Towards a core program for the measurement of screw rotor bodies by co-ordinate measuring machine

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Abstract

With the increasing use of the co-ordinate measuring machine (CMM) for measuring screw rotors has come a variety of methods of evaluating and presenting the data. This lack of standardisation has created a confusing situation both for rotor manufacturers and for CMM programmers. An attempt is made to consider from first principles the relationship between tolerancing and measurement in rotor manufacturing and to assess the role of the CMM in that context. The suitability of some of the current CMM methods is discussed. The paper concludes with proposals for standardising the expression of deviations.

Zusammenfassung

Durch den immer häufigeren Einsatz von Koordinaten-Meßmaschinen (CMM) für das Messen von Schraubschwungrädern werden mehr und mehr Methoden für die Bewertung und Verarbeitung der erarbeiteten Daten entwickelt. Aufgrund der Abwesenheit einer Standardisierung dieser Methoden ergibt sich eine verwirrende Situation für Schwungrad-Hersteller sowie fur CMM-Programmierer. Zur Zeit wird versucht, das Verhältnis zwischen Toleranzeintragen und Messen in der Laufradherstellung nach ersten Prinzipien zu untersuchen und die Rolle von Koordinaten-Meßmaschinen in dieser Hinsicht näher zu definieren. Die Eignung der gegenwärtigen CMM-Methoden wird diskutiert. Die Abwandlung schließt mit dem Vorschlag, die Formel der Abweichungen zu standardisieren.

Introduction

The co-ordinate measuring machine has established itself in the screw rotor manufacturing industry, but unfortunately, the variety of methods of collecting and presenting the measurement results is growing. A single CMM manufacturer might be required to produce vastly different programs for each of his customers, who each specify their own requirements. Holroyd, as a manufacturer of rotors for many compressor companies, find this 'Tower of Babel' situation at best inconvenient, and at worst a source of potentially expensive confusion, whilst the CMM suppliers must give considerable time to implementing multiple variations on a theme – a programmer's nightmare. This paper is an attempt to open discussion of the important elements of a CMM rotor program.

However, in order to put the role of the CMM in context, it is first necessary to consider the relationship between tolerancing and measurement in rotor design and manufacture, to keep ourselves focused, and to assess the likely developments.

1 Tolerancing, Measurement, and Manufacture

The search for perfection can result in three different strategies in the tolerancing of rotors, and these have wide implications for manufacturing. The methods can be termed 'relative tolerancing', 'absolute tolerancing', and 'combined tolerancing', and it is necessary to consider carefully the implications of these strategies for inspection and manufacture. However, even more fundamental is to consider the basic aim when applying tolerances to screw rotors.

1.1 The gap quality criterion

The purpose of rotor tolerancing must be considered with reference to the purpose of the rotors themselves, namely to trap and displace gas. The quality of the sealing zone between the rotors results from the clearance distribution being sufficiently small to prevent significant leakage, but sufficiently large to prevent interference at all running conditions. The uniformity of this gap over the engagement cycle can affect the contact pattern and transmission error of the pair, and hence the life and noise characteristics of the compressor. The sole purpose of the rotors, according to Jack Sauls, senior research and development engineer of the Trane Company, USA, is to produce this gap.

This is worth re-stating as an axiom:

> **The quality (suitability for purpose) of screw rotor bodies results from the quality of the gap between them.**

We can call this the *gap quality criterion.* Rotation of the rotors should produce negligible change in the backlash and transmission error, but both these can be related to their effect on the gap, and so the definition holds. (Material properties are also important, but are not relevant to our discussion.) We can now consider tolerancing strategies in the light of this definition.

1.2 Relative tolerancing

In this strategy, clearances are specified at designated points around the profile, the only absolute dimensions being the tip and root radii. Also specified are the location and extent of the contact band, and the backlash. These measure the net effect of all clearance variations, whether caused by profile, relative lead, or angular pitch deviations. This is the method in general use by the industry world-wide.

Two specific examples of this tolerancing should be kept in mind:

1. In order to ensure correct contact along the drive band, only the *relative axial pitch* of the rotor pair is important. If this value is close to zero, the absolute values may both deviate considerably from the designed value, with no measurable detriment to performance. Note that a difference of a few microns is sufficient to destroy the continuous contact pattern which is required. The relative axial pitch is determined by the two leads.
2. The profiles of opposite flanks may be considered as independent from each other. A thick male with a correspondingly thin female will result in the correct gap and backlash. As with axial pitch, the actual thickness of the lobes may deviate considerably from the designed value, with no measurable detriment to performance. Once again, however, a small mismatch is sufficient to destroy the required backlash and trailing flank clearance.

Note that modern machinery, properly used, is able to keep the shape of the two halves of the profile correct, i.e. it is not necessary to match waviness in the profiles, as was the case before the introduction of closed-loop control systems for tool dressing. This was largely responsible for screw rotor manufacture being called the 'black art' of the compressor industry, a reputation which is now, thankfully, being shed.

Note also that suitable depth probing systems now permit accurate and absolute control of cutting depth. This is necessary because the profile root must mate with the tip of the mating rotor, which in turn must have the correct clearance with the housing bore. Constancy of cutting depth also results in constancy of lobe thickness (disregarding tool wear).

Thirdly, note that is is generally safe to assume that systematic deviations in lead and divide will be negligible, because of the in-built accuracy of the machine tool. Regular machine condition monitoring is usually all that is required.

The built-in assumption of this strategy is that interchangeability is not an essential requirement. For example, if rotors become damaged during running, both would be replaced, since both are likely to be affected. In practical manufacture, some interchangeability is achieved, since batches of males and females are made to match, a process which can be called 'batch pairing'. (Note that this is not *selective* pairing, i.e. it does not involve *searching* for rotors which match, a misunderstanding which has been known to occur.)

The advantage of relative tolerancing is that it is not necessary to 'over-control' the manufacturing process, since only relative dimensions need be fine-tuned in order to satisfy the gap quality criterion. In the case of lobe thickness, this may be used to advantage by extending tool life.

It is natural to use pair measurement techniques in this case. Two further 'acid tests' of pair quality are transmission error and backlash plots, the latter resulting from the subtraction of the transmission error curves in each direction of rotation.

Traditionally, a pairing stand has been used, with feeler gauges to measure clearances, dial gauges to measure backlash, and a visual inspection to check the contact pattern. Putting the rotors together is the most sensitive method of revealing lead mis-match. However, the method suffers from the following limitations:

1. Limited resolution of clearance measurements, resulting from the difficulty of estimating between feeler gauges having 10 micron intervals.
2. Limited reproducibility of feeler gauge method. Significant variation in operator 'feel' and positioning can exist.
3. Difficulty of measuring backlash continuously over the engagement cycle, and of detecting the minimum. The method is time-consuming.
4. Lack of equipment suitable for measuring transmission error.

In an earlier paper I described a method of measuring screw rotor pairs which is accurate, fast and automatic [1]. The system may be termed a Conjugate Pair Measuring Machine, or CPMM. It measures clearances optically and gives a continuous plot of transmission error and backlash over the full cycle of engagements by means of rotary encoders. The first working machine is now in use at Holroyd, and is called the Automatic Rotor Analysis Centre, or ARAC. The system has been designed to overcome the aforementioned limitations of pair measurement, and will therefore assure the continuation of relative tolerancing into the future as requirements become more stringent, as for example in small refrigeration applications.

1.3 Absolute tolerancing

By this strategy, absolute tolerances are applied to each rotor, resulting in full interchangeability. The main consequence is to make tolerances extremely tight, as can be easily seen from the two examples quoted above. The difference in relative axial pitch for loss of contact at the drive band is only 2 or 3 microns, since the pitch difference accumulates along the rotors. The absolute tolerance on each rotor lead would therefore need to be half the relative tolerance to guarantee a correct result. A similar argument applies to the lobe thickness of each rotor.

The reasons this strategy has seemed attractive to some come firstly from the limitations of the feeler gauge method of measuring rotor clearances, compared with the accuracy offered by the CMM.

Another reason for absolute measurement is the need to perform statistical assessments of machine capability when shopping for machine tools, and here again, the feeler gauge method has proved inadequate.

A third reason is perhaps a 'gut feeling' that it should be possible to make every rotor exactly right. This challenge was taken on at Holroyd, and it was found that by extremely careful control of key process variables, absolute tolerances and full interchangeability can be achieved, even for the extremely tight tolerances of small refrigeration rotors. Nevertheless, the strategy leaves no room for even small errors at any stage in the process.

The CMM is clearly suited for this kind of measurement. It should also be noted that the CPMM may also be used for absolute measurements by pairing the rotor to be measured with a calibrated rotor, i.e. one which has been measured on a CMM. The limitations listed above have thus been eliminated, and the rush towards absolute tolerancing has receded, perhaps to await the time when there is rather more 'comfort' in the manufacturing process.

1.4 Combined tolerancing

Another alternative, a hybrid of the previous two, is to use relative tolerancing, within loose absolute tolerance limits. These absolute limits need only be applied to one rotor of the pair. This ensures in a formal way that deviations in profile, lobe thickness, lead, and divide are not excessive, whilst leaving their exact mix to the rotor manufacturer. This method is soundly based on the gap quality criterion, and has much to recommend it on economy grounds.

Here again, alternative methods of measurement are: a) CMM or b) CPMM with CMM-calibrated rotors.

1.5 Process control

Before summarising the role of the CMM, a word about process control will be useful. Process control, to be effective, should be as near instant as possible, so that useful feedback to the process is provided. Gauging of key dimensions is normally sufficient, either on or near the machine tool. Although not at present suited to providing timely control feedback from each rotor to the machining process, the CMM may be used on a sampling basis.

In monitoring machine condition, e.g. for long term maintenance, test batches can be cut from time to time and measured by a CMM.

It also has a role in providing feedback for tool preparation, where needed. In the case of precision profile milling, the tool blades are first ground to within 2 or 3 microns of the calculated profile on a cutter sharpener, and then a test rotor is cut. In some cases, for example, when the rotor material is very hard, the resulting rotor profile contains unacceptable deviations which are nevertheless repeatable. CMM profile measurements may be used to produce a compensated tool shape, which is done by modifying the target rotor profile data with deviations which are the negative of those measured, and re-calculating the tool profile.

2 Options for the CMM Program

The roles of the CMM in rotor manufacture, as we see them, may be summarised:

1. As a reference standard.
2. In the calibration of rotors for a CPMM.
3. For part sampling, where absolute tolerancing is used, as an alternative to the CPMM.
4. For tool compensation, where necessary.

5. For machine diagnostics.

We should now consider the alternative types of CMM program.

2.1 Basic procedure

It will be clear that a full measuring sequence would be excessive for some of these functions. For example, tool preparation only requires profile measurements. However, we should, as a principle of good practice, conceive the program as a whole, from which sub-routines may be selected.

The basic elements of the program are:

1. Establish the rotor Z axis with reference to the bearing cylinders and the rotor end plane.
2. Establish the rotor X and Y axes. By probing a specified point on one of the lobes, at the drive band, at a given Z section, the initial Cartesian system for the rotor is completed. (After measurement, the orientation of the axes relative to the rotor may be adjusted by rotating the data to give a 'best fit' of the corresponding points on all lobes, for example, at the drive band.)
3. Profile measurement, on one or more profiles, at one or more transverse sections.
4. Helix measurement (one or more lobes).
5. Divide (angular pitch) measurement.
6. Evaluation of deviations. The rotor's features must be presented clearly by graphical displays which allow at-a-glance identification of deviation types and magnitudes, in relation to tolerance zones. Data listings should be easily related to the graphical plots, with out-of-tolerance values high-lighted.

This list contains no surprises. However, some clear divergences of philosophy have arisen when deciding how to evaluate deviations.

2.2 The problem of projecting deviations

The first CMM screw rotor program at Holroyd, in use since 1986, is still in use on Holroyd's Leitz CMM. This evaluates profile and helix deviations normal to the surface, and displays them to a suitable magnification on the transverse profile, and on the helix base line respectively. All deviations are positive when there is excess metal. These conventions make the output easy to understand by all technical personnel.

Another approach is also in use in some programs on the Holroyd Leitz, at the request of some customers. These programs project deviations into the transverse and axial planes. Some authorities (not Holroyd) argue that because a helical surface is completely defined by its transverse section (end profile), and lead, surface deviations should therefore be evaluated in the same way. We have been able to make comparisons as to the usefulness of the two methods.

At this point we should keep in mind the rotor quality criterion, i.e. that the quality of the rotors results from the quality of the gap between them. The purpose of our CMM measurements is to determine the inter-lobe clearance distribution, and these clearances are affected, micron for micron, by deviations *normal to the surface*. For example, a 2-micron bump on one rotor, and a 2-micron bump at the corresponding position on the mating rotor, results in a 4 micron change in the gap. A similar argument applies to the calculation of transmission error, where a most useful convention used is that excess material on either rotor causes a positive transmission error, i.e. the driven rotor advances. Thus positive deviations should relate to the 'plus metal' condition. (For transmission error calculation, a conversion factor is also required based on the flank and helix angles at the drive band, with the result usually related to its effect at the pitch radius.)

2.3 Fault diagnosis

Projected deviations are not as useful for the diagnosis of certain faults as the surface normal method. For example, for deviations caused by surface roughness, waviness, tool frequency marks (feed marks), or scratches, the projection distorts their true size, and hence their relationship to their original cause.

Complications also occur reading profile tolerance diagrams, because the scaling factor to convert from normal to transverse deviations is not constant around the profile, but depends on the combined effects of profile flank angle and local helix angle. A constant surface tolerance, which under the surface normal convention would be represented by parallel lines on either side of the designed transverse profile, becomes a continuously varying quantity represented by a very complicated-looking tolerance zone.

2.4 Helix confusion

In the absence of any standards for rotors, we should at least be aware of the gear standards. ISO 1328 for parallel axis involute gears (i.e. small helix angles) [2] requires helix deviations to be projected into the transverse plane, whilst BS 521 for worm gears (large helix angles) [3] gives formulae for calculating surface normal deviations from lead and divide deviations.

Screw rotors fall between helical gears and worm gears, being generally between 30 and 60 degrees helix angle. At these angles, surface deviations may be almost doubled when projected into the transverse or axial planes. Note especially that clearances are not critical in gears, except possibly the Novikov–Wildhaber type. This is perhaps our first warning that gear standards might not be adequate for screw rotors.

Another argument says that it is natural to use transverse and axial projections, since the deviations follow the original definition of the helical surface, i.e. by transverse profile and lead. However, in the case of lead, another problem must be considered. Lead is an extremely useful quantity, being the axial distance traced by any surface helix in one revolution, and is the same for all profile points, unlike the helix angle, which depends on the radius. However, besides the distortion of deviation magnitudes, there are consequences for sign conventions which add unnecessary complexity to interpreting the direction of the deviations, and performing calculations to predict their combined effect on the pair.

If the lead definition is followed strictly, the deviations are positive when the lead is increased. Thus, for a local high spot on the surface, the sign of the deviation is positive when moving in the positive Z direction on the left flank of a right hand lobe, or the right flank of a left hand lobe. That is, the sign of the deviation is determined by the hand of the lobe, the flank being measured, and the axial direction defined as positive. If any one of these is reversed, or all three, the sign changes, whilst if any two are reversed, the sign is unchanged. This makes understanding the deviations confusing, and prone to mis-interpretation not only by the operator, but often by the experienced engineer who has to adapt his thinking from one method to another. It certainly lacks the simplicity of 2+2=4!

Perhaps the single case where projection is required is in the calculation of true lead and its deviation, based on the projection of the helix regression line over one revolution. These two values may be used to correct small errors in the manufacturing machine set-up.

2.5 The problem of combining deviations

Measuring rotor quality by means of a collection of projected deviations is not a easy, for the simple reason that the projections from a single surface deviation are not independent quantities. A single surface fault, say a lump on the flank, which would have a simple micron-for-micron effect on the gap, will appear in four projections. It is an interesting exercise to try and construct a spreadsheet model which combines tolerances in profile (transverse), lead (axial), divide (transverse angle), and surface texture (normal) into a measure of the surface form. This will necessarily involve assumptions about duplication and tolerance 'stack-up' probabilities, and is unlikely to result in simple answers.

Because the various projected deviations are not independent it is often difficult to separate out the sources of error. For instance, apparent divide error might be caused by faulty machine divide, cutting depth variations, lead error, or run-out in the reference cylinders used as the datum. Nevertheless, this is the task of the production engineer, based on his experience and the other process information and calculation tools available to him.

The rotor designer, whether he is using absolute or relative tolerancing, should avoid making the control of all these deviations an end in themselves. Instead, he should concentrate on tolerancing the rotors by defining the surface form which will produce the correct clearance distribution at all engagements.

3 Proposals

What is being argued here is that the practice of projecting deviations into several directions is intolerable, and one direction only should be chosen.

The gap quality criterion might well lead us to the conclusion that most tolerances and measurements should be relative to the defined surface, following the concept of surface form. Thus the deviation at any point has a single value, namely its perpendicular distance from the designed surface. This gives the simplest definition of profile tolerance. The designed and actual surfaces may be conveniently brought into relation with each other as mentioned above. The disadvantage is that calculation is needed to relate surface deviations at the contact band to the transmission error.

Alternatively, if all deviations were projected into the transverse plane, this would at least have the merit of consistency, and might have some advantages of its own, since a rotor is essentially a series of identical transverse slices with an angular orientation between them. Its main disadvantage would be the distortion of surface defects by varying amounts around the profile, and the related problem of relating the complex profile tolerance zone to the gap. As far as I know, this system has not yet been tried.

The third alternative, that all projections should be projected axially, has no obvious merit, and would in my opinion be hard to justify.

Perhaps the sensible way forward for now is to write CMM programs which allow easy switching from normal to transverse modes, and evaluate both systems side by side. In the proposals below, the word **'normal'** may be read as **'normal, or transverse, but not both'**.

For graphical displays (profile, helix, etc.), the deviations may be plotted in various ways, the important requirement being that the magnitude and sign of the deviation at any point on the surface stays the same regardless of the method of display. On these assumptions, we can now add some flesh to the bones, with a few definite proposals.

3.1 Sign convention

The most useful sign convention to adopt for deviations (other than true lead) is:

$$\text{`}+\text{ deviations} \Rightarrow +\text{ material'}$$

This is widely understood and will help to avoid expensive misunderstandings in manufacturing. It may be applied to helix as well as profile evaluations (see below). As already stated, this convention is useful when relating deviations to the gap, and when considering the transmission error of rotor pairs.

3.2 Profile

Deviations at any transverse section will appear magnified to a suitable scale and plotted super-imposed on the transverse profile. For surface normal deviations, the simplest tolerance band will then be a pair of parallel curves on each side of the profile. Different tolerance zones, e.g. for drive band and clearance zones, may be shown by a simple step or ramp from one parallel curve to the other. Transverse deviations will have a more complex tolerance zone.

3.3 Developed profile plot

A method proposed by S. Edström [4] is a useful addition to the CMM output for display of profile errors. This uses a horizontal base line, divided up according to the functional points on the seal line, and shows surface deviations vertically. If several transverse sections are shown on the same graph, the total body quality can be seen at a glance.

3.4 Helix

Normal deviations along a helix may be plotted super-imposed on an axial straight line, and analysed by familiar methods such as regression straight lines, total form, etc. Again, the important requirement is that these are alternative ways of showing the *same deviations.*

The following guidelines might then be applied to helix plots:

1. Deviations are normal to the surface.
2. An increase in *material*, rather than *lead*, should give a positive change in deviation, for the reasons given above. The term 'lead' should therefore be avoided, except when true lead is meant (see below).
3. It is particularly important to see at a glance where the material lies. For example, one must check whether the end of the rotor has some relief (desirable), or 'push-off' (undesirable). A short section of shading on the material side has been found to give immediate visual impact, especially when helix plots are arranged vertically according to the tradition with gear measuring systems.
4. The position of the helix plot at a chosen section should correspond to the divide error at that section. This was not generally possible with conventional gear testing machines, but is probably fairly easy for a CMM, where the whole component surface is known. The plot can then give a combined picture of the helices for the entire component, since each helix plot, by its position relative to the zero line, will be related to the others according to the angular pitch error.
5. In the case of an array of vertical helix plots, as is often used in helical gear measurements, 'up' in the plot may be made to correspond to 'up' on the measuring machine, giving a further visual grasp of the situation. The Z axis will follow the particular rotor's co-ordinate system.

3.5 True Lead

The true lead and lead deviation values should also be calculated from the regression line projected over 1 revolution. These are the only values where positive deviations should indicate a longer lead, regardless of the material side. An important use of the lead values in manufacturing is to fine-tune the CNC machine settings, e.g. to compensate for temperature effects. Only the values are required, i.e. no plot is needed. The message

$$\text{`+ deviations} \Rightarrow \text{+ lead (axial)'}$$

should appear with the lead deviation values only.

It is useful to specify an evaluation length which excludes the rotor ends, for the regression line and subsequent lead calculations. This allows any end effects, deliberate or otherwise, to be ignored. Typically, 5% of the body length at each end could be disregarded for the calculation of true lead and lead deviation only.

Average lead and lead deviation values should also be calculated from all measured lobes, to avoid the effects of run-out, etc.

3.6 Divide (angular pitch)

A 'divide' evaluation permits machine errors to be monitored, and is probably best expressed in the transverse plane, both as an angle (in micro-radians), and as an arc length (in microns) at a specified radius, in terms of both adjacent and accumulated values, according to standard definitions. Plots are useful here.

3.7 Profile output to disk

The *average* flute transverse profile (not profile deviations) should be calculated from all flutes measured, and saved to a file for input to a tool compensation program (usually a PC-based program), where required.

3.8 Individual rotor statistics

It is useful to extract some basic statistical data from all the measured flutes and cross-sections of an individual rotor, such as mean, maximum, minimum and range for selected features on the body.

3.9 Rotor batch statistics

It is also important to derive batch information such as $\overline{X}, R, \sigma, C_P, C_{pK}$ for key features on the rotors, to monitor the manufacturing process. These batch statistics should ideally be accumulated automatically in a separate file. During the run, the sampling rate for statistics might be, say, every 4th rotor, although some of the intermediate rotors might also be measured, and one or more set-up rotors might be measured first. To avoid statistical distortions, a rigid sampling rate is essential, and neither the set-up rotors, nor the intermediate rotors should be included in the calculations. The most flexible method is to have the freedom to specify retrospectively which rotors are to be included in the statistics.

3.10 Magnifications

Whenever possible, plot magnifications should be to a rational scale, e.g. X1, X2, X5, X10, X1000, etc., to make visual estimation easier and more habitual.

3.11 Special evaluations

It has been our experience that occasional special investigations are most easily done by transferring the CMM data to an individual's desktop computer, because this gives complete freedom to engineers who are not CMM programmers. We must avoid letting such occasional investigations have an undue influence on our efforts to standardise the basic program.

Conclusions

I am aware that this paper has given more emphasis to the fundamental dilemmas in rotor tolerancing and measurement, than to detailed proposals. This was not my original intention, but the need for some attempt to clarify the issues became more apparent the more I consulted with my colleagues in the industry. My purpose has been to stimulate wider discussion, and perhaps set the scene for a move towards some standardisation, whether formal or informal. Nevertheless, I believe two clear proposals have emerged, namely, the abandonment of multiple projections of deviations in favour of either surface normals or transverse projections, and the adoption of the sign convention based on the material side.

References

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