A study of screw compressor rotor geometry with a new method for the remote measurement of clearances

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Abstract

The search for an accurate method of clearance measurement suitable for screw compressor rotors has resulted in an optical technique which is especially suitable for measuring gaps of less than 100 microns between reflecting surfaces of large surface radius. The method uses a lamp and imaging/detector arrangement to measure the amount of transmitted light. Its application to rotors depends on the conjugate properties of the profiles, and on the existence of a basic normal rack form along whose surface the lines of sight lie. Computer methods are used to derive seal line parameters from the numerical data defining the rotor profiles. The surface shapes adjacent to the optical axis are calculated, to allow predictions of the calibration curves to be made based on empirical results. The system overcomes the problems of optical resolution normally associated with narrow gaps, and the problem of spurious multiple reflections between the surfaces. Patents are pending.

Abriß

Die Suche nach einer exakten Technik der Messung von Abständen bei Schraubenkompressor-Rotoren führte zu einer optischen Meßmethode, die sich für Abstände von weniger als 100 Mikron zwischen reflektierenden Oberflächen mit großem Oberflächenradius besonders eignet. Das Aggregat besteht aus einer Lampe und Abbildungs-/Detektoreinheit, mit der die Menge des durchgehenden Lichts gemessen wird. Die Anwendung dieser methode bei Rotoren hängt von der Art des Ineinandergreifens der Profile, sowie von der Regelmäßigkeit der Eingriffe ab, an deren Oberflächen die Sichtlinien verlaufen. Die Parameter der Abdichtungslinie werden vom Computer von den numerischen Daten der Rotorprofile abgeleitet. Die an die optische Achse angrenzenden Oberflächenformen werden berechnet, damit sich Voraussagen über die Eichkurven auf empirische Werte gründen lassen. Diese Technik ermöglicht es, Schwierigkeiten der optischen Auflösung bei besonders kleinen Spalten und der zufälligen, mehrfachen Reflexion zwischen den Oberflächen zu Überwinden. Die Patentanmeldung läuft.

1 Introduction

In the manufacture of screw compressor rotors it has long been recognised that a more efficient method of measuring the rotor clearances is desirable, both for accuracy and speed. The principal method currently employed in quantity production depends on the manual insertion of feeler gauges, with the rotors mounted between centre supports. For occasional measurements of individual rotors, a three-dimensional Co-ordinate Measuring Machine (CMM) may be used, and some CMMs have been developed specifically for rotor-type components [1,2]. In order to derive clearance information, CMM measurements of a rotor pair must undergo a computer simulation of engagement in order to derive the clearance pattern. Feeler gauges measure clearance directly, and being relatively quick, are suitable for the production process. However, the subjectivity introduced when estimating between sizes, together with the difficulty of positioning the feeler accurately, makes the method only accurate to about ± 10 microns (μm), and although quicker than the CMM for measuring clearances, the operation is still rather slow for large batches. In general, the smaller the rotors to be measured, the tighter are the tolerances on the specified clearances, and the demands placed on the manufacturing and inspection process are correspondingly greater. The purpose of the present research was to find a method of measurement which is suitable for the production environment, and is both accurate and cost-effective. Geometrical considerations (see section 2) suggested that a remote optical technique might offer the advantage of speed, provided sufficient accuracy could be obtained.

Three techniques were considered. The normal method of direct image measurement is used in optical projector and machine vision systems, and is well known, but some difficulty is experienced when measuring small gaps. A general discussion of the problems is given by Batchelor [3]. Willis and Seth [4,5] have used laser diffraction techniques for measuring the gap between rollers. Neither of these techniques is suitable for narrow gaps between objects with large surface radii such as compressor rotors.

The method described in section 3 uses the transmission principle, in which a uniform beam of light is directed at the gap and measured by means of a detector at the other side. A system using X-ray transmission for the measurement of elastohydrodynamic oil films is described by Sibley, Orcutt and Austin [6,7] and by Kannell and Bell [8]. Our experiments using ordinary visible light have showed that for a given object-pair a unique non-linear relationship exists between gap size and transmitted light energy, and the method is able to detect gaps down to 7.5 μm . The work is in a commercially sensitive phase, and a detailed disclosure is therefore not appropriate at this stage, but a general description of the operating principle is given below, followed by a description of the main features of an automated rotor clearance inspection machine.

2 Geometrical Considerations

2.1 The Normal Rack and Viewing Feasibility.

The line of minimum clearance between the rotors is a 3-dimensional curve called the seal line, which travels axially as the rotors rotate together. In order to apply an optical technique to the measurement of rotors it is first necessary to establish the correct viewing angle, and to be certain that the line of sight is not interrupted by either surface other than at the seal line.

The theoretical rotor profiles (i.e. without clearance allowance) are conjugate in the transverse section. (For a discussion of the conditions for conjugacy see a standard reference text on gears such as Merritt [9] or Buckingham [10].) It follows from this that a **basic rack form** exists for any given rotor pair. The corresponding normal projection of this basic rack form is called the **normal basic rack**, or more simply, the normal rack.

Early rotor profiles resembled circular arc gears, and being of simple form were susceptible to normal methods of analysis, an example of which is that carried out by Dyson, Evans and Snidle [11]. These simple types are becoming less common, and typical modern profiles are asymmetric, and have composite mutually-generated forms. Computer numerical methods are therefore preferable for calculations. Profile information is usually supplied as a co-ordinate list of points in the transverse (x-y) plane, together with the corresponding flank angles. Typically for each profile a list of 500-1000 x-y co-ordinate points is supplied, to 8 or 9 significant figures, together with the corresponding flank angles. These, together with the pitch line helix angle and pitch circle radii are sufficient to allow calculation of a set of corresponding points on the transverse basic rack, normal basic rack and seal line, the last two being most conveniently described in a co-ordinate system related to the normal plane, with associated seal line flank angles.

The normal rack could be passed between the engaged pair in a straight line parallel to the helix tangent at the pitch point, and would make tangential, or grazing contact with the conjugate forms. The analogous manufacturing process is planing. This being the case, it follows that if one views the rotor pair at this helix angle, one sees all the points where each rotor contacts the rack surface, and *hence* where contact between the conjugate forms occurs. These points taken together form the seal line, although with practical rotors, i.e. with clearance, actual contact is only permitted over a short section of the seal line at or near the pitch circle.

The normal basic rack surface could be considered as being made up of a series of straight lines parallel to the helix tangent at the pitch point. Each straight line would 'see' a point of contact and would have an unobstructed entry and exit path. This may be stated as follows:

For every point of contact between a pair of conjugate helical surfaces there exists a common tangent which is parallel to the helix tangent at the pitch point.

An uninterrupted view of the gap is therefore possible at this angle for all points on the seal line.



Figure 1: Elements of the Measuring Apparatus

2.2 Surface Curvature

The surfaces are curved both across the direction of view, and along it, and this curvature contributes to the transmitted light by multiple reflections which occur between the surfaces.

At any selected point on the seal line the normal to the surface of the normal rack defines the required scanning direction for the measurement, and it is useful to define the **measurement plane** as a plane containing this normal and the line of sight. The intersection of this plane with the rotor surfaces is a pair of adjacent convex curves whose common tangent lies at the point of contact between the surfaces (for theoretical rotors), or at the point of minimum separation (for real rotors with clearance). These curve pairs may be calculated and the instantaneous radii of curvature and their radii of curvature at the contact point derived. These surface radii can be large, especially at the pitch line. This data may then be related to empirical calibration graphs, although the exact nature of the relationship between surface shape and transmitted light is complex.

Before any measurements can be made it is necessary for the viewing apparatus to be accurately positioned in relation to the seal line. The scan must be made in the appropriate direction, i.e. normal to the gap image, and the effect on the gap of adjustments to the rotors must be accurately known.

3 The Measuring Apparatus

The basic elements of the system are shown in fig. 1. The projector and camera assembly are kept in fixed relationship to each other, and the rotors are supported



Figure 2: The Rotor Support Assembly

between centres in a purpose-built assembly.

The projector directs light at the gap which is viewed at a suitable magnification and working distance by the CCD camera. The image seen by the camera is displayed on a monitor, so that the shape of the gap can be seen, together with any dust or other contamination which might affect the readings. A typical gap image is shown in fig. 3, with cross-hairs superimposed as the screen datum. A frame capture board records the image in memory, and this is then analysed by software to give a measure of the gap.

The rotor support assembly is shown in fig. 2. It is designed so that fine adjustments of height, centre distance and viewing angle may be made. It is also provides for fine adjustment of the rotary position of one rotor relative to the other so that the gap can be varied as desired over the range of interest.

The upper rotor is locked against rotation, whilst the lower rotor is rotated by means of an arm fixed to the rotor shaft. The outer end of this arm carries a vertical adjusting screw which bears down under gravity on a pedestal sitting on the base plate. Extremely fine adjustments of the gap are thus possible. A dial indicator detects vertical movement of the arm at a known radius from the rotor axis. The rotation in degrees can be calculated and related to the change in gap by means of appropriate formulae.

The heights of the centres relative to the base plate are set by means of gauge blocks. If the height of the optical axis is also measured it is possible to know precisely which part of the seal line is in view. The plane containing the rotor axes is also set at the correct angle to the optical axis, i.e. the pitch line helix angle.



Figure 3: Gap image with cross-hairs.

The projector houses a tungsten filament lamp, and directs a uniform white spot of light at the object. The camera lenses are selected to give an optimum combination of working distance and magnification. Too low a magnification might result in a contact point being masked by the light on either side, whilst too large a magnification gives too localised a view and wastes light. The gap image is formed on the surface of the CCD array, which consists of a matrix of 512x512 pixels each measuring approximately 13 μm . A monitor displays the gap as seen by the camera, and software-generated cross-hairs are displayed across the screen centre. The lamp brightness is adjusted to avoid saturation, and an optimum sensitivity obtained.

A frame-grabber board within the host computer captures the image in the form of a memory map which is then analysed by the image analysis software. This detects the orientation of one edge forming the gap by fitting a least-squares straight line through the points at a selected grey level (see fig. 4). Alternatively the gap orientation can be calculated and input as a numerical value. The system then performs a series of scans at right angles to the image, covering a rectangle of selected width, and returns the central and minimum values. The minimum value is used for gap measurements. The monitor displays the scan in the form of an intensity graph or *trace* on the screen, which has a Gaussian form.

The trace area is integrated to return a number which is related to the transmitted light energy at the selected position. The system may be calibrated to read in convenient intensity units following integration of the trace. The intensity correction factor is set by means of a reference slit placed in the object position. The size of the slit in microns can be entered, thereby setting the intensity units returned



Figure 4: Straight line fit method of detecting gap orientation.



Figure 5: Scan line with intensity profile and integration result.



Figure 6: Gap Measurements on a Rotor Pair.

by the programme. It is convenient to describe these units as slit-equivalent units, or s.e.u. A scan line with its corresponding intensity trace is shown in fig. 5.

By adjusting the rotor gap through a range of sizes calibration curves can be drawn, and software look-up tables constructed from the calibrated points may then be tested on the same pair of rotors. Typically a resolution and repeatability of less than half a micron is achieved *for this object-pair*. The system may then be used to measure other rotors of a similar type at the same inspection position, as illustrated in fig. 6. It will be seen that although some accuracy has been lost, the measurements are quite acceptable. The distortions are caused by slight variations in shape between different rotors which affect the optical transmission characteristics of the gap.

Other effects might also be present, such as surface texture variations, which affect the proportion of specular and diffuse reflection. A useful study of these has been carried out by Baker [12]. Indications so far with rotors are that surface texture effects are of secondary importance.

The parallel lines enclosing the readings are arbitrary and indicate a range of $\pm 3 \ \mu m$, although this is not a claim for accuracy; such claims can only be made

after a large quantity of measurements have been taken and analysed, and this work is still continuing at Holroyd in England.

A full study of the effects of surface shape and texture on the optical transmission phenomena would be long and complex, and would represent an extensive research project in its own right. The picture is complicated by the fact that the transmission is also affected by the characteristics of the optical system employed, e.g. the numerical aperture of the camera lenses. Such a study might even allow a full prediction of the optical transmission characteristics of a given object-pair. Our own study has so far been limited to assembling the empirical data required for a functional measuring machine.

4 Automated Measurement of Rotors

The optical method of measurement described above offers several advantages over current production methods of inspection. A fully- automated computer-controlled (CNC) machine will overcome the difficulties mentioned in the introduction. With the rotors mounted one above the other between centre supports, the optical assembly will move to view a selected profile position and take measurements over relatively short sections of the seal line, typically around 0.5 mm. The minimum gap value detected in the field of view will be the required clearance. In fact a single scan line covers 0.2 μm approximately, but this is considered too narrow a sample to be of use, and the multiple scan method is preferable. Measurements may then be taken as the rotor pair is rotated through all its positions of engagement. and a full set of readings taken if required. The process may be repeated for other positions around the profile, and at various sections along the length of the rotor. Each frame capture takes only a fraction of a second, and the data will be processed as the rotors move on to the next position. Shaft rotation is measured by rotary encoders and this makes the measurement of backlash an easily-incorporated feature. It also becomes possible to include a single flank, or transmission test, such as is used in the measurement of gears, and the graphical output may well offer useful information where rotor vibration or noise is a problem.

Individual profiles may be measured by pairing with a master rotor which has been previously measured on a CMM, and the resulting clearance values may be used to derive information about the unknown rotors. It is envisaged that this information will be used to calculate cutter corrections where necessary.

The production environment is usually a hostile one, where temperature variations, vibration, and contamination are present. The effect of temperature on the measuring system is to cause variations in lamp brightness and camera element sensitivity. These effects can be eliminated by setting the sensitivity of the system with the reference slit. If no corrections are made, day-to-day variations are normally less than 1%. It is clearly not a simple matter to eliminate the effect of temperature on rotors in a factory environment which may be subject to many sources of temperature variation. However, further software correction may be applied based on an estimate of the material temperature, if the effects of thermal expansion on the various inspection positions are calculated and written into the program. The CCD camera system has an exposure time during which a frame is captured, and the duration of this is selectable over a range similar to that of an ordinary photographic camera. With normal settings the effect of vibrations is effectively eliminated.

In common with all optical sytems, the effect of contamination is a danger. The rotors must be clean, and if necessary an occasional jet of clean air may be used to clear dust from the gap.

The effect of ambient light has been completely eliminated by means of a telecentric filter in the camera optics.

5 Conclusion

The method as outlined above appears to be sufficiently sensitive and repeatable to offer a significant improvement over the feeler method for the measurement of screw compressor rotors, and by pairing with a known master it will supply information about individual rotors. The method is very appropriate for rotor production, since it is ideally suited to automation, whilst the advantages of convenience over CMM systems are likely to be considerable. Patents are pending.

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