Structure Design of Twin-Spirals Scroll Compressor Based on 3C

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Abstract—3C (CAD/CAM/CAE) method is put forward to optimize the structure of TSSC (twin-spirals scroll compressor) from conceptual design to finished products. The mathematical model and virtual model of TSSC are developed. A novel algorithm GA-HPSO combining with the advantages of GA (genetic algorithm), SA (simulated annealing) and PSO (particle swarm optimization) and NN (neural network) is applied to TSSC performance prediction. The swarm intelligence algorithm is used for structure optimization, and the final optimization design variables are gotten. CAE is performed to study the two key components of TSSC-orbiting and fixed scroll, which is useful for improving the quality and reliability of manufacturing and assembly accuracy at the later stages. The prototype of TSSC is manufactured based on 3C. The analysis results show that 3C method can well overcome the blindness and limitation of the traditional design. It offers a new method and idea for wide application of the scroll compressor.

Index Terms—TSSC; 3C; Optimization; Performance Prediction; Virtual prototype; GA-HPSO.

I. INTRODUCTION

In recent years, protecting environment and reducing energy consumption are becoming two big problems for the human being. In order to economize energy sources, many researchers concentrate on reducing machinery energy consumption, driving force waste and gaining better power characteristic. As a kind of new efficient positive replacement, scroll compressor has many advantages such as simple structure, high efficiency, low noise, high dependability, low vibration, light weight and small size compared with other types of compressors. It is becoming popular and widely used in refrigeration, air-conditioning, various kinds of gas compression and pressurized pump products, etc. At present with the wide application of the scroll compressor, its outstanding advantages have attracted the attention of a lot of countries. With the development of scroll compressor to bigger displacement and power, the advantages of scroll compressor employing twin-spirals, such as increasing the displacement and reducing the diameter of scroll plate, have gotten more attention recently. At the same time, it requires higher quality, more optimization structure, and better performance in shorter delivery time. However it is not easy, the key components-orbiting and fixed scroll have complex shapes. It will go through long cycle adopting traditional design method and can’t meet the fast update of the new-type scroll compressor and function demand. So 3C is applied to TSSC from conceptual design to finished products. Different advanced design and analysis methods go through the whole design process, which improves the initiative, scientificty and accuracy of design, accelerates the renewal speed of the products, improves performance, saves the cost, realizes rationalization of the design process and promotes more extensive application of the scroll compressor[1-2].

II. TSSC

Fig.1 is the structure of TSSC. It is made up of fixed scroll, orbiting scroll, frame, crankshaft, crank, rotor, main and assistant balance weight etc. The fixed and orbiting scroll are assembled at a relative angle of 180°, thus they touch at several points and form a series of crescent-shaped pockets. One of the scrolls is fixed and the other orbits around the centre of the fixed scroll. The orbiting scroll is driven by a simple short-crank throw mechanism. The pair of contact points between the two spiral walls are shifted along the spiral curves. The relative angle of the two scrolls is maintained by means of an anti-rotation coupling mechanism located between the back of the orbiting scroll and the frame. The working principle of TSSC is shown in Fig.2. The contact lines between the twin-spirals wraps are shifted along the spiral curve. The relative angle of the two scroll plates is
maintained by means of three cranks located between the orbiting scroll and frame. When the angle reached suction angle $\theta_s$, suction chamber closed. Crescent-shaped suction chamber(1) in Fig.2(a) formed. Suction chamber volume decreased when it moved to the centre with the clockwise, and thus it realized gas compression as illustrated in Fig.2 (b), (c), (d), (e) and (f). In TSSC, four suction chambers – (1), (2), (3) and (4) formed one by one every $2\pi$. Every suction chamber volume is same. Closed time interval of two adjacent chambers is $\pi/2$. There have two kinds of compression process. The one is (1) and (3) which are formed between the inner orbiting scroll wrap and the outer fixed scroll wrap. The other is (2) and (4) which are formed between the outer orbiting scroll wrap and the inner fixed scroll wrap. Four discharge chambers form one by one in every $2\pi$, and the beginning discharge time interval of two adjacent discharge chambers is $\pi/2$. The pressure change of four suction chambers is same in compression process, but phase difference of two adjacent pressure chambers is $\pi/2$. So the working process of TSSC is different from SSSC (single-spiral scroll compressor). For SSSC, two symmetry working chambers realize suction, compression and discharge at the same time. But for TSSC, four working chambers realize suction, compression and discharge one by one, so TSSC has lower discharge loss and flow pulsation compared with SSSC [3].


Fig.1. The Structure of TSSC


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(a) Chamber 1 Suction End  (b) Chamber 2 Suction End  (c) Chamber 3 Suction End

(a) Chamber 1 Suction End  (b) Chamber 2 Suction End  (c) Chamber 3 Suction End

(a) Chamber 1 Suction End  (b) Chamber 2 Suction End  (c) Chamber 3 Suction End

(f)Beginning Discharge of Chamber1  (e)Chamber1 Suction End Again  (d)Chamber4 Suction End

(f)Beginning Discharge of Chamber1  (e)Chamber1 Suction End Again  (d)Chamber4 Suction End

(f)Beginning Discharge of Chamber1  (e)Chamber1 Suction End Again  (d)Chamber4 Suction End

Fig.2. The Working Principle of TSSC

III. THE DESIGN SCHEDULE OF TSSC BASED ON 3C

The design schedule of TSSC based on 3C is shown in Fig.3. Market research of TSSC is the first step in this schedule. Project modification and analysis report is gotten through the results of market research, engineering analysis and decision-making. The data of design requirement are transferred to CAD system through interface of human and computer. In order to improve the performance of TSSC, profile optimization is very important. In order to absorb the advanced technology of other products, reverse engineering is applied to the design and development of TSSC. Digital model of scroll tooth surface can be gotten through three-coordinates measuring...
machine and applied to the present product design. CAE is used to analyse the Mises stress and deformation. The accurate stress and deformation distribution of components offers the theory foundation for the TSSC design. The compact structure is apt to produce interference which can be solved by virtual assembly, movement simulation and interference check-up. Craft plan and craft route design can be gotten directly through CAPP system. It can realize imitation processing and get processing code through the NC programming. The TSSC model strengthens the connection of design and manufacture, and improves the efficiency of product development. The CL file is transferred into the CNC machine. The prototype of TSSC is manufactured in CNC. TSSC performance is measured on testing rig. According to the analysis and simulation results the mathematical model is modified until the two results are same. The problems of long design cycle, low manufacture accuracy, great resources waste and low efficiency in traditional TSSC design are solved through application 3C method. It obtains the satisfactory results and offers a new thought and method for development of the high performance new-type scroll compressor [4].

Fig.3. The Design Schedule of TSSC Based on 3C

IV. MATHEMATICAL MODEL AND OPTIMIZATION

Fig.4 is mathematical model and optimization of TSSC. On the base of fully considering geometry structure, force, leakage, heat transfer and lubricating of TSSC, the optimization mathematical model is established including the geometry model, thermodynamics model, dynamics model, lubricating system model and loss model. GA-PSO is applied to optimize mathematical model. The nine design parameters (turn number: N, thickness: t, pitch: P, height: H, position of back pressure hole: \( \theta_b \), rotating speed: n, axial gap: \( \delta_a \), radial gap: \( \delta_r \) and oil-injected flow: \( Q_p \)) are selected as optimization variables. Objective function is specific power \( q \) [5-9].

The final optimization design variables are gotten based on the Fig.4 and Fig.5. Table I is optimization results. The results of GA-PSO are selected as final design parameters. Specific power decreased by 5 percent based on original foundation. The results indicate that GA-PSO is feasible and high-efficient.

V. PERFORMANCE PREDICTION BASED ON GA-HPSO-NN

TSSC system is a complex nonlinear system. Its performance is decided by a number of design parameters and restraint conditions. A complete model that includes all of the processes is very complicated and requires significant computer resources to get results. Sometimes we use simple linear formula to replace non-linear formula in the model. Some significant factors cannot be clearly expressed, while different working conditions also influence the performance. All of these results in prototypes performance cannot fully meet expectations. So for the TSSC system with non-linear features these factors should be considered in the performance prediction. The new optimization algorithm and NN supply a theoretical and technical basis for performance prediction of TSSC. A novel algorithm GA-HPSO-NN is used to establish performance prediction system [10-15].

The structure of NN and the corresponding training parameters are determined by the comparative analysis of various factors and the previous scholars work. In NN training, NN of 9x19x6 string-shaped structure single imply layer is adopted. Fig.6 is the structure of NN for TSSC. In order to have better generalization, the imply nodes should much smaller than the training samples. If there are too much network nodes, NN is tending to remember all the training samples. It reduces the generalization ability and needs more training time. For too few nodes, it reduces training time, at the same time generalization ability. In Fig.6, the input layer has 9 neurons, the imply layer has 19 neurons, the output layer has 6 neurons, which is established according to a test and structure growth method.
Start

Initialization of PSO

Evaluation Fitness

Calculation Pbest and Gbest

Update Speed and Position According to Standard PSO

Select, Crossover and Mutation

Max. Iterating Times or Min. Error Precision?

The final optimization results

End

Fig.4. Mathematical Model and Optimization of TSSC

Fig.5. GA-PSO Optimization Flow

Fig.6. The Structure of NN for TSSC
Input is:

\[ X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9] \]

\[ = [n, P, t, H, N, \theta, \delta, \delta', Q] \]  

(1)

Where \( x_i \sim x_9 \) are speed, pitch, teeth width, teeth height, turns, back-pressure angle, the radial clearance, the axial clearance and injection oil of TSSC respectively.

Output is:

\[ Y = [y_1, y_2, y_3, y_4, y_5, y_6] \]

\[ = [N_n, T_f, Q_r, \varepsilon, q, \eta] \]  

(2)

Where \( y_i \sim y_6 \) are input power, exhaust temperature, displacement, compression ratio, specific power and volume efficiency of TSSC respectively.

It results in implicit function from input to output:

\[ f(n, P, t, H, N, \theta, \delta, \delta', Q, x_1, \ldots, x_9) \]  

(3)

Fitness function of GA-PSO is \( F=1/E \). Output error \( E \) of NN is defined

\[ E = \frac{1}{N} \sum_{j=1}^{N} \sum_{i=1}^{C} (y_{ij} - O_{ij})^2 \]  

(4)

Where \( N \) is the number of test samples. \( y_{ij} \) is the expected output. \( O_{ij} \) is the prediction output of the network.

Fig.7 is the flow chart of GA-HPSO-NN. Fig.8 is iteration error of three kinds of algorithmics. The results show that GA-HPSO can rapidly and efficiently realize NN training. Trained NN model can fully meet TSSC design requirements.
VI. CAD/CAM

The equation of scroll profile is changeable and complex. So it is very important to set up accurate model for assembly, CAM and CAE analysis. The solid model of TSSC is obtained through the final optimization design variables. Solid model has emerged as a superb tool for component design. It is very important that solid model can be used as a powerful tool to bridge the gap between the designers and the manufacturing engineers, especially when there is added value in linking geometry to various forms of structure, finite element method, virtual manufacturing, intervening detecting and NC etc. The solid model is the key to realize CAD/CAM integration, CAD/CAM integration requires model which includes every stages messages of the whole life cycle of the product. Based on the characteristic parameter products model is a milestone development of based on geometry products model, because this kind of model focuses on intact technology of the products and production management information. It makes the design work go on higher level, and it is favorable to the improvement and innovation of the model. In the process of traditional design and manufacture, the prototype must be manufactured and tested after design finished, but some experiments are destructive. When the defect is found during experiment, the prototypes need modification and improvement, so the products reach the request performance only passing the circle process of design-experiment-design. This process is lengthiness, especially for the complex TSSC. But applied 3C method, the TSSC model is set up through virtual prototype technology. The movement of TSSC is simulated under the realistic environment. It can combine designer’s experience with the imagination in the virtual model. It lets the imagination and creativity of designer get full exertion and optimizes the whole design according to simulation results. It can reduce the cost of prototype model and shorten the research cycle of new products. After finished virtual assembly, it can get dynamic orbit, space size of components and the position of movement lock, and can also carry on dynamics interference and analysis through movement simulation. Fig.9 is model, assembly and movement analysis of TSSC. The manufacture process of TSSC is divided into simulation processing and numerical control processing. Simulation processing means that new product is manufactured in computer. The designer can get the virtual products before numerical control processing. The key components of TSSC are fixed and orbiting scroll. Because the manufacture accuracy of the scrolls must be very high and the scroll profile is complex, it must be manufactured on CNC. Using numerical control programming, cutter orbit is transferred to cutter points. According to the space geometry relation of components, jig and cutter characteristic parameters, the most suitable processing method can be gotten through analysis and comparison. It can also select entering route, cutting route and retreat route of cutter, check the probable position of interference and collision in the movement and adjust processing simulation in time. Fig.10 is manufacture simulation of scroll plate. Cutter location files are turned into NC codes through post processing programming. At present the manufacture methods of different scroll profiles have line-approximation method, curvature circle method, arc-approximation method, twin arc-approximation method, line-approximation method, curvature circle method, Archimedes curve-approximation method, etc. Different methods have different results for different type profile. According to the function characteristic and precision demand, many arc-approximation method and cross-coupling control algorithm are selected to manufacture the scroll tooth. The method can meet the processing need of different type profiles and improve processing precision of scroll profile. Finally the high accuracy manufacture is realized in the CNC machine.

VII. CAE

As the key component, the fixed and orbiting scroll should guarantee own high precision and request appropriate the axial and radial clearance. The appropriate axial clearance can be gotten through optimizing the position of back pressure hole at present. Radial clearance can be controlled by guaranteeing the crank radius and accuracy of scroll tooth. But for TSSC, the compressed gas will also produce the heat and pressure during working process which causes the deformation of the scroll tooth and influences the scroll tooth clearance. Different type profiles, different modification methods and discharge hole cause different pressure and deformation. All this will influence the working performance of TSSC. On the basis of the theories of elastic mechanics and finite element method, the analysis of temperature, the Mises stress and

TABLE I.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Original Data</th>
<th>GA</th>
<th>PSO</th>
<th>GA-PSO</th>
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<tr>
<td>$n$</td>
<td>3000</td>
<td>2691</td>
<td>3046</td>
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<td>$P$</td>
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<td>23.5</td>
<td>24.6</td>
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</tr>
<tr>
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<td>4.6</td>
<td>4.1</td>
<td>4.7</td>
<td>4.51</td>
</tr>
<tr>
<td>$H$</td>
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<td>51</td>
<td>45</td>
<td>50.4</td>
</tr>
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</tr>
<tr>
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<td>7.88</td>
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</tr>
<tr>
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<td>0.026</td>
<td>0.025</td>
</tr>
<tr>
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<td>0.031</td>
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<tr>
<td>$Q$</td>
<td>1.5</td>
<td>1.2</td>
<td>1.31</td>
<td>1.28</td>
</tr>
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</table>
deformation distribution for 3-D scroll plates are presented. The deformation and the Mises stress of scroll plates induced by non-uniform temperature distribution and subjected force are investigated. The Mises stress and deformation of scroll plates are gotten for different axial and radial gap. Fig.11 is temperature, deformation and Mises stress distribution of scroll plate. Fig.12 is axial and radial gap vs Mises stress and deformation of scrolls engaged with each other. On the basis of calculated results, the suitable gap value ($\delta_a=0.025\text{mm}$ and $\delta_r=0.03\text{mm}$) for engineering design is gotten, which provides useful data for the optimization design of scroll machine and the analysis results offer the theoretical foundation for developing the high performance TSSC [16].

Fig.9. Model, Assembly and Movement Analysis of TSSC

Fig.10. Manufacture Simulation of Scroll Plate

Fig.11. Temperature, Deformation and Mises Stress Distribution of Scroll Plate

Fig.12. Axial and Radial Gap vs Mises Stress and Deformation of Scrolls Engaged with Each Other
VIII. PROTOTYPE

Fig.13 is the TSSC prototype which is designed and developed based on 3C. Advanced 3-axis CMM is applied to the precision testing of manufactured products. According to comparing with the value of measurement points and theory points, the results give guide for the manufacture of scroll tooth. Dynamic balancing of revolution movement rotor has been accomplished using the way of "substitute mass, change speed, multi-plane and step by step balance". Experiment results show that dynamic balancing technique can greatly reduce the dynamic reverse force of bearing supporting and engine vibration. TSSC testing rig is built and TSSC performance is measured. The accuracy of the proposed 3C design methods is proved by the experiment.

IX. CONCLUSIONS

The design schedule of TSSC based on 3C is presented in this paper. CAD, CAE, optimization, and CAM etc. are applied to the design and development of TSSC from conceptual design to the end of manufacture. Parameter optimization of solid modeling, the virtual prototype manufacture, stress and deformation analysis are conducted. The application results indicate that 3C design method is beneficial to overcome the blindness and limitation of the traditional design. It can save cost, upgrade cycle, raise independent development ability and design quality. The design schedule of TSSC based on 3C offers the high efficient and practical research methods for design and improvement of TSSC. At the same time it can realize the transfer from traditional design to intelligence optimization design finally.

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