Statistical Capability Study of a Helical Grinding Machine Producing Screw Rotors

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Abstract. Screw compressors depend for their efficiency and reliability on the accuracy of the rotors, and therefore on the machinery used in their production. The machinery has evolved over more than half a century in response to customer demands for production accuracy, efficiency, and flexibility, and is now at a high level on all three criteria. Production equipment and processes must be capable of maintaining accuracy over a production run, and this must be assessed statistically under strictly controlled conditions. This paper gives numerical data from such a study of an innovative machine tool and shows that it is possible to meet the demanding statistical capability requirements.

1. Introduction
The performance of a screw compressor depends heavily on the machinery used in the production of the screw rotor pair. The machinery has evolved over more than half a century in response to customer demands for production accuracy, efficiency, and flexibility. To show fitness for purpose, production equipment and processes must be capable of maintaining accuracy over a production run, and this is best assessed statistically under controlled conditions. Some data for the accuracy of such machines has been published [1], [2], but this has not extended to statistical capability.

The performance behaviour depends primarily on the accuracy of the rotor pairs, as described by Sauls [3]. Methods of measuring rotor pairs have been developed which reveal their important characteristics. Specifically, the inter-lobe contact patterns, clearances and transmission errors are the key factors in determining efficiency, reliability, and noise. A full description of these measurement methods is given in [4]. Characteristics of interest include profile shape, depth, outside diameter, lobe divide (pitch), and lobe helix form and lead. Such measurements may also be used as inputs to a pair simulation program in order to give an approximate indication of the pair quality.

For process capability assessment, the measurement of individual rotors, e.g. by CMM, is preferable [5], [6]. The characteristics to be used for the statistical processing will depend on the individual user’s preferred methods of specifying tolerances, profile fitting, etc.

2. Machine and part used
The machine used for this study was a Holroyd Zenith 400, a general description of which has been given previously by the author [7]. The model used was the Mk 2 version, in dressable grinding mode. Measurements were made with a Leitz PMM C portal-frame CMM using a rotary table. The compressor rotor dimensions, and the features measured, are as shown in Figs. 1 & 2.
Outside diameter: 220 mm  
Pitch circle diameter: 150 mm  
Root diameter: 140 mm  
Body length: 320 mm  
Helix lead, left hand: 340 mm  
No. of flutes: 5  

Mean Profile (5 points)  
Mean Lead (left and right flank independently)  
Divide

3. Statistical Methods
The statistical methods owe much to the mass production developments in the automobile industry, and only came to be applied to the rotor industry during the mid-1990s. Clear definitions and procedures are given in [8].

The process variability (Cp), and the Process Capability (Cpk) are useful in distinguishing between basic repeatability and the centralisation adjustment. Both are dimensionless ratios relating the available tolerance on a feature to the variability achieved. Assuming the underlying data is normally distributed, the definitions are as follows (see also Fig. 3):

\[
Cp = \frac{\text{Total tolerance band}}{(6 \times \text{standard deviation})}
\]

Cpk adapts this to the condition where the distribution of achieved values is not centered in the tolerance band, and is defined as:

\[
Cpk = \frac{\text{Margin from mean achieved value to closest tolerance limit}}{(3 \times \text{standard deviation})}
\]

In both cases, a higher number represents a more closely-controlled process. A value of 1 corresponds to a 0.26% probability of a given part being out-of-tolerance. A value of 1.33 is often used as a pass/fail criterion, representing a probability of error of 6 parts per 100,000.

For most dimensional features of a rotor, the feature can deviate above or below the target value and normal distribution is common. There are well-defined and documented tests for normality of data, and methods for converting non-normal data into alternative forms which can be analysed as normal [8],[9]. However, there are parameters such as surface finish, or divide as described below, which have a lower bound of zero. These cannot be analysed in the same simple manner.

Capability trials follow procedures which are designed to reveal the behaviour of the process only and avoid extraneous influences. Infinite batch sizes may be desirable but are not feasible, and the specialist statistical software (Minitab) applies a statistical compensation for the actual batch size. Unnecessary interventions such as modifications to machine input settings are to be avoided, unless these are an essential part of the designated process. Also, abnormal events which have a clearly identifiable cause, initial warm-up parts, or a faulty part being used in error, should be excluded from the analysis. A careful log of the run is essential for this to be done legitimately. The log should include part number, time started, blank condition, and any observed events before, during, or after the cycle.
4. Conditions for the production run

In this instance the batch of parts was a production batch, and the additional controls were pared to a minimum to facilitate the process. In particular:

1. The machine was not in a temperature-controlled environment.
2. The order of flutes during machining and measurement was kept consistent.
3. Machined workpieces were stabilised in a temperature-controlled environment of 20°C ±1°C for 24 hours before measurement.
4. Profile errors were measured normal to the surface. Profile deviations were then minimised by a single bodily rotation, or ‘best fit’.
5. Blank run-out was measured before and after the grinding.

As permitted under the procedure, two initial warm-up parts were dropped from the analysis regardless of whether they were within tolerance. Also, the run was unavoidably interrupted, and a second warm up was required, with those parts also being omitted.

Unfortunately, time did not permit the ordering of the ideal wheel type for the cast iron material, and the actual wheel used was prone to ‘clogging’ or ‘loading’. Nevertheless, the results will be presented here for their learning value.

5. Results

5.1. Profile

A typical CMM scan of a profile is shown in Fig. 4, with points used in Fig. 5. Errors are measured normal to the metal surface. Profile data for the run is shown in Fig. 6, the error distribution in Fig. 7, and profile capabilities in Table 1. With one exception, the capability results are well above the 1.33 target, showing excellent machine suitability for consistent rotor production quality. The Cpk value for the root of the profile was slightly below the target, and this is revealing. On each rotor there was a progressive change in the profile depth from flute to flute, which followed the same order as the grinding sequence, and was quite consistent throughout the batch. This was diagnosed as being the result of ‘push-off’ of the rotor body as the wheel loaded with debris. This also affected the divide values.
Fig. 4. Transverse profile

Fig. 5. Profile points

KEY
Measurement points used for the capability analysis:

Point 1: Driving (‘round’) side mid flank
Point 2: Driving (‘round’) side pitch line
Point 3: Root
Point 4: Trailing (‘flat’) side mid flank
Point 5: Trailing (‘flat’) side pitch line

Fig. 6. Profile data
Table 1. Profile capabilities

| Profile point & Tolerance                  | Cp     | Cpk   |
|------------------------------------------|--------|-------|
| 1. Profile Mean, Round side, Mid flank, ±12.5µm | 2.40   | 2.15  |
| 2. Profile Mean, Round side, Pitch radius ±12.5µm | 4.91   | 3.85  |
| 3. Profile Mean, Root, ±12.5µm             | 1.33   | 1.23  |
| 4. Profile Mean, Flat side, Pitch radius ±12.5µm | 3.60   | 3.39  |
| 5. Profile Mean, Flat side, Mid flank ±12.5µm | 1.97   | 1.87  |

5.2. Lead

Lead error is derived from surface normal deviations from the theoretical helix over the length of the flute at the pitch radius. The lead was scanned on each flank independently and the results for each flank were averaged over all flutes. Lead error $H_a$ was the parameter chosen for analysis, being the slope error of the best-fit straight-line through the data. It must be remembered that the normal errors are magnified twice: firstly by projection of the surface normal error into the axial direction, and secondly by further axial projection from the body length to a ‘full wrap’ of the helix over 360 degrees. Thus surface errors might be 3 times larger when expressed as lead.

CMM scans of all flutes on one rotor are shown in Fig. 8. The raw data and frequency distribution are shown in Fig. 9 and Fig. 10. The capability values as shown in Table 2 are high, and this will have beneficial results for the noise behaviour of the rotors, as described in [10].

![Error frequency distribution for profile point 1 data set](image-url)
Fig. 8 Lead scans for all lobes on a typical rotor

Fig. 9 Round side lead data
Table 2. Lead capability

| Lead measurement position | Cp   | Cpk  |
|----------------------------|------|------|
| Lead Mean, Round side.     | 1.98 | 1.93 |
| Tolerance ±15µm            |      |      |
| Lead Mean, Flat side.      | 1.95 | 1.53 |
| Tolerance ±15µm            |      |      |

5.3. Divide (Angular Pitch)

Divide is determined from one selected point in the smoothed-profile of each flute. The parameter analysed is fu, the total range of individual pitch deviations measured tangential to the pitch circle in the transverse plane. This is an absolute value and not normally-distributed, so the standard calculation of Cpk can therefore not be used. As explained above, the divide was adversely affected by the wheel being unsuitable for the cast iron material. The results are shown in Fig. 11. This may be compared with data collected from a different trial using the same machine, but with a grinding wheel suited to the rotor material, as shown in Fig. 12.

![Fig. 10. Round side lead error frequency analysis](image)

![Fig. 11. Divide data](image)

![Fig. 12. Divide data from a different trial, without wheel ‘loading’](image)
6. Conclusions

Although such testing as described above is time-consuming and costly, the results, in addition to providing the machine user with confidence in its fitness for purpose, can also be very revealing about the many factors which affect the process. Besides wheel selection, the condition of blanks, centre holes, gripping journals, coolant application, thermal compensation, and other factors may be revealed as significant and their effects quantified by comparing different trials.

In this case, the lead and profile capabilities of the machine itself proved more than ample for the compressor application, but the wheel used for the trial was found to be unsuitable because its pores were prone to clogging by the cast iron material. Tests with a more porous wheel using the same machine but a different rotor size gave good results, the lesson being that the performance of a capable machine tool can be degraded significantly by an unsuitable tool.

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In section 5.3, first paragraph, the following text appears:

"Divide is determined from one selected point in the smoothed-profile of each flute. The
parameter analysed is fu, the total range of individual pitch deviations measured tangential to
the pitch circle in the transverse plane. This is an absolute value and not normally-
distributed, so the standard calculation of Cpk can therefore not be used. As explained
above, the divide was adversely affected by the wheel being unsuitable for the cast iron
material. The results are shown in Fig. 11. This may be compared with data collected from a
different trial using the same machine, but with a grinding wheel suited to the rotor material,
as shown in Fig. 12."

This should read:

"Divide is determined from one selected point in the smoothed-profile of each flute. The
parameter analysed is fu, the total range of individual pitch deviations measured tangential to
the pitch circle in the transverse plane. The target value is zero, but values vary only upwards
and are not normally-distributed, so the standard calculation of Cpk can therefore not be used.
The raw values are plotted in Fig. 11, and are higher than would normally be expected. It
was noticed that on each rotor there was a progressive change in the profile depth from flute
to flute, which followed the same order as the grinding sequence (1,4,2,5,3 clockwise from the
top flute in Fig. 4), and was quite consistent throughout the batch. This was diagnosed as being
the result of ‘push-off’ of the rotor body as the non-porous wheel loaded with debris from the
cast iron material.

Because of limited time it had not been possible obtain the preferred type of grinding wheel
for the material, and no more parts of the correct size were available for a repeat run in the
time available. Fortunately, data was available from a run on the same machine using different
rotors, but with a grinding wheel suited to the rotor material, and this is shown in Fig. 12.

Ignoring the auto-scaling, the difference is dramatic, and confirms the conclusion that wheel
loading of the non-porous wheel was the main factor affecting the divide capability in the trials.
The capabilities calculated by Matlab for the asymmetric distributions are as follows:

This run: Cp=0.54. Different run with a smaller, female rotor using a porous wheel:
Cp=1.77."

In section 6, first paragraph, the following text appears:

“Although such testing as described above is time-consuming and costly, the results, in addition to providing the machine user with confidence in its fitness for purpose, can also be very revealing about the many factors which affect the process. Besides wheel selection, the condition of blanks, centre holes, gripping journals, coolant application, thermal compensation, and other factors may be revealed as significant and their effects quantified by comparing different trials.

In this case, the lead and profile capabilities of the machine itself proved more than ample for the compressor application, but the wheel used for the trial was found to be unsuitable because its pores were prone to clogging by the cast iron material. Tests with a more porous wheel using the same machine but a different rotor size gave good results, the lesson being that the performance of a capable machine tool can be degraded significantly by an unsuitable tool.”

This should read:

“Although such testing as described above is time-consuming and costly, the results provide the user with evidence of the machine tool’s fitness for purpose. In this case, the lead and profile capabilities of the machine itself proved more than ample for the compressor application, but the wheel used for the trial was found to be unsuitable because its pores were prone to clogging by the cast iron material, leading to increasing ‘push off’ of the part with each flute ground.

In addition to providing the machine user with confidence in its fitness for purpose, can also be very revealing about the many factors which affect the process. Besides wheel selection, the condition of blanks, centre holes, gripping journals, coolant application, thermal compensation, and other factors may be revealed as significant and their effects quantified by comparing different trials.

Tests with a more porous wheel using the same machine but a different rotor size gave good results for divide, the lesson being that the performance of a capable machine tool can be degraded significantly by an unsuitable tool. Clearly, some short cuts can lead to a longer journey, and the best response to a proposal to carry out a capability run with an unsuitable wheel might well be “Push off”."