A Twin-Screw Rotor Profile Design Method Based on Computational Fluid Dynamics

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Abstract. Increasing demands for more efficient screw compressors design method to overcome the problems of rotor profile modification and compressor performance test establishment. A new method for the design of screw compressor shape, size and dimension is described here. As a result, NURBS curves and computational fluid dynamics (CFD) theory being applied to overcome these two problems. NURBS curves are introduced to construct a new rotor profile based on the rotor profile of unilateral asymmetric combined cycloid with pin gear arc. The numerical simulation models of the new profile and the original profile are built to find out the distribution law of pressure and velocity in twin-screw compressors under the operating speed by the means of FLUENT software. Finally, according to the simulation results, the rationality of the designed rotor profile is verified, and new schemes for further optimization are explored.

Keywords: Computational fluid dynamics, Freeform curves, Design, Rotor profile.

1 Introduction

Screw compressors are compact, efficient and reliable. Consequently, they are widely used in industrial application as well as refrigeration systems [1].

Rotor profile is the key factor of twin-screw compressor performance. There are a lot of rotor profile design methods. N. Stosic, et al. [2] proposed an optimization method for screw compressor. He Xueming, et al. [3] presented a positive and reverse design method of screw rotor profiles with freeform curves. Moreover, Yu-Ren Wu, et al. [4] proposed a method for screw compressor rotor profile design based on any arbitrary sealing line. With the development of computational fluid dynamics theory, numerical simulation is becoming increasingly widespread in the design of the screw compressor profile. Wen Jing, et al. [5] used numerical simulation technology in the design of a twin-screw kneader. Shi Wen, et al. [6] proposed an analysis model of twin-screw compressor rotor to provide a theoretical basis for profile design and optimization.

NURBS curves are the most general B-spline curves, which could be adjusted through changes of control points or modification of parametric equation weights [7].

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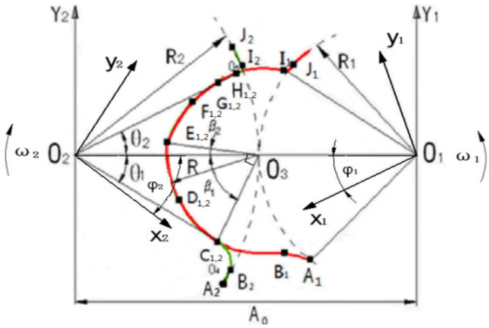
In this paper, rotor profile of unilateral asymmetric combined cycloid with pin gear arc is put as the research object to acquire a new rotor profile. The rotor profile is established by NURBS curves under the screw rotor meshing principle, and the parametric equations of rotor profiles are given. The numerical simulation method is applied to twin-screw rotor profile to improve the design efficiency. Computational fluid dynamics theory [8] is utilized in order to describe the pressure, velocity distribution of twin-screw compressor under the working speed 3000r/min.

2 Twin-Screw Compressor Design

2.1 General Coordinates System



A_0——distance between the rotor axes; O_1, O_2——rotation axis;
R_1, R_2——radii of rotor pitches; $Y_2O_2O_3$, $Y_1O_1O_3$——static coordinate systems;
O_3——intersection point; $O_2x_2y_2$, $O_1x_1y_1$——moving coordinate systems;
O_4, O_5——centers of arc B_2C_2 and H_2I_2; R——radii of arc $C_1D_1E_1$, $C_2D_2E_2$;
β_1,β_2——radians of point $C_{1,2}$ and point $E_{1,2}$; φ_1,φ_2——rotation angles;
ω_2,ω_1——rotation velocities; θ_1, θ_2——radians of point C and point H

The female and male rotor profiles are divided into 9 segments respectively, as is shown in Fig. 1. Female or male rotor profile of twin-screw compressor is predefined on each segment; while the other is deduced by the conversion relationship of the coordinate systems and meshing principles of twin-screw compressor in the process of rotor profile design. And the design or optimization operations could be made through redefining the curves in the corresponding segments of the predefined rotor profiles.

2.2 NURBS Curve

The Non-Uniform Rational B-Spline (NURBS) curves are known as the most common freeform curves. Their expressions could be written as follows:

$$P(t)=\sum_{i=0}^{n} Q_i L_{i,n}(t) \tag{1}$$

$$L_{i,n}(t) = \frac{V_i B_{i,n}(t)}{\sum_{j=0}^{n} V_j B_{j,n}(t)}$$

$$i=1,2,\ldots,nm-1 \tag{2}$$

Where Q_i represent the control points, V_i are weight factors of the parametric equation, m is the number of power, $B_{i,n}(t)$ represent rational basis functions. NURBS curves could be changed through adjusting either control points or weight factors. In this paper, NURBS curves are used to establish rotor profile to shorten profile design time as well as improving the design efficiency.

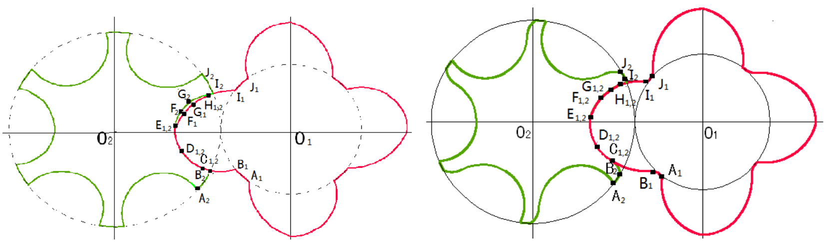
3 Design and Optimization

As is shown in Fig. 1, the female and male rotor profiles are divided into nine segments, respectively. According to the practical requirements, NURBS curves and other freeform curves are applied to the design of the female rotor profile and optimization. However, the male rotor profile is deduced from the equations of the female rotor profile. Since the freeform curves such as NURBS curves are applied to rotor profile, the twin-screw compressor rotor profile could be modified through either adjusting weight factors or control points easily.

Table 1. Comparison of the rotor profiles

Segments	Female rotor		Segments	Male rotor	
	Origin	New		Origin	New
A_2B_2	Arc	Arc	A_1B_1	Cycloid	Arc
B_2C_2	Line	Arc	B_1C_1		
C_2D_2	Arc	Arc	C_1D_1	Arc	Arc envelope
D_2E_2			D_1E_1		
E_2F_2	Cycloid	NU	E_1F_1	Cycloid	NURBS
F_2G_2		RBS	F_1G_1		curve
G_2H_2	Line	curve	G_1H_1		envelope
H_2I_2	None	Arc	H_1I_1	Line	Cycloid

The rotor profile of unilateral asymmetric combined cycloid with pin gear arc is shown in Fig.2(a). There's a long contact line and sealed volume on the profile, which results in loudly operating noise, air leakage, and low working efficiency in practical applications. As is described above, freeform curves such as NURBS curves are introduced in this paper, and the newly designed rotor profile is shown in Fig.2 (b). All the new designs are listed in Table 1.



(a) The original rotor profile (b) The new rotor profile

Fig. 2. Rotor profiles

4 Numerical Simulation

4.1 Numerical Simulation Models

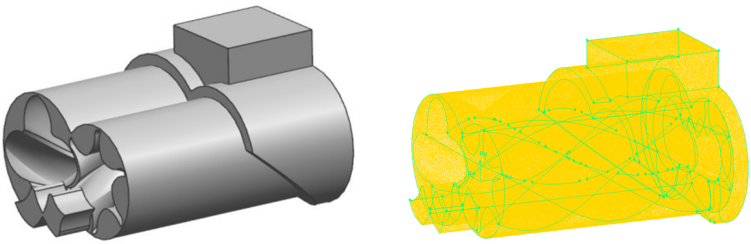
Taking into account of the specific twin-screw compressor air conditions and the airflow characteristics, the following assumptions are made: 1) The air flow is stable, isothermal, isotropic. 2) Since the Reynolds number of the air flow is large, the air flow is considered as a kind of turbulent flows. 3) Affects of inertia are ignored as well as gravity. 4) There is no effect of lubricating oil on the nature of the air flow. 5) There is no air leaking outside of the compressor in the compression process. 6) The twin-screw compressor working cycle is theoretical. Consequently, the air flow numerical model is defined as follows:

$$\mu_t = \rho C_\mu \frac{r^2}{\varepsilon} \tag{3}$$

μ_t——turbulent viscosity; ρ——gas density;

C_μ——empirical constant; r, ε——turbulent kinetic energy; turbulent dissipate rate.

If the profiles of female and male rotor spiral up about their rotation axes on the radial cross section, the corresponding screw rotor three-dimensional model could be formed. Through a Boolean operation, the twin-screw compressor flow models are established. Finally, they are classified into unstructured tetrahedral meshes by dynamic mesh methods, which is shown in Fig.3 (a) (b).

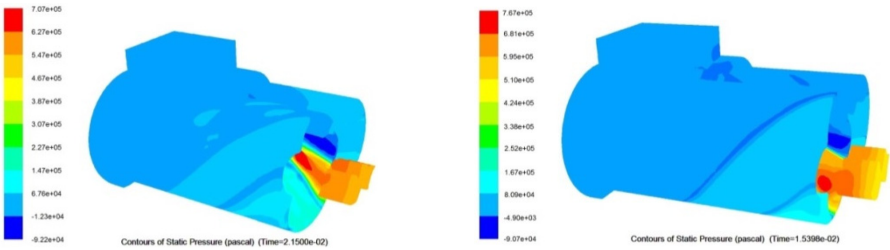


(a) Assembled model (b) Meshing generation results

Fig. 3. Three-dimensional models

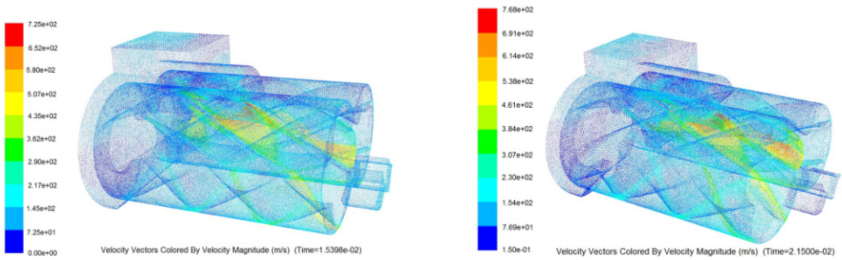
4.2 Simulation Results and Further Optimization

As is shown in Fig.4, the lowest pressure of the intake port is -0.0922MPa on the original air flow field, and the pressure of the new flow field is -0.0907MPa; the highest pressure of exhaust port is 0.707MPa on original air flow, the new one's is 0.767MPa. Based on the above results, the pressure distribution of the new designed air flow field is improved: the intake pressure increased by 1.6%, the highest exhaust pressure increased by 8.5%, and the maximum pressure difference increased by 7.3 %.



(a) The original flow field (b) The new flow field

Fig. 4. Dynamic simulation results of pressure



(a) Velocity vector of the original flow field (b) Velocity vector of the new flow field

Fig. 5. Dynamic simulation results of velocity

In Fig.5, it is easy to see that the maximum leaking velocity of the original flow is 725m/s. The maximum leaking velocity of new flow field is 768m/s, which is increased by 5.6% compared to the original flow field. The velocity of intake flow field is calculated as the displacement of the compressor. The displacement of the original compressor flow field is 15.5m3/min, and the displacement of the new compressor is 16.1m3/min, which is increased by 3.9%.

According to the dynamic simulation analysis results, the maximum differential pressure of newly designed flow is increased significantly, which indicates a certain rationality of the new rotor profile compared to the original profile. However, the leakage triangle is expanded. Moreover, the further growth in displacement of compressor is affected.

The further improvements of the new designed twin-screw compressor rotor profile are still needed. Freeform curves such as NURBS curves could be used instead of the cycloid and the arcs in segment H_1I_1. The radius of arc H_2I_2 is expanded and points $H_{1,2}$ are moved some distance towards the upper right of their original position. These optimizations could be obtained through adjusting control points or weight factors in parametric equations of curves. Then numerical models would be built to make dynamic simulation again. The rotor profile would be modified until a good performance rotor profile to be obtained based on the simulation results. Finally, a prototype of the twin-screw compressor rotor profile would be produced and a confirmatory experiment is to be made to verify performance of the rotor profile.

5 Conclusion

In this paper, the freeform curves (NURBS curves) are used to establish rotor profiles to achieve a smooth mesh of the rotors, and the modification of rotor profile could be made through adjusting the control points or weight factors of the curves. The CFD theories and freeform curves are introduced to twin-screw rotor profile design. Based on the numerical simulation results, freeform curves are applied to the design or optimization of the rotor profile until a newly good performance profile to be acquired. Through the new design method, the number of physical experiments is reduced as few as possible to achieve the superiorities of time, cost, reliability and agility.

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