ATLANTIS PRESS
Advances in Engineering Research, volume 181
International Conference on Electronical, Mechanical and Materials Engineering (ICE2ME 2019)

Optimization of Spiral Shaft Parameters of Particle Type Conveyor Based on Particle Swarm Optimization

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***Abstract*—Design parameters for the helical axis are heavily dependent on empirical performance data. In this paper, Optimization of Spiral Shaft Parameters for screw conveyor based on the Particle swarm optimization (PSO) is studied. The PSO algorithm is used to solve the problem of parameter optimization under different initial conditions. Firstly, according to the orthogonal experimental method, the screw shaft finite element simulation test was carried out to obtain the maximum principal stress of the spiral blades of each group. Secondly, the numerical model of maximum principal stress and design variable were established by the numerical fitting. What's more, with the optimization goal of minimum surface stress and maximum conveying capacity, two targets are converted into single-objective optimization problem by the form of ratio. Compared with the traditional design method show that this method made the maximum principal stress decreases significantly and effectively extending its service life.**

Keywords*—screw axis; particle swarm optimization; orthogonal test; parameter optimization; finite element method

I INTRODUCTION

Spiral Conveyor was a common continuous bulk material conveying equipment [1], as an important part of food filling machine, the working performance, production efficiency and service life of the screw conveyor were mainly determined by the helical axis of its core components [2]. Because the spiral shaft blade has long been affected by the alternating stress formed by its own gravity, the torque of the transmission end and the reaction force applied to the blade by the material, the fatigue failure appears, shortens the service life of the spiral shaft and increases the cost.

The optimization of structural parameters of spiral conveyor can help to improve its service life. Jia Caobin [3] designed the "man-machine Dialogue" parameter design system, according to the filling coefficient range of different materials on the spiral diameter and rotational speed of repeated verification until the finding of a suitable screw conveyor design parameters; Wang Dongxia [4] summarized the influence of the main design parameters in the horizontal screw conveyor conveying the wheat material on the conveying process , and the mathematical model of the spiral body optimization was established with the aim of reducing the quality of the helix. The mathematical models such as Xue Feng [5] were established to demonstrate the influence of the change of spiral angle on material transportation. Jian Donglu and other [6] based on the discrete element method, the influence of particles on the performance of the conveyor in the conveying state is verified by simulation, and Duan Yi Wang [7] takes the minimum weight of the screw conveyor and the maximum driving efficiency as the optimization object, and uses genetic algorithm to optimize the multi-objective optimization, While reducing the quality of the helical shaft, the driving efficiency was improved.

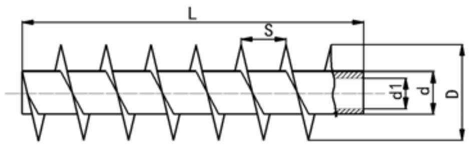
Conveying quantity was an important index to measure the production capacity of spiral conveyor [8]. By optimizing the structural parameters, the stress concentration of the spiral shaft can be improved, but it will affect the size of the conveyor, while ensuring the conveying capacity of the screw conveyor, effectively reducing the maximum principal stress, evolving into a multi-objective optimization problem, PSO was an effective means to solve the multi-objective combinatorial optimization problem [9].Kennedy and Eberhart [10] initially proposed the swarm strategy for optimization. The particle swarm optimization (PSO) algorithm was a population-based search algorithm based on the simulation of the social behavior of birds within a flock.Mortazavi, A [11]studied the weight minimization of truss structures and proposed integrated particle swarm optimizer (iPSO) as an optimization tool.The iPSO combines favorable features of the standard PSO with an efficient concept of weighted particle to improve its performance and to accomplish the simultaneous shape,size,and topology optimization.If the current angles and the detect errors were known, the solution of angle increment can be transformed to a question of optimization based on the movement analysis of three-axis tracking equipment.And the angle increment of different initial condition can be solved by particle swarm optimization [12]. Intelligent operation parameters optimization for screw conveyor based on PSO was studied by Cai, Jianghui [13] . An optimization model of screw conveyer optimal design was established with the maximum transmission efficiency as the optimizing objectives and optimization was carried out with PSO algorithm.

There was not a simple linear relationship between the optimization objective function and the variable, and in the production and processing, the two optimization objectives were often contradictory. In this paper, a parameter optimization method of spiral conveyor based on multi-objective particle swarm algorithm was proposed, and a numerical model of maximum principal stress and design variables was established by numerical fitting, and the design variables of double target were optimized by PSO with the minimum and maximum conveying capacity of the model.

This paper is organized as follows. The basic design theory is reviewed in Section II. In Section III,we describe our proposed approach. The obtained results and discussion were presented in Section IV. Finally,the conclusions is described in Section V.

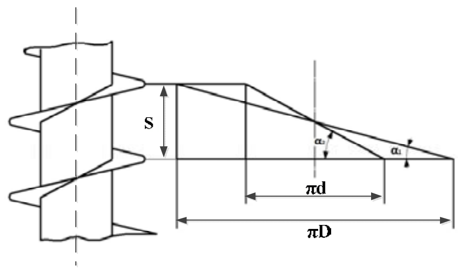
II BASIC DESIGN THEORY

The Designed spiral conveyor is a horizontal conveyor, the conveying object is granular pepper products and other mixtures, the helical shaft is the core component of the conveyor, which mainly affects the working performance of the conveyor, so it is very important to analyze the performance of the spiral shaft, and the structural parameters were the best embodiment of the helical shaft, the spiral shaft structure is shown in Figure I. The spiral blades were approximately expanded as shown in Figure II.



L-SPIRAL SHAFT LENGTH, S-PITCH, D_1-SPIRAL HOLLOW SHAFT INNER DIAMETER, D-SPIRAL HOLLOW SHAFT OUTER DIAMETER, D-SPIRAL BLADE DIAMETER

FIGURE I. SPIRAL SHAFT STRUCTURE



A_1-SPIRAL RISE ANGLE OF BLADE DIAMETER; A_2-SPIRAL ASCENDING ANGLE OF OUTER DIAMETER OF HOLLOW SHAFT

FIGURE II. SPIRAL BLADES APPROXIMATE EXPANSION

A Spiral Blade Diameter D

Refer to the non-standard mechanical equipment Design manual, according to the type of material to be transported, the structure of the spiral shaft, the layout form and the production capacity of the spiral shaft to determine the diameter of the spiral blade *D*, the calculation formula of the solid spiral blade diameter is [14]:

$$D = K \times \left[\frac{Q}{\Phi \times \lambda \times \varepsilon} \right]^{\frac{2}{5}} \tag{1}$$

Where *K* is the material characteristic parameter, *Q* is the material conveying quantity t/h;Φ is the filling coefficient, the λ is the unit volume quality of the material, and the ε is the tilt conveying coefficient.

B Spiral Hollow Shaft Outer Diameter d

The calculation formula of the outer diameter d of Spiral hollow shaft is

$$d = (0.2 \sim 0.35)D \tag{2}$$

C Spiral Hollow Shaft Inner Diameter d_1

In order to prevent torsional instability, hollow shaft wall thickness is required: $t=(d-d_1)/2 \geq 0.05$, so the range of values for d_1 was expressed as:

$$d_1 \leq d - 0.01 \tag{3}$$

D Pitch S

The calculation formula for pitch *S* is:

$$S = k_1 D \tag{4}$$

Where k_1 is the material filling coefficient. When the spiral shaft takes tilt arrangement, transports the friction material and transports the fluidity difference, generally takes the $k_1=0.8$.

E Spiral Ascending Angle α_1

According to the literature [5], the change of the spiral angle α_1 will cause the axial velocity difference due to the friction force along the radial direction of the helical blade when the material is transported. Spiral Ascending angle α_1 calculation formula is:

$$\alpha_1 = \tan^{-1}\left(\frac{S}{\pi D}\right) \tag{5}$$

F Stress Analysis of Spiral Shaft Statics

The force acting on the spiral blade and the force acting on the granular pepper mixture were equal, large and reverse. Material force analysis as shown in Figure III. *M* is the point of force of the spiral blade, *r* for the spiral blade by the distance of the stress distance axis line, m, f_1 for tangential friction, *F* for the spiral blade of the joint force, F_T for the spiral blade circumference, F_Z for the Spiral blade axial Force, N_1 as the normal direction, ρ for the dynamic friction angle.

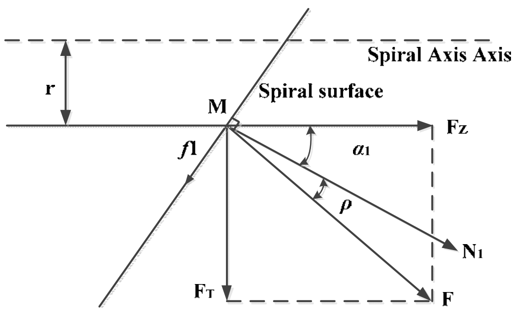


FIGURE III. MATERIAL STRESS ANALYSIS

The calculation formula of the circumferential force F_T and the axial force F_Z of the spiral blades was expressed as:

$$\begin{cases} F_T = F\sin(\alpha_1+\rho) \\ F_Z = F\cos(\alpha_1+\rho) \end{cases} \tag{6}$$

Where F is the joint force of the spiral blade, F_T is the circumference of the spiral blade, the F_Z is the axial force of the spiral Blade, and the ρ is the dynamic friction angle.

The helical shaft is driven by an end motor, and F_T can be obtained by means of a torque formula (7):

$$\begin{cases} F_T = \dfrac{T}{r} \\ T = \dfrac{9549P}{n} \end{cases} \tag{7}$$

Where T is the torque of the motor; P is the power of the motor; n is the speed of the motor.

Combination (6) and formula (7) Get formula (8):

$$\begin{cases} F_T = \dfrac{9549P}{nr} \\ F_Z = \dfrac{9549P}{nr\tan(\alpha_1+\rho)} \\ F = \sqrt{F_T{}^2 + F_Z{}^2} \end{cases} \tag{8}$$

Where R is the distance of the spiral blade from the axis line of the stress, the m; ρ is the dynamic friction angle, the F is the joint force of the spiral Blade, and the α_1 is the angle of F_Z and N_1, that is, the spiral rise angle.

The granular pepper mixture is affected by tangential friction f_1, according to the force and reaction forces, the spiral blades were also affected by such large tangential friction F_1, which can be obtained by $f_1=\mu$, $N_1=N_1\tan\rho$, $N_1=F\cos\rho$ and the calculation formula of tangential friction f_1 of spiral blades is sorted as follows:

$$f = F\sin\rho \tag{9}$$

From the formula (8), it is a key problem to distance the value of R from the axis line. The mixture flow on the transverse truncation surface of the material groove shown in Figure 4 is regarded as a continuous uniform particle system, and the total mass of the particle system is assumed to be concentrated on the particle at the centroid A, and the force on the particle is equal to the vector and after all the external forces acting on the particle system were panned to this point.

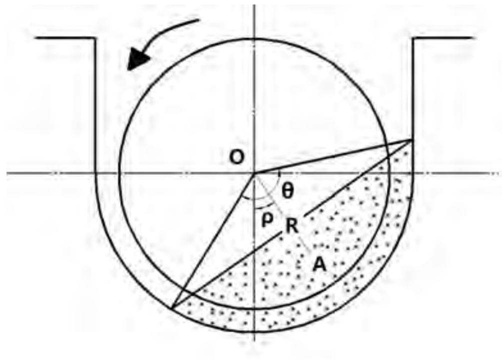


FIGURE IV. MATERIAL GROOVE TRANSVERSE TRUNCATION SURFACE

The particle system is about the symmetry of a certain radius of the spiral blade, so it is necessary to calculate the reasonable radius value on the helical blade, which is called the centroid radius, that is, the distance point O dot A is represented by R, so that the center angle corresponding to the cross section of the material is θ. According to the literature [15] to establish the equation:

$$S_b = \phi S_c \tag{10}$$

Where S_b is the cross-sectional area of the material, the m^2; Φ is the material coefficient, and the S_c is the cross-sectional area of the spiral, m^2.

$$\begin{aligned} S_b &= \frac{1}{2}\left(\frac{D}{2}\right)^2(\theta \quad \sin\theta) \\ S_c &= \pi\left(\frac{D}{2}\right)^2 \end{aligned} \tag{11}$$

The calculation formula of Circle corner θ and material coefficient Φ is deduced from formula (10) and formula (11) as:

$$\theta - \sin\theta = 2\pi\Phi \tag{12}$$

The calculation formula for centroid radius R is:

$$R = \frac{2D\sin^3\left(\frac{\theta}{2}\right)}{3(\theta - \sin\theta)} \tag{13}$$

III MATHEMATICAL MODEL ESTABLISHMENT

A. Design Variables and Constraints

The design variables were the main factors that affect the performance of the helical axis, and the main dimensions of the main stress of the blades that affect the helical axis were parameters D, S, d and d_1, so the design variables were:

$$X = [x_1, x_2, x_3, x_4] = [D, S, d, d_1] \tag{14}$$

From the literature [16] table 1 known granular material filling coefficient φ=0.3, K=0.06, conveyor tilt angle of 0°,ε=1, λ=0.4kg/m^3, the requirement of unit time material conveying Q at least to 12.09 t·h^{-1}, by the formula (1) calculation $d_{\min}$=0.38m, The conventional design standard diameter d=0.40m, in order to study the effect of D on the principal stress under non-standard, the upper limit of D is set to 0.42m. by formula (2) ~ (4) set parameter boundary limit condition: 1) $0.38 \le d \le 0.42$; 2) $0.30 \le s \le 0.34$; 3) $0.08 \le d \le 0.14$; 4) $0.01 \le d1 \le 0.05$.

B. Orthogonal Test

Orthogonal test method is a multi-factor multi-level optimization design method, which can generalize the relationship between the design variables of spiral conveying and the optimization target from the simulation analysis of fewer times. Three levels of four factor orthogonal test were designed, and the orthogonal level is shown in Table I.

TABLE I. ORTHOGONAL TEST LEVEL

Factors	Level		
	1	2	3
D/m	0.38	0.40	0.42
d/m	0.08	0.11	0.14
S/m	0.30	0.32	0.34
d_1/m	0.01	0.03	0.05

C. Numerical Fitting of Maximum Principal Stress

Known in the production of the drive motor power p=0.52kw, speed N=50r/min, granular pepper mixed material material comprehensive characteristics belong to the powder granular, so take the filling coefficient Φ=0.3, by the formula (12) calculation of the material stacking angle (that is, the material cross section corresponding to the center angle) θ=2.4908. The friction coefficient of the material and the blade f_{mo}=0.1405, by the formula (15) can be obtained ρ=8°.

$$f_{mo} = \tan\rho \tag{15}$$

The data of each group in Table I were obtained by substituting (13), and the results R, p=0.52kw and N=50r/min (8) were obtained by F_T, F_Z and F, and the ρ=8° generation (9) is obtained f_1, and 9 sets of models were established according to the parameters to import Ansys in IGES format. Workbench software for statics analysis; selected Q235 materials, using hex dominant mesh division; Adding displacement boundary conditions, adding X, Y, Z three directional displacement constraints at the beginning of the shaft, adding displacement constraints in X and Y two directions at the end of the shaft, and z direction to the axial of the helical axis ; The force boundary constraint is added, and the axial, circumferential and tangential three directional forces calculated by formula (8) and formula (9) were applied to the model, and the maximum principal stress δ in the same position concentration of 9 sets of different helical axis roots is obtained by solving the results. Figure V shows the maximum principal stress distribution cloud map for the test Group 4, and Figure VI shows the maximum principal stress distribution cloud map for the test Group 7.

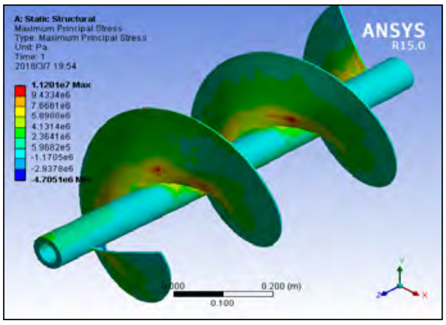


FIGURE V. MAXIMUM PRINCIPAL STRESS DISTRIBUTION CLOUD MAP FOR TEST GROUP 4

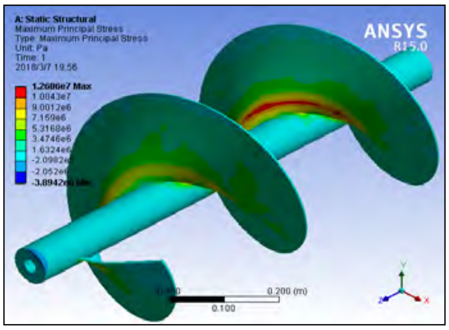


FIGURE VI. MAXIMUM PRINCIPAL STRESS DISTRIBUTION CLOUD MAP FOR TEST GROUP 7

The maximum principal stress δ of each group obtained by the conveyor Q and the simulation calculated according to Formula (16) is recorded in Table II.

$$Q = 47D^2 \cdot S \cdot n \cdot \Phi \cdot \lambda \cdot \varepsilon \tag{16}$$

The orthogonal test results were numerically fitted to establish the mathematical model expression of the design variable and the maximum principal stress δ:

$$\delta = -291.42D + 369.09D^2 - 272.58d + 849.61d^2 + 533.16S - 805.18S^2 - 81.636d_1 + 719.22d_1^2 \tag{17}$$

TABLE II. ORTHOGONAL TEST ARRANGEMENT AND RESULTS

number	D/m	d/m	S/m	d_1/m	Q/(t·h^{-1})	δ/MPa
1	0.38	0.08	0.3	0.01	12.216	13.012
2	0.38	0.11	0.32	0.03	13.031	9.1977
3	0.38	0.14	0.34	0.05	13.845	7.0411
4	0.4	0.08	0.32	0.05	14.438	11.201
5	0.4	0.11	0.34	0.01	15.341	10.163
6	0.4	0.14	0.3	0.03	13.536	6.5939
7	0.42	0.08	0.34	0.03	16.913	12.686
8	0.42	0.11	0.3	0.05	14.923	8.2818
9	0.42	0.14	0.32	0.01	15.918	8.6039

In Table II, the data of each group is used to solve the corresponding calculated value Delta, and the test value in TABLE II is compared with the calculated value Delta to verify the accuracy of the model (17), and the relative error is shown in Table III.

TABLE III. RELATIVE ERROR TABLE

Test group	Test values /MPa	Calculate values /MPa	Error rate /%
1	13.012	12.925	0.66506
2	9.1977	9.2125	0.16051
3	7.0411	6.96	1.1519
4	11.201	11.995	7.0886
5	10.163	10.234	0.69896
6	6.5939	6.6576	0.96565
7	12.686	12.736	0.39413
8	8.2818	8.2056	0.92001
9	8.6039	8.6186	0.17041

As shown in Table III, the average error of the test value δ and the calculated value δ is 1.357%, the error is small, and the illustrative (17) model has high precision.

IV Optimization of Spiral Axis Parameters Based on Particle Swarm Optimization

A Objective Function

The mathematical expressions as:

$$W_1 = \max Q[D, S] \tag{18}$$

$$W_2 = \min \delta[D, S, d, d_1] \tag{19}$$

The position parameter limit is set as follows:

$$s.t.\begin{cases} 0.38 \le D \le 0.42 \\ 0.30 \le S \le 0.34 \\ 0.08 \le d \le 0.14 \\ 0.01 \le d_1 \le 0.05 \end{cases} \tag{20}$$

Where W_1 and W_2 were the mathematical expressions of the objective function parameter optimization.

Based on the particle swarm algorithm, the two-objective optimization makes the transmission Q (18) value as large as possible, the maximum principal stress δ (Formula (19)) as small as possible, in order to facilitate the solution to convert multiple targets into single targets, single-objective model (21):

$$\max Y(D, S, d, d_1) = \frac{W_1}{W_2} \tag{21}$$

The initial population size m=500, the maximum evolutionary algebra g=100, the spatial dimension v=4, the speed limit v range is [-1,1], the inertial weight p=0.8, the self-learning factor c_1=0.5, and the group Learning Factor c_2=0.5.

B Optimization Results

The optimal value parameter is solved by PSO: D_{best}=0.4010; d_{best}=0.1733; S_{best}=0.3219;d_{1best}=0.0389. The iterative process curve of the optimal solution is shown in Figure VII.

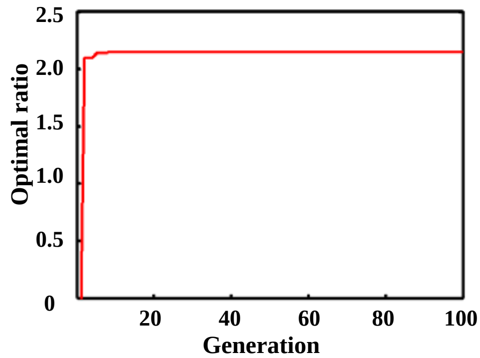


FIGURE VII. ITERATIVE PROCESS OF OPTIMAL PSO ALGORITHM

The results of particle swarm algorithm optimization were compared with those obtained by traditional and orthogonal optimization methods, and the optimization results were shown in Table IV. Table IV is a conventional design, B is orthogonal optimization, and C is particle swarm algorithm optimization.

Comparing the ratio of the data in Table IV, the ratio of Group C is the largest, which indicates that the optimization effect of particle swarm algorithm is the best. After optimizing the parameters by particle swarm algorithm algorithm, not only the conveying quantity of Group C is 1.09% and 5.4% respectively relative to group A and B, but also the maximum principal stress in the root concentration of spiral axis in group A and B decreases by 35.99% and 2.36 respectively, which greatly reduces the stress concentrated on the root.

TABLE IV. OPTIMIZATION RESULTS

Results	D/m	d/m	S/m	d_1/m	minδ/MPa	max$Q$/(t·h^{-1})	Ratio
A	0.400	0.100	0.320	0.010	10.74	14.440	1.346
B	0.380	0.140	0.340	0.050	7.040	13.850	1.967
C	0.401	0.173	0.322	0.039	6.874	14.598	2.124

V Conclusion

1) the diameter of spiral blade, the outer diameter of Spiral hollow shaft, the inner diameter of hollow shaft, pitch and helical angle were analyzed, and the statics force analysis of helical shaft is carried out.

2) based on orthogonal experiment, a numerical model of design variable and maximum principal stress is established, and the accuracy of the model is verified by contrast error.

3) based on the particle swarm algorithm, the maximum principal stress minimum and the maximum conveying capacity were the objective functions, and the target

optimization of the design parameters is carried out. The results show that, under the premise of satisfying the production requirements, the maximum principal stress at the root of the spiral shaft is reduced by 35.99% and 2.36 percent respectively compared with the conventional design and orthogonal design, which effectively improves the service life.

REFERENCE

[1] Song huan. (2016). Optimization design and simulation of the quantitative spiral conveyor. (Doctoral dissertation).

[2] Yuan-Rui, L. U. , Yao-Hong, M. A. , Shao-Hua, G. , & Zhen-Jing, Z. . (2014). Finite element analysis of spiral shaft based on fatigue discussion. Chemical Engineering & Machinery.

[3] Jia zhao-bin, & cheng heng. (2015). Research on parametric design method of screw conveyor. Mechanical design and manufacturing (4), 206-208.

[4] Wang dongxia. (2012). The study of the numerical analysis and the optimization design of the spiral conveyor. (henan university of technology).

[5] Xue Feng, Pan Jiang such as, & Muk. (2015). Discussion on the problem of spiral surface lifting angle of spiral conveying variable. Mining Machinery (8), 69-71.

[6] Jiandong Lu, Tianshu Zhao, Lizheng Zhang, et al .(2016). Simulation Research About the Influence of Particle Characteristics on Transition of Particles in the Horizontal Screw Conveyor. China Academic Conference on Printing & Packaging & Media Technology.

[7] Wang, & Yi, D. . (2013). Multi-objective optimization design of screw conveyor using genetic algorithm. Advanced Materials Research, 732-733, 402-406.

[8] Xiang dongzhi, & Xu Yuwei. (2008). The selection of screw conveyor design parameters. Modern flour Industry (5), 29-33.

[9] Xiaosong Zhao, Chia-Yu Hsu, Pei-Chann Chang, et a.l.(2016).A genetic algorithm for the multi-objective optimization of mixed-model assembly line based on the mental workload[J]. Engineering Applications of Artificial Intelligence,(47):140-160.

[10] Kennedy, J., Eberhart, R.C.: Particle Swarm Optimization. In: Proceedings of the 1995 IEEE International Conference on Neural Networks, Piscataway, New Jersey, IEEE Service Center(1995) 1942 -1948.

[11] Mortazavi, A. . (2016). Simultaneous size, shape, and topology optimization of truss structures using integrated particle swarm optimizer. Structural & Multidisciplinary Optimization,54(4), 1-22.

[12] Daxing, Z. , Jianyuan, J. , Weidong, W. , & Wei, J. . (2009). Research on Tracking Optimization Strategy of Three-Axis Tacking Equipment Based on Particle Swarm Optimization. International Conference on Intelligent Human-machine Systems & Cybernetics. IEEE.

[13] Cai, J. , & Meng, W. . (2010). A New Parameters Optimization Method for Screw Conveyor Based on PSO. International Conference on Emerging Trends in Engineering & Technology. IEEE Computer Society.

[14] Hu Zongwu, Xu Xuebing, Shi Laide (2003). Non-standard mechanical equipment Design manual. Machinery Industry Press.

[15] Kong Lingde, Ji XinPei, Wang Ying, & sang in the middle. (1996). Finite element analysis of deflection of spiral conveyor helix. Journal of Jiangsu University (Natural Science Edition) (5), 1-9.

[16] Shu Fuhua.Gui ZhongHua.(2008) Optimal design of pulp screw conveyor based on genetic algorithm. China paper, 29 (24).