doi:10.11835/j.issn.1671-8224.2016.03.02

To cite this article: CAI Ying-jie, YAO Li-gang, DU Bei-jiang. Modelling and verification of a new Roots blower profile based on analysis of performance of different leaf contour [J]. J Chongqing Univ Eng Ed [ISSN 1671-8224], 2016, 15(3): 95-102.

Modelling and verification of a new Roots blower profile based on analysis of performance of different leaf contour *

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Received 12 April 2016; received in revised form 23 May 2016

Abstract: The rotor of a Roots blower is the key component relating to its capability, so the profile design of the rotor in a Roots blower is extremely important. We focused on the modelling and verification for a novel Roots blower tooth profile based on the performance analysis. By comparing the area utilization coefficient and the ratio of several traditional rotor profiles, we proposed a new rotor profile. Then, we further accomplished the mathematical modelling of the proposed rotor profile and the computational fluid dynamics (CFD) simulation, and obtained the Roots blower outlet flow monitoring curves. Finally, we verified the characteristics by a physical experiment.

Keywords: Roots blower; mathematical modelling; rotor contours

CLC number: TH444 Document code: A

1 Introduction

The Roots blower provides higher and greater air flow than a conventional pump due to a high speed with non-contact techniques and it is commonly used in the sewage treatment, the fish and shrimp pond aeration, smelting, and the chemical industry [1]. To achieve a greater air flow for a Roots blower, the rotor profile design and characteristic analysis are essential and have attracted wide attention [2-3].

Liu et al. [4] proposed a kind of Roots blower rotor tooth profile composed of two section arcs and one envelope curve and proved that the proposed tooth profile can increase the blower efficiency. Ye et al. [5-6] analyzed the rotor tooth profile curves, and put forward a kind of rotor profile curves composed of convex arc, concave arc and cycloidal curve. By contrast, the proposed tooth profile can effectively reduce the air pressure pulsation, thereby reduce the working noise of blower. Zhang et al. [7] analyzed the involute profile of Roots blower rotor. Peng et al. [8] carried on improvement design of involute profile of Roots rotor, and put forward an improved involute profile, which led to that the area utilization coefficient reached 0.53, higher than the traditional involute, while its noise was also reduced by 2 dB to 4 dB compared to the traditional profile [6-9]. Xu et al. [10] carried out the analysis and

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* Funded by the National Natural Science Foundation of China (No. 51375013) and Fujian Provincial Research and Development Platform for Industrial Robotic Fundamental Components Technology (No. 2014H2004).
research of the Roots blower with eccentric arcs tooth profile and pointed out that the two-leaf eccentric arc rotor had higher area utilization coefficient, more consistent meshing gap, better sealing, and higher strength of the rotor. Zhou et al. [11] studied the optimal area utilization coefficient of Roots blower, and put forward a convenient method for the rotor profile design. Zhai et al. [12] and Zhou et al. [13] carried out the simulation of the internal flow field of Roots blower and summarized the change law of performance parameters and the effect of profile parameters on the exhaust volume. Mimmi et al. [14] determined the pressure loads acting on the rotors of Roots blower, starting from the geometry of the chambers that were formed during the rotor meshing and the thermodynamic transformation of the working fluid. Furthermore, they improved the model by taking into account the effects due to a closed volume chamber at the discharge. Their assumption better reproduced the real cases and allowed researchers to perform more efficient calculations and more reliable predictions [14-16]. Hsieh et al. [17] proposed a cycloid profile design based on the theory of gearing. Cai et al. [18] proposed a modified Roots profile and used 3D software to complete the Roots rotor of parametric modelling and dynamic simulation.

In summary, a good rotor profile can make Roots blower obtain larger volumetric efficiency, higher stability, better sealing performance and lower noise. Therefore, based on the analysis of the existing blower type profile, we put forward a new type of Roots blower with a three-lobe eccentric arc and cycloidal curves leaf profile [19], completed the mathematical modelling of the new profile, and carried out the analysis and calculation of fluid dynamics simulation. At last, we conducted the actual production of the new Roots blower, and carried out experiments and tests. Experiment results show that the characteristics of the blower with eccentric arcs and cycloidal curves profile are improved obviously.

2 Performance analysis and comparison

In addition to good processing performance, the ratio of diameter and center distance ($D/a$), area utilization coefficient, the meshing clearance stability, sealing performance and the working noise are important indicators of the new rotor type profile. To explain the performance of the new type profile, we analyzed and compared the main performance of three type profiles (Table 1).

2.1 Ratio of diameter and center distance

$D/a$ is an important parameter of Roots blower, which affects the volume of the air. Higher the ratio is, taller the rotor is, and bigger the volume of air is. The following is the analysis and comparison of rotors with old profiles [1].

1) The involute type

The maximum ratio of involute type can be calculated by

$$
(D/a)_{\text{max}} = 1 + \frac{\pi \cos(\arctan \frac{\pi}{2Z})}{2Z}.
$$

<table>
<thead>
<tr>
<th>Profile type</th>
<th>Center distance/mm</th>
<th>Gap between rotors/mm</th>
<th>Gap between rotor and wall/mm</th>
<th>Diameter of inlet and outlet/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Involute</td>
<td>127</td>
<td>0.2</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td>The outer convex arc and its envelope</td>
<td>127</td>
<td>0.2</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td>Arc and cycloid</td>
<td>127</td>
<td>0.2</td>
<td>0.2</td>
<td>40</td>
</tr>
</tbody>
</table>
For the three-lobe rotors $z = 3$ and $(D/a)_{\text{max}} = 1.463 \, 9$. The actual values are taken as $D/a \leq 1.463 \, 9$.

2) The outer convex arcs and its envelopes
The addendum of this profile is convex arcs, and the dedendum is arc envelopes, as shown in Fig. 1. Its maximum ratio $D/a$ can be calculated by

$$
(D/a)_{\text{max}} = \sqrt{1 + (b/r)^2} - \sqrt{3(b/r) + b/r}.
$$

(2)

![Fig. 1 The outer convex arcs and its envelopes](image1)

To avoid the envelope type profile self-intersecting (under cut), when $b/r$ takes the maximum value $^{[18]}$,

$$
-5b^2 + \sqrt{3}br + 3r^2 = 0.
$$

(3)

Deducing the formula leads to

$$
(b/r)_{\text{max}} = \frac{\sqrt{3} + \sqrt{63}}{10} = 0.966 \, 93.
$$

(4)

Putting Eq. (4) into Eq. (2) leads to

$$
(D/a)_{\text{max}} = 1.477 \, 0.
$$

(5)

3) The concave/convex arcs and cycloidal curves
Arc centers of the concave/convex arcs and cycloidal curves are all located in the pitch circle (as shown in Fig. 2). When the center distance is determined, the pitch circle is determined, and the concave/convex arcs radiiuses are also determined, so the ratio is a fixed value as

$$
D/a = \frac{r + 2r \sin 15^\circ}{r} = 1 + 2\sin 15^\circ = 1.517 \, 6.
$$

(6)

![Fig. 2 Concave/convex arcs and cycloid](image2)

From the above analysis, it can be concluded that $D/a$ of the involute profile is the smallest, and that of the concave/convex arcs and cycloidal curves is the largest.

2.2 Area utilization coefficient comparison

When the rotor rotates a circle, the area the outer circle radius sweeping is $S$ and the cross-sectional area of the rotor is $S_0$. The difference between them is $\Delta S = S - S_0$. Then we define $\lambda = \Delta S / S$ as the rotor area utilization coefficient. Obviously, when $\lambda$ is larger, the corresponding efficiency of Roots blower is higher.

$S$ can be calculated by $S = \pi R^2$. All the cross-sectional area available of various profiles is get by geometric calculation and integral, also by the CAD software. Because of the limitation of paper length, the process of solving is not given here. The utilization coefficient of area with the largest ratio of the three type profiles is shown in Table 2.
Table 2 shows that larger $D/a$ is, larger the area utilization coefficient is. The concave/convex arcs and cycloidal curves rotor has the largest ratio, and its area utilization coefficient is the largest.

To improve the rotor area utilization coefficient, the cross section area of the rotor must be reduced. By this way, the ratio $D/a$ of the rotor should be improved. Limited by the profile of rotor and the request of “gear”, the method of reducing the cross section area of the rotor would not work, so we have to improve the ratio $D/a$ only. As mentioned above, due to the traditional profile limited by its shape, the increasing ratio $D/a$ will lead to profile interference. Therefore, we must remove the constraint of the profile.

2.3 Novel eccentric arcs and cycloidal curves Roots blower profile

We kept the middle section cycloidal curves unchanged, changed the tooth addendum arc into an eccentric arc, and adjusted the dedendum arc center position properly. This would ensure “engagement” requirements, but also can improve the ratio of the profile. Due to the adoption of eccentric arcs, which made the profile interference disappear in “engagement” process of the two rotors, the traditional profile ratio restrictions were removed. Based on the 3D software simulation calculation, the model of eccentric arcs and cycloidal curves area utilization rate reached up to 0.572, and its ratio can be more than 1.59.

3 Mathematical model and CFD simulation

The model of Roots blower rotor profile (Fig. 3) is composed of an eccentric arc and cycloidal curve. The AB segment is a tooth top arc, the arc tooth matches with another dedendum, and ensures the sealing of the tooth top. The BC segment is an eccentric arc. The CD segment is a cycloidal curve. The DE segment is an arc for tooth dedendum.

![Eccentric arcs and cycloidal curves Roots blower profile](image)

For the analysis and simulation for model rotor contour profile, a plane coordinate system $(O−x,y)$ is established in Fig. 3. Fig. 4 is the meshing rotors in Roots blower. Because of its symmetry, the mathematical equations are given for only half of the profile and the equations of the new type profile are given as below.

1) Addendum arc AB

$$\begin{cases} x = r_1 \cos \alpha, \\ y = r_1 \sin \alpha + l, \end{cases} \quad \phi \leq \alpha \leq 90^\circ, \quad (7)$$

where $l$ is the center longitudinal coordinates of the addendum arc AB and $r_1$ is its radius.
2) Eccentric arc segment BC

\[
\begin{align*}
x &= r_2 \cos \beta + m, \\
y &= r_2 \sin \beta + n,
\end{align*}
\]

where \( m \) and \( n \) are the center coordinates values of the eccentric arc BC, and \( r_2 \) is the radius of arc BC.

3) Cycloidal curve CD

\[
\begin{align*}
x &= 2r \sin \gamma - r \sin(2\gamma - 30^\circ), \\
y &= 2r \cos \gamma - r \cos(2\gamma - 30^\circ),
\end{align*}
\]

where \( r \) is the radius of the pitch circle, and the range of the angle \( \gamma \) is from 0° to 30°.

4) Tooth dedendum arc DE

\[
\begin{align*}
x &= r_1 \cos \alpha + s, \\
y &= r_1 \sin \alpha + g,
\end{align*}
\]

where \( s \) and \( g \) are the coordinates values of tooth dedendum DE.

By using the FLUENT software, we carried out simulation calculation of the internal flow field of the new profile of Roots blower, modelling with 2D, selecting the RNG \( k - \varepsilon \) turbulence model and PISO algorithm, setting the environmental pressure to a standard atmospheric pressure 101 325 Pa, setting the outlet gauge pressure to 70 000 Pa (0.7 kgf/cm²), and setting the rotor speed to 1 460 r/min. Fig. 5 shows the distributions of flow velocities. As we can see from Fig. 5, the magnitudes of flow velocities distribute uniformly, meanwhile there are flow leakages through the gaps. So the actual value of the volumetric flow rate must be lower than the theoretical value.

Fig. 6 shows the monitor outlet flow rates of the simulation. The minimum flow rate is \( Q_{\text{min}} = 0.63 \text{ m}^3/\text{s} \), the maximum flow rate is \( Q_{\text{max}} = 0.80 \text{ m}^3/\text{s} \), the mean value is \( Q_{\text{mean}} = 0.715 \text{ m}^3/\text{s} \), and the pulsating flow ratio is

\[
\delta = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_{\text{mean}}} = \frac{0.80 - 0.63}{0.715} = 23.78\%.
\]

Because the default length of the rotor is \( l_0 = 1000 \text{ mm} \), and the length of the testing rotors is \( l_{\text{test}} = 164 \text{ mm} \), so the actual average flow rate is

\[
Q = \frac{Q_{\text{mean}} l_{\text{test}}}{l_0} \times 60 = \frac{0.715 \times 164}{1000} \times 60 = 7.04 \text{ m}^3/\text{min}.
\]

4 Physical verification

To verify the performance of the new type rotors, the eccentric arcs and cycloidal curves rotors are processed and tested compared with the traditional involute profile rotors. Fig. 7 shows the new type profile rotors and Fig. 8 shows the test bench.

Table 3 shows the test data on the same conditions. As shown in Table 3, in the same conditions, with the new profile, the Roots blower’s export air volume increases 15.3%, while the vibration and noise are reduced obviously, the temperature of the machine parts has a different degree of decline, only the air outlet temperature increased slightly. Compared with the original profiles profile, the new type profile rotors have an outstanding performance.

It is necessary to explain that the slip speed of the new profile rotors is 124 r/min, so the theoretical flow rate 7.04 m³/min calculated by Eq. (12) shall be corrected.
A new Roots blower profile

Fig. 5  Distributions of flow velocities

Fig. 6  Outlet flow simulation results

Fig. 7  New type profile rotors

\[ Q_t = \frac{1460 - 124}{1460} = 6.44 \text{ m}^3/\text{min}. \]  \hspace{1cm} (13)

The test volumetric flow rate is 6.03 m$^3$/min, which is less than the simulation results 6.44 m$^3$/min. The test results and simulation results are basically consistent.
Table 3  Comparison of test data where $v_1$ is the Rotor speed, $v_2$ is the slip speed, $p$ is the outlet pressure, $v_1$ is the volumetric flow rate, $A$ is the strength of the current, $V$ is voltage, $a$ is vibration, $b$ is noise, $T_1$ is the bearing temperature of drive side, $T_2$ is the bearing temperature of gear side, $T_3$ is the lubricating oil temperature, and $T_4$ is the outlet air temperature

<table>
<thead>
<tr>
<th>Type</th>
<th>$v_1$/(r/min)</th>
<th>$v_2$/(r/min)</th>
<th>$p$/Pa</th>
<th>$v_1$/(m³/min)</th>
<th>$A$/$V$</th>
<th>$a$(mm/s)</th>
<th>$b$/dBA</th>
<th>$T_1/℃$</th>
<th>$T_2/℃$</th>
<th>$T_3/℃$</th>
<th>$T_4/℃$</th>
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<tr>
<td>Ordinary</td>
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<td>157</td>
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<td>5.23</td>
<td>26.0</td>
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</tbody>
</table>

5 Conclusions

Compared with the traditional Roots blower rotors including the involute, the outer convex arc and its envelope, and the concave/convex arcs and cycloidal curves, the deficiency and limitation of the traditional profiles were pointed out. A new type profile was put forward, namely the eccentric arcs and cycloidal curves. The mathematical model of the new type profile was established, and the comprehensive performances had been simulated and tested. The simulation and experiment results show that the characteristics of the new type of Roots blower are improved obviously.

References


102