# An Analytical Study of the Effects of Manufactoring Variations on Screw Rotor Profiles and Rotor Pair Clearances

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**Zusammenfassung**

*Eine Simulation von Rotorprofilherstellung wird verwendet, um die Effekte von Varianten in einigen Bearbeitungsparametern auf Rotorprofilform und der Spalte der Rotorpaare zu beschreiben. Abweichungen in Achsabstand zwischen Werkzeug und Rotor, der Einstellungswinkel des Werkzeuges, die Stelle des Werkzeuges an seiner Arbeitsspindel und die Herstellungssteigung werden analysiert. Auch behandelt werden die Auswirkung der Herstellungsvarianten auf der Auslegung der Rotorprofile und der Gebrauch von einfachen statistischen Analysen um die Effekte der kombinierten Abweichungen auf typischen Produktionsquantitäten zu studieren.*

**Summary**

*A simulation of rotor profile manufacturing is used to describe the effects of variations in several machining parameters on rotor profile shape and subsequently on the clearances of rotor pairs. Variations in the distance between the tool and rotor axes, setting angle of the tool, the position of the tool in its spindle and the manufacturing lead are analyzed. The impact of manufacturing variations on the design of the rotor profiles and the use of simple statistical analyses to study the effects of combined manufacturing deviations on typical production quantities are also discussed.*

## 1.0 Introduction

Mathematical models for computation of cutting tool profiles from screw rotor transverse plane data and for the computation of the rotor profiles given the tool plane profile can provide both the rotor manufacturer and the compressor designer with important information. A particular form of tool and rotor profile calculation theory developed by Stošic', et al /1/ has been used to study the effect of variations in manufacturing parameters on the shape of the rotor profile. Theories of mutual computation of tool and rotor profiles are well known and widely used throughout the screw compressor industry and studies similar to those reported here have been carried out by others. However, to the author's knowledge the results of such studies have not been widely distributed due to contractual or confidentiality considerations. This paper reports on the methods applied at the author's company for a particular rotor design.

This report shows how variations of selected manufacturing parameters from their nominal values affect the shape of the rotor profile. Information from this work can be used in two ways. First, the computed deviations in profile form can be used by the rotor manufacturer to demonstrate where particular profile errors can come from and what form of adjustment to the machine tool could be used to improve the shape of the finished rotor. The rotor designer can also use the simulation to include information about manufacturing process capability in the selection of rotor pair clearances. Accuracy and repeatability data from the machine tool manufacturer or from manufacturing experience can be analyzed in terms of rotor profile deviations. Rotors with particular deviations can be paired to show the effects on intermesh clearances and statistical methods can be used to determine the appropriate profile modifications to provide both reliable and efficient designs.

There are numerous parameters that affect the final form of a rotor finished by milling or grinding processes. In addition to the shape of the cutting tool itself, there are tool setting angles and positions as illustrated in Figure 1.1. The location of the tool along the machine spindle (Zt), the distance between tool and workpiece axes (R), the setting angle of the tool ($\beta$), the slant of the wheel ($\Delta\psi$), runout of the wheel and rotor, and lead -- the combined deviation in tool translation (Zpr) and workpiece rotation ($\varphi$) -- all vary within particular tolerances and each variation contributes to deviation in the finished rotor.

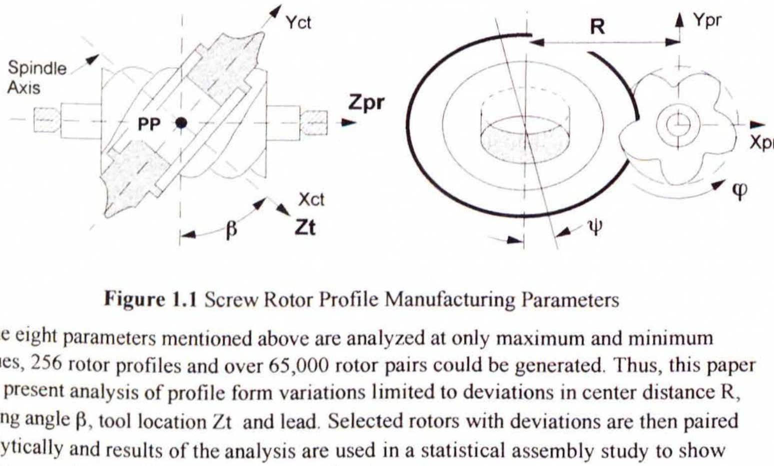


**Figure 1.1** Screw Rotor Profile Manufacturing Parameters

If the eight parameters mentioned above are analyzed at only maximum and minimum values, 256 rotor profiles and over 65,000 rotor pairs could be generated. Thus, this paper will present analysis of profile form variations limited to deviations in center distance R, setting angle $\beta$, tool location Zt and lead. Selected rotors with deviations are then paired analytically and results of the analysis are used in a statistical assembly study to show how appropriate profile designs can be defined.

## 2.0 Calculation Methods

The rotor manufacturing analysis uses four separate computer programs. These programs and the flow of data between them are illustrated in Figure 2.1. First, the theoretical profile forms ($x_{pr}$, $y_{pr}$) for male and female rotors with appropriate modifications for intermesh clearance of the pair are computed (program A). A second program (B) calculates the theoretical tool form ($x_{ct}$, $y_{ct}$) which would define the shape of a milling cutter or grinding wheel profile. A manufacturing simulation program (C) is used to compute the rotor profile from the tool data. This program allows specification of variations in the tool form, setting angle, tool-to-rotor center distance, tool location on the spindle and runout. The rotor profile generated by this simulation is compared to the theoretical shape in program D, the computational equivalent of a coordinate measuring machine. The profile deviations can be returned to the rotor design program (A) to use in computation of the clearances between male and female rotors with the effect of deviations included. Finally, information about the rotor profile tolerances based on the manufacturing simulation can be used in a statistical assembly analysis (program E) to demonstrate the characteristics of rotor pairs made in typical production quantities.

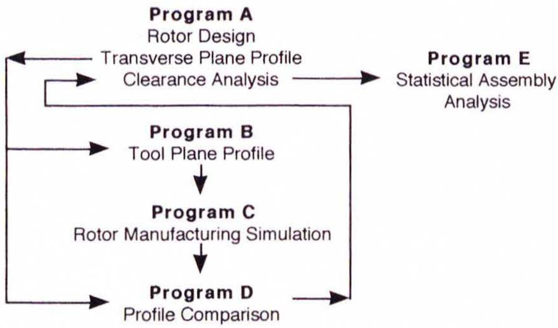


**Figure 2.1** Manufacturing Simulation Programs and Data Flow

**3.0 Effects of Manufacturing Variations on Rotor Profile**

All analyses are carried out for a rotor pair with a 246mm diameter, 5 lobe male rotor and a 217 mm diameter, 7 lobe female as illustrated in Figure 3.1. The location of points at which key rotor-to-rotor (or 'intermesh') clearances are defined are also shown. These points are used in Section 4 when the effects of individual rotor manufacturing deviations on rotor pair characteristics are described.

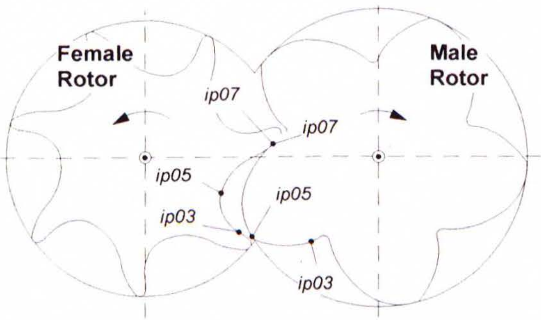


**Figure 3.1** Rotor Pair and Inspection Point Definitions

Manufacturing variation effects on individual rotors are computed for selected parameters using the rotor manufacturing simulation program (C). The 'computer manufactured' profiles are compared to the nominal using the profile comparison program (D).

Variation in the following parameters are considered in the remainder of this report:

R -- Distance between the cutting tool and workpiece centerlines;
β -- Tool setting angle;
Zt -- Location of the cutting wheel on the machine spindle;
L -- Lead (dZpr / dφ)

Variations in these parameters are examined one at a time so that the unique characteristics of the variation of each parameter on the shape of the rotor profile can be clearly seen.

The magnitude of the deviation in each parameter is selected to produce a maximum rotor profile deviation of ±10μm. In practice, of course, the analysis would be carried out using estimated or measured manufacturing capability data. Both positive and negative variations are computed. In each case, male and female rotors are analyzed. Results for the four parameters listed above are discussed briefly in Sections 3.1 through 3.4, respectively.

**3.1 Tool-to-Rotor Center Distance**

Rotor profile variations that come from moving the tool closer to or farther from the workpiece are easy to imagine. At the rotor root and outside diameters, the profile variation is equal to the center distance variation. Between these sections, the profile deviation is less than the change in center distance by an amount dependent on the slope of rotor flank. Figure 3.2 shows profile deviations for changes in center distance of ±10μm.

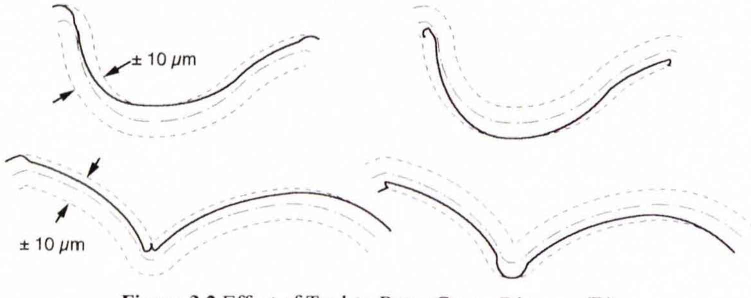


**Figure 3.2** Effect of Tool-to-Rotor Center Distance (R)

The information shown in Figure 3.2 is arranged according to the following format: female rotor profiles (($x_{pr}$, $y_{pr}$) coordinates - see Figure 1.1) are shown on the top row with male profiles below. The nominal profile is shown with the centerline style. Profiles that represent nominal ±10μm are shown with the dashed lines. The profile computed with deviation is the heavier, solid line. Profiles computed with a positive deviation in the manufacturing parameter being considered are shown on the left side of the figure. The effects of negative deviations are shown on the right side. The profile with deviation is plotted with the differences between the nominal and deviation forms magnified 600 times. This formatting applies to Figure 3.2 through Figure 3.5.

### 3.2 Tool Setting Angle

Normally, the tool is designed to cut through the rotor when set at an angle equal to the rotor helix angle measured at the pitch line. The maximum variation in rotor profile reaches 10μm for deviations in setting angle of ±0.029° for both the male and female rotors. The effect of setting angle variation is shown in Figure 3.3.

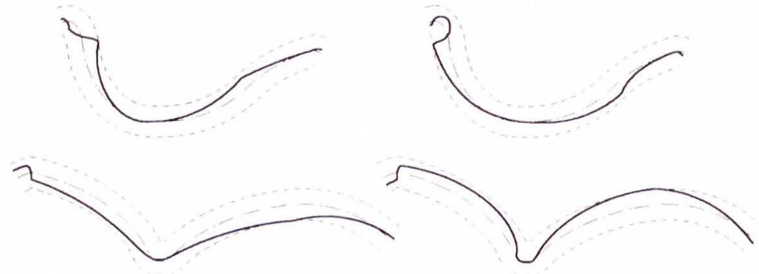

**Figure 3.3** Effect of Tool Setting Angle (β)

### 3.3 Location of the Cutting Tool on its Spindle

The origin of the tool profile coordinate system **PP** as shown in Figure 1.1 must be located on the same plane as the workpiece axis (Zpr in Figure 1.1). This point can move up and down along the spindle axis (Zt in Figure 1) because of deviations in the wheel, spindle and in the positioning variables which may be shims or programmable settings. Figure 3.4 shows the effects of deviation in the location of point **PP** along the spindle axis. Profile errors of ±10μm are generated when the tool location varies ±150μm for the male rotor and ±110μm for the female.

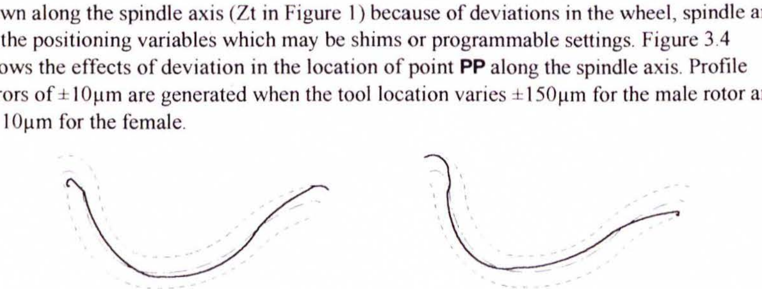

**Figure 3.4** Effect of Tool Location on Spindle (Zt)

### 3.4 Lead

The lead at which the rotor is made is determined by rotation of the workpiece (φ in Figure 1.1) and translation of the tool relative to the workpiece (Zpr). When this lead varies from the nominal value for which the tool form was designed, the profile shape is changed.

Figure 3.5 shows the effect of a lead variation of ±20μm, resulting in the target 10μm profile deviation.

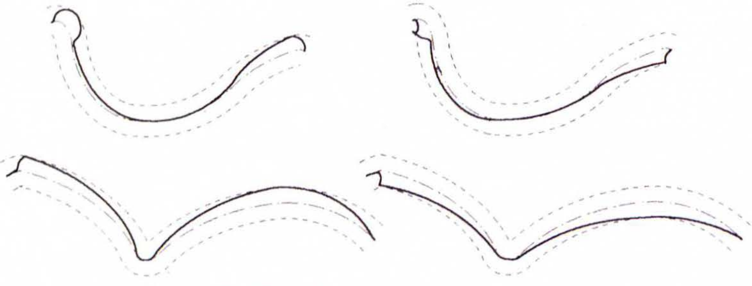

**Figure 3.5** Effect of Manufacturing Lead Variation

**4.0 Rotor Pair Analyses**

Computation of the effects of deviations in the manufacturing variables provides useful information for the manufacturing operation. Errors in machine setup can be found by their characteristic effects on the shape of the rotor profiles and appropriate adjustments can be made. The analyses are also useful to the designer. It is necessary to provide proper clearance between the rotors for efficient and reliable operation. Clearances must be small enough for low leakage losses, but large enough to avoid undesirable contact leading to rotor damage. The designer must consider the effects of the operating conditions on changes in shape and position of all of the parts, but must also take into account manufacturing variations.

The intermesh clearance concept and definitions of terms are illustrated in Figure 4.1.

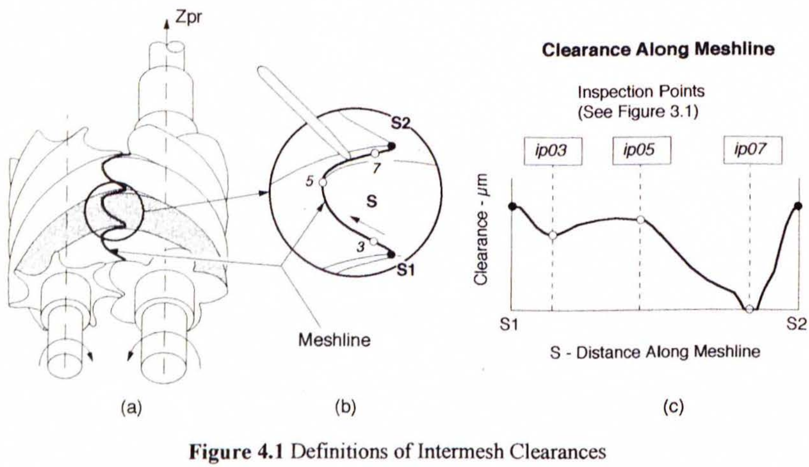


**Figure 4.1** Definitions of Intermesh Clearances

When the rotor pair is viewed in the direction of its normal rack, the meshline appears as shown in Figure 4.1a. This is the view seen when rotor pair are inspected where clearances may be measured with a feeler gauge as shown in 4.1b. Figure 4.1c shows a typical characteristic when clearances are plotted as a function of distance along the meshline.

The first step in designing profiles with consideration of manufacturing variability is to determine the effects of the these variations on the clearance characteristics of a rotor pair. In this section, various rotor pair are assembled analytically from male and female rotors with selected deviations computed as described in Section 3. First, a rotor pair is defined with the clearance characteristic shown in Figure 4.2. The central line (centerline format) shows the clearances for nominal profiles and the dashed lines above and below show the case for rotors with uniform $\pm 10\mu m$ material.

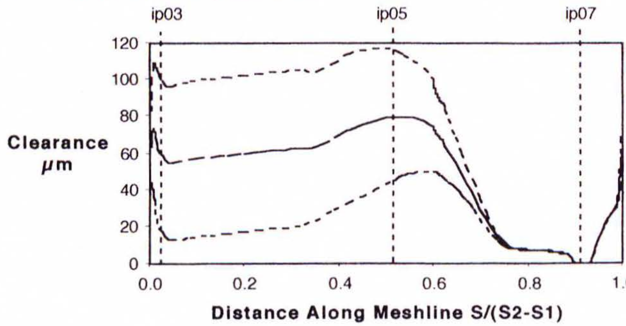


**Figure 4.2** Meshline Clearances for Nominal $\pm 10\mu m$ Rotors

Of interest are clearance characteristics with rotors whose shape varies non-uniformly as a result of the manufacturing deviations computed in Section 3.

First, clearances for a female rotor with a -Zt deviation paired to a male with a +Zt deviation (profiles as defined in Section 3.3) are shown in Figure 4.3. This combination reduces the clearance near the target contact region (*ip07*) in the direction of the outer diameter (towards *ip05*) of the male rotor.

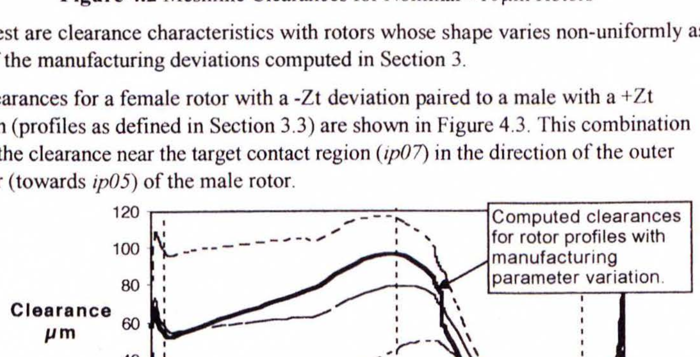


**Figure 4.3** Computed Effect of $-\Delta Zt_{female}$ and $+\Delta Zt_{male}$

This analysis immediately shows the value of the computerized manufacturing simulation. Even though the individual rotor profiles computed with the Zt deviations lie within the assumed target tolerance band of ±10μm, the rotor pair have unacceptable meshing characteristics -- in this case a contact that has moved away from the target location.

Because of this, a modification to the nominal clearance distribution is made by changing the shape of the male rotor in the vicinity of *ip07*. With this modification, the intermesh clearances with the Zt deviations as before are as shown in Figure 4.4.

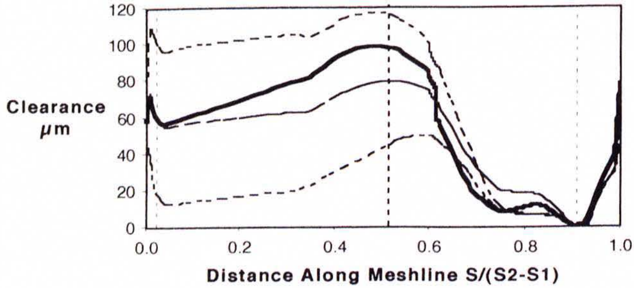


**Figure 4.4** Modified Profile with $-\Delta Zt_{female}$ and $+\Delta Zt_{male}$

In this case, the contact zone remains in the target location around *ip07* and the minimum clearance between *ip07* and *ip05* is very nearly at the original profile target.

Figure 4.5 shows the effect of manufacturing lead variation on the pair characteristics. Here, there are two computed clearance distributions displayed. With lead variation on both rotors such that there is a maximum error in relative lead, there will be contact at *ip07* at only one end of the rotors, the case shown with the dark, solid line. The data plotted with the circle symbols shows the effect on clearance at the opposite end where the full relative lead error is seen as a 20μm clearance at *ip07*.

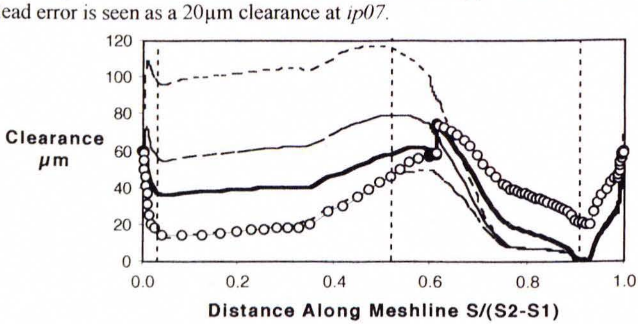


**Figure 4.5** Effect of Manufacturing Lead Variation

Using only the individual rotor deviations computed in Section 3, there were 17 pair of rotors studied, only 3 of which are presented here. While each of the other rotor pair clearance characteristics cannot be presented separately in this report, it is interesting to look at the total range of clearance possibilities. This range is shown in Figure 4.6.

The dark, solid lines show the envelope of all of the rotor pair clearances computed. It is important to note that this represents only a small portion of the total number of possible combinations. The data plotted with the circle symbols shows the enlargement of the envelope when the effect of the maximum relative lead error is considered.

Without the relative lead effect, we can see that the rotor pair clearances all lie well within the range that would be generated for rotors with profiles that vary from uniformly +10μm to -10μm. In fact there are no individual manufacturing variations (except for appropriate shape variations in the tool form itself) that would produce a profile at precisely the nominal shape shifted ±10μm.

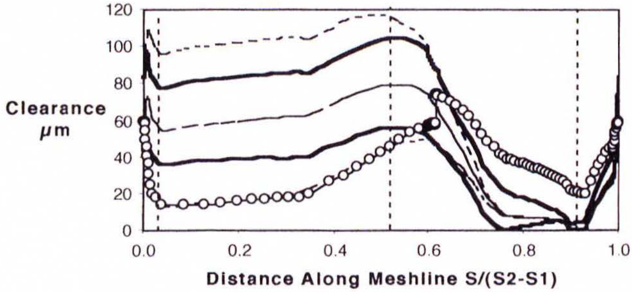


**Figure 4.6** Range of Rotor Pair Clearances for Variations in Parameters Studied

**5.0 Statistical Rotor Pairing Study**

Results from an analytical rotor manufacturing study can be used to determine profile modifications for acceptable rotor clearance characteristics. As noted in this report, there are many parameters that contribute to the shape of each rotor profile. Further, since rotors are paired, the total number of parameters affecting clearances is doubled. Thus, it seems appropriate to consider statistical methods to set either the rotor clearance for a given center distance or to determine the center distance for a particular rotor pair.

A statistical rotor pair assembly model was written using the Mathcad® 7 program. Rotors are assumed to be made with profiles that vary ±10μm at *ip03*, *ip05* and *ip07* with an additional 10μm variation due to relative lead error. Assembly analyses were run assuming that the profiles varied within these tolerances with both normal and uniform distributions across the tolerance band.

Here, the analysis is used to find the minimum allowable center distance for rotor pair with the assumed clearances. A center distance was assumed and a total of 10,000 trial assemblies were generated. Intermesh clearances at *ip03* and *ip05* were checked for possible negative values (unacceptable assemblies). The appropriate center distance was assumed to be that at clearance at *ip05* is always greater than zero and where no more than 5 assemblies out of 1,000 have clearance less than zero at *ip03*. The clearance at *ip07* was always greater than or equal zero since all analyses were for rotors rotated to be in contact at this point or offset to positive clearance by the effect of the relative lead error.

At the design center distance for which all analyses in Section 4 were carried out, the nominal clearance at *ip03* is 55µm with a minimum of zero if relative lead error is added to the minimum clearances shown. Thus, the nominal center distance is the minimum allowable for this 'worst case' analysis.

If profile and lead deviations are assumed to have a uniform distribution across their assumed tolerances, the analytical statistical assembly study shows that the center distance can be reduced by 18µm with the mean value for clearance at *ip03* being reduced to approximately 40µm. This means that average performance of production compressors would increase.

Then, if the profiles and lead were assumed to have a normal distribution within their tolerance bands, the statistical assembly study shows that the applied center distance could be reduced by 33µm. In this case, the mean clearance at *ip03* is 25µm, representing a potential for even higher performance. The Mathcad chart for the assemblies with center distance reduced by 33µm is shown in Figure 5.1. This chart shows the results for both the uniform (line) and normal (columns) distributions.

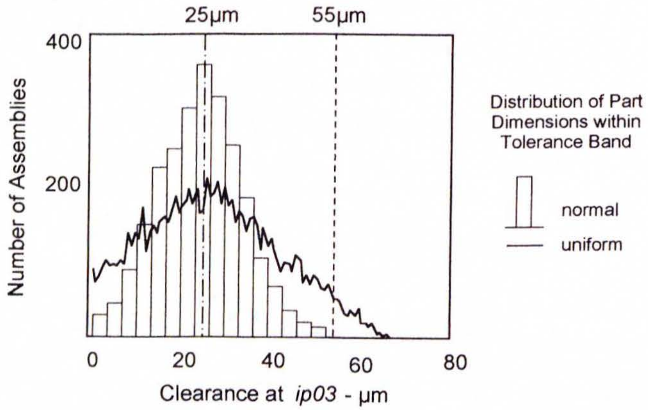


**Figure 5.1** Statistical Assembly Results at -33µm Center Distance

This last example illustrates both the advantage of using the statistical assembly approach and the importance of having accurate information about the manufacturing capabilities to use in the assembly simulations. The analysis for a 33µm reduction in center distance resulted in an acceptable condition (no more than 5 unacceptable assemblies per 1,000 trials) for the assumed case of normal distribution of deviations. However, as seen in Figure 5.1, if the variations in parts are uniform across their tolerance bands, there are many assemblies with clearances below zero. In fact, there would be more than 70 unacceptable rotor pair per 1,000 samples in this case.

### 6.0 Summary and Conclusions

A simulation of screw rotor profile manufacturing is used to demonstrate the deviations in rotor profile shape that are characteristic of variations in particular manufacturing parameters. Rotors with the computed deviations are then paired analytically to illustrate how selected profile variations will effect the clearance characteristics of a rotor pair. This analysis shows that even rotor profiles made to tolerances that would appear under simple analysis to be sufficient for good rotor pair may in fact lead to unacceptable rotor pairs.

Computed rotor profile and clearance characteristics are then used in a simple statistical analysis. Results of this study show that knowledge of manufacturing process capability and tools to use this information in manufacturing and assembly analyses can lead to improved performance (lower applied clearances) without the risk of reliability problems associated with assemblies whose clearances are too low. However, the analysis also shows that application of the statistical assembly method with information not representative of the actual manufacturing processes can lead to undesirable results.

### 7.0 References

/1/ Stošic', Prof. Dr. Nikola; Smith, Prof. Dr. Ian; Kovačevic', Dipl. Ing. Ahmed; *Some Aspects of Tool Design for Screw Compressor Rotor Manufacturing*; Proceedings of the 5th International Design Conference "Design 98"; Dubrovnik, Croatia; May 19-22, 1998.

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