
F_2 = F_{max} \cos \left( \arctan \left( \frac{mL_1}{d_{ned} L_1} \right)^{(m-1)/m} \right).
\]

Also, from Figure 7(b), the relationship between \( F_1 \) and \( F_2 \) is
\[
\frac{F_2}{F_1} = \tan \left( \frac{\pi}{2} - \theta \right) = \frac{mL_1}{d_{ned} L_1} \left( \frac{x}{L_1} \right)^{(m-1)/m}.
\]

2.2.2. Strength Constraint Condition When Bottom of Steel Needle Is Fixed. According to the force analysis of Figure 7(c), the cross section of \( A'A'' \) is a dangerous section. To analyze the position of the dangerous point in the section \( A'A'' \), the stress distributions of (a) the force component \( F_1 \), (b) the additional force moment, and (c) the axial force component \( F_1 \) are plotted in Figure 8.

Figure 8 shows that point \( A' \) and point \( A'' \) are the dangerous points of the needle, and the maximum stress condition at \( A' \) meeting the strength requirement is
\[
\sigma_{max} = \frac{M_2}{W_2} - \frac{M_1}{W_1} - \frac{F_1}{A} \leq \frac{\sigma}{n}.
\]
\[
\left| \frac{M_2}{W_2} - \frac{M_1}{W_1} - \frac{F_1}{A} \right| \leq \frac{\sigma}{n}.
\]

Similarly, the maximum stress condition at \( A'' \) satisfying the strength requirements is
\[
\left| \frac{M_2}{W_2} + \frac{M_1}{W_1} - \frac{F_1}{A} \right| \leq \frac{\sigma}{n}.
\]

Combining equations (11) and (16) gives
\[
4F_2 (L_2 + L_1 - x) - 5F_1 (x/L_1)^{2/m} - \sigma \leq 0.
\]
\[
4F_2 (L_2 + L_1 - x) + 3F_1 (x/L_1)^{2/m} - \sigma \leq 0.
\]

2.2.3. Modeling of Needle Displacement during Integrated Piercing. The needle displacement from the center of the corresponding hole in the piercing plate is affected by many factors, such as the fabric structural parameters, the needle shape parameters, and the orifice parameters. Herein, a model for calculating the IP needle displacement under
carbon fiber yarn tension is converted into one for calculating the deflection of the combined variable cross-sectional cantilever beam under concentrated load. The authors in [28–30] consider how to calculate the deflection of various variable-section cantilever beams under different loads. Unlike [8], the present paper considers the deflection caused by the cumulative cornering of segmental steel.

Figure 9 shows the calculation and analysis of the deflection of the cantilever beam of the piercing steel needle. Figure 9(a) shows the needle force as the fiber bends around the needle, in which \( AB \) is a constant cross-sectional needle bar, \( BO \) is a variable cross-sectional needle tip, and \( F_2 \) acts at any point \( C \). Figure 9(b) shows the additional force moment required for \( F_2 \) to translate to point \( B \), which is determined by the principle of force translation, namely,

\[
M_x = -F_2(L_1 - x). \tag{20}
\]

Calculating the forced needle displacement is equivalent to calculating the deflection of the combined variable-section cantilever beam. For small deformation, it is analyzed in a stepwise manner, as shown in Figures 9(c)–9(f). The deflection \( v \) of a composite variable cross-sectional cantilever beam has four parts, namely,

\[
v = (v_1 + v_2 + v_3 + v_4), \tag{21}
\]

where \( v_1 \) is the deflection under the concentrated load \( F_2 \) after the tempered section \( AB \) (Figure 9(c)), \( v_2 \) is the deflection of the concentrated load \( F_2 \) after the tempered segment \( BO \) is translated to point \( B \) and \( F_2' \) (Figure 9(d)), \( v_3 \) is deflection due to additional moment \( M \) of force \( F_2 \) after translation to point \( B \) (Figure 9(e)), and \( v_4 \) is the deflection of the \( O \) point caused by the rotation at the connection point \( B \) (Figure 9(f)).

Beam deflection can be calculated by the integral method, the superposition method, the graph multiplication method, or the Mohr integral method, among others [31, 32]. The double integral method and the singular-point function method are mainly used to calculate the complete deflection curve of the beam. However, only the displacement of the maximum deflection point of the cantilever beam is calculated herein, and the maximum displacement of the curved cantilever beam can be calculated by the method of moment area [31, 33]. Figure 10 shows the piecewise deflection analysis.

(1) Displacement \( v_1 \) and Rotation Angle \( \theta_1 \). The action of the fiber on the tip of the variable cross section is equivalent to \( F_2 \) acting on any point \( C' \) of the variable cross-sectional cantilever beam. In this case, the method of using the moment area is complicated, and the midsection moment of inertia of the straight-line cantilever beam after the second integral can be replaced by \( I_x \) for analysis, expressed as

\[
I_x = \frac{\pi d^4}{4} \left( \frac{x}{L_1} \right)^{4/m}. \tag{22}
\]

The maximum angle at point \( O \) of the cantilever beam in Figure 9(c) is

\[
\theta_1 = \frac{2F_2(L_1 - x)^2}{E\pi d^4 \text{ned} (x/L_1)^{4/m}}. \tag{23}
\]

The maximum displacement at point \( O \) of the cantilever beam in Figure 9(c) is

\[
v_1 = \frac{2F_2(L_1 - x)^2}{3E\pi d^4 \text{ned} (2L_1 + x)} \left( \frac{x}{L_1} \right)^{-4/m}. \tag{24}
\]

(2) Displacement \( v_2 \) and Rotation Angle \( \theta_2 \). For Figure 9(d) under small deformation, the moment area method gives

\[
\theta_2 = \tan \theta_2 = \frac{2F_2L_2^3}{E\pi d^4 \text{ned}}. \tag{25}
\]
where $E$ is the modulus of elasticity of the steel needle, and

$$v_2 = v_B = \frac{4F_2L_1^3}{3\pi d^4_{\text{ned}}}$$  \hspace{1cm} (26)

(3) Displacement $v_3$ and Rotation Angle $\theta_3$. For Figure 9(e) under small deformation, this study selects the free end $B$ of the cantilever beam as the origin and substitutes $M_x$, $I$, and $AB$ to obtain

$$\theta_3 = \left( \frac{dv}{dx} \right)_B = \frac{4F_2}{E\pi d^4_{\text{ned}}} \left( L_1L_2 - \left( \frac{L_2^3}{2} \right) \right).$$  \hspace{1cm} (27)

$$v_3 = v_B = \frac{4F_2}{E\pi d^4_{\text{ned}}} \left( \left( \frac{L_1L_2^2}{2} \right) - \left( \frac{L_2^3}{3} \right) \right).$$  \hspace{1cm} (28)

(4) Calculation of Cantilever Beam Deflection $v$. The displacement $v_4$ of $L_1$ in Figure 9(f) is due to the rotation angles of Figures 9(d) and 9(e). Therefore,
The calculated maximum needle deflection obtained by substituting equations (24), (26), (28), and (29) into equation (25) is:

\[ v_4 = (\theta_2 + \theta_3) \frac{4F_2^2L_1^2L_2}{Ea d_{ned}^4}. \]  

Then, substituting equation (14) into (30) gives:

\[ v = \frac{2F_2}{3Ea d_{ned}^2} \left[ (2L_1 + x)\left(-L_1 + x\right)^2 \left(\frac{E}{L}\right)^{-4/m} + 6L_1^2L_2 + 3L_1L_2^2 \right] \]  

3. Optimization of Needle Shape Parameters Based on Selection of Key Features

The main difficulty in optimizing the needle shape is that the model is multiobjective and multivariable. In machine learning, variable parameters are known as features, and a very important issue is determining how each feature influences the optimization objective. Herein, the machine learning method of feature selection is used to evaluate and sort the correlation between features and the optimization objective, and these features with large correlation are selected for example optimization. Then, the optimal needle shape parameters that meet the strength and displacement conditions are determined by deflection calculation and cross-validation.

Al Nuaimi et al. [34] review the traditional feature selection algorithms and then scrutinize the current algorithms that use streaming feature selection to determine their strengths and weaknesses. The authors in [35] provide the basic concepts necessary to build an ensemble for feature selection, as well as reviewing the up-to-date advances and commenting on future trends. The authors in [31] provide an overview of feature selection techniques and the instability of the feature selection algorithm.

3.1. Selection of Key Characteristic Variables for Optimization Problems

Feature selection usually considers (i) whether a feature is divergent and (ii) the relationship between a feature and the target, and those features with high relevance to the target should be selected. Feature selection comes in three forms, namely, filter, wrapper, or embedded. The common feature selection algorithms are compared in Table 2, showing that the Pearson coefficient method is suitable for continuous, linear, and normally distributed data, which is not the case in the present study. Mutual information can be regarded as the uncertainty of one random variable being reduced because another random variable is known [32]. Proposed in 2011, the maximum information coefficient (MIC) [36] is the latest method for detecting nonlinear correlations between variables. Applying the concepts of information theory and probability to continuous data, the MIC algorithm can represent various linear and nonlinear relationships and has been used widely. Its range is between 0 and 1, and the higher the value, the stronger the correlation.

To study the relationship between needle displacement and the various influencing factors, it is necessary to provide batch sample data for the feature selection algorithm. The range and iteration step of each variable in equation (31) are given in Table 3.

Set \( F_{max} = 15 \text{ N} \) and \( E = 2.11 \times 10^{11} \text{ Pa} \) and use Maple 2019 to calculate equation (31) numerically to obtain 97,510 data. The MIC calculation process discussed in [32] can be described as:

\[ \text{MIC} = \max_{(x, y) \in B} \left\{ \frac{\max / \text{Different grids}}{\log \min \{X, Y\}} \left( \sum_{x, y} P(x, y) \log \left( \frac{P(x, y)}{\sum_{x} P(x, y) \sum_{y} P(x, y)} \right) \right) \right\}, \]  

where \((x, y)\) represents the sample value and \((X, Y)\) represents the sample set. The results calculated using Python 3.7.3 and minepy 1.2.3 are given in Table 4, where MIC is the maximum information coefficient, MAS is the maximum asymmetry score, MEV is the maximum edge value, GMIC is the generalized MIC, and TIC is the total information coefficient.

To analyze the positive and negative effects of the parameter characteristics on the objective function, the Kendall coefficient is used. The results calculated by using Python 3.7.4 and scikit-learn 0.21.3 are given in Table 5.

3.2. Optimization Example of Needle Diameter and Bar Length

Based on the conclusion reached in Section 3.1, this study optimizes the two most important characteristics that affect needle displacement, namely, \( d_{ned} \) and \( L_2 \).
3.2.1. Constraint Analysis of Displacement Conditions on Key Morphological Parameters. The displacement constraint is the result of equation (31) must be less than \((0.5d_k \times \beta)\) to ensure that the needle tip does not collide with the hole wall, where \(\beta\) is the safety factor.

(1) Needle Diameter. Given the process conditions of \(L_2 = 7\) mm, \(d_k = 2.3\) mm, and \(\beta = 0.7\), constraint conditions become as follows:

\[
\nu = \frac{1.795 \times 10^{-16} F_{\text{max}}}{d_{\text{ned}}^4 \left[ \left( d_{\text{ned}}^2 + (1/10000) \right) L_{\text{ned}}^2 \right]^{1/2}},
\]

\(< 8.05 \times 10^{-4} \ (m)\).

For \(F_{\text{max}} = 0 \) to \(50\) N and \(d_{\text{ned}} = 0.8\) to \(2.0\) mm, the contour relationship among \(v, F_{\text{max}},\) and \(d_{\text{ned}}\) is as shown in Figure 11.

The constraint condition in equation (33) shows that the region above and to the left of the \(8.05 \times 10^{-4}\) displacement contour in Figure 11 is safe and feasible. From equation (33), this can be obtained by solving the boundary condition \(0.805\) mm. For \(F_{\text{max}} \leq 23\) N, \(d_{\text{ned}}\) satisfies the displacement safety requirements of the current example in the range of \(0.8\) to \(2.0\) mm. For \(F_{\text{max}} = 50\) N, \(d_{\text{ned}} \geq 1.035\) mm meets the safety requirements of the current example of displacement.

### Table 2: Comparison of commonly used feature selection algorithms.

| Type                  | Scope of application                      | Complexity | Robustness |
|-----------------------|------------------------------------------|------------|------------|
| Pearson               | Linear                                   | Low        | Low        |
| Spearman              | Linear or simple monotonic nonlinearity   | Low        | Medium     |
| Kendall               | Linear or simple monotonic nonlinearity   | Low        | Medium     |
| Maximum correlation coefficient | Linear or nonlinear                    | High       | Medium     |
| Distance dependent    | Linear or nonlinear                       | Medium     | High       |
| KNN                   | Linear or nonlinear                       | High       | High       |
| MIC                   | Linear or nonlinear                       | Low        | Low        |

### Table 3: Iterative parameters for change in needle displacement.

| Type | Start | End  | Step  | Unit |
|------|-------|------|-------|------|
| \(m\) | 0.1   | 3    | 0.25  | mm   |
| \(d_{\text{ned}}\) | 1     | 3    | 0.5   | mm   |
| \(L_1\) | 1     | 10   | 1     | mm   |
| \(L_2\) | 1     | 30   | 2     | mm   |
| \(x\)  | 1     | 10   | 1     | mm   |

### Table 4: Definition of modeling variables.

| MIC | MAS | MEV | GMIC | TIC |
|-----|-----|-----|------|-----|
| 0.1588 | 0.0410 | 0.1588 | 0.1450 | 438.7405 |
| 0.2964 | 0.0945 | 0.2964 | 0.2718 | 794.1484 |
| 0.1567 | 0.0762 | 0.1567 | 0.1382 | 355.7005 |
| 0.2004 | 0.0280 | 0.2004 | 0.1887 | 569.5243 |
| 0.1025 | 0.0355 | 0.0923 | 0.0923 | 282.1031 |

### Table 5: Kendall’s relational matrix coefficients.

|          | \(m\) | \(d_{\text{ned}}\) | \(L_1\) | \(L_2\) | \(x\) | \(\nu\) |
|----------|-------|---------------------|--------|--------|------|-------|
| \(m\)   | 1.000 | 0.000               | 0.000  | 0.000  | 0.000 | -0.270 |
| \(d_{\text{ned}}\) | 0.000 | 1.000               | 0.000  | 0.000  | 0.000 | -0.391 |
| \(L_1\) | 0.000 | 0.000               | 1.000  | 0.000  | 0.000 | 0.292  |
| \(L_2\) | 0.000 | 0.000               | 0.000  | 1.000  | 0.000 | 0.294  |
| \(x\)   | 0.000 | 0.000               | 0.000  | 0.000  | 1.000 | -0.211 |
| \(\nu\) | -0.263| -0.401              | 0.278  | 0.310  | -0.196| 1.000  |

Figs. 11 and 12: Contour relationship among \(v, F_{\text{max}},\) and \(d_{\text{ned}}\), \(v, F_{\text{max}},\) and \(L_2\).
(2) Needle Rod Length. Given the engineering conditions of \( d_{\text{ned}} = 1.1 \text{ mm}, d_k = 2.3 \text{ mm}, \) and \( \beta = 0.7, \) equation (31) becomes as follows:

\[
v = 0.225 \times L_2 \left( \frac{1}{200} + \frac{L_2}{2} \right) \times F_{\text{max}},
\]

\[
< 8.05 \times 10^{-4} \text{ (m)}.
\]

For \( F_{\text{max}} = 0 \) to 50 N and \( L_2 = 5 \) to 20 mm, the contour relationship among \( v, F_{\text{max}}, \) and \( L_2 \) is as shown in Figure 12.

The constraint conditions of equation (35) show that the area below and to the left of the \( 8.05 \times 10^{-4} \text{ m} \) displacement contour in Figure 12 is safe and feasible. Equation (34) can be obtained by solving the constraint boundary condition \( 8.05 \times 10^{-4} \text{ m} \). For \( L_2 = 20 \text{ mm}, F_{\text{max}} \) meets the displacement safety requirements of the current example within the range of 0 to 11.9 N. For \( F_{\text{max}} = 50 \text{ N}, L_2 \leq 7.95 \text{ mm} \) meets the displacement safety requirements of the current example.

### 3.2.2. Analysis of the Strength Constraint of the Needle under Stress

(1) Needle Diameter. Given that the commonly used conditions of the project are \( L_1 = 5 \text{ mm}, L_2 = 7 \text{ mm}, \) \( \sigma = 1.514 \times 10^6 \text{ Pa}, \) and a safety factor of \( n = 2.5, \) equations (17)–(19) become as follows:

\[
\begin{aligned}
&\left| \frac{7(1 + (1/(10^4 d_{\text{ned}}^2)))^{1/2}}{250d_{\text{ned}}^2 F_{\text{max}}} - \left( \frac{F_{\text{max}}/200d_{\text{ned}}^2}{\sqrt{1 + (1/(10^4 d_{\text{ned}}^2))}} \right) \right| \leq 6.056 \times 10^7 \text{ (Pa)}, \\
&\left| -\frac{7(1 + (1/(10^4 d_{\text{ned}}^2)))^{1/2}}{250d_{\text{ned}}^2 F_{\text{max}}} + \frac{3F_{\text{max}}/(100d_{\text{ned}}^3)}{\sqrt{1 + (1/(10^4 d_{\text{ned}}^2))}} \right| \leq 6.056 \times 10^7 \text{ (Pa)}. 
\end{aligned}
\]

For \( F_{\text{max}} = 0 \) to 50 N and \( d_{\text{ned}} = 0.8 \) to 2.0 mm, the contour relationships among \( \sigma, F_{\text{max}}, \) and \( d_{\text{ned}} \) are as shown in Figure 13.

Figures 13(a) and 13(b) show that the areas (i) above and to the right of the \( 6.056 \times 10^7 \text{ strength contour} \) at point \( A' \) for 0 to 10 N and (ii) above and to the left of the \( -6.056 \times 10^7 \text{ Pa} \) strength contour at point \( A' \) for 10 to 50 N constitute the allowable safety range of needle strength. Figures 13(c) and 13(d) show that the areas (i) above and to the right of the \( -6.056 \times 10^7 \text{ strength} \) contour at point \( A'' \) for 0–10 N and (ii) above and to the left of the \( 6.056 \times 10^7 \text{ Pa} \) strength contour at point \( A'' \) for 10 to 50 N constitute the allowable safety range of needle strength. The results obtained by solving equation (36) subject to the boundary conditions of \( 6.056 \times 10^7 \text{ Pa} \) and \( -6.056 \times 10^7 \text{ Pa} \) are given in Table 6.

(2) Needle Rod Length. Given that the commonly used conditions of the project are \( L_1 = 5 \text{ mm}, d_{\text{ned}} = 1.1 \text{ mm}, \sigma = 1.514 \times 10^6 \text{ Pa}, \) and a safety factor of \( n = 2.5, \) equations (17) and (19) become

\[
\begin{aligned}
&\left| \frac{8.749 \times 10^9 L_2}{F_{\text{max}}} - 1.307 \times 10^6 F_{\text{max}} \right| \leq 6.056 \times 10^7 \text{ (Pa)}, \\
&\left| -8.749 \times 10^9 L_2 \right| + \frac{7.845 \times 10^6 F_{\text{max}}}{F_{\text{max}}} \right| \leq 6.056 \times 10^7 \text{ (Pa)}. 
\end{aligned}
\]

For \( F_{\text{max}} = 0 \) to 50 N and \( L_2 = 5 \) to 20 mm, the contour relationships among \( \sigma, F_{\text{max}}, \) and \( L_2 \) are as shown in Figure 14.

Figure 14(a) shows that the area below and to the right of the \( 6.056 \times 10^7 \text{ strength contour} \) at point \( A' \) for 0 to 10 N is the safe range allowed by the needle strength. However, the \( -6.056 \times 10^7 \text{ strength} \) contour at point \( A' \) does not appear in the range of 10 to 50 N in Figure 14(b), so all that can be inferred is that most of the areas in Figure 15(b) satisfy the requirements of the needle strength. Figure 14(c) shows that the area below and to the right of the \( 6.056 \times 10^7 \text{ strength} \) contour at point \( A'' \) in the range of 0 to 10 N is the safe range allowed by the needle strength. Similar to Figure 13(b), the \( 6.056 \times 10^7 \text{ strength} \) contour at point \( A'' \) does not appear in the range of 10 to 50 N in Figure 14(d). Figures 14(b) and 14(d) show that the solution corresponding to the boundary condition at this time is not within the scope of the previous domain. The results obtained by solving equation (37) subject to the boundary conditions of \( 6.056 \times 10^7 \text{ and } -6.056 \times 10^7 \) are given in Table 7.

### 3.2.3. Optimization Results of \( d_{\text{ned}} \) and \( L_2 \) Example

The paper gives the range of parameters allowed by the process: \( F_{\text{max}} = 0 \) to 50 N, \( d_{\text{ned}} = 0.8 \) to 20 mm, \( L_2 = 5 \) to 20 mm, and the feasible domain that satisfies the displacement and strength constraint mentioned above is \( d_{\text{ned}} = 1.159 \) to 2.0 mm and \( L_2 = 7.07 \) to 7.96 mm.

The calculation parameters in Table 8 are substituted into equation (31) to obtain the partial derivatives of \( d_{\text{ned}} \) and \( L_2 \) as follows:
Equation (37) shows that displacement \( v \) is decremented monotonically with \( d_{ned} \), and \( v \) increases monotonically with \( L_2 \). However, the thicker the needle bar is, the more the fiber is squeezed, which reduces the fiber volume fraction of the 3D fabric, and the shorter the needle bar is, the fewer the carbon cloth layers that can be pierced at once, which reduces the work efficiency. Therefore, the optimization results of this example are \( d_{ned} = 1.159 \times 10^{-3} \) m and \( L_2 = 7.95 \times 10^{-3} \) m.

Obtained numerically with four groups of parameters, the results given in Table 9 show that the theoretical displacement of this example varies from 0.206 to 0.45 mm, and the effect of parameter optimization on reducing displacement is obvious.
4. Experiment and Results

The randomness of the yarn around the needle bending direction means that the direction of the resultant force of the needle tip during IP is unknown. Therefore, it is difficult to compare directly the calculation results of the needle displacement in the theoretical model with the displacement of each steel needle in the experiment. This paper designs a verification scheme based on machine vision to measure tip displacement. Four sets of results were obtained using a combination of two needle diameters (1.0 mm and 1.159 mm) and two puncture needle lengths (7.95 mm and 10 mm). After image processing, four sample data sets for tip displacement were obtained, and the mean and variance

| Point | Constraint plane | $F_{\text{max}}$ | $d_{\text{max}}$ |
|-------|----------------|----------------|-----------------|
| $A'$  | $Z = 6.056 \times 10^7$ Pa | $\geq 3.18$ N | $0.8 \times 10^{-3}$ m |
|       | $Z = 6.056 \times 10^7$ Pa | $1$ N | $\geq 1.1 \times 10^{-3}$ m |
|       | $Z = -6.056 \times 10^7$ Pa | $\leq 27.62$ N | $0.8 \times 10^{-3}$ m |
|       | $Z = -6.056 \times 10^7$ Pa | $50$ N | $\geq 1.159 \times 10^{-3}$ m |
|       | $Z = 6.056 \times 10^7$ Pa | $\leq 44$ N | $0.8 \times 10^{-3}$ m |
|       | $Z = 6.056 \times 10^7$ Pa | $50$ N | $\geq 0.86 \times 10^{-3}$ m |
| $A''$ | $Z = -6.056 \times 10^7$ Pa | $\geq 3.33$ N | $0.8 \times 10^{-3}$ m |
|       | $Z = 6.056 \times 10^7$ Pa | $1$ N | $\geq 1.1 \times 10^{-3}$ m |

**Figure 14:** Contour relationships among $\sigma$, $F_{\text{max}}$, and $L_2$: (a) point $A'$ for 0 to 10 N; (b) point $A'$ for 10 to 50 N; (c) point $A''$ for 0 to 10 N; (d) point $A''$ for 10 to 50 N.
were calculated to assess how optimizing the needle shape parameters affected the displacement of the needle array.

### 4.1. Experimental Parameters

The system has three main parts, namely, (i) integral puncture tooling, (ii) an industrial camera, and (iii) a light source. The tooling and material parameters of the experiment are given in Table 10, and the

### Table 7: Feasible area of length of steel needle rod under strength constraint.

| Point | Constraint plane | $F_{\text{max}}$ | $L_2$ |
|-------|------------------|------------------|-------|
| $A'$  | $Z = 6.056 \times 10^2 \text{ Pa}$ | $\geq 2.73 \text{ N}$ | $20 \text{ mm}$ |
|       | $Z = 6.056 \times 10^2 \text{ Pa}$ | $1 \text{ N}$ | $\geq 7.07 \text{ mm}$ |
|       | $Z = -6.056 \times 10^2 \text{ Pa}$ | $\leq 46.36 \text{ N}$ | $20 \text{ mm}$ |
|       | $Z = -6.056 \times 10^2 \text{ Pa}$ | $50 \text{ N}$ | $\leq 27.5 \text{ mm}$ |
|       | $Z = 6.056 \times 10^2 \text{ Pa}$ | $\geq 79.98 \text{ N}$ (not in defined domain) | $20 \text{ mm}$ |
| $A''$ | $Z = 6.056 \times 10^2 \text{ Pa}$ | $50 \text{ N}$ | $\leq 121.94 \text{ mm}$ (not in defined domain) |
|       | $Z = -6.056 \times 10^2 \text{ Pa}$ | $\geq 2.79 \text{ N}$ | $20 \text{ mm}$ |
|       | $Z = -6.056 \times 10^2 \text{ Pa}$ | $1 \text{ N}$ | $\geq 7.01 \text{ mm}$ |

### Table 8: Example parameters.

| Parameter | Meaning | Value |
|-----------|---------|-------|
| $E$       | Elastic modulus of steel needle | $2.11 \times 10^{11} \text{ Pa}$ |
| $m$       | Exponent in power function of tip shape curve | 2 |
| $L_1$     | Tip length | $5 \times 10^{-3} \text{ m}$ |
| $x$       | Distance between fiber and tip | $L_1$ |
measurement requirements and camera parameters are given in Table 11.

### 4.2. Experimental Operation

In the experiment, the tip states of four groups of parameters were photographed. Two photographs were taken for each group of states to reduce the error caused by lighting and equipment stability. Figure 15(a) shows the machine vision image-acquisition experimental platform. Figure 15(b) shows four situations, namely, (i) a damaged needle, (ii) an intact needle, (iii) a dangerous position, and (iv) a safe position. Figure 15(c) shows the designed experimental process.

### 4.3. Image Processing

Computer vision technology is used widely in various fields, such as industrial automation, inspection and monitoring, visual navigation, human-computer interaction, and virtual reality. The application of image processing technology to the positioning of steel needle tips generally requires three main stages, namely, (i) preprocessing, (ii) image segmentation, and (iii) feature extraction. As shown in Figure 15(b), the unsafe and dangerous positions are divided according to the distance of the needle tip from the hole wall. An example of the detailed image processing algorithmic flow and image processing is shown in Figure 16.

The data acquired in the actual project will inevitably contain missing values, abnormal points, and noisy data. The data are cleaned as follows: first, this paper observed the basic distribution of the data through histograms, density maps, and box plots. Then, because the missing data in this data set accounted for only 0.05% in the statistical analysis of the sample set, the direct deletion was used for simple processing. Finally, a box chart was used to analyze the outliers in the sample data, and these were replaced by the average value calculated from the data around the outliers.

### 4.4. Analysis of Results

As mentioned earlier, the present research aims to reduce the collision damage caused by the excessive displacement of the steel needles in contact with the hole walls during the overall puncture process. Table 12 shows that the recognition rate for the needle tip displacement is above 99%, and the experimental design is safe and reliable; at the same time, the proportion of needle tip displacement danger areas has been reduced from 43.13% to 5.54%. The displacement safety rate and dangerous rate indicate that the needle tip displacement safety rate is higher when the needle is wider and the needle bar is shorter and is lower when the needle is narrower and the needle bar is longer.

The analytical results of the data in Table 13 show that the mean and variance of needle array displacement are smaller when the needle tip is wider and the needle bar is shorter, and the mean and variance of needle array displacement are larger when the needle tip is narrower and the needle bar is longer. Compared with the fourth group of experiments, in the other three groups with optimized parameters, the average tip displacement of the needle array is reduced by 18.16–31.42%, and the variance is reduced by 22.51–27.71%. Comparing the results of the two experiments in each group, the reliability of the experimental sample collection can be seen from Tables 12 and 13.

Figure 17 shows the distributions of needle tip displacement under all four sets of parameters. Figures 17(a) and 17(b) show the average and variance of the steel needle array with small displacements, but the curve fluctuates more obviously. The effect of the thread on the complex tension of the steel needle is relatively obvious. Figures 17(c) and 17(d) show the large displacement mean and variance of the steel needle array, and the curve fluctuations have
The statistics and analysis results of the image processing results are consistent with the laws of the theoretical model, and although they deviate from the calculations of the theoretical model, this is acceptable. During the experiment, the displacement unit used pixels without camera calibration and distance conversion. This is because the purpose of this experiment is not to calculate the actual physical displacement of a single steel needle but to verify the correctness of

![Diagram of image processing algorithmic flow and processing example](image)

**Figure 16**: Image processing algorithmic flow and processing example: (a) algorithmic flow; (b) processing example.

| Group no. | Picture no. | $L_2$ (mm) | $d_{ned}$ (mm) | Safety holes | Dangerous holes | Total number of holes | Recognition rate (%) | Safety rate (%) | Dangerous rate (%) |
|-----------|-------------|------------|----------------|--------------|-----------------|----------------------|---------------------|----------------|-------------------|
| 1         | 1-1         | 7.95       | 1.159          | 2092         | 123             | 2219                 | 99.82               | 94.28           | 5.54              |
| 1         | 1-2         | 7.95       | 1.159          | 2092         | 124             | 2219                 | 99.86               | 94.28           | 5.59              |
| 2         | 2-1         | 10         | 1.159          | 2054         | 159             | 2219                 | 99.73               | 92.56           | 7.17              |
| 2         | 2-2         | 10         | 1.159          | 2062         | 151             | 2219                 | 99.73               | 92.92           | 6.80              |
| 3         | 3-1         | 7.95       | 1.0            | 1643         | 567             | 2219                 | 99.59               | 74.04           | 25.55             |
| 3         | 3-2         | 7.95       | 1.0            | 1651         | 560             | 2219                 | 99.64               | 74.40           | 25.24             |
| 4         | 4-1         | 10         | 1.0            | 1284         | 914             | 2219                 | 99.05               | 57.86           | 41.19             |
| 4         | 4-2         | 10         | 1.0            | 1240         | 957             | 2219                 | 99.01               | 55.88           | 43.13             |
the laws in the theoretical model based on statistical analysis. Without coordinate transformation, the experimental steps are simplified and the experimental purpose is satisfied.

5. Conclusions

Previous studies have modeled the yarn tension around the needle bending stage during the IP of woven carbon cloth, and the curve of the needle tip has been optimized for the different IP stages, but most of those studies did not consider comprehensively how the displacement is influenced by the fabric structure, the piercing-needle shape parameters, and the piercing template parameters. However, the combined variable-section cantilever beam deflection model based on a variable concentration load proposed herein does consider the above three factors comprehensively. In addition, previous studies have mainly optimized the tip shape curve. However, the present research results based on machine

| Group no. | Picture no. | $L_2$ (mm) | $d_{ned}$ (mm) | Sum of safety distance | Sum of hazard distance | Mean | Variance | Percentage reduction of mean | Percentage reduction of variance |
|-----------|-------------|-----------|----------------|-----------------------|-----------------------|------|----------|----------------------------|--------------------------------|
| 1         | 1-1         | 7.95      | 1.159          | 17957                 | 2083.37               | 9.0476 | 20.2631  | 31.42%                     | 27.71%                         |
| 1         | 1-2         | 7.95      | 1.159          | 17941.2               | 2118.16               | 9.0521 | 20.5721  | 30.14%                     | 23.51%                         |
| 2         | 2-1         | 10        | 1.159          | 18150.9               | 2834.78               | 9.4829 | 21.9266  | 28.14%                     | 22.51%                         |
| 2         | 2-2         | 10        | 1.159          | 18274.4               | 2713.99               | 9.4841 | 21.8438  | 28.14%                     | 22.51%                         |
| 3         | 3-1         | 7.95      | 1.0            | 15092                 | 8769.49               | 10.7971 | 21.5330  | 18.16%                     | 23.99%                         |
| 3         | 3-2         | 7.95      | 1.0            | 15202.9               | 8684.43               | 10.8039 | 21.4010  | 18.16%                     | 23.99%                         |
| 4         | 4-1         | 10        | 1.0            | 12919.7               | 16050.4               | 13.1802 | 28.0658  | 0                          | 0                              |
| 4         | 4-2         | 10        | 1.0            | 12288                 | 16743                 | 13.2139 | 28.4195  | 0                          | 0                              |

Figure 17: Histogram of displacement distribution of steel needle array in four groups of experiments: (a) group 1; (b) group 2; (c) group 3; (d) group 4.
and (ii) the structure with the smallest needle array unit.
The yarn tension model herein compensates the yarn structure parameters for the yarn stretch and the Z-direction slip of the yarn during the piercing process, thereby improving the compatibility and applicability of the tension model. The mean and variance results from the needle displacement experiment based on machine vision show that the representative single-needle displacement model for woven carbon cloth has obvious importance for reducing the displacement after being applied to the needle array. Therefore, the theoretical model is effective for reducing the collision between the steel needle and the hole wall, thereby indirectly improving the uniformity of the Z-direction fiber distribution.

Using an RPC fabric structure in the present study simplifies the IP model, thereby making it feasible to perform finite-element simulations on the mechanics and motion mechanisms of the IP process. However, some limitations should be noted: the minimum structural elements corresponding to various structures of woven fabric are different, and the minimum structural elements of the needle array are determined by different engineering backgrounds. Future work should include (i) the piercing mechanism for a combination of multiple fabric structures and (ii) the structure with the smallest needle array unit.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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