Reconstruction on Rotor Profile of Twin Screw Compressor Based on Cubic B-spline Curve

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Abstract. In order to overcome the inconvenience of adjusting the rotor profile of twin screw compressor, the method of using cubic B-spline curve to express the rotor profile is put forward. CFD simulation analysis of the rotor compressor formed by the modified cubic B-spline curve shows that the performance of the rotor profile described by the cubic B-spline curve has little difference with that of the original profile line, and the rotor profile described by cubic B-spline curve is more convenient to modify.

1. Introduction
Twin screw compressor plays an important role in many fields such as machinery, electric power, chemical industry, pharmaceutical industry, energy and military industry due to its simple structure, good power balance and high reliability [1]. Through the research on the rotor profile of twin screw compressor, the curve types of the profile mainly include arc, involute, cycloid and straight line [2]. The composition curve of rotor tooth profile is expressed by cubic B-spline curve, and the design results show that this method is feasible, which provides an idea for the design of rotor profile on twin screw compressor.

2. Rotor profile design of twin screw compressor
As the core component of twin screw compressor, the rotor is particularly important for the performance of the compressor. The design method of rotor profile adopted in this paper is to define the tooth profile of a female rotor in advance, use cubic B-spline curve to describe the female rotor profile, and then model it in 3d software, and then solve the conjugate tooth profile of the corresponding male rotor by means of three-dimensional solid modeling [3].

2.1. Design of female rotor profile
A unilateral asymmetric female rotor profile formed by a combination of straight line, arc and cycloid is shown in figure 1. This profile is modified by radial line and chamfering, and the cycloid forms a point moving inward. In addition, the arc tooth curve is extended to a certain angle to form a protection angle. Its rotor engagement line seal and continuous contact line can be better applied in production [4]. Where, AB and DE are straight lines, BC and EF are arcs, CD is cycloid and D is cycloid forming point, which constitute a complete and continuous female profile line.
2.2. Cubic B-spline curve expression of rotor profile

Cubic B-spline curve has a series of excellent properties, such as local properties, variation reduction and convexity, etc., which are conducive to realizing the control of spline curve shape, especially the local shape control of spline curve. By adjusting the control points rather than modifying data points, spline curves can be smoothed and convex preserving requirements can be achieved [5]. When using cubic B-spline to describe the tooth curve of female rotor, the basic curve segments AB, BC, CD, DE and EF are defined first. The five-segment curve is described by a complete cubic B-spline curve, and the parametric equation of cubic B-spline curve \( p(u) \) is shown as follows:

\[
p(u) = \sum_{j=0}^{n} d_j N_{j,3}(u) \quad u \in [u_i, u_{i+1}] \subseteq [u_0, u_{n+1}] \quad i = 3, 4, \ldots, n+1
\]

Where \( d_j \) is the control vertex and \( U = \{u_0, u_1, \ldots, u_n, u_{n+4}\} \) is the node vector.

Since the rotor profile line is an open curve, the fixed support condition of the endpoints of quadruple nodes is taken, and the standard definition domain is taken, so \( u_0 = u_1 = u_2 = u_3 = 0 \), and \( u_{n+1} = u_{n+2} = u_{n+3} = u_{n+4} = 1 \). A number of coordinate points of rotor profile line were selected, and the parametric method of normalizing accumulated chord length was adopted. As shown in equation (2), the data points were parameterized.

\[
\begin{align*}
\{ & u_3 = 0 \\
& u_{s+i} = u_{s+i-2} + |\Delta q_{s+i}|, i = 1, 2, \cdots, n \}
\end{align*}
\]

Where \( u \) is node vector, \( \Delta q_{s+i} = q_{s+i} - q_{s+i-2} \) is string vector, and \( q \) is coordinate point of rotor profile line.

In combination with the conditions of the initial and terminal points, the additional equation of the head and end points is given by using the tangent vector conditions. The arc length parameter is usually the tangent vector equivalent to the unit tangent vector under the parametric method of cumulative chord length, that is, the module length is set as \( p_0 = |\Delta p_0(\Delta u_0)^{-1} \), \( p_n = |\Delta p_n(\Delta u_n)^{-1} \), so that the additional equation of the initial and terminal points is shown in equation (3):

\[
\begin{align*}
\{ & p_0 = d_0 \\
& p_n = d_n \}
\end{align*}
\]

Where \( d_0 \) and \( d_n \) are given initial and terminal tangent vectors.

By successively substituting the node values in the defined domain \( u \in [u_i, u_{i+1}] \subseteq [u_3, u_{n+1}] \) into cubic B-spline equation (1), the linear equations can be obtained as shown in equation (4):

Figure 1. Composition of female rotor profile line.
The elements in the coefficient matrix are the values of the B-spline basis function, which are only related to the node values. It is more convenient to use the matrix equation as follows.

\[
\begin{bmatrix}
N_{0,3}(u_0)N_{1,3}(u_3) \\
N_{0,3}(u_1)N_{1,3}(u_3)N_{2,3}(u_3) \\
N_{0,3}(u_2)N_{1,3}(u_3)N_{2,3}(u_3)N_{3,3}(u_3) \\
N_{n-3,3}(u_3)N_{n-2,3}(u_3)N_{n-1,3}(u_3) \\
N_{n-2,3}(u_3)N_{n-1,3}(u_3)
\end{bmatrix}
\begin{bmatrix}
d_0 \\
d_1 \\
d_2 \\
d_{n-2} \\
d_{n-1}
\end{bmatrix}
= 
\begin{bmatrix}
p_{n-1} \\
p_0 \\
p_{n-3} \\
p_{n-2}
\end{bmatrix}
\]  
(4)

Tangent vector conditions for the first and end.

\[
\begin{align*}
b_i &= 1, c_i = a_i = 0, e_i = q_0 + \frac{\Delta_i}{3} q_0 \\
c_n & = a_n = 0, b_n = 1, e_n = q_{n-2} + \frac{\Delta_n}{3} q_{n-2}
\end{align*}
\]  
(7, 8)

According to equations (5), (6), (7) and (8), the control point \(d_i\) can be obtained by solving the equation with the chase method. Then, the equation and shape of cubic B-spline curve can be determined by substituting the obtained parameters into equation (4). In this paper, Matlab is used to inversely solve cubic B-spline curves, as shown in figure 2, to obtain the control points and curve equations of cubic B-spline curves of the female rotor. In the three-dimensional software SolidWorks, by using the spatial solid envelope, the profile line of the corresponding conjugate curve segment of the female rotor is obtained, that is, the profile line of the male rotor.
3. Performance analysis of rotor profile

In order to judge the performance of the rotor profile described by cubic B-spline curves, the reconstructed cubic B-spline female rotor profile data points and the calculated male rotor profile data points are imported into SolidWorks to generate the three-dimensional solid model of the rotor, as shown in figure 3. Then, the performance of the new rotor profile line is judged by CFD simulation analysis. Since the volume of the rotor teeth and the volume of the working cavity of the compressor are continuously and periodically changing, the gas in the compressor cavity is compressed and flowing, and the process is unsteady. In order to study the internal pressure distribution and fluid velocity of the compressor, Fluent software was used to establish the fluid models of the unilateral asymmetric linear rotor compressor and the new linear rotor compressor, and the dynamic numerical simulation of the internal flow field of the compressor was carried out by using the dynamic grid technology. Finally, the characteristics of flow field inside compressor are compared and analyzed.

Figure 3. Three-dimensional solid model of the rotor.

Figure 4 and figure 5 respectively show the pressure cloud diagram of the new-type profile line compressor and the unilateral asymmetric profile line compressor. By comparing the two figures, it can be found that the axial upward pressure of the female and male rotors of the new-type profile line rotor compressor and the unilateral asymmetric profile line rotor compressor has increased significantly. The air pressure at the exhaust end of the new-type profile line rotor compressor is up to 0.7989MPa, while that at the exhaust end of the prototype profile line rotor compressor is 0.809MPa. There is no significant difference between the two, indicating that the compression performance of the new profile line is little different from that of the prototype profile line in the design of the rotor profile using the cubic B-spline curve as the rotor tooth curve.
Figure 5. Pressure cloud diagram of unilateral asymmetric line compressor.

Figure 6 and figure 7 are respectively the fluid pressure cloud images of the middle section of the new-type profile line rotor compressor and unilateral asymmetric profile line rotor compressor. By comparing the two figures, it can be found that the pressure has an obvious change trend near the contact line, indicating that the sealing effect of the engagement line is good, which is consistent with the actual situation. At the same time, the gas pressure changes on both sides of the two contact lines are obvious, and the gas pressure on the low pressure side is relatively low, which indicates that when the cubic B-spline curve is used as the rotor tooth curve to design the rotor profile line, the sealing performance of the engagement line obtained is not much different from that of the prototype profile line.

Figure 6. The section pressure diagram of profile after reconstruction.

Figure 7. The section pressure diagram of unilateral asymmetric profile.

Figure 8 and figure 9 show the fluid velocity of the new-type profile line rotor and unilateral asymmetric profile line rotor compressor respectively. As there is a certain gap between the female and male rotors, the gas on the high-pressure side will leak to the low-pressure side through the gap. The maximum fluid velocity of the new linear rotor compressor is 274.3 m/s, and that of the unilateral asymmetric rotor compressor is 294.3 m/s, which indicates that the new rotor line contact line can effectively prevent fluid leakage from the high-pressure side to the low-pressure side, which is not much different from the sealing performance of the original contact line.
Figure 8. Internal velocity diagram of rotor compressor after reconstruction.

Figure 9. Internal velocity diagram of unilateral asymmetric rotor compressor.

4. Conclusions
Using cubic B-spline curve, the control point of tooth curve of female rotor is obtained, and the reverse process of cubic b-spline curve section is introduced in detail. The simulation results show that the performance of the newly designed rotor profile is little different from that of the original profile under the same parameters, and the rotor profile composed of cubic b-spline curve is more convenient to modify.

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