An analysis of manufacturing factors’ influences on the actual screw compressor rotors' profile clearances

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Abstract. One of the most important parameters, which have high influence on screw compressor characteristics, are rotors’ profile clearances. They determine in general the smooth of the rotors' gearing and influence on the screw compressor vibration level. Analyse of actual rotor profile clearances depending on the actual rotor temperature fields and on the manufacturing imperfection was done. Specially profiled milling tools were chosen as rotor profile manufacturing tools. Following four types of the manufacturing error, which have the highest influence on the accuracy and quality of rotors’ profile surface, were chosen to analyses: the centre distance deviation between the rotor and the milling tool axises (dAi), the departure of the milling tool position from their basic plate (dZf), the milling tool mounting position angle departure (dβ) and the milling tool radii departure (dRf). The actual screw compressor profile coordinates can be obtained by taken into account all factors presented above. They determine the actual rotor profile clearances on "cold" state when screw compressor is on shutdown conditions and can be measured during a compressor assembling or a compressor stripping. However, it should be noted that they are changed depending on the screw compressor working conditions. To correctly determining actual profile clearances depending on working condition also needs to take into account rotors' thermal deformation. The presented multifaceted approach of the screw compressor actual rotor profile clearances calculation improves an accuracy compressor characteristic obtained by their mathematical model. A deep analysis of the obtained results can pointed to the rotors’ manufacturing factors, which should be improved firstly during the compressors’ mass production.

1. Introduction

At present, the rotary compressors have become more widespread in the area of small and medium-size unit capacities. The profile surfaces of rotors made with high accuracy and determining the main power characteristics of the compressor are the main working element of these compressors. The optimization of both the theoretical and actual rotor profiles is one of the major directions in the development of rotary compressors. At the same time, for this optimization, the actual operating clearances in the compressor should be known and, consequently, the actual position of the rotors' profile surfaces relative to the casing and to each other should also be known.
It has to be noted that the main method of surface preparation is milling and, therefore, it is especially important to assign tolerances to both disk mills and to their settings in the processing machine. At present, qualitative analysis of these errors influence is provided in the studies [1, 2, 3, 4]. They mainly analyze the resulting profile of rotors, but their mutual meshing is actually not analyzed. The purpose of the study is to fill this gap and justify the choice of tolerances.

2. Mathematical Description of meshing clearances

As a rule, the coordinates of the rotor actual profile are obtained by derating the coordinates of the theoretical profile or calculating based on actual milling tool profile coordinates. For the convenience of the coordinates description and subsequent use, it is rational to present their nominal values in a parametric form via the radius vector:

\[
\begin{align*}
    r_{M_n} &= r_{M_n}(X_{M_n}(t_{M_n}; \theta_1); Y_{M_n}(t_{M_n}; \theta_1); p_{M_n} \cdot \theta_1) = r_{M_n}(t_{M_n}, \theta_1), \\
r_{G_n} &= r_{G_n}(X_{G_n}(t_{G_n}; \theta_2); Y_{G_n}(t_{G_n}; \theta_2); p_{G_n} \cdot \theta_2) = r_{G_n}(t_{G_n}, \theta_2)
\end{align*}
\]

where \(X, Y\) are the profile coordinates; \(t\) – the parameter of the profile shape; \(\theta\) – the angle of the rotor rotation; \(p\) – the screw parameter; the "\(M_n\)" index and index "1" mean that the parameter refers to the male rotor; the "\(G_n\)" index and index "2" mean that the parameter refers to the free rotor. The required initial coordinates of the rotor profile for subsequent analysis are calculated on the basis of the equation [4] of the shaping by a disk mill:

\[
\begin{align*}
    X_{M_n(G_n)} &= \left(Rf_{M_n(G_n)} \cdot \cos \gamma_{M_n(G_n)} + A_{M_n(G_n)} \right) \cdot \cos \left(\theta_{(2)}\right) - \left(Zf_{M_n(G_n)} \cdot \sin \beta_{M_n(G_n)} - Rf_{M_n(G_n)} \cdot \sin \gamma_{M_n(G_n)} \cdot \cos \beta_{M_n(G_n)}\right) \cdot \sin \left(\theta_{(2)}\right) \\
    Y_{M_n(G_n)} &= -\left(Rf_{M_n(G_n)} \cdot \cos \gamma_{M_n(G_n)} + A_{M_n(G_n)} \right) \cdot \sin \left(\theta_{(2)}\right) + \left(Zf_{M_n(G_n)} \cdot \sin \beta_{M_n(G_n)} - Rf_{M_n(G_n)} \cdot \sin \gamma_{M_n(G_n)} \cdot \cos \beta_{M_n(G_n)}\right) \cdot \cos \left(\theta_{(2)}\right) \\
    \theta_{(2)} &= \frac{-Rf_{M_n(G_n)} \cdot \sin \gamma_{M_n(G_n)} \cdot \sin \beta_{M_n(G_n)} + Zf_{M_n(G_n)} \cdot \cos \beta_{M_n(G_n)}}{p_{M_n(G_n)}},
\end{align*}
\]

where \(Rf\) and \(Zf\) are the milling tool profile coordinates (Fig. 1), \(\beta\) – the angle between the milling axis and the rotor axis, \(A\) – the distance between the milling tool axis and the rotor axis, \(\gamma\) - the milling tool rotation angle around its axis.

![Figure 1. Schematic of determining the impact of major manufacturing deviations.](Image)
The free rotor position is determined by the extreme positions when the rotors contact one of the sides, or by some intermediate positions when moving to a particular extreme position. To determine the positions, it is necessary to determine the frameworks within which the free rotor can rotate till contacting the female rotor [5, 6]. Let's consider a similar approach in the example of determining the female rotor correction angle till contacting the free rotor. To do this, let's consider the position of the rotors when the male rotor is turned at an angle $\theta_1$ (Fig. 2), while the female rotor, respectively, must be nominally turned at an angle of:

$$\theta_2 = \theta_1 \frac{z_1}{z_2}$$

where $z_1, z_2$ – the number of teeth of the male and female rotors. The schematic shown in Figure 1 is given for the nominal positions of the rotor centers and does not require a fundamental change to account for their movement in the presented procedure.

**Figure 2.** Schematic of the mutual position of the screw compressor rotors in meshing.
Let us choose an arbitrary point $A$ on the section $A_1D_1$ with angular coordinate $\alpha_1$. At the front of the female rotor profile (section $A_2D_2$) rotated by an angle $\theta_1$, we find the point $B$, the radial coordinate $R_2$ of which is equal to $R_1$. The difference of the angular coordinates $\beta$ of $A$ and $B$ points gives the value of the male rotor correction angle to the touching of the female rotor profile by point $A$

$$\beta = \alpha_2 - t_{\alpha_1}. \quad (5)$$

It is worth noting that:

$$R_2 - R_1 = 0. \quad (6)$$

Thereby the radial coordinate of point $A$ is determined by the formula:

$$R_2 = f_S(t_{\alpha_1}, \theta_1), \quad (7)$$

where $S_1$ is the function describing the male rotor profile. And the dependence of point $B$ for determining the coordinates is as follows.

$$R_2 = f_S(\alpha_2, \theta_2), \quad (8)$$

where $S_2$ is the function describing the female rotor profile. By solving equations (5) – (8) together, we obtain the dependence

$$\xi^+ = f(t_{\alpha_1}, \theta_1), \quad (9)$$

The solution to these equations is found by numerical methods.

Having found the minimum of the function (9) with respect to the variable $\alpha_1$, we obtain the value of the male rotor correction angle before it touches the profile of the female rotor for the considered position:

$$\xi_{\text{min}}^+ = f(\theta_1), \quad (10)$$

For the entire range of the correction angle $\theta_1$ from dependence (10), within the limits of the contact line along the front side of the rotor tooth profile, we determine the minimum correction angle of the male rotor $\xi^+_{\text{min}}$.

Thus, when calculating the total profile clearance, the male rotor will be additionally turned at an angle $\xi^+_{\text{min}}$, emitting the contact of the rotors along the front side of the profile.

The total meshing clearance will be determined on the back side of the profiles. For this it is necessary to find the distance between the intersection points of the profiles with the straight line passing through the contact point and the meshing pole.

So for an arbitrary point $A(x_1, y_1)$ (Figure 2) chosen on the drive profile, the equation of the straight line passing through point $A$ and the meshing pole $P(x_0, y_0)$ is as follows

$$y = f_S(\alpha_1), \theta_1, \xi^+_{\text{min}}, x). \quad (11)$$

Let us find point $B(x_2, y_2)$ as an intersection of the straight line described by formula (11) with the profile of the female rotor.

For this, it is necessary to solve jointly the equations (4), (8), and (11) and determine the distance between points $A$ and $B$

$$\delta = \sqrt{(x_2 - x_1)^2 - (y_2 - y_1)^2}. \quad (12)$$

Solving equation (12), we obtain the dependence

$$\delta = f(\alpha_1, \theta_1). \quad (13)$$

The initial data for the analysis are the results of calculating the screw compressor profile by taking into account the errors in cutting the profile part of the rotors.

3. Calculation Results

For the calculations, four types of errors in the technological system were chosen, which had a significant impact on the made screw surfaces of the rotor: $dA_i$ – deviation of the distance between the
rotor axes and tool, \( dZfi \) – deviation of the tool position relative to reference plane, \( d\beta_i \) – deviation of the tool setting angle, and \( dRfi \) – deviation of the tool radius. For making the calculations, the profiles of a screw compressor with a 200 mm external diameter and SKBK [3, 5, 6, 7, 8] profile were chosen.

A typical graph of the total profile clearance variation from the male rotor rotation angle is shown in Figure 3a, and the clearance size in relation to the contact line on the male rotor surface is shown in Figure 3b.

![Figure 3](image.png)

**Figure 3.** Clearance in the meshing of rotors.

The first section \( C_1D_1 \) is determined by the cylindrical sections in the male rotor convex and female rotor tip. The clearance at this section is determined by the radial lowering of the male rotor.

After that, the dependence curve has a sharp spike of the clearance variation at the \( C_1B_1 \) section; this is explained by the fact that in the accepted method of determining the clearance, the side clearance is defined as a sum of the clearances on the front and rear faces of the rotors. A change from radial to double side lowering occurs at this section.

The clearance value at point \( B_1 \) is determined by the total side lowering. Section \( B_1A_1 \) is determined by an algorithm of the lowering of a small section of the female rotor below the initial circle. The results of calculating the impact of the position deviation and the cutting tool profile on the resulting meshing clearance are shown in Figures 4 – 7.

From the above graphs it is apparent that the influence of various technological system errors on the profile clearance change is not the same. In general, a common similarity of the influence of the technological errors of the cutting tool setting on the resulting meshing clearance, when cutting the female and male rotors of the screw compressor, should be noted. At the same time, the influence of the tool profile deviations \( dRfi \) and \( dZfi \) is significantly different for the cutting of the male and female rotor. These data should be taken into account when assigning tolerances in the technology of profile cutting with the help of profile milling cutters. Also it should be noted that due to some rotors’ manufacture errors contact between rotors occurs at the point \( A_1 \). In this case the profile clearance value dependence on the rotation angle is changed dramatically. It explains some appear steps in the diagrams (Figures 4-7)
Figure 4. Impact of the distance deviation between the rotor and tool axes $dA_i$ on the profile clearance when cutting the rotors:

a) female rotor cutting;
b) male rotor cutting

Figure 5. Impact of the tool setting angle deviation $dβ_i$ on the profile clearance when cutting the rotors:

a) female rotor cutting;
b) male rotor cutting
Figure 6. Impact of the tool profile deviation $dZ_f$ on the profile clearance when cutting the rotors:
   a) female rotor cutting;
   b) male rotor cutting

Figure 7. Impact of the tool profile deviation $dR_f$ on the profile clearance when cutting the rotors:
   a) female rotor cutting;
   b) male rotor cutting

The profile clearance in the meshing of rotors is also heavily influenced by the error in the screw compressor casing parts manufacturing, namely the error in the position of the bearing supports. For making these calculations, three types of error in the manufacture of casing parts were chosen: deviation (tolerance zone) of the center-to-center distance between the rotors $d_A$, parallel alignment of the rotor axes $\Delta X$, misalignment of the rotor axes $\Delta Y$ (Figure 2). Their effect on the meshing profile clearance for the same pair of rotors, for which the previous calculations were performed, is shown in Figures 8-9.
Figure 8. Influence of the center-to-center distance deviation between the rotors $dA$ on the profile clearance.

Figure 9. The impact of the rotor axes position deviation on the profile clearance:

a) misalignment of axes $\Delta Y$;
b) deviation of axes parallel alignment $\Delta X$

The analysis of the dependences obtained allows us to draw the following conclusions about the influence of errors in the manufacture of casing parts on the meshing profile clearance:

1. The deviation of the center-to-center distance results in a proportional even change in the profile clearance. With the maximum deviation of the center-to-center distance, the change in the profile clearance is 15%.

2. The misalignment of rotors' axes results in a change of the lateral profile clearance and does not cause a change in the radial clearance. With a maximum skew of the rotors' axes, the deviation of the profile clearance is 8%.
3. It can be seen from the graph that at a negative deviation from the parallel alignment of the rotors' axes, the change in the profile clearance is similar to the changes in the deviation of the center-to-center distance. The positive deviations in the parallel alignment of the rotors' axes results in a change of the radial clearance, but the effect on the lateral clearances is much less. The maximum clearances deviation is 23%.

4. Conclusion
The analysis of the results obtained allows to justify and optimize the assigned technological tolerances for both the rotors and the casing parts of screw compressors. The profile clearances obtained as a result of calculation, taking into account their correction with respect to the temperature deformation at the compressor operating conditions [7], can be subsequently used for mathematical simulation of the thermodynamic processes and compressor performance data. This, in turn, will allow us to estimate the design ranges of the compressor characteristics at the design stage, by taking into account not only the nominal dimensions but also the set technological tolerances for the of compressor parts dimensions.

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References
[1] Stosic N, Smith I K, Kovacevic A and Mujic E, Geometry of screw compressor rotors and their tools 2011 Journal of Zhejiang University: Science A, 12 (4), pp 310–326
[2] Sauls J, Application of Manufacturing Simulation for Screw Compressor Rotors 2000 International Compressor Engineering Conference Paper 1475
[3] Stosic N, Smith I K and Kovacevic A 2005 Screw Compressors: Mathematical Modeling and Performance Calculation (Springer Verlag, Berlin, Germany)
[4] Abdreev M M 2005 Povyishenie effektivnosti izgotovleniya rabochih poverhnostey rotorov vintovih kompressorov diskovym instrumentom (The efficiency improvement of a screw compressor rotor working surface manufacturing by cutting with milling tools) (PhD Thesis), Kazan (in Russian)
[5] Yakupov R R, Mustafin T N, Nalimov V N, Khamidullin M S and Khisameev I G 2013 Discussion of actual profile clearances’ calculation method in rotary compressors in the absence of rotor timing units 8th Int. Conf. on Compressors and their Systems (London: City University) 209
[6] Yakupov R R, Mustafin T N, Nalimov V N, Khamidullin M S and Khisameev I G 2014 Analysis of transmission error depending on compressor working conditions J of Proc. Mechanical Engineering (Proc. of the Institution of Mechanical Engineers) Part E (London: SAGE Publications)
[7] Amosov P E, Bobrikov N I, Svarc I I and Vernii A L 1977 Vintovie Kompresornie Mashinii Spravochnik (Screw Compression Machines-Handbook) (Mashinstroienie, Leningrad) (in Russian)
[8] Mustafin T N, Yakupov R R, Burmistrov A V, Khamidullin M S, Khisameev I G 2015 Analysis of the screw compressor rotors’ non-uniform thermal field effect on transmission error IOP Conf. Ser.: Mater. Sci. Eng. 90