Geometrical Arrangement in the Needle Loop of Multifilament Yarn using Genetic Algorithm

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ABSTRACT
In this paper, the loop structure of plain knitted fabric, constructed from multifilament yarns is geometrically modeled. This model is based on post-buckling behavior of multifilament yarns composed of two, three or seven filaments with circular cross sections. In the first step, the classic theory of Elastica 2-D post-buckled shape of each filament position on the yarn structure was investigated. In this step, volumetric intersections between filaments on the yarn occurred. In the Second step, the arrangement of the filaments in 3-D space was predicted applying an out-plane bending force. To find the minimized bending force and reducing the volumetric intersections between filaments, we used genetic algorithm. Genetic Algorithm was used for reducing the problem complexity and optimizing that complexity by replacing contact forces between filaments with a concentrated out-plane force. The geometry position of yarn filaments is also modeled using finite element method. Comparison of results shows small difference between the two models and confirms that the analytical proposed model is acceptable.

Keywords: needle loop; multifilament yarn; post-buckling; genetic algorithm; finite element method

INTRODUCTION
Understanding the loop geometry of knitted structures is very important in the study of dimensional and mechanical behavior of knitted fabrics. Leaf [1] proposed the mathematical model of Elastica that can be used for loop structure. Munden [2] recommended a loop configuration determined by condition of minimum energy and suggested his model independent of yarn properties and stitch length. Grosberg [3] also worked on the geometrical properties of the simple warp-knitted fabrics. An energy minimization technique has been also used to describe the shape of the single bar warp knitted fabric structures [4]. Recently, many researchers have worked on the loop geometry of the fabrics. A new 3-D image of the basic warp-knitted structure was created in a CAD program by employing the data obtained from the real loops in fabric [5]. A knitted fabric mechanical model was developed using the energy model of knitted loop that the shape of the yarn after knitting was curved and had non-linear mechanical properties. In the developed model, the effect of residual torque on yarn was also taken into consideration [6, 7]. The 3-D model of a plain weft-knitted structure results from the assumption that yarn cross section changes to ellipse along the loop [8]. In the other work, the geometrical model of a tuck stitch and its effect on the plain knitted fabric structure were introduced [9]. Also, the elliptical shape for the head of loops and general helices for the other parts including arms of the loops were used for single pique, half and full cardigan weft knitted structures [10]. Using a buckled-twisted elastic rod, Ajeli et al. found a 3-D geometry of knitted loop structure [11]. Furthermore, Durville approached the textile simulation of woven structures problem at the fibers scale using 3-D beam model [12]. He also proposed a finite element approach which simulates the mechanical behavior of beam assemblies that are subject to large deformations and that develop contact-friction interactions [13]. Robitaille et al. presented an algorithm that generates geometric descriptions of unit cells of textiles and composite materials [14]. Lomove et al. used finite element model of a unit cell of a textile [15].

In the previous studies, modeling was carried out on a plain loop knitted from mono-filament yarns or the yarn structure has been assumed as a continuous media. In a real state, knitted loops are produced from multi-filaments yarns. Regarding Elastica theory, this study aimed at modeling loop geometry in a multifilament knitted structure.

3-D GEOMETRICAL LOOP MODEL
First Step, 2-D Post-Bucking
It is assumed for simplicity of the model that the multifilament yarns are composed of two, three and seven filaments with circular cross section. Post-

buckling behavior of multifilament yarn was investigated with respect to Elastica model (*Figure 1*). According to Leaf's Elastica formulation which describes the deflection of elastic rod, the dimension of the loop at any arbitrary point(x,y) is as follows [1]:

$$x=b[2E(\kappa,\varphi)-F(\kappa,\varphi)] \quad (1)$$

$$y=\pm 2b\kappa(\cos(\varphi)-\cos(\varphi_0)) \quad (2)$$

$$a=[2E(\kappa,\varphi_0)-F(\kappa,\varphi_0)]/F(\kappa,\varphi_0) \quad (3)$$

Where $F(\kappa,\varphi)$ is an elliptic integral of the first kind with modulus κ, $E(\kappa,\varphi)$ is an elliptic integral of the second kind with modulus κ and index a is the proportion of distance of the base(AA') to the rod length. Parameter b can be obtained using the equation $b=\sqrt{B/P}$ and B and P denote the flexural rigidity and buckling load, respectively.

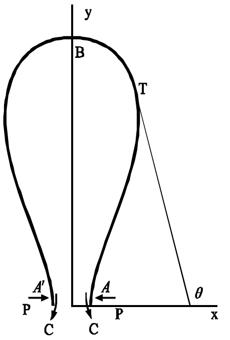


FIGURE 1. Elastica shape.

Solution procedure of Eq. (1), Eq. (2) and Eq. (3) with different base distance of Elastica curvature, by assuming the yarn cross section arrangement as shown in *Figure 2* with circular cross section of diameter 1 *cm* and length of 100 *cm* of each monofilament is provided in *Table I.*

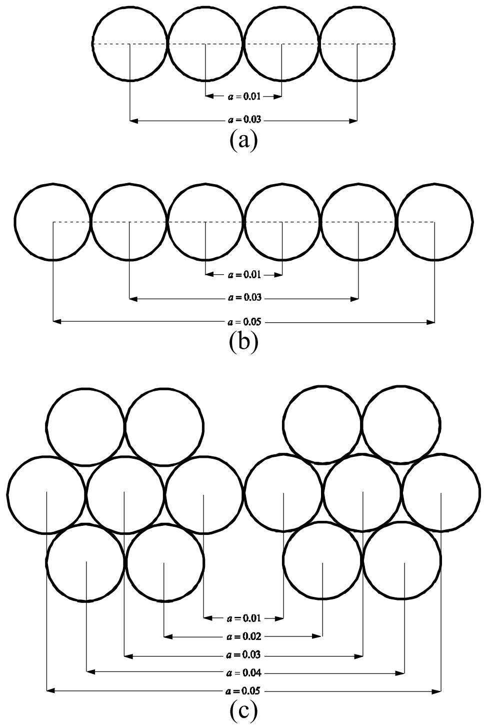


FIGURE 2. Proposed Elastica legs cross-section with different filaments arrangement. (a), (b) and (c) are ordered two, three and seven filaments yarn cross-section.

TABLE I. Critical results in 2-D Post-Buckling using Elastica model.

a	y_m	x_m
0.01	42.48	10.35
0.03	42.56	10.65
0.02	42.53	10.50
0.04	42.60	10.80
0.05	42.62	10.95

y_m and x_m are the maximum x and y.

Figures 3, 4 and 5 show the monofilament's position in the yarn using proposed loop model for two, three and seven monofilament, respectively. Volumetric intersections between filaments can be easily seen in these figures which must be eliminated. Elimination process was performed using out-plane deflection method of mono filaments and genetic algorithm.

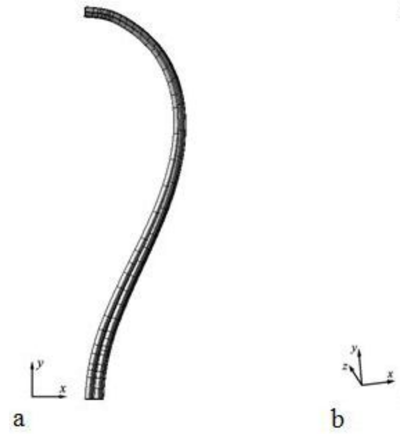


FIGURE 3. The shape of Post-Buckled yarn composed of 2 filaments, a. Front view b. Perspective view.

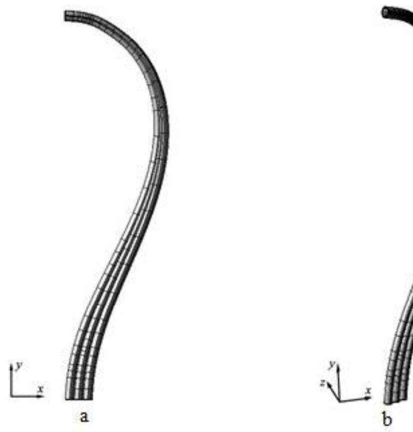


FIGURE 4. The shape of Post-Buckled yarn composed of 3 filaments, Front view b. Perspective view.

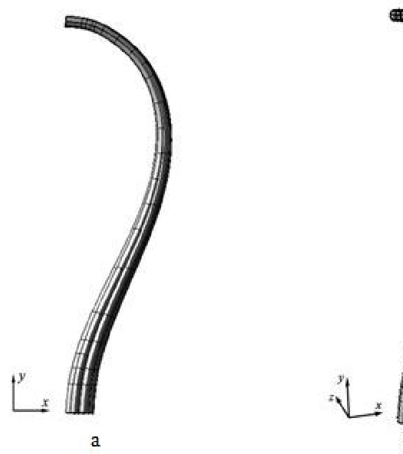


FIGURE 5.The shape of Post-Buckled yarn composed of 7 filaments, a. Front view b. Perspective view.

Second Step, Out-Plane Deflection

In this step, an out-plane bending force was used to eliminate the volumetric intersections of monofilament in the yarn model. Furthermore, genetic algorithm was utilized to reduce the problem complexity and to optimize the contact force.

All the interactions on a filament have been replaced by an out-plane force on the loop head which causes bending in the YZ plane. The diagram of a simply supported beam under a concentrated load is illustrated In *Figure 6*. According to Bishop and Drucker [16], large deflection of a beam due to bending under a concentrated load can be expressed as follows:

$$B d\varphi/ds = P(L-\Delta-y) \tag{4}$$

Where B is bending rigidity, P is bending load, s and φ are arc length and slope angle, respectively. y is also the horizontal coordinate measured from the fixed end of the beam. L is the beam length. According to *Figure 6*, δ and Δ are structure deflection for corresponding θ and s.

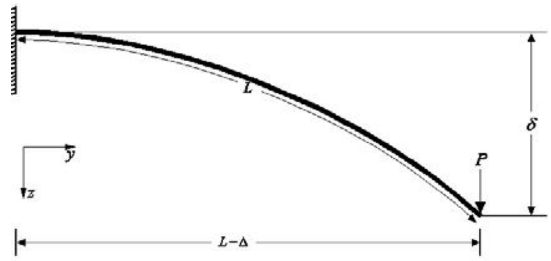


FIGURE 6. Large deflection of a beam using load F [16].

Solving Eq. (4), gives:

$$z = L\left(1 - \frac{2}{\alpha}[E(k,\theta) - E(k,\theta_1)]\right) \tag{5}$$

$$y = \sqrt{\frac{2P}{B}}(2k^2 - 2k^2\sin^2\theta)^{1/2} \tag{6}$$

Where $F(\kappa,\theta)$ and $E(\kappa,\theta)$ are elliptic integral of first and second kind with modulus κ, respectively and;

$$\alpha = F(k,\theta) - F(k,\theta_1) \tag{7}$$

$$1 + \sin\varphi = 2k^2 \sin^2\theta \tag{8}$$

If $\varphi=\varphi_0$ then $\theta=\theta_1$ and φ_0 denotes the tangent of free beam end.

Considering the last four equations, the 3-D shape of elastic in *Figures 3, 4 and 5* was achieved. Filament interactions complexity of this case result from friction, torsion, and bending forces that make the problem really complicated to be analytically solved. Numerical approaches are recommended in these situations; provided that filament interactions are simplified.

Genetic Algorithm (GA) was taken for optimizing the out-plane bending forces in the structure and elimination of volumetric intersection of the yarn filaments. GA is a search method in which the possible solutions space (search space) is studied to find an optimal solution. Each possible solution can be marked by its fitness value, depending on the problem definition. GA has a number of important features. The first feature is that it is a stochastic algorithm; randomness plays an essential role in GA. Second point is that a population of solution is taken into account. Keeping in memory more than a single solution offers a lot of advantages. The algorithm can recombine different solutions to get better ones and so, it can benefit from assortment. All the above mentioned features make GA a powerful optimization tool [17].

Each solution is represented through a chromosome. After encoding a solution into a chromosome, GA starts by generating an initial population of chromosomes. Generally the initial population is generated randomly. Then the GA loops over an iteration process to make the population evolve. Each iteration consists of the following steps: *Selection*, *Reproduction, Evaluation, and Replacement.*

In the present research, The GA's chromosome includes seven genes, one for each filament, holding the value of bending force. GA minimizes fitness function which is as follows [17]:

$$f(V) = \sum_{i=1}^{6} \sum_{j=i+1}^{7} V_{ij} \tag{9}$$

Where V_{ij} is volumetric intersection between i^{th} and j^{th} filament. Since $V_{ij} = V_{ji}$, the summations indexes are chosen in a way to remove repetitive terms. By expansion the Eq. (9), it can be seen that there is no repetitive term in the fitness function. The above mentioned terms reduce the algorithm performance and make the fitness function noisier. The Roulette Wheel was chosen as selection operator. Arithmetic crossover and uniform mutation were used for reproduction operator in which mutation and crossover rate were 0.8 and 0.01 respectively. Population number was 100. Arithmetic crossover operator linearly combines two parents using a weighting factor α according to the following expressions.

$$offspring1 = \alpha \ parent1 + (1-\alpha) \ parent2$$
$$offspring2 = (1-\alpha) \ parent1 + \alpha \ parent2$$

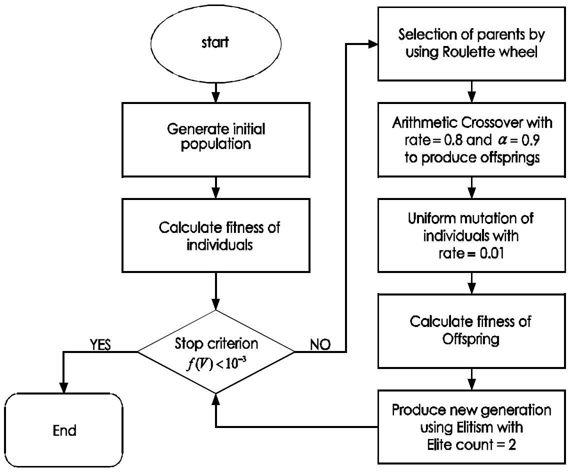


FIGURE 7. Flowchart of GA process.

The flowchart of GA process is shown in *Figure 7*. Optimization has been performed on three cases including 2, 3 and 7 filaments.

Case I

In this case, a yarn composed of two filaments has been optimized. Since the genes were real values and the search space was very large, constrains have been defined to reduce the search space size and consequently computing time. Filaments bending directions are opposite; therefore one of them can bend in positive direction of axis *z* while another one bends in the reverse direction. It is clear that such constrain prevents the filaments from being on the same side of *z*-plane simultaneously.

Case II

The purpose of this case was to optimize a yarn composed of three filaments. Like the previous case, some constrains have been applied on filaments. In this case, bending directions of neighbor filaments are opposite. Filaments bending directions are depicted in *Figure 8*.

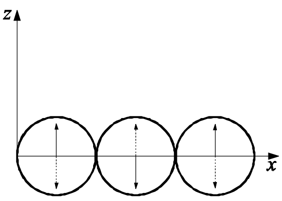


FIGURE 8. Bending direction of filaments in a yarn composed of 3 filaments.

Case III

In Case III a yarn composed of seven filaments has been optimized. In this case, optimization has been performed in two steps. In the first step, three filaments placed on plane *z=0* have been optimized then in the second step, optimization of other four filaments has been carried out based on fix position of three initial ones. Constrains applied on filaments are shown in *Figure 8.* Bending directions of the filaments placed on plane *z=0* are mutually opposite. Dashed directions in *Figure 9* indicate this constrain.

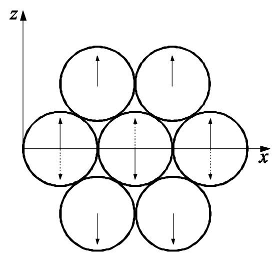


FIGURE 9. Bending direction of filaments in a yarn composed of 3 filaments.

GEOMETRIC LOOP MODEL RESULTS

The optimized structures of the 3-D yarn shape obtained by proposed model are illustrated in *Figures 10, 11 and 12.*

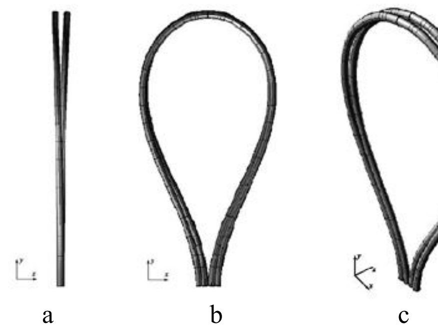


FIGURE 10. Optimal form of the yarn composed of 2 filaments obtained by proposed model. a, b and c is the side view, front view and 3-D view, respectively.

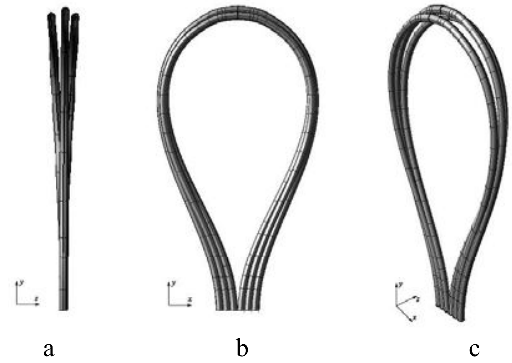


FIGURE 11. Optimal form of the yarn composed of 3 filaments obtained by proposed model. a, b and c is the side view, front view and 3-D view, respectively.

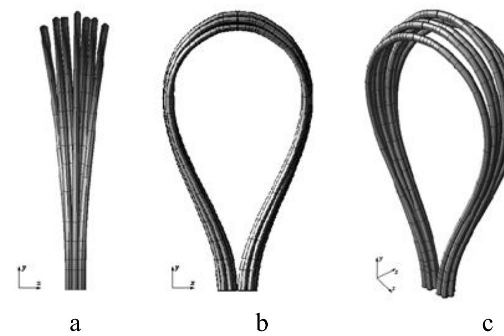


FIGURE 12.Optimal form of the yarn composed of 7 filaments obtained by proposed model. a, b and c is the side view, front view and 3-D view, respectively.

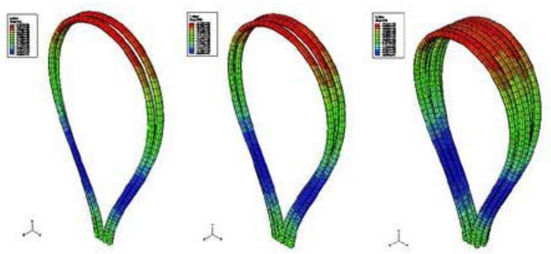
FINITE ELEMENT METHOD MODELING

The Finite element method (FEM) was utilized to verify the results of optimized yarn structure based on the proposed model. The Finite element method is a numerical computing technique for finding a solution for partial differential equations. The principle is to break a complicated problem into smaller interconnected sub-regions to facilitate solution procedure [18].

Yarn parameters modeled by finite element are the same as those of proposed model. The yarn is composed of elastic rods with circular cross section of diameter 1 *cm* and length of 100 *cm*. two, three and seven rods with arrangement on *Figure 2* was considered for multifilament yarns FEM model. The main rod parameters of the structure used in FEM model are listed in *Table II*. The dynamic explicit method is considered for this analysis. For simple 2-D problems, static implicit analysis models are generally known to be more accurate and efficient than dynamic explicit analysis models. However, for complex 3-D forming problems, the static implicit procedures encounter a number of inherent difficulties. Static implicit finite element formulations require a very long computational time for the analysis of the model. The dynamic explicit method on the other hand appears to be very effective in analyzing complex incremental forming problems. In this paper, a comparison of the analysis results obtained using dynamic explicit finite element method. *Figure 13* depicts illustrations of filament position in the loop structure.

TABLE II. Setting for finite element modeling of the problem.

Parameters	Value
Solver	Dynamic/ Explicit
Friction Coefficient	0.8
Element Type	3D Stress
Elements No.	400 per filament
Shape/Type	Solid/Sweep
Young's Modulus	200 *GPa*
Poisson's Ratio	0.3
Mass Density	7870 Kg/m^3
Section	Solid, Homogeneous



a b c

FIGURE 13. Finite element results. a, b, and c is a loop composed of 2, 3 and 7 rods, respectively.

COMPARING LOOP MODEL AND FEM

The results of the proposed loop model and FEM model were compared. The results of the proposed model are listed in *Tables III, IV and V*. The indexes *d*, *D* and z_{max} are maximum width, maximum height and maximum deflection of the filament along *z* direction, respectively. Bending load *F* corresponds with calculated force of respective filament in the yarn. Plus and minus sign of the *F* shows the direction of the force along *z* direction hence it shows bending direction of the filament. -*z* and +*z* in Tables III, IV, and V show the initial position of the filament in negative and positive space of *z* plane, respectively.

Comparison between two models is provided in *Table VI.* The percentage of error is calculated as below:

$$\%Error = \frac{V_p - V_{fem}}{V_{fem}} \times 100 \tag{10}$$

Where V_p and V_{fem} account for values of the proposed and finite element model, respectively. Maximum error happens in *z* direction of the yarn which is composed of two filaments. Small amount of error in all cases show that the proposed model results are acceptable.

TABLE III. Proposed model results for the yarn composed of 2 filaments.

a	Bending Load F	*d (cm)*	*D (cm)*	Z_{max}*(cm)*
0.01	0.035	20.69	41.92	-0.95
0.03	0.032	21.25	42.05	+0.87

TABLE IV. Proposed model results for the yarn composed of 3 filaments.

a	Bending Load F	*d (cm)*	*D (cm)*	Z_{max}*(cm)*
0.01	-0.056	20.70	41.57	-1.52
0.03	+0.055	21.25	41.67	+1.50
0.05	-0.010	21.88	42.46	-0.27

TABLE V. Proposed model results for the yarn composed of 7 filaments.

a	Bending Load F	*d (cm)*	*D (cm)*	Z_{max}*(cm)*
0.01	0.056	20.69	41.57	-1.52
0.03	0.055	21.25	41.67	+1.50
0.05	0.010	21.88	42.46	-0.27
-*z* 0.02	0.065	20.97	41.46	-2.63
+*z* 0.02	0.013	20.96	40.33	+4.41
-*z* 0.04	0.119	21.56	40.60	-4.11
+*z* 0.04	0.065	21.56	41.53	+2.64

TABLE VI. Comparison between proposed model and finite element models.

	n	*d (cm)*	Error %	*D (cm)*	Error %	$Z_{\pm max}$ *(cm)*	Error %
Proposed Model FEM Model	2	21.25 21.70	2.1	42.05 43.43	3.2	1.82 1.89	4.0
Proposed Model FEM Model	3	21.88 22.65	3.4	42.46 43.36	2.1	3.02 2.93	2.8
Proposed Model FEM Model	7	21.88 22.35	2.1	42.46 43.78	3.0	8.52 8.74	2.5

CONCLUSION

In the present study a geometrical model of a multifilament yarn is proposed. The model is composed of two steps including 2-D post-buckling of the filaments yarn and 3-D optimization of the filament interactions using genetic algorithm. In the first step, the multifilament yarn undergoes post-buckling phenomenon in 2-D. It is shown that there are volumetric overlaps between post-buckled filaments which are needed to be eliminated. Determining the deflection of the structure is analytically impossible, since there is a complicated collection of interactions between filaments during the post-buckling process. The interactions are replaced by an out-plane force which causes the filaments to be bent along the out-plane direction. Step two is associated with determining the force using genetic algorithm. Fitness function of the genetic algorithm is a summation of the overlaps between 2-D post-buckled filaments and is needed to be minimized. In order to verify the results of the proposed model, the yarn is modeled by the finite element method. The small difference between the two models confirms the acceptability of proposed model.

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