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# APPLICATION OF MANUFACTURING SIMULATION FOR SCREW COMPRESSOR ROTORS

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## ABSTRACT

This paper shows how simulation of screw rotor profile manufacturing can be used in the design phase to assess profile alternatives. To do this, variations in manufacturing parameters are studied to illustrate how these deviations affect different rotor profile shapes and the resulting rotor pair clearances.

## INTRODUCTION

Clearances between rotors in a twin screw compressor play a key role in determining the compressor's performance and reliability. A balancing act is played between clearances small enough for good performance yet large enough for high reliability. To achieve the proper balance requires knowledge of all of the factors that affect rotor-to-rotor clearance and the ability to control these factors during design and production. The two significant issues facing the designer are the effects of operating load induced deformations of the rotors and manufactured rotor variability; this paper addresses the latter.

A computer simulation allowing investigation into the effects of variability that might occur during the manufacturing process has been developed. Using this simulation, we first consider how selected variations in the profile manufacturing process affect the profiles of two different rotor designs. Then the effect of these profile variations on clearances of a rotor pair is examined.

Rotors considered were designed for different models of screw compressors used in air-cooled refrigeration systems. The profiles are designated E and J. The E profile is an older design used in larger capacity compressors; the J is a second generation design for smaller compressors. Both profiles are designed by specifying a generating rack /1/. The E profile uses a simple rack with four circular arcs and two straight lines. The J rack is more complex, with 12 rack segments, including three generated curves. Rotors with both the E and J profiles have five male and seven female lobes and are designed with a 300° male wrap angle and 1.5 L/D. Production profiles are applied to rotors with displacements of 34 $m^3min^{-1}$ at 3600 rpm. Rotor pairs and their generating racks are compared in the transverse plane in Figure 1.

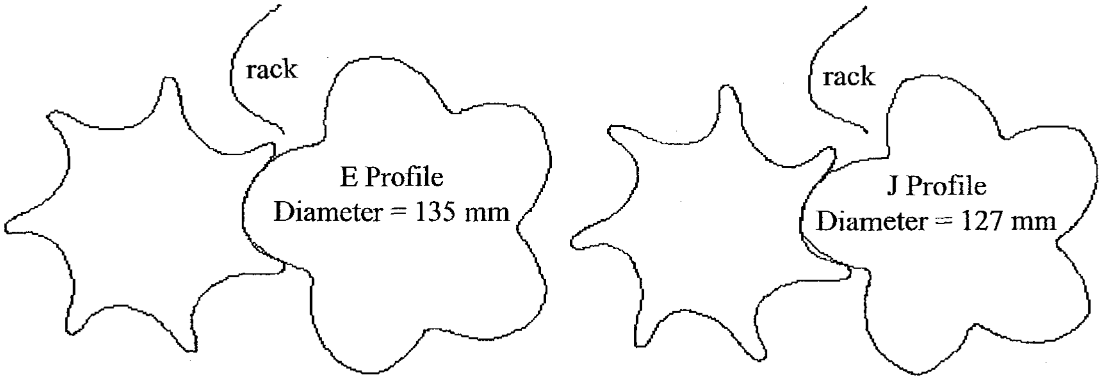


Figure 1 -- Comparison of E and J Rotor Pair and Generating Racks

There are many variables to consider when looking into rotor manufacturing variability – too many to address in this short paper. Thus, the study will be limited to the male rotor only. In addition, only three manufacturing parameters will be considered. The purpose of the study is to see how the rotor profiles respond to variations in the manufacturing process, to show how these profile variations affect clearances in a rotor pair (where the female rotor is considered to be nominal) and to compare the way in which the two designs differ from each other in their response to the variations.

## ANALYSIS METHODS

A rotor profile manufacturing simulation has been developed and included in a rotor design system, illustrated in Figure 2. Program A computes rotor profiles based on rack definitions and a modification to apply clearances. The profile data is used in program B to compute the theoretical shape of the profile manufacturing tool (grinding wheel or milling cutter). In addition to the profile definition, certain manufacturing parameters are specified here. The computation process is reversed in program C where the cutting tool shape and manufacturing parameters are defined and the rotor profile is computed. The manufacturing parameters can be set to nominal values, in which case the original profile will be reproduced. Deviations in the manufacturing parameters can also be specified in the simulation. In this case, the profile computed will have deviations relative to the nominal form. Program D is essentially a numerical coordinate measuring machine. It reads profile definitions from the design program (A) and the simulation program (C) and compares the two. Data generated can be plotted as an actual form with deviations magnified to be compared with the original, theoretical form. The deviations can also be delivered to the profile design/analysis program (A) for computation of rotor pair clearances. An example of the application of this process can be found in /2/.

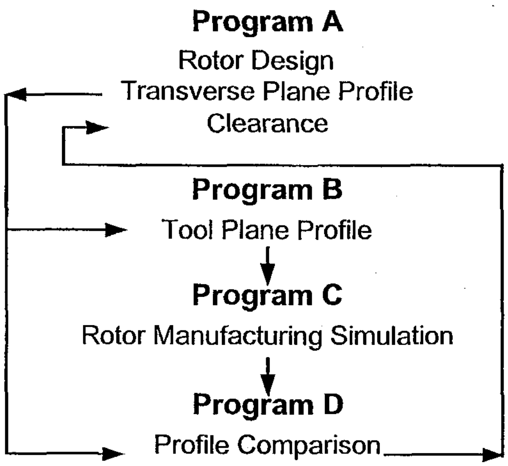


Figure 2 -- Rotor Profile Design System

The theory of mutual computation of tool and rotor profiles is well known and widely used in the screw compressor industry. A particular form of tool and rotor profile calculation theory developed by Stošić, et al /3/ is used in the tool and rotor profile analyses, programs, B and C respectively. As stated above, many manufacturing parameters can be studied; three have been selected for this study. A tool and rotor engaged as they might be in rotor grinding or milling operations are illustrated in Figure 3. The three parameters chosen to vary in this study are also shown. These are: 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.

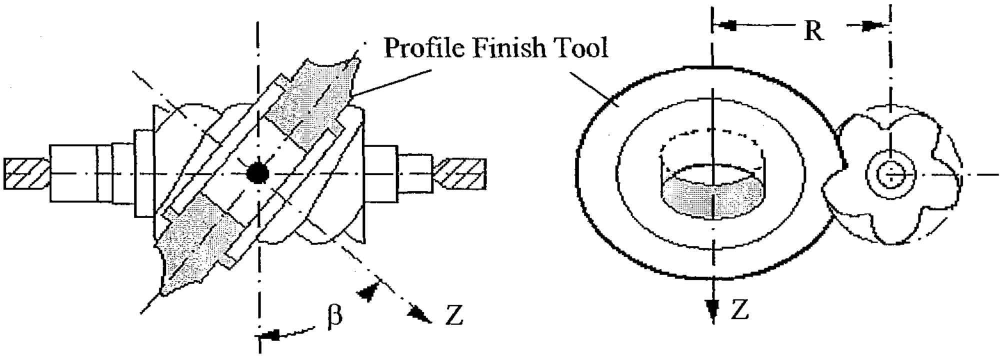


Figure 3 -- Rotor Profile Manufacturing Setup and Parameters

A male rotor profile is computed for variation of each parameter with the other two held at nominal values. The magnitude of the deviation of a parameter from its nominal value is chosen to be the value for which the maximum deviation of the rotor profile is 10 μm. Both positive and negative variations of each parameter are considered. In all cases, the shape of the tool is assumed to be nominal. Results of the profile calculations are given in the next section.

## ROTOR PROFILE CALCULATIONS

Figure 4 shows the computed effect of variation of the wheel setting angle, β on the E and J male rotor profiles. In this and all subsequent illustrations, the three lighter lines show the nominal profile and the ±10 μm band. The computed profile with the effects of the manufacturing parameter deviation is plotted with the heavy line. The rotor pair are male rotor drive and the target for rotor-to-rotor contact is on the round side in the area marked C in Figure 4.

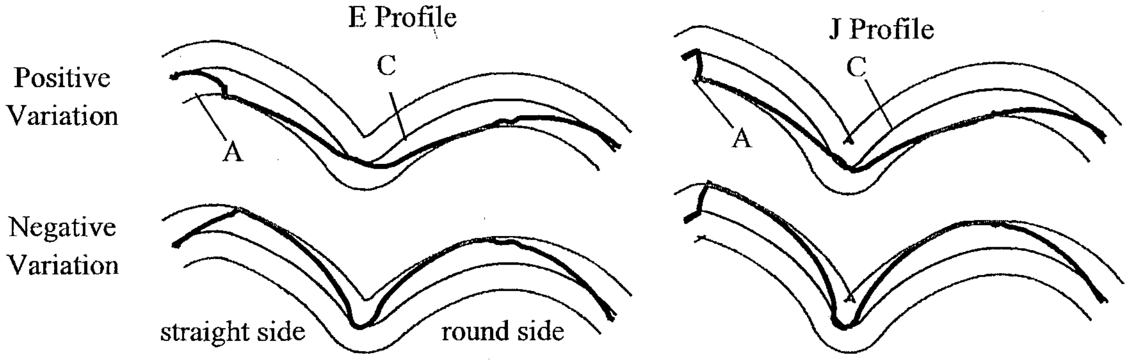


Figure 4 -- Effect of Cutting Wheel Setting Angle (β) on Male Rotor Profile

For both profiles a variation in β of ±0.044° generated the target maximum deviation of ±10 μm. Varying the setting angle has no effect at the rotor root or outer diameter (OD). A noticeable difference in the profiles occurs on the straight side in the area marked A. The change from the maximum deviation back to nominal at the OD occurs over a greater length in the E profile than for the J, where the transition is quite sudden. This is due to the use of a short generating curve on the J rack as opposed to a fairly large circular arc on the E. The benefit to the J profile is a smaller blowhole.

We can try to draw some conclusions about the effect of the differences in profile variation. On the J rotor, the profile at A is 0.8% of the total rotor profile arc length, but accounts for 23.5% of the rotor-to-rotor seal line length. On the E profile, the section at A is 12.0% of the rotor profile length and accounts for 24.3% of the seal line length. Since both profiles show a 10 mm variation in profile in a part affecting about 24% of the seal line length, we might conclude that the rotor clearances for both designs are affected equally by the β variation. We will see in the next section, however, that analysis of the actual rotor-to-rotor clearances shows otherwise.

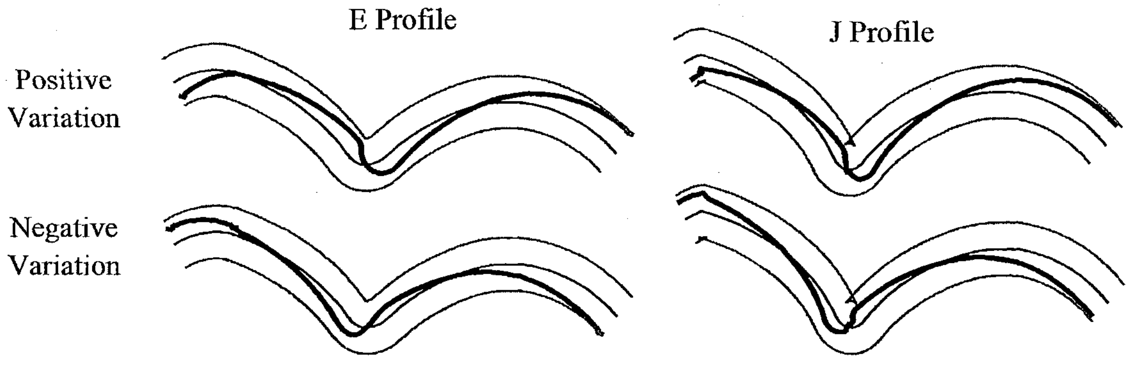


Figure 5 -- Effect of Tool Location on Spindle (Z) on Male Rotor Profile

The effect of varying the location of the cutting wheel along its spindle axis (Z) is shown in Figure 5. For both profiles, Z direction shifts of 115 μm in each direction resulted in the maximum ±10 μm profile deviations. Moving the cutting wheel along its spindle axis shifts and rotates the resultant profile. The root diameter is held to its target value, but the location of the minimum diameter shifts towards either the round or straight side depending on the direction of the wheel shift. Both profiles are similarly affected by the Z axis shift, although the variations in the J profile in the vicinity of the root and near the OD on the straight side (A in Figure 4) are somewhat more pronounced than for the E profile.

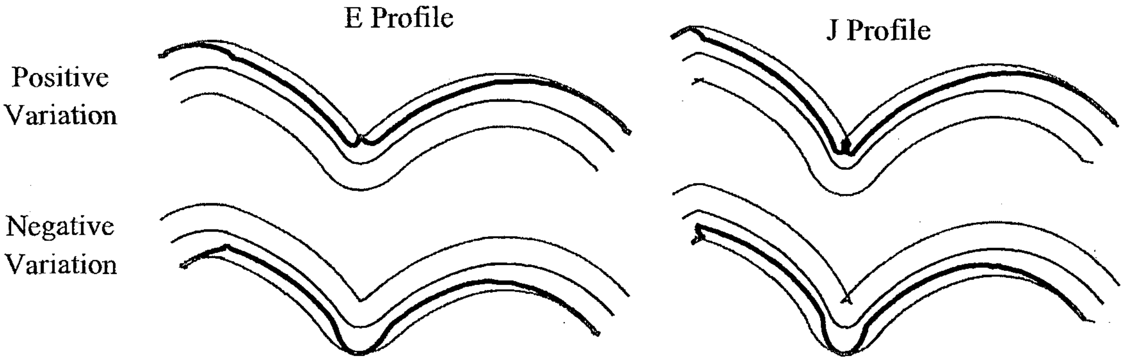


Figure 6 -- Effect of Tool-to-Rotor Center Distance (R) on Male Rotor Profile

Figure 6 shows the effect of changing the tool-to-rotor center distance. The maximum profile deviations of 10 mm occur at the rotor root and OD as a result of 10 mm shift of the tool. The profile shapes that result from this variation are as would be expected. Deviations near the OD and root are equal to the change in tool-to-rotor center distance and deviations along the steeper sides of the profile are less.

Comparisons in Figures 4 through 6 show the computed profiles plotted within a tolerance band created by defining ±10 μm offsets all around the nominal profile. We might imagine that manufacturing variations will result in profiles that are always somewhere between maximum and minimum metal conditions with some rotors looking like the limiting cases at ±10 μm. However, in this study, the one reported in /2/ and in other calculation studies considering concurrent variations in multiple manufacturing parameters, no manufacturing deviations have been found, individually or in combination, that will produce a uniform profile at either + or -10 μm.

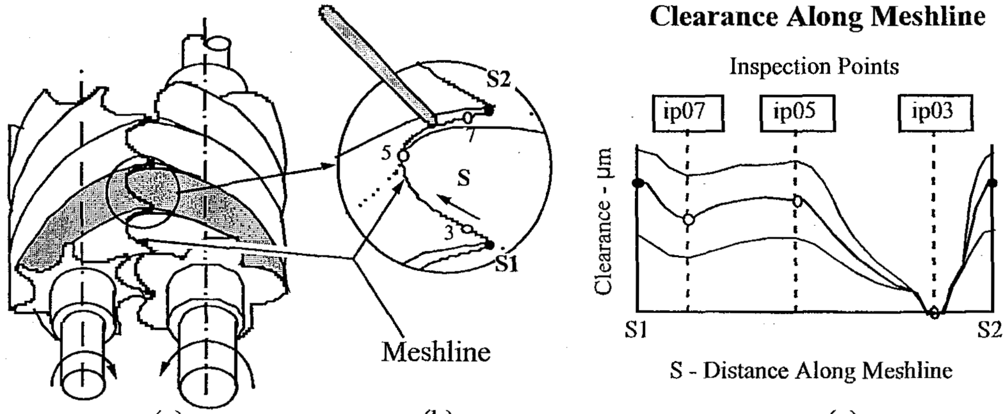
Simulation of manufacturing deviation effects on rotor profile form as have been presented so far are useful in understanding how the profile shapes are affected. However, in designing a rotor pair, the goal is to arrive at an acceptable clearance distribution between the rotors—we are actually designing the "hole". In the next section, the effects of the profile deviations caused by manufacturing parameter variation on the rotor pair clearances are investigated.

## ROTOR PAIR CLEARANCES

Definition of rotor intermesh clearance and a form for displaying this clearance are shown in Figure 7. When the rotor pair is viewed in the direction of its normal rack, the meshline appears as shown in Figure 7a with the heavy, wavy line between the rotors. This is generally the way a rotor pair is manually inspected with clearances measured with a feeler gauge as shown in 7b. Figure 7c shows a typical characteristic when measured clearances are plotted as a function of distance along the meshline.

Three inspection points are highlighted in 7b and 7c. The point identified as ip03 on the round side is in the middle of the target rotor-to-rotor contact band when the pair is applied with male rotor drive. Point ip05 is at the OD of the male rotor and root of the female rotor. Point ip07 on the straight side locates a target for rotor-to-rotor contact in a reverse drive case. The clearance at ip07 is roughly equal to the rotor pair backlash. In the schematic in Figure 7c, three clearance distributions are shown. The central line represents clearances for a nominal rotor pair and the lines above and below represent extremes where rotors are either uniformly minus or plus metal, respectively.

In the clearance-meshline length plane of Figure 7c, the area under the clearance curve is the total rotor-to-rotor leakage area; this area divided by the 3D meshline length (S2-S1) is the mean mesh clearance, the clearance we seek to minimize for the sake of performance. We must also be aware of local minimums. The clearances shown in Figure 7c represent clearance for a rotor pair at room temperature mounted at the design center distance. This is hardly the situation in operation where the rotors and housing parts determining the running center distance will be deformed by pressure and temperature loads. Finally, the designer must accommodate variation in the rotor profiles resulting from manufacturing variability. It is this issue that is considered in the remainder of this section.



(a) (b) (c)

Figure 7 -- Rotor Pair Intermesh Clearances

Examination of pair clearances is carried out using programs shown in Figure 2. As the analyses described in the preceding section are carried out, data files describing profile deviation are created by program D. These files are read by the rotor design program (A), which can modify the design profile to represent the new shape. This new rotor is then used in a pairing analysis to determine rotor pair clearances. In this study, only variations in the male rotor are considered. All clearances are computed assuming nominal female rotors with the rotors at their design center distance. With nominal male rotors, the mean clearance for both the E and J profile rotor pairs is 43 μm.

The effect of variation in the tool setting angle β on the rotor clearances is illustrated in Figure 8. In this and all subsequent clearance figures, the heavy line represents clearances for a nominal rotor pair. The lighter, solid lines above and below show the clearances that would result if male profiles at ±10 μm were paired with a nominal female. The mean clearances for these limiting cases are 30 μm and 55 μm. Dashed lines show clearances computed for a male rotor with the manufacturing variation considered.

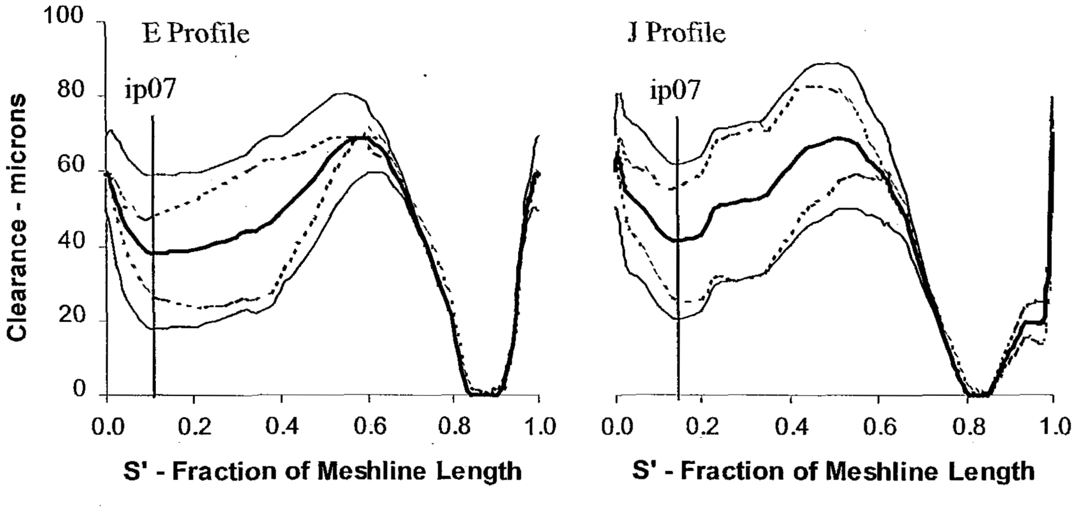


Figure 8 -- Effect of Tool Setting Angle (β) on Rotor Pair Clearances

From Figure 8, we notice that the effect of the angle variation (0.044° for both rotors) results in the J profile using somewhat more of the total tolerance band than with the E profile. In the low clearance case (generated by the –0.044° deviation), average clearance for the E and J rotors are 35.6 μm and 34.5 μm, respectively. For the high clearance condition, the clearances are 48.7 μm for the E and 50.7 μm for the J. So, in terms of the average clearance, the β variation uses 52% of the tolerance for E rotors and 65% for the J.

As noted above, examination of the rotor profiles might lead to the conclusion the β variation would have about the same effect on both profiles. The clearance analyses, however, shows that there is a noticeable difference in the β variation effect on the two profiles.

We also see an undesirable change in the shape of the minimum clearance for the E profile. Here, the location of the minimum clearance on the straight side has moved from its target at about S' = 0.10, the ip07 inspection point, to a point closer to the male rotor OD, about S' = 0.30. While a local minimum appears for the J profile at S' = 0.55, the absolute minimum on the straight side still occurs at the desired ip07 location of S' = 0.15.

Finally, we see that there is an area around S' = 0.9 on the J profile where the computed clearances are outside of the tolerance band. This happens in the E profile as well, although it is not so evident in the plot because of the scale and the slope of the clearance vs. S' curve. The tolerance band is computed assuming profiles of nominal shape with uniformly plus or minus metal. In this case, clearances between rotors near the contact band will be nearly the same regardless of metal condition since, by definition, we always evaluate the clearance for rotors in contact. Effects of the change in material state for profiles parallel to the nominal form are seen as changes in clearance on the straight side. However, the manufacturing variations do not generate profiles that are parallel to the nominal form. With profiles as shown in Figure 4 we get the computed clearances falling outside of the (very small ) tolerance band on the round side above the contact band (S' > 0.85).

Figure 9 shows the clearance distributions computed using male rotors with profile variation caused by the variation in the tool location on the spindle (Z). Here the effect of the manufacturing deviation is much less pronounced in the clearance plane than we saw for the angle variation. In terms of average clearance, the Z shift effect uses only 3% of the tolerance band for the E profile and 10% for the J. We can say based on the average clearances that the E profile is less sensitive to Z shift than is the J. In neither case do we see any particular problems.

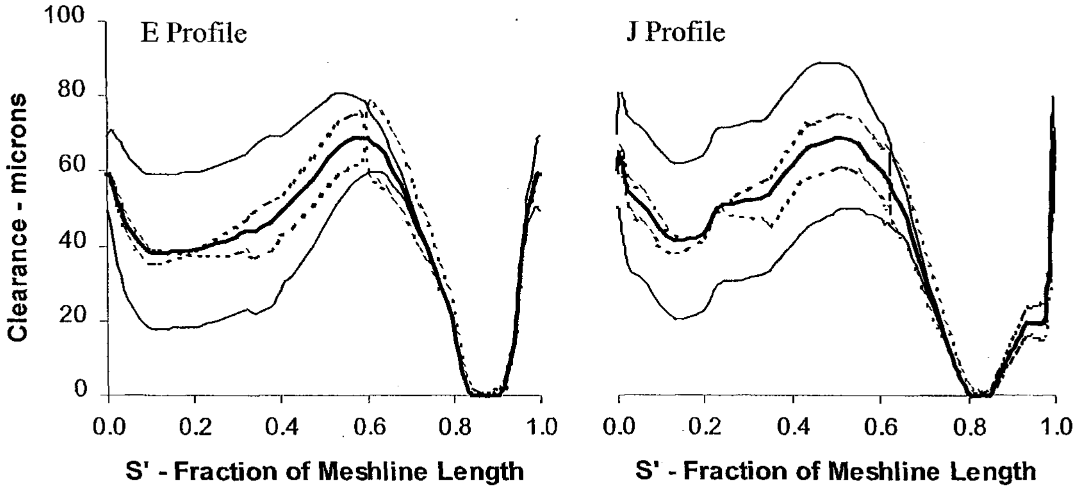


Figure 9 -- Effect of Tool Location (Z) on Rotor Pair Clearances

An interesting feature in the clearances that results from the Z variation is the step change in clearance between the round and straight sides at the rotor OD, seen at about S' = 0.65 for both rotors. This is due to the fact the tool cuts one rotor space at a time from the OD on the straight side to the OD on the round side. The Z shift effect is to rotate the profile, creating a discontinuity between the straight and round sides at the rotor OD in the full rotor.

The effect of changing tool-to-rotor center distance (R) is illustrated in Figure 10. In this case, both the E and J rotors use 60% of the tolerance band as measured by the mean clearance. In addition, the resulting clearance distributions are nearly parallel to the nominal – no unusual shifts in shape creating new, undesirable minimum clearances are seen.

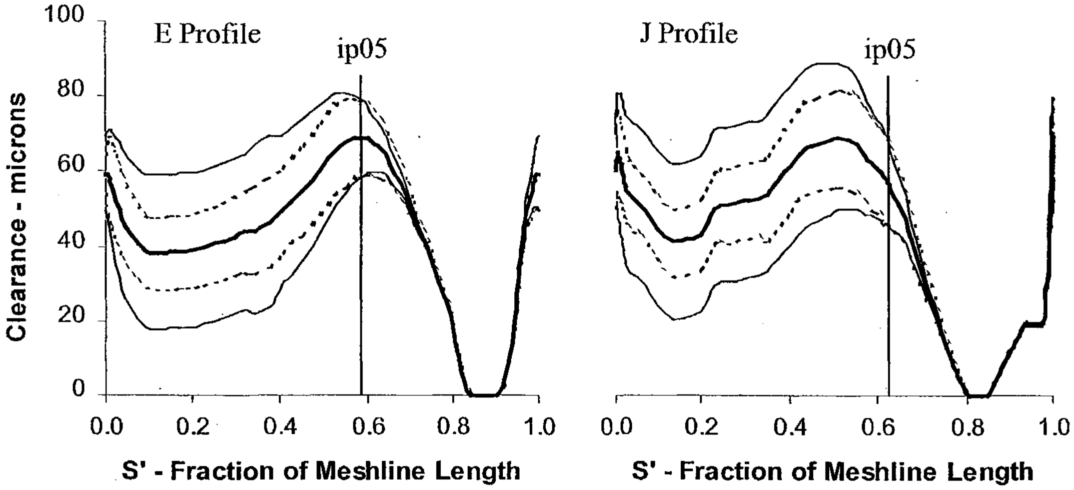


Figure 10 -- Effect of Tool-to-Rotor Center Distance (R) on Rotor Pair Clearances

The E and J profiles have a different clearance distribution philosophy that is made evident in the tool-to-rotor center distance effect. For the E, the maximum clearance occurs very near to the point of engagement between the male rotor OD and female rotor root, ip05, where S' = 0.59. The male OD, female root engagement point is found at S' = 0.62 for the J. For the J profile, the maximum pair clearance is put somewhat to the straight side of the male OD, occurring at S' = 0.53. Since the variation in center distance will, by definition, use all of the tolerance at the male OD, female root engagement point and less than this everywhere else (except, of course, at the female OD, male root engagement), the result is that the variation in wheel-to-rotor center distance uses all of the tolerance in the vicinity of the maximum clearance for the E profile, but only about 70% of this tolerance for the J.

This characteristic is also seen in the effects of the Z variation. The differences between the E and J in this regard may mean that more machine tool accuracy would be required for the E profile. Since more of the local tolerance band is used when the Z and R shifts are considered separately, we would assume that if they occur together, variations in each would need to be smaller for the E profile to remain within its clearance boundaries than would be the case for the J.

## SUMMARY AND CONCLUSIONS

A screw rotor manufacturing simulation has been used to study the effects of variation in selected machine tool setup parameters on the male rotors using two different profile designs. These calculations reveal that the two profile designs respond differently to manufacturing variations, although the significance of the differences is difficult to judge from the profile shapes alone. It is noted that the type of deviations studied do not result in profiles that use all of the tolerance band defined by a uniform variation in material all around the nominal profile.

Because of this, the profiles that result from the selected manufacturing deviations are paired with nominal female rotors at the rotor pair design center distance to see the effect of the profile variations on the important clearance distribution characteristics. In this comparison, the E profile shows up as being somewhat more tolerant to manufacturing variations when it comes to average rotor pair clearance. Table 1 compares the average clearances for the E and J profiles with the β, Z and R variations studied. The range value tabulated is defined as the difference between the high (max) and low (min) values compared to the total range defined by the ±10 μm profiles.

Table 1
Computed Rotor Pair Clearance Comparison
Average Clearance in μm

| | **E Profile** | | | **J Profile** | | |
|---|---|---|---|---|---|---|
| **Parameter** | min | max | range | min | max | range |
| Tool Angle β | 35.6 | 48.7 | 52% | 34.5 | 50.7 | 65% |
| Tool Location Z | 41.7 | 42.4 | 3% | 41.1 | 43.5 | 10% |
| Center Distance R | 34.7 | 49.8 | 60% | 35.0 | 50.0 | 60% |

While the E profile is less sensitive to variations with regards to overall clearance, certain details of the E profile clearance distributions are less favorable. In some locations along the meshline, more of the tolerance band is used on the E in response to manufacturing variation than is used by this same variation with the J profile. There is also a tendency for any off-drive side rotor contact that may occur to happen away from the desired location on the E profile with rotors made with a variation in the setting angle.

There is much yet to learn about manufacturing variation effects on actual rotor profiles and work is underway to acquire data from the factory. However, simple simulations of manufacturing effects such as demonstrated here provide the designer with valuable insights. Continuing improvements in the simulation tools and better understanding of the manufacturing process capabilities will allow rotors with any profile to be designed with clearances that represent the best balance of performance and reliability. This will mean fewer surprises as new designs are tested in the laboratory and less time adjusting the designs based on the laboratory experience. In addition, the manufacturing simulation provides another tool which the designer can use to evaluate alternative profiles to find a more optimum design for his or her particular application.

## ACKNOWLEDGMENTS

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