Research and optimization on stator curve for roller pump

G L Yang 1,2, a, J F Zhang 1,2, b, H S Su 1,2, c and L Q Zhang 1,2, d

1 School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, 730050, China
2 Wenzhou Academy of Pump and Valve Engineering, Lanzhou University of Technology, Wenzhou, 325105, China

E-mail: ’yanggl@lut.cn, ’z0j1f2@163.com, ’suhuashan123456@163.com, ’zhangage@163.com

Abstract. By analyzing the advantages and disadvantages of common roller pump’s stator curve (assuming that the roller on this stator curve has eliminated the void point), using curve fitting transitional method to pass the soft and hard impact point, then we can obtain a high order stator curve which has lower noise. By creating a smooth stator curve (and an inflection point with a common tangent) radial velocity mutation is eliminated. In order to avoid radial velocity mutation a symmetrical radial acceleration curve is used. In order to eliminate radial acceleration mutation, both ends of the radial acceleration change rate curve are valued zero. The results showed that due to the catastrophe point of the roller’s stator curve, improving its stator curve eliminates the void point and the soft and hard impact point of the roller on the stator transition curve. Compare the eighth-power stator curve with the improved stator curve, the improved curve also has the same superior performance. On the improved stator curve, the flow pulsation could be decreased by 241.39mL/min, with which the abrasion of the roller, the impact of the pump and the noise of the pump can be reduced.

1. Introduction

The basic function of Electric fuel pump is to suck the fuel from the fuel tank continuously, Provide fuel system with the rated pressure and the flow capacity’s fuel oil, the structure of the electric fuel pump showed in figure 1. Based on the function of electric fuel pump, it is well know that the performance of the engine is affected by the property of the electric fuel pump directly, the electric fuel pump’s core component in this paper is roller pump. In terms of roller pumps and pumps of the same type, stator curve is crucial, it can determine whether the product works normal, at the same time also affects the pump noise and service life. Through the analysis of a roller pump stator curve in a type of electric fuel pump, improve its stator curve in order to eliminate the void point and the soft/hard impact point of roller on stator transition curve, in order to achieve the purpose of reducing the impact, noise and wear [1].
2. Analysis of scanning stator curve

2.1. Determination of scanning stator curve
The stator profile of the roller pump is obtained by the three-dimensional scanner. It consists of a big radius arc AD, a small radius arc BC and two sections of symmetrical elliptic arcs AB, DC. As known in figure 2, in the composition of stator curve, the small circular radius and the big arc radius are two definite values, and usually design according to the parameters and the structure optimization of the pump, therefore, research focuses on the transition curve of the stator curve. In order to analysis the characteristics of the stator transition curve conveniently, curve equation using polar coordinates. The stator centre O to the any point P of the curve, the point P corresponding to radius vector is the function of the angle $\phi$, the angle counts from the starting point B in the radial line of the pump’s stator transitional curve, the range of angle changes from $\beta_b$ to $\beta_a$, $\beta_1 = \beta_b$, $\beta_2 = (\beta_a - \beta_b)$. The range angle of the stator transitional curve is $\beta_2$.

Establish polar coordinate plane is showed in figure 2, stator curve derived from the scanning polar equation is by follow equations (1).

$$
\rho(\phi) = \begin{cases} 
R_1 (0 \leq \phi < \frac{\pi}{2}) \\
\frac{R_1 R_2}{(R_2^2 \sin^2 \phi + R_1^2 \cos^2 \phi)^{1/2}} (\frac{\pi}{2} \leq \phi < \pi) \\
R_2 (\frac{\pi}{2} \leq \phi < \frac{3\pi}{2}) \\
\frac{R_1 R_3}{(R_3^2 \sin^2 \phi + R_1^2 \cos^2 \phi)^{1/2}} (\frac{3\pi}{2} \leq \phi \leq 2\pi)
\end{cases}
$$

2.2. The motion characteristics of the scanning stator curve
The theoretical calculation obtains the roller’s radial velocity, acceleration and rate of acceleration change on the stator curve, the equation (2), (3), (4) is showed as follow.

$$
v(\phi) = \frac{d\rho}{dt} = \frac{d\phi}{dt} \frac{d\rho}{d\phi} = \omega \frac{d\rho(\phi)}{d\phi}
$$

$$
a(\phi) = \frac{d^2\rho}{dt^2} = \frac{d^2\phi}{dt^2} \frac{d^2\rho}{d\phi^2} = \omega^2 \frac{d^2\rho(\phi)}{d\phi^2}
$$

Figure 1. The inner structure of electric fuel pump.

Figure 2. The stator curve of polar coordinates.
$$J(\phi) = \frac{d^3 \rho}{dt^3} = \frac{d^3 \phi}{dt^3} \frac{d^3 \rho}{d \phi^3} = \omega^3 \frac{d^3 \rho(\phi)}{d \phi^3}$$ \hspace{1cm} (4)$$

Where $\omega$ —— Angular velocity, $\omega = \frac{d \phi}{dt} = \text{constant}$

$v(\phi)$, $a(\phi)$, $J(\phi)$ reflect the effects on roller pump’s stator transitional curve of radial velocity and inertia forces and vibration separately [3].

The design parameters of the pump: $R_1=15\text{mm}$, $R_2=17\text{mm}$, $n=2073\text{r/min}$. The radius vector of equations (1) is substituted into equation (2), (3), (4) for the derivative. Get the scanning curve’s velocity $v$, acceleration $a$ and rate of acceleration change $J$ with the relation function of the angle $\phi$, substituting into the design parameters, plot the velocity, acceleration, acceleration change rate curves[4], as shown in figure 3,4,5.

**Figure 3.** The radial velocity $v$ of the scanning stator curve.

**Figure 4.** The acceleration $a$ of the scanning stator curve.

**Figure 5.** The rate of acceleration change $J$ of the scanning stator curve.

From the figure: at angle $\phi = \beta_b$ and $\phi = \beta_s$, in the oil adsorption area, the velocity curve exist speed mutation phenomenon, lead to a greater flow pulsation; the acceleration curve exist acceleration mutation phenomenon, lead to a greater flexible impact; the rate of acceleration change exist acceleration rate mutation phenomenon, lead to excitation effects.

3. **Improved stator curve and motion characteristic**

3.1. Improved method

(1) By making the stator curve smoothly, continuously and letting its inflection point has common tangent to eliminate radial velocity mutation;
(2) During $\varphi = \beta_b$, set $a(\beta_b) = 0$, to $\varphi = (\beta_a - \beta_b)/2$ for axis, in order to avoid radial velocity mutation use the symmetrical radial acceleration curve, eliminate radial acceleration mutation that caused from radial velocity mutation;
(3) Ensure that roller stress is good, restrict $a_{\text{max}}$, by making the both ends of the radial acceleration change rate curve for zero value to eliminate the radial acceleration change rate mutation.

3.2. Improved stator curve polar equation is by follow equations (5):

$$
\rho(\varphi) = \begin{cases} 
R_1 (0 \leq \varphi < \frac{\pi}{2}) \\
\frac{108444494}{2(R_1 + R_2)(R_1 + R_2)\sin(4\varphi) + R_1 R_2} \varphi^2 + 165515 \times \frac{(5\pi/8 - \varphi)^6}{3} - 29707 \times \varphi^2 \\
+ 12305\varphi - 151015) / 5019 (\frac{\pi}{2} \leq \varphi < \frac{3\pi}{4}) \\
\frac{108444494}{2(R_1 + R_2)(R_1 R_2 - (R_1 + R_2)\sin(4\varphi))} \varphi^2 - 165515 \times \frac{(7\pi/8 - \varphi)^6}{3} + 29707 \times \varphi^2 \\
- 156932\varphi + 391455.5) / 5019 (\frac{3\pi}{4} \leq \varphi < \pi) \\
R_2 (\pi \leq \varphi < \frac{3\pi}{2}) \\
\frac{108444494}{2(R_1 + R_2)((R_1 + R_2)\sin(4\varphi) + R_1 R_2)} \varphi^2 - 165515 \times \frac{(13\pi/8 - \varphi)^6}{3} + 29707 \times \varphi^2 \\
- 309705\varphi + 991394.2) / 5019 (\frac{3\pi}{2} \leq \varphi < \frac{7\pi}{4}) \\
\frac{108444494}{2(R_1 + R_2)(R_1 R_2 - (R_1 + R_2)\sin(4\varphi))} \varphi^2 + 165515 \times \frac{(15\pi/8 - \varphi)^6}{3} - 29707 \times \varphi^2 \\
+ 343586\varphi - 1017056.7) / 5019 (\frac{7\pi}{4} \leq \varphi < 2\pi) 
\end{cases}
$$

Similarly, the radius vector of equation s (5) is substituted into equation (2), (3), (4) for the derivative. Get the improved curve’s velocity $v$, acceleration $a$ and rate of acceleration change $J$ with the relation function of the angle $\varphi$, substituting into the design parameters, plot the velocity, acceleration, acceleration change rate curves, as shown in figure 6,7,8.

**Figure 6.** The radial velocity $v$ of the improved stator curve and the eighth-power stator curve.

**Figure 7.** The acceleration $a$ of the improved stator curve and the eighth-power stator curve.
Due to the catastrophe point of roller’s stator curve, improve its stator curve in order to eliminate the void point, the soft and hard impact point of the roller on the stator transitional curve. Compare with the eighth-power stator curve, the improved curve also has the same superior performance curves.

4. Effect of the improved curve on pump flow

4.1. The calculation of the roller pump’s theoretical instantaneous flow

The roller imposition is equal in the vane pump that the blade inclination angle uses the zero angle, so the roller pump’s instantaneous flow by follow equation (6)[5]:

\[ Q_{sh} = B \omega (R^2 - r^2) / 2 - BS(\sum V_i) \]  

(6)

Where \( Q_{sh} \) —— the roller pump’s instantaneous flow

\( R \) —— Stator long radius

\( r \) —— Stator short radius

\( B \) —— Roller width

\( \omega \) —— The rotor angular velocity

\( S \) —— Roller thickness

\( \sum V_i \) —— The sum of all the roller radial velocity in oil expulsion and oil adsorption chamber

It is observed that the roller pump instantaneous flow rate \( Q_{sh} \) comes under influence of \( \sum V_i \) from equation (6). If \( \sum V_i \) change is a constant as the rotor angular \( \varphi \) change, then the delivery rate is uniform and the flow pulsation is small, or the delivery rate is non-uniform and the flow pulsation is big.

4.2. The analysis of the roller pump’s theoretical instantaneous flow

(1)Method of calculation and analysis: in Excel software, first of all, divide the rotor into 360 sections corner by every 1°gap. Then, enter the curve polar formulas into the corresponding cells, may obtain the curve’s polar coordinate value \( \rho \). At last, calculate the radial motion velocity of each roller due to the rotor’s angular velocity \( \omega \) and the polar lift value \( \Delta \rho \), as shown in table 1. When calculating the sum of all the roller radial velocity \( \sum V_i \), it should be noted that in five rollers, two of them in oil
expulsion or oil adsorption chamber at the same time. So just calculate the sum of two rollers’ radial velocity.

**Table 1.** Angle, polar coordinate, roller radial velocity correspondence value table (improved curve).

| φ  | ρ  | V₁ | V₂ | ∑VI |
|----|----|----|----|------|
|.....|.....|.....|.....|.....|
| 96 | 15.00146681 | 11.52675423 | 70.09804897 | 81.62480319 |
| 97 | 15.00262437 | 17.50161467 | 56.56148893 | 74.0631036 |
| 98 | 15.00432217 | 24.96945403 | 44.50230361 | 69.47175764 |
|.....|.....|.....|.....|.....|

(2) Calculation and analysis results: according to the above calculation, may obtain the scanning curve, the improved curve and the eight-power curve’s numerical table, draw these three kind of curves’ flow pulsation characteristic curve, as shown in figure 9.

**Figure 9.** Three kind of curves’ flow pulsation characteristic curve.

Through above calculation and analysis, the improved curve and the eight-power curve’s flow pulsation characteristic is approximate, proving that the improved curve also has the same superior performance curves; the difference value of these three kind of curves’ instantaneous flow is: the scanning curve with 1201.12mL/min, the improved curve with 959.73mL/min and the eight-power curve with 902.84mL/min. On the improved stator curve, the roller pump’s flow pulsation could be decreased by 241.39mL/min.

5. Conclusions
(1) Due to the catastrophe point of roller’s stator curve, improve its stator curve in order to eliminate the void point, the soft and hard impact point of the roller on the stator transitional curve. Compare with the eight-power stator curve, the improved curve also has the same superior performance curves.
(2) Same with the eight-power stator curve, the improved stator curve also has least effect on the flow pulsation, \(V_{max1}=552.586\text{mm/s}, V_{max2}=552.644\text{mm/s}, \Delta Q_{\text{sh}1}=902.84\text{mL/min}, \Delta Q_{\text{sh}2}=959.73\text{mL/min}\). 
(3) On the improved stator curve, the difference value of the roller pump’s instantaneous flow is 959.73mL/min and the difference value is 1201.12mL/min before the improvement, the flow pulsation could be decreased by 241.39mL/min, with which the abrasion of the roller, the impact of the pump and the noise of the pump can be reduced.
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