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An innovative rotor milling method for flexible multifunctional machines

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Abstract. In this work we present an innovative method of rotor milling for flexible multifunctional machines. As an alternative to the disc cutters which are often employed in traditional milling machines, we propose a new tool, a finger cutter, which integrates easily with flexible multi-functional machines. This allows much smoother operation with lower required torque which is in line with the characteristics of flexible machines. This paper describes basic geometrical condition to generate the finger cutter profile from the rotor profile, the mathematical formulation, the basic tool design and grinding procedure of the cutter blades. It also discusses the machining process, productivity and accuracy of the proposed method. We believe that this method opens a new way of manufacturing large rotors with fewer production steps while maintaining required tolerances.

1. Introduction

Screw machines are categorised as positive displacement machines where their functionality is directly connected to the rotation of helical-shaped rotor-pairs in a casing, i.e. suction, compression/expansion and discharge processes are entirely influenced by the geometrical properties of the rotors. Therefore, high quality rotor manufacturing is essential in producing high performance and reliable screw machines. In this work we will discuss an innovative method in manufacturing process of rotors which gives an opportunity to use standard machines with fewer production steps while maintaining acceptable tolerances.

Screw machine rotors are traditionally manufactured employing specialized milling machines with disc cutters. In figure 1, we display a milling operation with this kind of machine where the cutter is rigidly supported on both sides. A disc cutter rotates around its axis which is located outside the rotor body while the cutter blade removes the material from inside of the rotor body. Principally, the whole profile is cut with the same blade (can also be divided into smaller blades). The specialized machines with disc cutter have the advantage of high productivity milling, however, they require high torque due to the large cutter diameter, usually in the same order of magnitude as the rotor diameter. This often induces high vibration and leads to the selection of a larger/stronger milling machine.

Lately, rotor manufacturers tend to employ more flexible multi-functional machines in their production line where fewer production steps is preferred. Multi-functional machines have less maximum torque and lower stability in comparison to traditional milling machines therefore tools with smaller rotating diameters can be of significant help. In this work, we will introduce such a tool, discuss the principle of tool design and argue productivity and accuracy of the proposed method.



Figure 1. Milling a screw rotor with a traditional milling machine using a rough disc cutter equipped with sectional blades (standard inserts)

2. Methodology

Considering the abovementioned shortcoming of multi-functional machines, in this work we introduce newly developed cutters so-called Finger Cutters (FC). FC rotates around its axis which is located inside the rotor body unlike the traditional disc cutter which has its axis outside the rotor body. This results in a significant reduction in the required torque and consequently lower vibration. The schematic of cutter placement inside the rotor is shown in figure 2.



Figure 2. FC rotates around its axis which is located inside the rotor body

Combining a finger cutter with a multi-functional machine, we provide a smooth milling operation where the cutter only needs to be supported from one side due to the lower applied torque and force. The finger cutter in operation is shown in figure 3.



Figure 3. A multi-functional machine using a finger cutter to cut a screw compressor rotor.

Note that an alternative to the presented method is the method of free formed surface machining [1], which has the advantage of higher flexibility and the possibility to use standard tools, but with the disadvantage of much lower productivity.

3. The principal of cutter profile design

The cutter profile is generated when the three-dimensional normal vectors of the rotor profile align with the rotational axis of the cutter as shown in figure 4.



Figure 4. The three-dimensional normal vectors of the rotor profile align with the rotational axis of the cutter

3.1. Theoretical description



Figure 5. Left: Rotor coordinate system, Right: Finger Cutter coordinate system

The mathematical description of cutter profile is fundamental in the tool design process where the goal is to transform the rotor body coordinates into tool coordinates. The complication of mathematical descriptions is often reflected in the complexity of the tool design (see for example [2]).

Here we describe the mathematics needed to design the cutter profile. It is based on the transformation between a point on the rotor profile into the corresponding point on the cutter. Let's $R_x(\alpha)$, $R_y(\alpha)$ and $R_z(\alpha)$ denote rotation matrixes, 3×3 , of angle α around the x-, y- and z-axis respectively (see figure 5). Function $\mathbf{0}: \mathbb{R} \times \mathbb{R}^3 \to \mathbb{R}^3$ describes the motion of a point on the profile depending on angle, θ , and position of that point, \mathbf{P} ,

$$\boldsymbol{O}(\theta, \boldsymbol{P}) = \boldsymbol{R}_{\boldsymbol{z}}(\theta)\boldsymbol{P} + (0, 0, l \cdot \theta) \tag{1}$$

where *l* indicates the lead (length per radian) with which the profile moves along the z-axis. Note that the profile does not have translational movement along the x and y-axis. Changing the coordinate system (x, y, x) to the coordinate system at the cutter position (x_c, y_c, z_c) , the new coordinate of the point on the profile becomes,

$$\boldsymbol{C}(\boldsymbol{P}) = \boldsymbol{R}_{\boldsymbol{\chi}}(\alpha)\boldsymbol{R}_{\boldsymbol{\gamma}}(\beta)\boldsymbol{R}_{\boldsymbol{z}}(\boldsymbol{\gamma})\boldsymbol{P} - (m_{\boldsymbol{\chi}}, m_{\boldsymbol{\gamma}}, m_{\boldsymbol{z}})$$
(2)

where the first term on the left-hand side indicates the rotation around x-, y- and z-axis of angle α , β and γ and the second term denotes the displacement vector.

Following the point on the profile along its normal, we define vector $F(\theta, s)$ as a function of angle and displacement along the normal, s,

$$F(\theta, s) = C(O(\theta, P) + R_z(\theta)\mathbf{n} \cdot s)$$
(3)

where **n** is the normal vector at the point on the profile. To find when this point hits the cutter which is oriented along y_c -axis, we solve the following non-linear system of equations where θ and s are unknown variables for any given point **P**,

$$\boldsymbol{\pi}_1 \boldsymbol{F}(\theta, s) = 0, \ \boldsymbol{\pi}_3 \boldsymbol{F}(\theta, s) = 0. \tag{4}$$

Here π_1 and π_3 are the first and third projection operators. We indicate the solution of these equations by θ^* , s^* . Next, we solve for the angle ω to rotate back the point to the $x_c y_c$ -plane of the cutter in order to get the corresponding point on the cutter profile,

$$\pi_3 R_{\nu}(\omega) F(\theta^*, 0) = 0. \tag{5}$$

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The solution of equation (5), ω^* , is then employed to compute the desired point on the cutter profile,

$$\boldsymbol{P}_{\boldsymbol{C}} = \boldsymbol{R}_{\boldsymbol{y}}(\boldsymbol{\omega}^*)\boldsymbol{F}(\boldsymbol{\theta}^*, \boldsymbol{0}). \tag{6}$$

3.2. Cutter design

The cutter profile is generated from the corresponding rotor profile. Considering that the cutter is rotational symmetric while most of the profiles are asymmetric, a minimum of two cutters is needed for milling an asymmetric profile. The left and right side of the profile generate the corresponding left and right cutter profiles. In practice however, more than two cutter profiles are needed to optimize the milling process of a certain rotor profile. In this case the cutter axis can be tilted in two directions and be moved perpendicular to the center axis of the rotor. The restriction of the setting data (tilting and movement) is governed by the requirement that the mill does not touch the side it will not process.

In particular, milling the root of the male rotor is challenging. Therefore, while the female rotor normally needs three or four cutters, the male rotor needs approximately three cutters more. In figure 6 we display the four female cutters which. The two cutters to the left are used to machine the inner part of the rotor, left and right side. The two cutters to the right are used to machine the outer part of the rotor, left and right side.



Figure 6. Finger cutters for female screw compressor rotors

When designing the cutter there are as usually compromises that need to be considered:

- The profile is normally divided into axial segments, to optimize the position of the blades, to reduce the grinding allowance.
- A higher number of segments might reduce the possible number of effective blades.
- To get as many effective blades as possible the rake angle (see 3.3) will normally become negative. This is not optimal from a cutting perspective especially with rotors of softer steel.

3.3. Grinding the blade

The cutter profile is generated to match the profile of the rotational body and the blades are normally tilted around two axes, shown in figure 7 and 8.



Figure 7. Helix angle

The helix angle is defined as shown in figure 7, a normal value for FC tool is about 20°. The reason for having a helix angle is to get a smoother cut as a result of entering the blades successively.



Figure 8. Rake angle

The rake angle is defined as shown in figure 8 and describes the angle of the cutting face relative to the work piece. The figure above shows a negative rake angle, which tends to be used for these FC, due to geometrical limitations. Normally a positive rake angle is preferable, more positive for softer materials.

To grind the blades to the rotational profile a built-in probe in the grinding machine will measure the plane of the blades and the plane will be defined mathematically, see figure 9. During the grinding cycle the cutter will be rotated to ground each point of the profile at the horizontal center plane.



Figure 9. Measuring the plane of the insert

The cutter blades also need to have clearance angles as shown in figure 10. The preliminary clearance angle (Ω) is normally 5-10° depending of the material. A harder material needs a smaller angle. To avoid back-cut a secondary clearance angle (ω) is needed, a normal value is between 10-20°.

To grind an FC from new rectangular inserts takes about two hours. To regrind or to grind from preprofiled inserts takes about 30 minutes. Finally, we note that a coated carbide blade has an expected life of 10 cutting meters.



Figure 10. The clearance angles of a cutter blade

4. Productivity and accuracy

In addition to what we discussed so far, the productivity must be evaluated with respect to the complete machining process and available machines. The method is most beneficial for small batches, for larger batches the traditional milling machines are competitive. A significant advantage of using flexible multi-functional machines is that one can manufacture components in single setup, which significantly affects both productivity and accuracy.

The FC is optimized for machining the final profile but can be used for roughing as well. Due to the cost of the FC the rotor should preferably be rough machined with standard cutters of various sizes. It is

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possible to grind the blades within ± 0.002 mm, but the accuracy of the rotor depends, among other factors, on the multi-functional machine and rotor deflection. A reasonable accuracy of the rotor profile is ± 0.015 mm regardless of the rotor size. Considering accuracy, size of the cutters and machining time, the presented method is most advantageous for larger rotors (diameter >400 mm).

5. Conclusion

In this work Finger Cutter (FC) is introduced as an innovative tool for rotor milling which can be easily integrated with multi-functional flexible machines. FCs are operating inside the rotor body with the rotational axis almost parallel to the profile surface. The small rotational diameter of FCs, compared to traditional disc cutters, gives the opportunity to employ standard machines with lower required torque. Considering the accuracy and machining time, this method is considered one of the best alternative for manufacturing large rotors (diameter > 400 mm) where smooth operation, lower vibration and acceptable tolerances are desirable simultaneously.

References

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