1992

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S. E. Edstrom
Edstroem Consulting AB; Sweden

Edstrom, S. E., "A Modern Way to Good Screw Rotors" (1992). *International Compressor Engineering Conference.* Paper 832.
https://docs.lib.purdue.edu/icec/832

A MODERN WAY TO GOOD SCREW ROTORS

Sören E. Edström
EDSTROEM CONSULTING AB
Uppsala, Sweden

ABSTRACT

A computerized system is discussed that will allow a generalized treatment of screw compressor rotors with different profiles, from profile definition, through theoretical coordinates, clearance application, tool coordinates, simulation of the machining process and different schemes for rotor checking, all with the aim of obtaining a better quality at a lower cost.

INTRODUCTION

The idea of having screw-shaped rotors as pumping machine elements is more than a hundred years old. When Carl Montelius was struggling with the mathematical expressions for his rotor profile back in Stockholm in the early twenties, he was not the first person to become intrigued by the idea of a positive displacement machine with pure rotary motion. It was easy to imagine the great benefits of such a machine. It was also relatively easy to describe how the rotors should look. The difficulties, and frustrations, came when it was time to make those crucial elements.

Carl Montelius dreamt about screw compressors as well as about screw pumps, but it was only the screw pumps that made it to the market place at that time. They are still there, under the name of IMO. Immersed in oil, the screw pump rotors have a more forgiving environment to work in than the dry running compressor rotors that were in creative men's thoughts during the early days. It is quite logical that Alf Lysholm's screw compressor, which came about a few years later, had much greater difficulties in making it in the real world.

But eventually also the screw compressor came around in a very convincing way. Several screw compressor manufacturers appeared, but most of them were not very interested in telling the world how they made the rotors. It could be taken for granted, though, that there was some "back generation" involved (a physical generation of the shape of the tool from the shape of the rotor end plane) - and that there had to be some kind of hand fitting of the rotors after the machining.

When the oil flooded type appeared on the scene, the slope of the growth curve for the screw compressor industry increased abruptly. There are now many manufacturers to be found and most of them have their somewhat special screw rotor technology. The bigger companies normally make their own rotors, but there are also quite a few that are buying the rotors from somebody else. We will in the following be thinking primarily about rotors for oil flooded compressors. Many different rotor profiles are being used, all with their specific descriptions, often under the same roof. Most rotors are being milled, but some are hobbed and some are finished by form grinding. The quality assurance procedures can be quite different for different profiles and different manufacturing methods. Confusion and mistakes can easily be the result of all this variety.

Now to our help have come the computer, the numerically controlled tool machines and the intelligent coordinate measuring machine - and the time appears to be ripe for some attempts to create a more "streamlined" way from rotor definition, through rotor manufacture, to quality control of the typical modern screw rotor. The basic aim is better control over the whole process, resulting in better rotors at lower costs.

BACKGROUND

The basic geometry of a screw rotor profile has traditionally been given by some kind of "recipe", where the "ingredients" have been points, straight lines and parts of mathematical curves that are mixed in suitable proportions. (How to mix will not be discussed here.) The rest of the profile is then made up of segments that are generated by those parts. For the designer of a certain profile it is natural to mark out where those specific ingredients are located, but for the people who shall make and control the rotors these "design points" are not so interesting.

For quite some time now, computer programs have been used for the creation of coordinate points that are describing the actual shape of the rotor in a plane perpendicular to the axis of rotation. These coordinate points are numbered and distributed along the flanks of the two rotors. However, often a very short part of one rotor is generating a long part on the other rotor, and for the sheer description of the form it is then natural to use more points on the long part than on the short part. This will result in a mis-match of the points, so one is loosing track of where a certain point on one rotor will make contact with the other rotor. In this situation the design points are serving as "meeting points" all right, but they are normally too few and too unevenly spaced to be of any real value when the ambition is to map the interaction between the two rotors.

After the design of the basic profile comes the application of clearances. Some clearances are needed between the rotors (except in the contact zone, of course) under actual working conditions. The cold rotors must contain these clearances plus what comes from the change in temperature. To obtain a good cold clearance distribution, the theoretical, zero clearance coordinates must be modified in a large number of points.

When thinking ahead, and knowing that the next step in the making of a screw rotor is to calculate the shape of the tool to be used, it is natural to think about possible tool modifications already at this stage. Some parts of the tool are wearing faster than others and there are elastic deformations and temperature effects that will influence the result of the operation. It is quite foreseeable that a tool could need modification in many places. For the profile designer with a good feed-back from the rotor manufacturing floor, it can be convenient and expeditious to "tweak" the design clearances a little bit to accommodate also these aspects. Such a method is not to be recommended, however, if the goal is the best possible understanding of the process.

For the calculation of the tool coordinates, many rotor manufacturers have developed their own computer programs, but often it is very difficult to correlate these coordinates with the corresponding rotor coordinates. By this, of course, much of the preciseness in the quality control chain is lost. Cumulative errors in grinding templates, for instance, cannot be related to the variations in clearances they will create.

Something that has entered the scene, and shows great promise, is a numerically controlled machine, dedicated to the grinding of cutters for screw rotors. Providing a direct step from tool coordinates to cutters ready to use, such machines are introducing a new flexibility into the rotor making process. These new possibilities should be further explored and will undoubtedly pave the way to significantly more accurate screw rotors.

For the actual machining of the flutes of the screw rotor, there are now different CNC machines available, employing the milling, hobbing or grinding principle. The details of these machines or those processes will not be discussed in this context, but they are a very important part of the background to be kept in mind when a software package for the whole screw making process is contemplated.

The final check of the rotors has traditionally been in the form of a "pairing" operation. Two promising candidates are mounted between centers at a given center distance and the clearances are checked by means of feeler gauges in a certain number of places. If the clearances are off, it is next to impossible to see directly which rotor is at fault. (Or if both are to blame.) This is the place where "intuition", based on a deep familiarity with the whole process, has been of extreme value - and correspondingly, where a newcomer to the field could feel something close to desperation. Often trial and error has been the last recourse, with many costly errors in the log book.

The coordinate measuring machine (CMM) is becoming more common, and is providing a more direct indication of the accuracy of the individual rotor. What can be controlled most easily, is the form of the cross-section of the flutes, which is related to the form of the tool. To survey the whole surface area of the rotor in order to make a complete map, would be next to impossible. That fact, together with the often impractically arranged data has made it very difficult to arrive at dependable predictions regarding the clearances between a pair of measured rotors, based only on these measurements. The full benefits of having access to a CMM have therefore in most cases not been realized.

Holroyd (well known company in this area), have announced that they are working with a very interesting alternative to the CMM, in the form of an automatic profile inspection machine (PIM) that can measure the clearances between two rotors by means of light. [1]. Also individual rotors can be checked by pairing them with some very accurate and well defined "master rotors". An added advantage of that machine is that a direct check of the rotational interaction between the rotors can be arranged, giving information on backlash and possible errors in the transfer of the angular motion from one rotor to the other.

Numerically controlled measuring machines can easily put out an enormous amount of data, so the question is always how to reduce and refine all that information to something that is to the point and easy to grasp.

IDENTIFICATION POINTS

From the foregoing it should be clear, that there is still much that can be desired. We will now walk through the process again and keep an eye out for what "soft" improvements that could be made in the process of making screw rotors.

Starting with the basic profile, we can see that it is necessary to have a generalized description that can be used for ANY screw rotor profile, to be able to lay out fixed ways through the rest of the work. The details of that work are presented in the parallel paper "Software support for screw rotor design, manufacture and quality control". [2].

Of great importance in this rotor making process is the ability to check every step, directly after that it has been taken. According to the traditional way one has, however, been working fairly much "in the dark". What we need now is to know where we are, and for that we need some fixed points that are easy to find; let us call them "identification points", abbreviated to IDPs.

Much of the action in a screw compressor takes place along what is often referred to as the "sealing line", which is the threedimensional curve described by the contact between two perfect, zero-clearance rotors at the theoretical center distance. When the rotors turn, this sealing line moves axially. Looking at what is taking place in one fixed cross-section, we will see that for modern profiles there is sometimes one contact point in action and sometimes three. Therefore it will be impractical to number the points based on when they are engaged.

The most important quality of a pair of rotors is their ability to "seal" between each other. (To be strict, one should say: "control the leakage".) This "sealing quality" of a pair of rotors is mainly dependent on the average clearance, counted over the length of the sealing line. To be able to form that average clearance in a convenient way, it is practical to get the individual clearance values at equidistant points along the sealing line. If we elect to relate our IDPs to the sealing line, then we will automatically get a pair of cooperating points on the rotors, namely the ones that come together right at that point on the sealing line. Therefore, the IDP on the sealing line and the corresponding IDPs on the rotors could preferably have the same designation, see Figure 1.

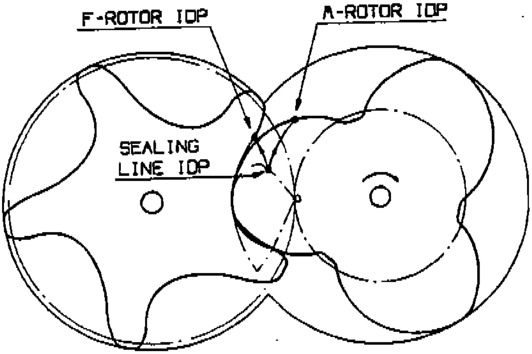


Figure 1. Creation of identification points.

Regarding the appropriate number of IDPs, one could say that ten would be too few and one thousand definitely too many, so we arrive at something in the neighborhood of one hundred. (One hundred is actually a number that plays a rather central role in our life with percentages and centigrades.) For the checking in a CMM, one hundred points is adequate in most cases and for the detailed application of clearances and other form modifications it will be more than adequate. Different sub-series can be created, to be used in different cases, e.g. every tenth for feeler gauge measurements.

If we put those IDPs in basically the same place on all commonly used compressor rotors, then it would be much easier to communicate in matters of rotor quality. As practically all modern screw compressor profiles are of the asymmetric type, we could make use of that fact, which means that the sealing line between the rotors has one "long" and one "short" part.

Thinking of the sealing line, straightened out and put alongside a ruler, will lead us to the idea of calling the starting point "IDP No 0", abbreviated to "I0", and the last point "I100". (The centigrade scale for screw compressors.) Traditionally, one has paid most attention to the "high pressure part" of the sealing line (on the discharge side of the line between the rotor centers), which is the same as the long part. When checking a pair of rotors in a "pairing stand", it is most convenient to mount the rotors with this long part of the sealing line facing upwards. Thus it becomes natural to start the count of the IDPs on this part of the sealing line.

If we start with I0 at the tip of the female rotor lobe, corresponding to the center of the groove of the male rotor, and walk along the long part of the sealing line, the first point we come to that would be easy to identify is the point that is closest to the "high pressure cusp" (the intersection of the rotor bores on the high pressure side). This is also the point of interest when the size of the "blowhole" is calculated. As we now have walked roughly 40% of the way, we could call this point "I40".

The next easily identifiable point would be at the tip of the male rotor, corresponding to the bottom of the female rotor - "I60". When we have come to the other female lobe tip, we are "home", at "I100" (which is the same as "I0" of the next thread.) If we divide the distances along the sealing line between these basic IDPs in equally long parts, then the intermediate points will appear in proportional places for most commonly used rotors and will thus be easy to recognize. These IDPs are shown in Figure 2, where they appear on the rotors as well as on the sealing line.

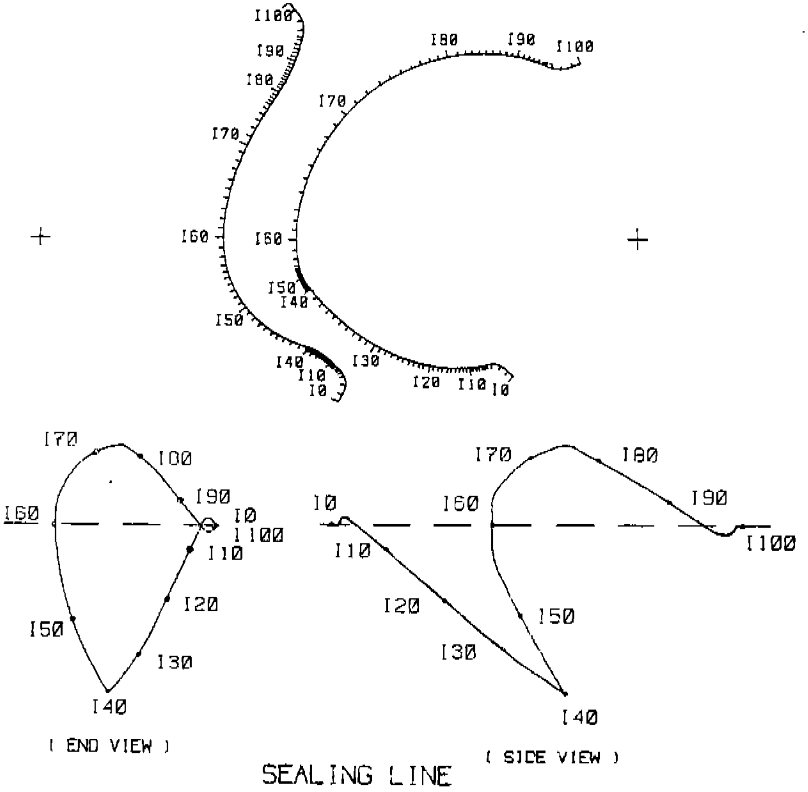


Figure 2. Identification points on rotors and on sealing line.

Still it is not quite clear how, more exactly, we should be able to arrive at those identification points. For a given profile, the relative length of the different parts of the sealing line is dependent on the helix angle at the pitch radius for the rotor in question. Often, however, the same profile is used for rotors having quite different helix angles, and it would be unpractical to have different sets of IDPs in those cases. Therefore, we may opt for something in the middle, e.g. the angle that corresponds to a length-to-diameter ratio of 1.5, when the wrap angle is 300 degrees. In case the rotors have different diameters, the mean value should be used.

Having access to a flexible computer program we can create a large number of coordinate points to choose from, and then "baptize" the points that are closest to the theoretically correct distances along the sealing line. (It would, of course, be possible to calculate these points more exactly by doing it "backwards", but that does not seem to be worth the effort.) The IDPs found in this way should always stay with a given profile, irrespective of the number of points one is electing to use for the profile definition, the tool calculations, etc.

From now on everything will be easy. (At least more clear.) The backbone of the quality assurance structure will be those IDPs, positioned on a straight line, which is what remains of the three-dimensional sealing line after two flattening operations to better make it fit on a piece of paper. As we will have to use that backbone fairly often, we should have a name for it, e.g. "IDP-line". Figure 3 shows how it will look.

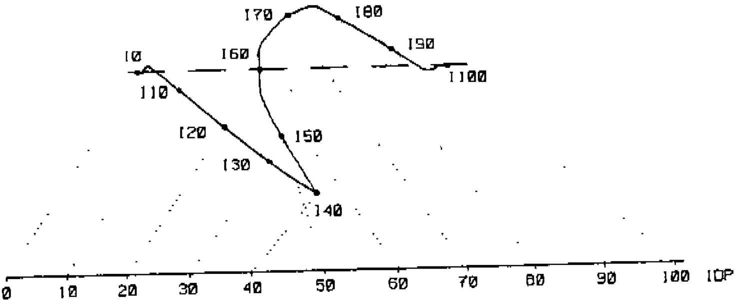


Figure 3. Basic IDP-line.

TOLERANCES

Tolerances, clearances, rotor quality, compressor efficiency and product viability are often discussed at the same time and they are indeed strongly inter-related. The designer of a new product has to put down some numbers on a piece of paper so that the manufacturer of the prototype knows what he has to work with. However, the total situation is so complex that it is impossible for the first man to know up-front what would be the "best" tolerances in the long run. To be quite realistic, for instance, there should be varying form tolerances along the flanks of the rotors. Thus, the tolerancing issue must be given much attention, before a design can be released for production.

The first question regarding the screw rotor tolerances is if they should be symmetric or asymmetric. Traditionally, most clearance-related tolerances have been asymmetric. The designer felt more at ease with tolerances that "went in the safe direction". At that time he probably did not worry much about the profile form or rotor contact pattern going out of shape as the actual dimensions moved away from the nominal.

To-day, when the possibilities for much better control over the whole process are here, there is no reason why we should not design for the case in the middle of the tolerance field, i.e. use symmetric tolerances. In that way the likelihood of getting good rotors will be enhanced as compared with the case with asymmetric tolerances. That system will, however, give the designer a little more work, as he has to go through some calculations to find out what the probability is for problems due to everything "going in the tight direction". The problem with "too tight rotors" is, of course, that they can give mechanical problems, while "too loose" rotors give efficiency problems.

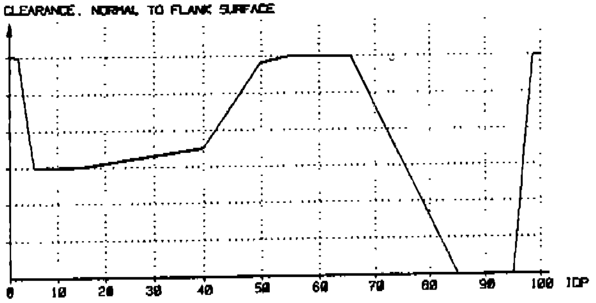
Form tolerances for the lobes of the rotors are being discussed more and more, largely because there is a general desire to be able to get away from the individual pairing of the rotors, especially the small ones. The subject of form tolerances for individual rotors is, however, a very large and difficult one and cannot be given a comprehensive treatment in this paper.

CLEARANCES

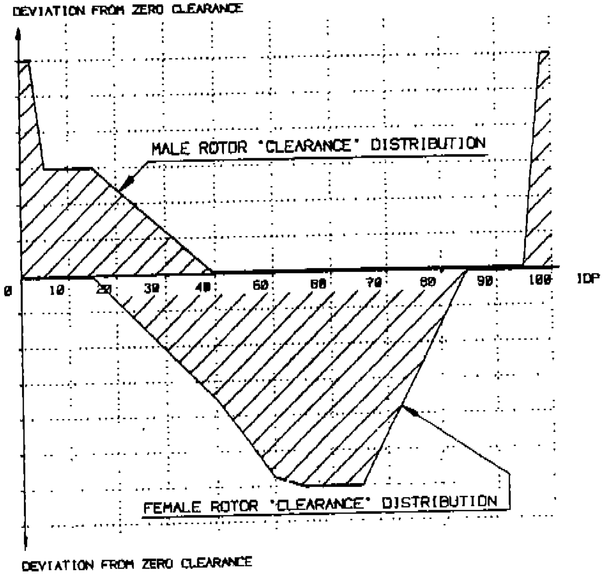
As the quality of a rotor pair to a large extent is a question of how well the "design clearances" have been realized, it is important that these design clearances are well documented. When dealing with clearances it seems to be most practical to work in the direction of the normal to the surface at the point in question. Those clearances are often referred to as "interlobe clearances" to distinguish them from "end plane clearances". It is the interlobe clearances that normally are measured and they are the ones that are most directly related to the sealing quality of the rotor pair.

If the design clearances, at the theoretical center distance, are plotted over the "IDP-line", a "basic clearance diagram", or a "primary clearance distribution diagram" will be obtained. Such a diagram can serve as a basis for all clearance-related checks. Figure 4 shows an example. Before the work can be regarded as completed, some limits for what is an acceptable variation of these design clearances should be worked out. In the same diagram are shown the two "secondary clearance distribution diagrams" that show how the design clearance is made up of the "clearance allocations" from the two rotors. (Strictly speaking, we cannot talk about a clearance when we have only one rotor.)

As we can see here, a program that allows us to apply the clearances very freely would be of great value. Normally, the hundred IDPs give enough flexibility, but if need be, also other coordinate points can come to use for the application of certain clearances.



PRIMARY CLEARANCE DISTRIBUTION



SECONDARY CLEARANCE DISTRIBUTION

Figure 4. Primary and secondary clearance distributions.

TOOLS

We are now coming to the transition from the "soft world" to the "hard world". Soft errors turn into hard errors. It is important that the small errors are caught before they have grown into big errors. Knowledge is helpful. The modern computer is a "soft" tool that should be used as much as possible before the step is taken into the "hard" world. With suitable programs, much of the rotor machining process can be simulated and the results of different kinds of errors can be studied.

One big step on this road is, of course, the transformation of the rotor end plane coordinates to some type of tool coordinates. When this has been done, there is always a question lingering around the corner: "How can we be sure that these tool coordinates are correct?"

To be able to answer that question with authority, one must have access to a program that can take the tool coordinates and go back to the rotor coordinates along a different route than the one used for the creation of the tool coordinates in the first place.

Assuming that we have such a rotor machining simulation program to work with, we can already there, in front of the computer screen, study many things - for instance, how different variations in the settings of the tool will influence the shape of the rotor, or how an improved shape of the tool could show up in the form of a modified rotor profile. What we cannot simulate with a strictly geometrical method is, of course, the physical behaviour of everything that is involved in the machining process. We must keep the "physical deviations" apart from the rest.

If we now look at the most common method of making screw rotors, namely by means of single-index milling, using bladed cutters, we might be able to see a few things there that could be done to minimize the risks for making big errors. We assume that we have already checked the tool coordinates by means of that simulation program, so the next step would be to make the grinding templates - unless one was able to use the latest CNC cutter grinder which does not require the use of templates. The question of appropriate tolerances will always be with us though, and we can basically apply the same general reasoning as before.

As mentioned at the outset, we must also count on having a numerically controlled coordinate measuring machine to work with, and the checking of the templates will be its first task during this exercise. Normally, templates are being used in pairs, like the rotors, and therefore it is natural to add the errors (with sign) of one template to the errors of the other template, and in such a way be able to directly see the influence of those errors on the clearances between the rotors. A computer program can be developed, that will take the measurements directly from the CMM and plot such a curve over the IDP-line. It could also compare these results with the design clearances to show, for instance, where the contact between the rotors would take place (assuming the rotors to be exact "reproductions" of the templates). We understand, that it is logical to demand a higher accuracy of the templates in those possible contact zones than in other places.

From the approved templates, the tools are now ground - and checked on a CMM, at the IDPs. The data from the CMM can be fed into the cutting simulation program and the deviations from correct rotor form caused by the errors in cutter form can "directly" be observed. Then another program for the pairing of these two rotors can be used, resulting in a plot that shows the deviation from the design clearances. The same basic reasoning can be applied also for the case when a numerically controlled tool grinding machine has been used.

When the first rotors are being cut, everything has to be very well documented and checked, in order for us to be able to sort out the deviations in rotor form that are coming from the "physics" of the cutting operation. Those deviations should be fed back into the tool coordinates directly, by means of a "tool modification program", and should never be allowed to appear in the clearance coordinates for the rotors.

Specific tolerances for the tool form could be developed after having gone through a large number of studies of the above mentioned sort - and after having received adequate feed-back from the rotor manufacturing facility. With that accomplished, it should be possible to catch all tool errors before they have a chance to develop into real problems.

ROTORS

The step from the tool to the rotor also means a step from a basically two-dimensional problem to a three-dimensional one. To carry out a complete CMM-mapping of every rotor would be unthinkable in this context - and the basic question is: "How much is good enough?" Clearly, we are here getting close to the realm of statistical process control (SPC). For large series of small rotors, for instance, the employment of SPC would most certainly enhance the efficiency of the rotor production. [3].

As the rotors in oil flooded screw compressors work as gears at the same time as they perform the task of pumping, the quality checks would have to address these aspects. We could be looking for a "sealing quality", an "angular meshing quality" and a "contact pattern quality". Assuming that one has a fair number of CMM-measurements of the rotors to work with, it should be possible to write a computer program that would take the individual measurements from two rotors and calculate some characteristic quality numbers in these respects. Such a number would, of course, be somewhat "soft", due to the incomplete mapping of the rotor surfaces in question. The PIM machine could, as mentioned earlier, produce "harder" numbers in a more direct way. Further details are given in the references [1], [2] and [4].

CONCLUSIONS

By making full use of the modern possibilities offered by the numerically controlled tool machines, the sofisticated measuring machines and the powerful desktop computers, significant improvements can be made in the process of making screw compressor rotors. A homogeneous system is required, with tailor made computer programs, for efficient feed-back, evaluation and steering of the process.

ACKNOWLEDGEMENTS

Over the years, a large number of people I have worked with have provided valuable input into these specific issues - especially R&D and rotor technology personnel at Gardner-Denver Company in the seventies and Benneth Gustafson and Robin High, rotor manufacture and quality control specialists at Svenska Rotor Maskiner (SRM) in the eighties - to all of them my sincere thanks.

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