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3D NUMERICAL MODEL TO INVESTIGETE CABLE TWISTING PATTERN FOR SUPERCONDUCTING CENTARAL SOLENOID OF SST-1

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Abstract- *Under upgradation activities for SST-1, it is decided to design and manufacture superconducting central solenoid based on Nb_3Sn cable in conduit conductor (CICC). Optimization of cabling technology is under progress with simulation and cabling trials. Multi-stage twisted superconducting cable is the main component of SST-1 CS. It is critical to understand twisting pattern to estimate the performance of conductor. 3D Numerical model is developed using matrix methodology to project trajectories of strands during cabling process for Nb_3Sn CICC of CS.*

The neighbouring relation between the Nb_3Sn and copper as well as the contact angle between the strands in the superconducting cable has been identified using simulation of the twisting pattern. Multistage twisting pattern for 3×3×4×5 configuration with required twist pitch for single strand and multistrands in each stage is modelled in this 3D model. The inputs obtained from this numerical investigation will used to study stress-strain state of strands for optimization of cabling process using finite element method.

Keywords: *Central Solenoid, CICC, Trajectory, Twist pitch, Strands*

I. INTRODUCTION

Under upgradation activities for SST-1, it is decided to design and manufacture superconducting central solenoid (CS) based on Nb_3Sn cable in conduit conductor (CICC). The design and manufacturing plan for same has been completed [1]. Under development of cabling technology for CS, cabling trial supported with simulation is under progress. CICC consists of hybrid superconducting cable wrapped with SS316L foil jacketed in SS316LN tube.

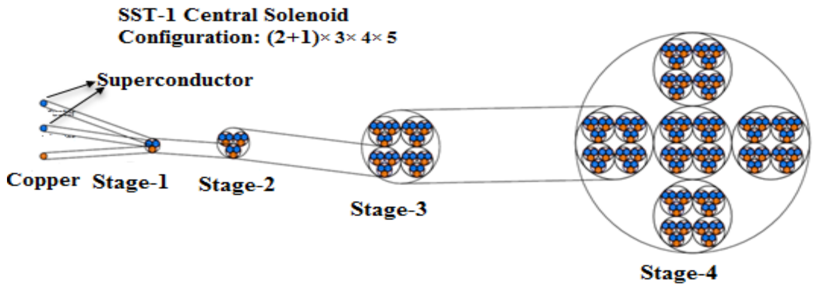

Figure 1: Configuration for SST-1 CS

The schematic of cabling for the SST-1 CS is given in Figure 1. Detail for the cabling scheme is given in Table 1.

TABLE 1: Technical specification for cabling of SST-1 CS

Stage	Cabling Configuration	Total No. of Strands	Twist Pitch (mm)
Stage-1	1 × 3	3	30

Stage-2	1×3 ×3	9	70
Stage-3	1×3 × 3×4	36	120
Stage-4	1× 3×3×4×5	180	240

Hybrid combination of Nb_3Sn superconductor and copper is twisted at different pitches in proper combination to provide mechanical support against lorentz force. As shown in Figure 1 in first stage two strand of Nb3Sn and one strand of copper is twisted at 30mm pitch. In second stage this kind of the three bunches is twisted at the 70mm pitch. In third and fourth stages 4 and 5 this kind of bunches are twisted on the 120mm and 240mm pitch respectively. Total number of the strand in each stages and twist pitch in each stages is shown in the Table 1. It is well known that the performance of Nb_3Sn superconductor is greatly affected by the mechanical strain. Strain between two strands is greatly affected by neighbouring relation between strand like Nb_3Sn-Nb_3Sn and Nb_3Sn-Copper contact performance and contact angle of two strands. 3D twisting model of superconducting cable gives the information about the neighbouring relation between the Nb_3Sn and copper and provide the position of each strand during the twisting in each stage. The twist matrix method has been used to model the twisting pattern for each stage. Transformation matrix and rotation matrix are use to model the twisting pattern of superconducting cable.

Nomenclature:

d = Diameter of single strand

pi= Twist pitch of the i^{th} stage of cable

Z= Increment in z direction

ξi= Twist starting angle of i^{th} stage

ri= Twisting radius for i^{th} stage

α = Twist angle

Xi,j= x-coordinates of the j^{th} strand in the i^{th} stage of cable

Yi,j =y-coordinates of the j^{th} strand in the i^{th} stage of cable

Zi,j= z-coordinates of the j^{th} strand in the i^{th} stage of cable

II. SIMULATION METHODOLOGY

To simulate cabling process for CICC, parametric equations are used to make a pattern. To obtain coordinates of single strand in first stage, equation of cylindrical spiral [2] is used.

$$\begin{cases} X1 = r1\cos(\theta 1 + \xi 1) \\ Y1 = r1\sin(\theta 1 + \xi 1) \\ Z1 = Z \end{cases} \qquad (1)$$

Where, $r_1 = d/\sqrt{3}, \theta = 2\pi \frac{z}{\sqrt{(2\pi r1)^2 + p_1{}^2}}$

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$r_1$can be measured using simple geometry as shown in Figure 2. In this figure, twisting radius for each stage is derived assuming ideal contact between strands and subcables for each stage. Strand has been positioned to form symmetry using their centre. Using equation 1 trajectory of single strand for first stage is generated in commercially available MATLAB software. The trajectory of single strand is shown in Figure 3(a). Coordinates of single strand in i^{th}stage of cable is obtained by multiplying the transfer matrix (eq. 2) to the $(i\text{-}1)^{th}$ stage [3]. The trajectory of single strand for further stages of cabling with required twit pitch is obtained by following similar methodology as mention earlier. Figure 3(b) – Figure 3(d) shows trajectory of single strand in stage 2, stage 3 and stage 4 respectively. In this figures, X and Y axis gives coordinates of strands at given positions. Z axis represents the length of the cable. The trajectory of single strand for each stage provides information about relative changes in its position and its bending radius. This information can be further used in the simulation for finding the bending stress at particular position in any stage of the cabling process.

$$A = \begin{bmatrix} \sqrt{(1 - sin^2\theta_i . sin^2\alpha_i)} & 0 & 0 \\ \frac{sin\,\theta_i cos\theta_i sin^2\alpha_i}{\sqrt{(1-sin^2\theta_i sin^2\alpha_i)}} & \frac{cos\alpha_i}{\sqrt{(1-sin^2\theta_i sin^2\alpha_i)}} & 0 \\ \frac{sin\theta_i cos\theta_i sin\alpha_i}{\sqrt{(1-sin^2\theta_i sin^2\alpha_i)}} & \frac{-sin\alpha_i . cos\theta_i}{\sqrt{(1-sin^2\theta_i sin^2\alpha_i)}} & cos\alpha_i \end{bmatrix} \qquad (2)$$

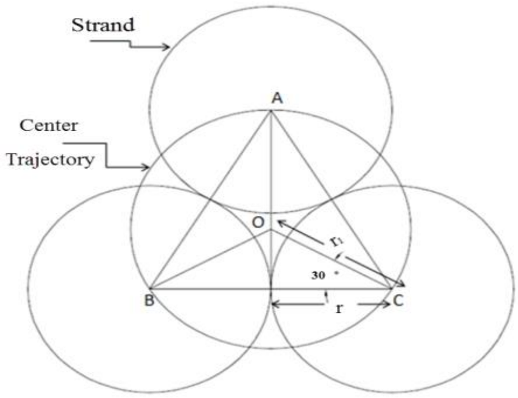
Here,

$$\theta_i = 2\pi \frac{z}{\sqrt{(2\pi r_i)^2 + p_i^2}} \quad , \alpha_i = \arctan\left(\frac{2\pi r_i}{p_i}\right)$$

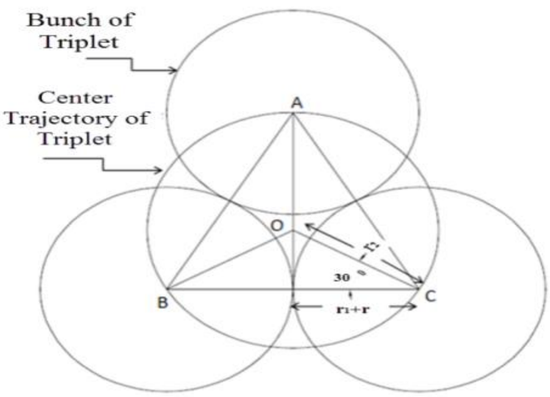
For finding the other twisting trajectory for strands in each stage the rotation matrix [4] (eq. 3) is used, which is given by.

$$B = \begin{bmatrix} cos\gamma_i & -sin\gamma_i & 0 \\ sin\gamma_i & cos\gamma_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

With application of this rotation matrix to coordinates of each single strand, trajectories of all strands in each stages is obtained for each stage. Figure 4 (a) - Figure (d) shows twisting trajectories of all strands in each stage. The position of each strands and contact between them can be easily traced in this model. Developed 3D model is capable of accommodating various twist pitch, twist radius and length as required investigating g effect of various parameters on cabling.



(a)



(b)

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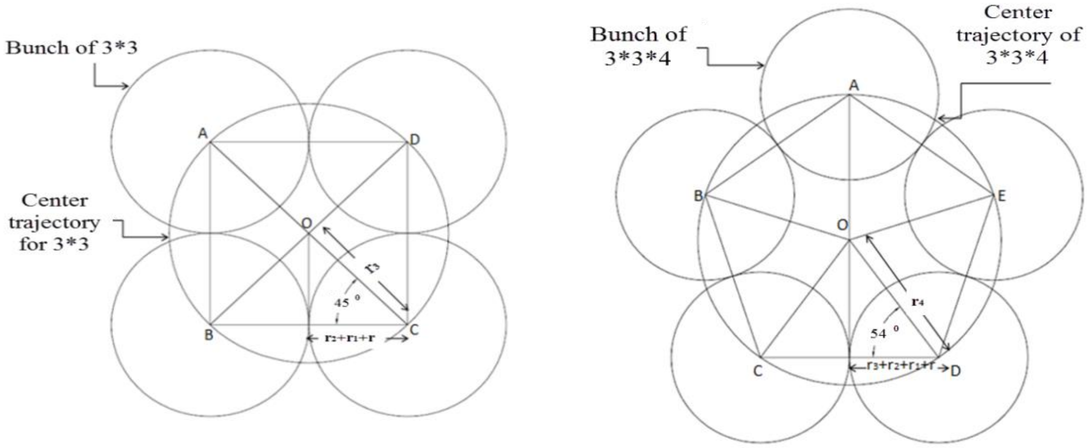
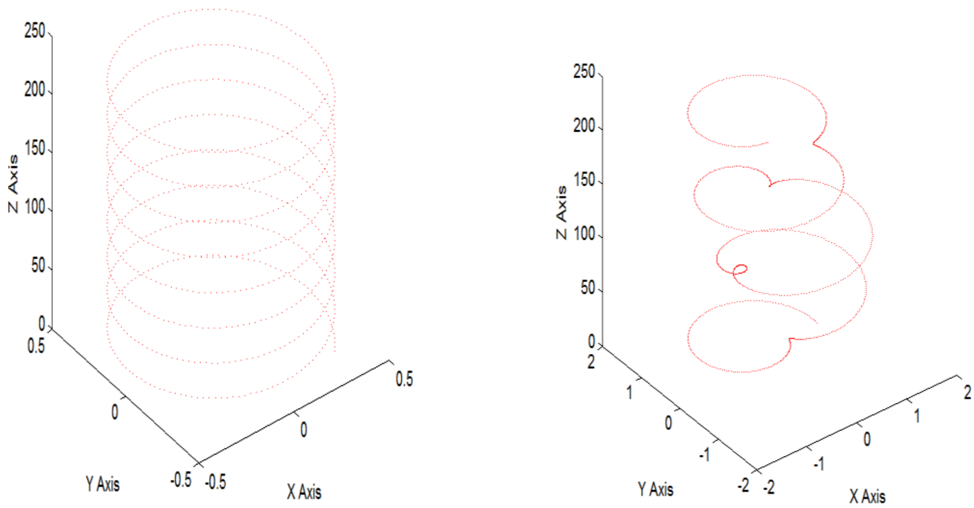
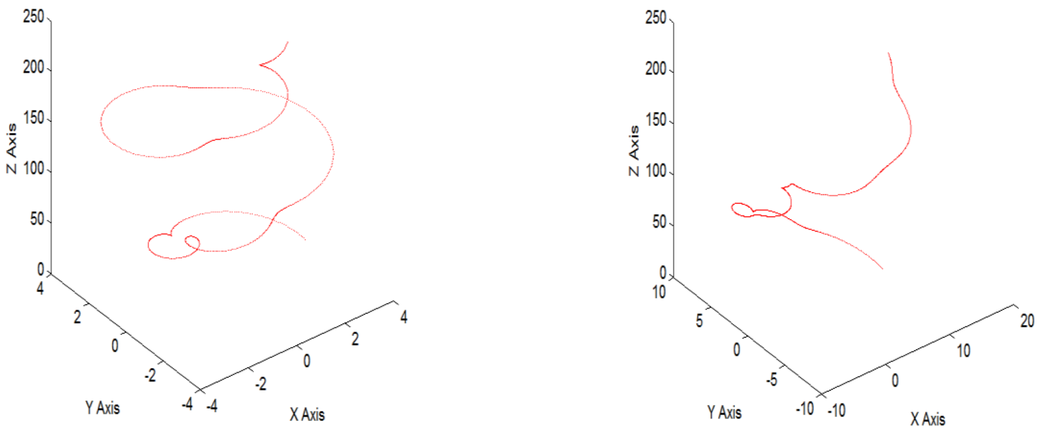


(c) (d)

Figure2: Twisting Radius calculation for (a) Stage-1 (b) Stage-2 (c) Stage-3 (d) Stage-4

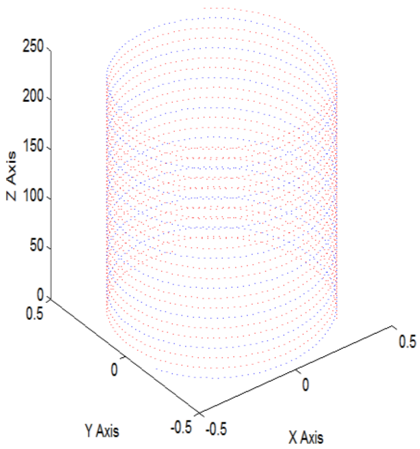


(a) (b)

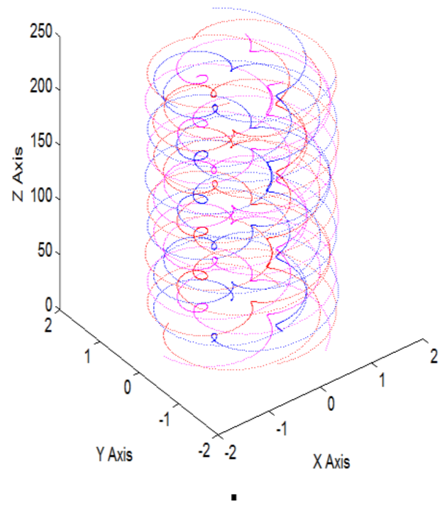


(c) (d)

Figure 3: Trajectory of single strands (a) First stage (b) Second stage (c) Third stage (d) Fourth stage (unit: mm)



(a)



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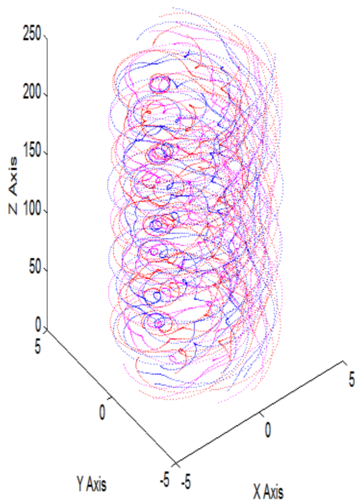
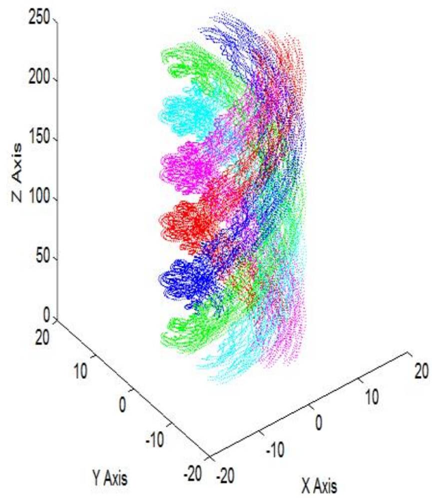


(c)



(d)

Figure 4: Twisting trajectories of all strands in (a) First stage (b) Second stage (c) Third stage (d) Fourth Stage (unit : mm

III. RESULTS AND DISCUSSION

The effect of neighbouring relation between Nb_3Sn and copper is critical to know the stress strain effect in cable for CICC. Stress strain values for the Nb_3Sn-Nb_3Sn strands and Nb_3Sn-copper strands at contact are different due to their material properties [5]. It is important to locate and estimate the contact area between strands during its cabling to investigate stress-strain state by FEM analysis. The developed model can provide the information of contact details for the superconducting cable. The precise location of the copper strand in cable of any stage can be found out using this model. Figure 5(a) – Figure 5(c) shows positions of copper strands for triplet derived from fourth stage, subcable of third stage derived from fourth stage, and cable of fourth stage respectively. Blue line in these figures shows trajectories of the copper and magenta colour shows trajectories of Nb_3Sn in the cable. Developed 3D model can also provide contact angle

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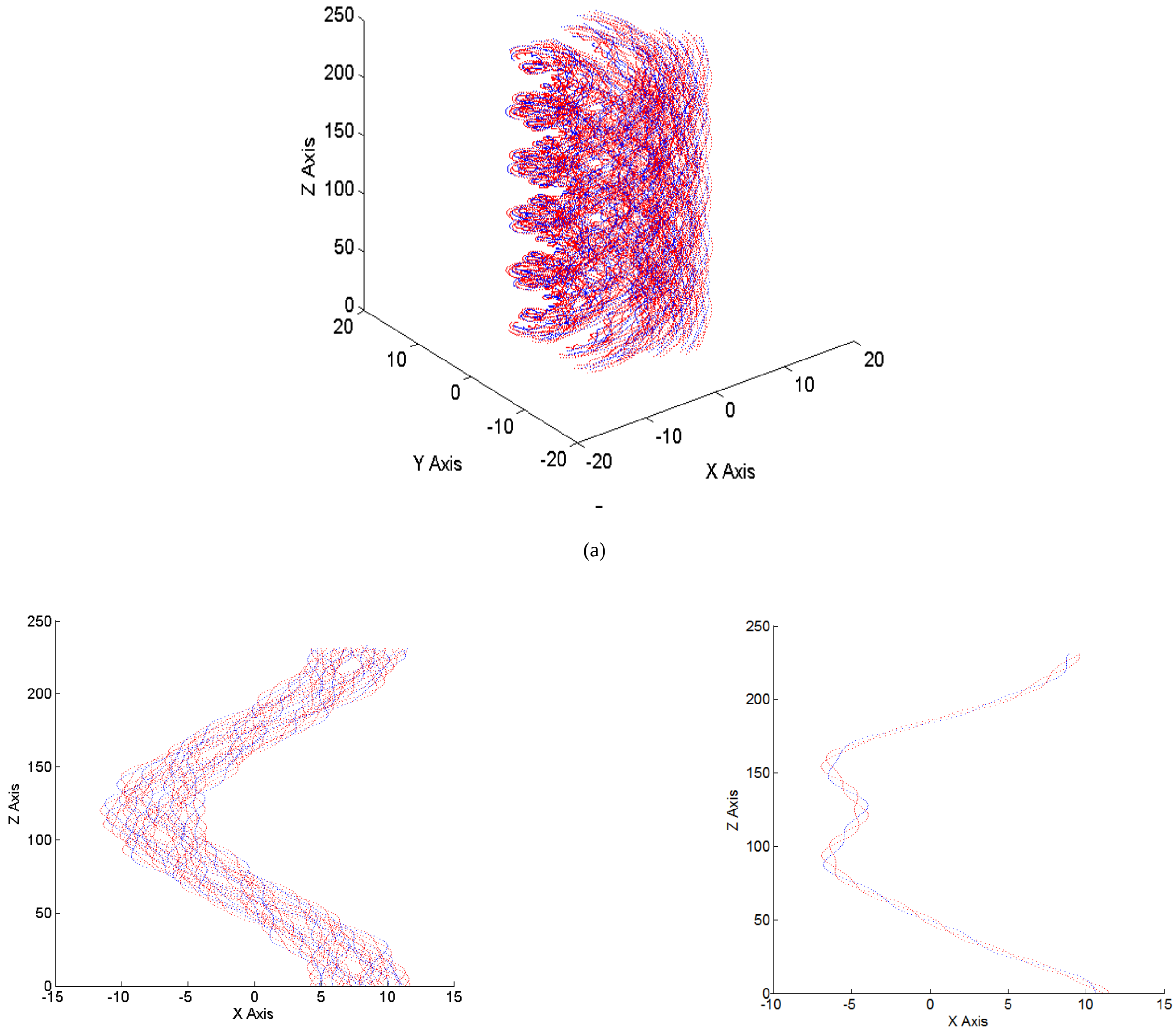
between various strands at any positions as well as effect of several of parameters on it. The twist pitch of each stage during cabling affects the contact angle of strand. An effect of pitch on contact angle is investigated by taking two cases for second stage (a) Pitch (30 mm, 70 mm) (b) Pitch (60 mm, 140 mm). It is observed that the contact angle between two strands in subcable decreases as twist pitch increases.

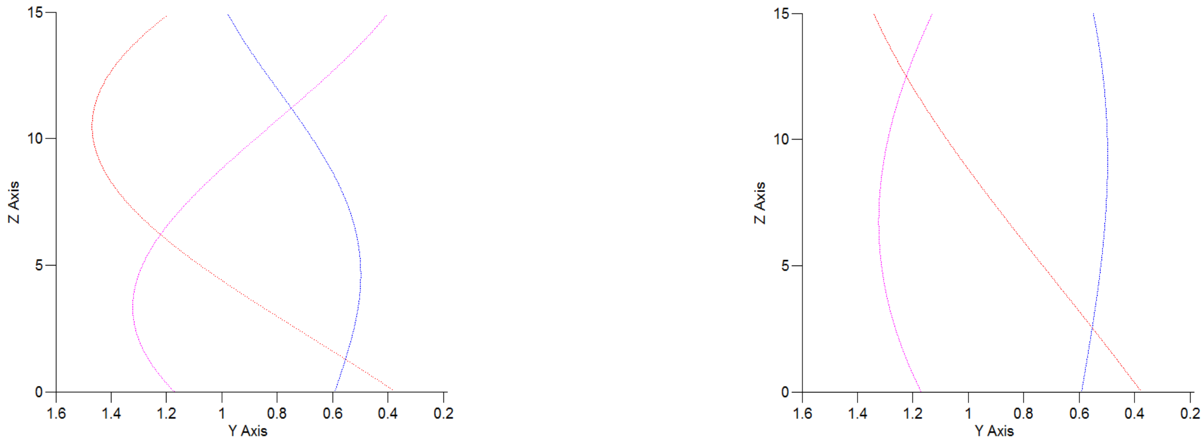


(a)

(b)

(c)

Figure 5: Positioning of copper strands in the last stage for (a) Cable from fourth stage (b) subcable from third stage (c) Triplet (unit mm)



(a) (b)

Figure 6: Effect of the twist pitch on the contact angle (unit mm) (a) Original pitch for second stage (b) Double pitch for second stage

III. CONCLUSION

3D numerical model to study and investigate the cabling pattern of Nb_3Sn CICC for CS is developed using established matrix methodology. Simulation to find trajectory of single strand in various stages cabling is completed and presented. The trajectories of all 180 strands with required twist pitch for four stages (30 mm, 70 mm, 120 mm and 240 mm respectively) of cabling process is simulated and investigated. The working space for all strands in first, second, third and fourth stages are found to be 0.47 mm, 1.49 mm, 4.04 mm, 11.74 mm respectively which is similar to the theoretical value. This model can be used to study effect of twist pitch on contact angle, contact areas and neighbouring relation between various strands in superconducting cable.

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