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ROTOR EVALUATION REGARDING RUNOUT

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ABSTRACT

The latest development in screw compressor (helical lobed compressor) rotor profile design and rotor manufacturing machinery have prioritized basic rotor profile surface, lead and divide. However, one error that at first looks very basic but at the same time almost impossible to eliminate, is dealt with in this paper. The error is rotor runout.

INTRODUCTION

Runout is created by the fact that it is very hard to make two circles or two cylinders that are concentric to each other. This happens especially when the two runout objects are made in different set-ups or machines. The TIR (Total Indicator Reading) is defined by, for example, letting a shaft rotate on two features (diameters or center holes) and on a third feature (usually a diameter) measuring the range an indicator sees while rotating the part 360 degrees.

DEFINITIONS OF DATUMS

Datum A: Discharge side radial bearing journal. Datum B: Suction side radial bearing journal.
Datum C: Discharge side center hole. Datum D: Suction side center hole.
Datum E: Discharge side rotor tip diameter. Datum F: Suction side rotor tip diameter.
Datum I: Discharge side rotor profile cross section. Datum J: Suction side rotor profile cross section.
See figure 1.

DEFINITIONS OF ROTOR RUNOUTS

There are many different rotor runouts. The most commons are:
Runout between a rotor tip diameter and the bearing journals, i.e., datum E or F vs. datum A-B.
Runout between a root diameter and the bearing journals, i.e., datum G or H vs. datum A-B.
Runout between a rotor profile cross section and the bearing journals, i.e., datum I or J vs. datum A-B.
Runout between a bearing journal and the center holes, i.e., datum A or B vs. datum C-D.
Runout between a rotor tip diameter and the center holes, i.e., datum E or F vs. datum C-D.
Runout between a rotor root diameter and the center holes, i.e., datum G or H vs. datum C-D.
Runout between a rotor profile cross section and the center holes, i.e., datum I or J vs. datum C-D.

In addition to the above runouts, there could be combined features creating the center line. For example, the runout between a bearing journal and the center line based on the other bearing journal and one center hole, i.e., datum B vs. datum A-D.

EFFECTS OF ROTOR RUNOUT

Runout effect the profile form, lead and divide. In this section we assume some kind of runout between the profile part of the rotor versus the bearing journals.

Profile Form
The profile form becomes distorted in four basic ways by rotor runout. The rotor flute can be too fat or too slim similar to an infed problem. It can also be distorted like a tool offset error or cutter angle error in one or the other direction. The type of error seen depends on what flute on the rotor is measured.

Lead
When measuring lead based on one flute while having a runout error, it looks as if there is a lead error. There are two ways to take care of this problem. One way is to design a profile with a pure straight radial portion of the profile and measure the lead at this portion. This is not practical because it can make the rotor profile hard to machine. The other way is to measure one lead for each flute and average the lead for the entire rotor. This way the influence of the runout is eliminated, but it is very time consuming.

Divide
When measuring divide (also called pitch) in one cross section of the rotor while having a runout error, it looks as if there is a divide error. There are two ways to take care of this problem. One way is to design a profile with a pure straight radial portion and measure the divide at this portion. This is not practical because it can make the rotor profile hard to machine. The other way is to measure the divide at a cross section axially far away from the place where the runout is large. If this is not known or there is a combined runout problem, the best cross section at which to measure divide is in the middle of the rotor.

TYPES OF CENTER POSITIONING MEANS

There are basically four types of center positioning means, i.e., tapered center hole, cylindrical center hole, cylindrical outside diameter or external taper. The most common is the tapered center hole. Some machine operations use a tapered center hole on one end and a cylindrical outside diameter on the other end of a rotor.

Tapered Center Hole
The tapered center hole has both a radial and an axial positioning of a rotor. The most common is a 60 degree combined with a 120 degree to create a protective center, compare DIN332-B. See figure 2. The protective feature is quite important so the center can not be nicked during handling of the rotor. The problem with this center hole is that it might be hard to maintain the center exactly at 60 degrees. If it is larger than 60 degrees, there will be a line contact at a very small radius, assuming a perfect dub center. This means an unstable center hole. If the center is smaller than 60 degrees, there will be a line contact at quite a large radius. This would be better than the small radius line contact.
However, a line contact does not serve very well as a bearing load surface.

One alteration of the tapered center hole is a center hole with a radius form instead of a taper, compare DIN332-R. See figure 3. The nice thing about this center is that it contacts a 60 degree dub about the same place every time. However, it is hard to grind such a hole.

Cylindrical Center Hole

This type has probably never been used within the rotor industry. Such a diameter does not have axial positioning and can not to be a functional bearing journal.

Cylindrical Outside Diameter

This type has been used more often lately. It is the natural choice if the two diameters are the journals for the two radial bearings. However, it does not have any axial positioning so special collets have to be used. The collet has to rotate with the rotor, hold uniformly on the journal and center the rotor journal as good as possible. So far this type has only been used on one side of the rotor. It is hard to have room for two collets both on the machine and on the rotor.

External Taper

See figure 4. The main advantage with this type is that it can be made in the same operation as the bearing journal. However, the taper becomes poorly protected and quite large velocities relative to a fixed tapered hole dub. One alteration of the taper is the drive tang that usually uses a key as positive drive mechanism. The drive tang however, usually add to machining time as well as set up times. It is only practical in small volume production with a large number of rotor sizes.

RUNOUT DISTRIBUTION

While measuring and analyzing rotor runout, it is important to know what kind of distribution runout has so control limits and process control can be exercised, besides specification limits. Most features in production follow the normal curve, where +/- 3 standard deviations commonly are used to calculate process capability. The process capability should be better than 1.33. Runout is not a normal distribution. It is a skewed distribution. See Figure 5. A practical control limit would be the peak value plus four standard deviations.

![RUNOUT DISTRIBUTION](image)

**FIGURE 5**
To have control in the beginning of a process is as important here like many other situations, i.e., runout must be measured and be kept under several process controls to make the final runout as small as possible.

Most common center positioning types, at least at the start of the process, is the tapered center hole. Some process factors affecting rotor runout regarding center hole are: Accuracy of center hole and dub: Drilled, bored or ground. Surface finishes of center hole and dub. Drilled, bored or ground. Burrs in center hole and dub. Type of machining to avoid burrs or deburring method. Hardness of rotor at center hole and dub. Type of materials. Cleanliness of center hole. Type of cleaning media and method. Type and amount of lubricating grease for the center hole. Amount of axial force on the center hole.

In the case of positioning the rotor radial with some kind of collet gripping on a bearing journal surface, following factors play a role: Roundness or cylindricity of the bearing journal. Surface finish of the bearing journal. Adjacent burrs to the bearing journal. Hardness of the bearing journal. Cleanliness of the bearing journal and the collet. Amount of radial and axial force on the bearing journal. Clearance of the bearing for the turning collet or collet runout.

Sometimes a rotor shaft is so long or the machining force so large that steady rests are needed to support a rotor shaft or the rotor body. This kind of situation puts very specific requirements on the involved diameters. Steady rests introduce errors that can look like lead, divide and even runout errors. The most common or easiest recognizable error is probably shown with a lead measurement. The development of automatic adjustable steady rest would significantly diminish the problems.

On top of this there are some general features that effect rotor runout or its measurement: Stability and deflection of the rotor body and lobes. Machine scales, accuracy and maintenance. Constant temperatures. Stability of fixtures. Stability and accuracy of tools. Accuracy, reproducibility, repeatability, traceability and stability of gauging.

In Process Measurement of Rotor Runout

It is important to catch an error as soon as possible which means that in process measurement is desirable, especially if they do not add to the cycling time. There are machines on the market with in process runout measurement, usually on machines with collet positioning drive on one bearing journal and center positioning on the other side. The runout is measured on the bearing journal that is closest to the operating center hole with a probe while the rotor is rotated. The measurement is usually done just before the machining process. Machines can be programmed to stop if the runout is larger than a programmed value. It can be beneficial to add the runout measurement during the machining or after the machining.

CMM Measurement of Rotor Runout

This section could be made very extensive, specific details have to be referred to the CMM (Coordinate Measurement Machine) producers. A general rule is: Smoother surface finish and larger stylus mean more repeatable measurement. The task comes down to: How to find a center for a bearing journal, a center and the rotor profile.

Finding The Center of a Bearing Journal (Datum A or B)

This task is usually the easiest but this has to be considered: Number of probings per object. Circular or cylindrical evaluation.

Finding The Center of a Center (Datum C or D)

This is not so easy, especially if the CMM should have the same set up as for the other standard rotor profile measurement tasks. First, most rotors are measured in a vertical position, which makes it hard to access both centers. Secondly, the diameter of the stylus has to be much larger than the stylus used for the standard profile measurement. It is usually relatively time consuming to find the center of an internal cone with a large stylus. The alternative is to go in with a very small stylus, measuring two circles and creating a cone. However, the very small stylus may create repeatability problems.
Finding The Center of a Rotor Profile

There are three basic ways to do this: Finding the center of the root diameter (datum G or H) may at first look very easy, but take into account that the landing section for a stylus is quite small both on most male and female rotor designs. This makes the measurement not so accurate. The second option is to use the rotor tip (datum E or F). This is only a valid option if there is full profile machining. It is most common to machine the outside profile diameter on the same machine as where the bearing journals are machined. Besides this, the tip diameter is usually surrounded by sharp corners creating headaches for any mathematical fitting process. The third option is to use the entire profile cross section, datum I or J (except the rotor tip in case of non full profile machining). The landing section is large but this means time consuming probing or scanning. The mathematical fitting situation easily becomes a nightmare and stability problems may occur.

 ROTOR RUNOUT WITH TODAY'S MACHINES

See figure 6 for rotor diameter versus rotor runout. The runout for the picture could be datum I or J vs. datum A-B, datum G or H vs. datum A-B or datum A or B vs. datum C-D. The area between the "old" and the "new" lines is probably where most people operate today.

![Figure 6](image_url)

FIGURE 6

ROTOR PROFILE CORRECTION TAKING ROTOR RUNOUT INTO ACCOUNT

Since rotor runout affects the profile form, it is easy to get into a hunting scenario when trying to adjust the profile form based on one flute measurement, especially when the size and the direction of the rotor runout are unknown. To avoid this situation there are basically two possibilities. The first one is to measure the rotor profile at a flute position with known runout characteristics. The profile evaluation is based on datum A-B. The other way would be to evaluate the rotor profile form based on datum G-H or datum I-J and use a nominal profile form and tolerances for the process where runout has not been taken into account. Even better would be to develop processes and machinery that probe both bearing journals and adjust the profile machining accordingly. The other alternative would be to develop collets that could position and drive the rotor on both bearing journals.
EXAMPLE

You are a design/manufacturing engineer for company X. Marketing has concluded that a screw compressor with 100 mm diameter rotors needs an improved specific power consumption by a given percent. You have studied the case and come to the conclusion that a tighter clearance between the rotors would do the job. This could be done by changing the nominal rotor profile surface and bring a specific rotor runout down to 0.010 mm. You have performed a capability study of the runout in question and found that one standard deviation corresponds to 0.001 mm. The peak runout (most common) corresponds to 0.008 mm. We assume that the capability study was done with a CMM as gauge with sufficient repeatability and reproducibility. The manufacturing line also has a pairing stand accompanied by a screw compressor old timer Mr. "Know It All". What do you do?

You happen to work at a place with very helpful co-workers. Before you have had a chance to fully comprehend the capability and repeatability/reproducibility study you have been overwhelmed with suggestions of "What to do".

Here they are:
a. Just change the nominal profile surface. The production line can probably handle it. Don’t you trust them?
b. Change the paint on the compressor, give it a new name and tell your customers that the new compressor has lower specific power consumption.
c. Change the nominal profile surface and pair all rotors on the pairing stand. Mr. "Know It All" is known to make perfect pairs of scrap rotors.
d. Change the nominal profile surface and do one hundred per cent runout inspection and sort out the bad rotors.
e. Change the nominal profile surface and add a lapping stage to the end of the rotor line.
f. Coat the rotors.
g. Your mind tells you that your management will never understand your suggestions, so you might as well find a new job.

At this point you have to react to all suggestions before you present your suggestion.
a. Never change any nominal data before it is proven that the process can handle it. Remember, you are testing machinery, not people.
b. This will never be good in the long run.
c. The most runout problems can not be eliminated by a pairing process. It is better to eliminate the pairing stand based on a repeatability/reproducibility test. The pairing stand can be good for finding nicks on the rotors.
d. This is too expensive.
e. Only if you have given up a controllable process.
f. To get the coating process capable is probably more work than making the rotor runout smaller.
g. If you can not get your viewpoints across at one place, you probably can not get them across anywhere else either.

Finally your suggestion: Change the process or use 0.016 mm as rotor runout specification limit.

A practical control limit based on the capability study is 0.012 mm (0.008 + 4 * 0.001).
If there is a process capability requirement of 1.33 a practical specification limit will be 0.016 mm (1.33 * 0.012). The desired specification limit is 0.010 mm. The process needs to be changed to reach 0.010 mm rotor runout.

CONCLUSION

The screw compressor is a very reliable and durable compressor with high efficiency. To maintain its position and conquer new applications, further improvements have to be made. One of the improvements is to make the rotor runout smaller. It needs to be between a quarter to a half of today’s rotor runout, for the screw compressor to be competitive into the next century. Compare figure 6.

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