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Comparison Of Screw Rotor Profiles From A Manufacturing Perspective

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ABSTRACT

Two different rotor profiles are compared based on their manufacturing characteristics. The comparison is based on application of a profile manufacturing simulation which is used to analyze the effect of variability in the profile finishing. A Monte Carlo model is used to create sample outputs of the simulated manufacturing process with defined elemental process step capabilities. Rotors are compared on the basis of the difference in the number of useable profiles in a production run of 1,000 samples.

INTRODUCTION

A good rotor profile represents a balance between characteristics such as blowhole size and seal line length on the one hand and manufacturability on the other. We need the right design features for performance and noise considerations. At the same time, we must insure that the profile can be made economically and consistently to our target tolerances. In addition to a capable rotor finishing process, it is important to understand the interactions between the profile and the manufacturing process so that during the profile and tool design process, each can be rationalized to the other to provide the best rotor possible.

Some of this understanding can come from use of a computer simulation of the rotor profile finishing process. Use of this process to study the effect of extremes in the variation of selected manufacturing process parameters on rotor profile form and rotor pair clearances has been reported in /1/ and /2/. For this study, a different approach is taken. Here, we will use the simulation to look directly at the effect of random manufacturing process variations on individual profiles produced over time – the time span being represented in the study by the simulation of the manufacture of 1,000 profiles.

In this study, we will simulate the manufacture of male and female rotors of two different profile designs. The profiles are designated K and E. The E profile is an older design used in R22 compressors; the K is a third generation design for R134a compressors. The K is a derivative of the J profile which was compared to the E profile in /2/. Both profiles are defined by first specifying the shape of a generating rack, which is then used to generate the theoretical male and female rotor profiles. These profiles are then modified to produce a desired rotor pair clearance distribution.

Simulation of 1,000 samples of male and female rotors of two different designs means we will have 4,000 separate profiles to look for this study. Thus, it becomes necessary to define rotor quality measures that are simple yet meaningful. A clearance limit quality chart and a drive band location parameter are introduced in this report to serve this purpose.

The manufacturing process simulation is briefly reviewed in the next section. Profile quality assessment methods are then introduced followed by a discussion of the set-up of the Monte Carlo model of the process. Results of application of the simulation to the K and E rotors are then presented using the quality measurements proposed. The paper concludes with some closing comments about the rotors and the use of the simulation process.
PROFILE FINISHING PROCESS SIMULATION

The profile finishing process simulation has been described in /1/ and /2/ so only a brief review will be presented here. As reported in these references, the original modeling system was made up of four computer programs. These programs in the simulation system are:

a) **Rotor profile design** Theoretical profiles and profiles modified to provide for the desired rotor pair clearance distribution are computed. Profile data is written to files for use by other programs.

b) **Cutting tool design** The shape of the milling cutter or grinding wheel profile is computed from the profile data and specifications of nominal manufacturing process parameters.

c) **Profile finishing simulation** The tool form and specified values of the manufacturing process parameters are used to compute a rotor profile form. If the nominal tool form and nominal values of the process parameters are used, the result is a computation of the nominal profile defined in program a). However, if variations from the nominal process are defined, a different profile will result.

d) **Profile comparison** This is a “numerical CMM”. The profile as made in program c) is compared to the nominal defined in program a). Deviations are computed and the results stored in files for subsequent analysis.

For the analyses in /1/ and /2/, a limited number of values for selected manufacturing process parameters were evaluated and the programs c) and d) were run manually to simulate the process. For this study, 4000 separate cases are to be run, so a new program was written. This program combines the functions of the profile finishing and profile comparison steps. The program reads the cutter profile and nominal rotor profile data, then reads from a file of manufacturing process parameter specifications. This new input file has one line for each profile to be made. The values of the process parameters are read from one line at a time; the profile is made, compared to the nominal and results are written to a data file for subsequent processing. This process will make as many profiles as there are input lines in the process parameter definition file.

The methods for calculation of the rotor and tool profiles are those developed by Stošić, et al /3/. There are numerous manufacturing parameters and three have been selected for this study. The tool and rotor engaged for the profile finishing operations are illustrated in Figure 1. The cutting wheel setting angle, β, the location of the wheel on its spindle, Z, and the distance between the wheel and rotor axes, R, are the three manufacturing process parameters chosen for investigation. These are the same parameters used in the study reported at the 2000 International Compressor Engineering Conference at Purdue /2/.

Figure 1: Rotor Profile Manufacturing Setup and Parameters

The approach taken to selection of the process parameter variation is also the same as used in /2/. The K profile design is selected as the baseline. The manufacturing simulation is then used to determine the amount of variation in each of the parameters that will, alone, produce a maximum deviation of 10µm
somewhere along the profile. The values determined for the K profile male and female rotors are shown in Table 1.

Table 1
Process Variations Resulting in Maximum 10μm Profile Deviation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Angle β (°)</td>
<td>±0.029</td>
<td>±0.027</td>
</tr>
<tr>
<td>Tool Location Z (mm)</td>
<td>±0.119</td>
<td>±0.119</td>
</tr>
<tr>
<td>Center Distance R (mm)</td>
<td>±0.0100</td>
<td>±0.0100</td>
</tr>
</tbody>
</table>

For the simulation of rotor manufacturing over time, variation in each of the process parameters is assumed to follow a normal distribution. In each case, the mean value of the distribution is 0 and the standard deviation is assumed to be 1/3 of the value listed in Table 1. For the simulations, these variations are used for both the K and E profiles, so one measure for the difference in the profile design becomes the differences in the profiles’ response to these identical manufacturing process variations.

**ROTOR PROFILE QUALITY MEASUREMENTS**

When only a few rotors are being examined, it is not unusual to look at measured profiles compared to the nominal form and a tolerance band, as shown in Figure 2, where the deviations of the actual profile and the tolerance band are highly magnified. Such a plot can come from the measurement of an actual profile on a coordinate measuring machine (CMM) or from the manufacturing process simulation. This plot provides much information about the profile. However, this method of examining manufacturing results is not practical for production over long periods of time with hundreds or even thousands of rotors.

Figure 2: General Profile Form and Error Definition

In this situation, we need a few key measures to assess the response of the profile to manufacturing process variations and to compare profile designs for suitability in long term production. Two measures to accomplish this are derived based on selected profile errors as illustrated in Figures 3(a) and 3(b).

Figure 3(a): Maximum Plus-Metal ($\delta^+$) and Minus-Metal ($\delta^-$) Deviations
Figure 3(b): Round Side Contact Band ($\delta_{rs_1}$) and Outer Flank ($\delta_{rs_2}$) Deviations
Figure 3(a) shows the selection of the two extreme profile deviations, $\delta^+$ and $\delta^-$. These are the maximum deviations found anywhere around the profile in the plus- and minus-metal directions, respectively. These extreme values can, of course, be compared to the tolerance limits to determine if the profile exceeds these limits (for at least one point). As will be shown later in this section, much more information about how the profile has responded to the manufacturing process variations can be derived from these two values.

Figure 3(b) shows the selection of two additional deviations that are combined to provide information about the location of the drive band. The profile shown in the figure is the K male and the deviation marked $\delta_{rs,1}$ is located at the center of the target drive band on the round or driving side (both the K and E profiles are designed for male rotor drive). The deviation marked $\delta_{rs,2}$ is located at a point on the outer edge of a region where rotor contact could be allowed, but is undesirable. Undesirable contact can occur high on the male rotor round side when $\delta_{rs,1}$ is negative and $\delta_{rs,2}$ is positive, as shown in the illustration. In this case, the male rotor must rotate towards the female to make up for the material deficit at point $rs_1$. This causes the region around point $rs_2$ to rotate towards the female flank, and if this area is in a plus-metal state there is a further reduction in clearance. Both of these conditions add up to reduce the clearance between the male and female flanks around $rs_2$. To measure this tendency, the parameter $\delta_n = \delta_{rs,2} - \delta_{rs,1}$ is computed for all of the male rotors calculated during the manufacturing simulation.

As mentioned, the extreme profile deviations $\delta^+$ and $\delta^-$ can be used to provide more information than just the maximum deviation magnitudes. Figure 4 shows a chart – the clearance limit profile quality plot – on which we plot $\delta^-$ versus $\delta^+$. About 20 points from one of the manufacturing simulations are shown on the chart (▲ symbols). Deviations are measured in microns (µm), the scale of the axes in the chart.

The origin represents a nominal profile...maximum plus- and minus-metal deviations are equal to 0, thus all deviations are 0. The square in the center of the chart shows the 10 micron limit. Any profile with deviations $\delta^+$ and $\delta^-$ that generate a point outside of this area is out of tolerance.
The diagonal line AB represents the special case of the actual profile having exactly the same form as the nominal, but with errors in size. A point that lies on this line has $\delta^+ = \delta^-$. In other words, we have cases where the largest minus-metal deviation is actually a plus-metal state of the same magnitude as the largest plus-metal state found or, the largest plus-metal condition is actually a minus-metal state equal to the largest minus-metal condition found. In either case, this means, of course, that all deviations from one end of the profile to the other have the same sign and the same magnitude. The profile has the nominal shape, offset by the amount $\delta^+ = \delta^-$. 

If we move away from line AB in the direction of the line from the origin (point O) towards point C, we find profiles with some asymmetry, with the asymmetry increasing with distance of the point from the line AB. Points on the line OC have a balanced or “symmetrical” asymmetry. In this case, the magnitude of $\delta^-$ is the same as the magnitude of $\delta^+$ and the signs of the two are opposite.

The dotted lines aa, bb and cc are parallel to AB and represent constant levels of profile asymmetry, defined as $\delta^+ - \delta^-$. For line AB, this difference is 0. For aa, the difference is 5$\mu$m, for bb it is 10$\mu$m and for cc it is 15$\mu$m.

If we move along one of these lines and away from the line OC, the asymmetry remains the same, but the profile is seen to be biased towards either a plus- or minus-metal condition as shown in the chart. Moving along aa, bb or cc above line OC, we have $\delta^+ - \delta^- = $ constant and $|\delta^+| > |\delta^-|$. For points below line OC, $\delta^- - \delta^+ = $ constant and $|\delta^-| > |\delta^+|$. 

For points that are in the first quadrant triangle area above the X axis and below the line AB, the profile is entirely plus-metal. Likewise, for points in the third quadrant triangle area to the left of the Y axis and below the line AB, the profile is entirely minus-metal.

In the simulations run for this study, the deviations will be plotted in the clearance limit profile quality plot format. The following values will be computed for each profile made:

- $\delta^+$ and $\delta^-$ These are measures of the magnitude of the profile deviation from nominal. These values are used in the plot. $|\delta| > 10\mu$m will be considered an unacceptable profile.

- $\delta^+ - \delta^-$ This parameter measures profile asymmetry. $\delta^+ - \delta^- > 15\mu$m will be used to identify unacceptable profiles.

- $\delta_{rs}$ This parameter measures the asymmetry of the round side and when $> 0$ indicates a tendency for the drive band to move along the male rotor flank towards the rotor OD. The condition of $\delta_{rs} > 10\mu$m will be used to identify unacceptable profiles.

Charts of these parameters, counts of instances where deviations exceed the limits set, mean values and standard deviations will all be used to judge the profiles.

The next section describes the set-up of the Monte Carlo model used to simulate the manufacture of 1,000 male and 1,000 female profiles for both the K and E designs.

**MONTE CARLO SIMULATION OF PROFILE FINISHING PROCESS**

The profile finishing manufacturing process is modeled using the Monte Carlo simulation method. Mean and standard deviation values are set for each of the three process parameters that are allowed to vary for this study. Variations of the process parameters are assumed to follow a normal distribution. Definitions for the process variation distribution are defined in the PROFILE FINISHING PROCESS SIMULATION section of the paper.
To simulate the finishing of one profile form, values of each of the parameters are chosen randomly from the assumed distributions and input into the simulation. A single process parameter file is generated for male rotors for both the K and E profiles. A separate file is generated for the female rotors. This way, both of the profiles will be processed through exactly the same set of manufacturing process parameter variations.

Profile form is computed then compared to the nominal. Quality parameters are calculated and saved and the process is repeated until 1000 profiles are manufactured. This process is carried out for the male and female rotors for both the K and E profiles. Results of the simulation are discussed in the next section.

**RESULTS OF MONTE CARLO SIMULATION FOR K AND E PROFILES**

Results of the manufacturing simulation are first compared using the clearance limit quality chart shown in Figure 4. These results are shown in Figure 5 for the female rotors and in Figure 6 for the male rotors.

![Figure 5: Simulation Results for Female Rotors](image1)

![Figure 6: Simulation Results for Male Rotors](image2)
Examination of these figures provides some general information about the different rotors and profiles in their response to the manufacturing variations. We see that in every case there are a significant number of profiles with errors outside of the ±10µm tolerance. We can also see that there are no rotors that fall along the diagonal that defines the state of nominal profile form with size errors (line AB in Figure 4). This has been the experience with all manufacturing simulations carried out – it seems impossible to create a nominal profile form with the only error being one of size.

The K design has some profiles nearer the origin than we see for the E, meaning that the best profiles made for the K are slightly better than the best made for the E. However, the cloud of points for the E profile is marginally more concentrated, meaning that this design responds to the variation in manufacturing inputs with less variation in the finished product.

Quantitative analysis of the δ⁺ and δ⁻ data is collected in Table 2. Here, the maximum deviations and their difference, the asymmetry parameter, are compared. The number of profiles (#) with maximum errors exceeding the 10µm limit and with asymmetry greater that 15µm are shown. In addition, mean and standard deviation values (in µm) for the asymmetry parameter are listed.

Table 2
Rotor Quality as Measured by the Deviation Extremes δ⁺ and δ⁻

<table>
<thead>
<tr>
<th>Profile</th>
<th>Rotor</th>
<th># δ⁺ &gt; 10µm</th>
<th># δ⁻ &lt; -10µm</th>
<th># &gt; 15µm</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Total out of Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Male</td>
<td>47</td>
<td>49</td>
<td>46</td>
<td>7.6</td>
<td>3.8</td>
<td>110</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Male</td>
<td>43</td>
<td>40</td>
<td>27</td>
<td>7.1</td>
<td>3.4</td>
<td>89</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td>40</td>
<td>31</td>
<td>19</td>
<td>7.3</td>
<td>3.1</td>
<td>77</td>
</tr>
</tbody>
</table>

The data in Table 2 supports the general observations of the results plotted in Figures 5 and 6. The total number of rotors that exceed the limits set for maximum deviation and asymmetry is greater by just more than 2% of total rotors made for the K profile than for the E. The total is not the sum of the three individual tests since many rotors fail on the extreme and asymmetry tests at the same time. There is only one rotor made, a K profile male, that failed on both δ⁺ and δ⁻ at the same time. When compared on the extreme tests only, the E profile male and female fail 1.3% and 0.9% fewer rotors than for the K. However, on the asymmetry test, the E failure rate is 1.9% and 2.7% (male and female, respectively) lower than for the K. The mean and standard deviation for the E rotors are less than for the K, again indicating marginally better E profiles are made from this process than are produced for the K profile.

Results of comparisons of the male rotor round side deviation, δₘ, are given in Table 3. A count of the number of rotors where δₘ exceeds the limit of 10µm, the maximum value found in the batch of 1,000 rotors and the mean and standard distributions (in µm) are tabulated.

Table 3
Rotor Quality as Measured by the Round Side Asymmetry Parameter δₘ

<table>
<thead>
<tr>
<th>Profile</th>
<th>Rotor</th>
<th># &gt; 10µm</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Male</td>
<td>12</td>
<td>14.5</td>
<td>0.02</td>
<td>4.4</td>
</tr>
<tr>
<td>E</td>
<td>Male</td>
<td>10</td>
<td>13.3</td>
<td>-0.01</td>
<td>4.0</td>
</tr>
</tbody>
</table>

In this comparison, the E profile again appears to respond more favorably to the manufacturing variations imposed, but by only a small amount. As with the overall profile asymmetry documented in Table 2, the variation in the round side asymmetry measured by the standard deviation is less for the E than for the K.
Examination of the results reveals that all 12 of the K and all 10 of the E profile rotors that fail the round side asymmetry test ($\delta_{rs} > 10\mu m$) also fail one of the deviation extreme tests. Thus, the total number of failures for all three causes is still the total listed in the right hand column of Table 2.

**SUMMARY AND CONCLUSIONS**

The analysis of this study created a controlled manufacturing environment and compared the response of two profile designs to the process variations defined. The purpose of this study is to identify links between screw rotor profile design and manufacturing characteristics of the rotors. Earlier studies, /1/ and /2/, looked at extremes in the variations of the process parameters, demonstrating the effect that such variations had on profile form and resulting clearances of paired rotors. In this study, we considered the complete range of process variation by assuming a normal distribution with defined mean and standard deviation for selected parameters. A method was created based on the previous work where the computer simulation of manufacturing and inspection of many profiles, 1,000 per case for this study, could be executed automatically. The result is a large sample of rotor profiles to be examined. To deal with this, a profile quality plot is defined and used to display the results of the tests. In addition, the round or drive side asymmetry of the male profile is quantified with the parameter $\delta_{rs}$.

The process was run on two profile designs, which are seen to respond differently to the same manufacturing process variations, albeit by a small amount. Interestingly, the differences between the E and K designs are greater than the differences between the male and female rotors for each profile, although the differences between the profile forms and the tool profiles of males and females seem to be at least as great as the differences in the E and K designs. This is an area of ongoing study as we seek to identify how specific profile details result in the various manufacturing characteristics.

A simple conclusion to be drawn from all of this is that profile design affects manufacturability. Further, we can see how use of analytical tools such as the simulation system presented in this report can quantify this difference and thus can be used to guide designers to the right profile—right being the best balance between profile design characteristics and manufacturing effort required to make quality rotors on a consistent basis.

**REFERENCES**

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/2/ Sauls, J.; Application of Manufacturing Simulation for Screw Compressor Rotors; Proceedings of the 2000 International Compressor Engineering Conference at Purdue; Purdue University; 2000.