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Christopher S. Holmes
Holroyd

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Christopher S. HOLMES

HOLROYD, Research & Development Department
Rochdale, OL16 3LQ, U. K.
Email: cholmes@holroyd.renold.com

ABSTRACT

The relationship between screw compressor problems and characteristics of the rotors themselves continues to interest designers, even though manufacturing accuracy has been vastly improved over the last decade, largely due to the benefits offered by the Co-ordinate Measuring Machine (CMM). Contrary to some predictions, however, pair inspection has not been eliminated, even though the feeler gauge method has well known limitations. The paper presents a modern method of pair measurement which is the result of a long development, and which has a number of capabilities not available from the CMM, even with the addition of simulation software. This fully-automated measuring system for rotors offers an opportunity for improved prediction and understanding of compressor performance, reliability, and noise. ***Keywords***: Screw compressor, rotors, measurement, optical, clearances, gaps, transmission error, noise.

1 INTRODUCTION

The question of rotor measurement has occupied many of those involved in the design and production of screw compressors ever since their first commercial application. Until 1989, no alternative existed to the traditional pairing stand, feeler gauges, and dial indicator. The co-ordinate measuring machine (CMM) greatly improved the situation, as described below, but did not eliminate compressor problems, some of which continued to puzzle designers. The effect of the quasi-static interaction of the rotors was still not entirely understood, let alone the dynamic behaviours which could apparently destroy a perfectly respectable pair of rotors by mechanisms which were even less understood. The effects of misalignment, gas forces, and rotor-induced transmission error, could lead to undesirable phenomena such as friction, buzz, rattle, and associated distortions, which could have alarming results. It is not the intention here to offer solutions to these problems, but to describe a rotor measurement system which might shed light on the contribution of the rotors, and invite further research interest.

It will be useful to begin by reflecting on what is important when considering the effects on compressor performance of the rotor pair. For this, the machine tool builder must have regard to experts within the compressor industry. In the opinion of J. Sauls, Principal Compressor Designer, Trane, U.S.A.: “The quality (suitability for purpose) of screw rotors results primarily from the geometry of the gap between them.” From this it must be concluded that the inter-lobe gap is the principal determinant of efficiency, reliability, and noise.

The gap between rotors and housing, and the ‘blow hole’ area, will not be considered here, although gas flow simulations in this region have been the subject of research by others. Also, it is not relevant to consider whether the rotors have been manufactured as matched pairs or as individuals, as this subject has been discussed in another paper by the author Holmes (1994).

It is helpful to consider the relation between compressor quality and rotor quality. Table 1 indicates that a simple measurement of profile, lead and divide, e.g. by CMM, will leave many important questions unanswered, and that another approach is needed. The inspection system described below will be put in the context of the other methods, so that its unique features can be understood. A general description of its geometrical aspects and measurements will be given, with suggestions as to how the latter might be used to improve compressor design.

Table 1 Effect of inter-lobe gap on compressor

Inter-lobe Feature	Efficiency	Reliability	Noise
Inter-lobe Leakage area	Y		
Contact band location	Y	Y	Y
Contact band width	Y	Y	Y
Clearance distribution	Y	Y	Y
Transmission error (displacements)		Y	Y
Transmission error (velocities)		Y	Y
Transmission error (accelerations)		Y	Y
Fourier spectrum of the above		Y	Y
Backlash	Y	Y	Y

2 REVIEW OF ROTOR MEASUREMENT METHODS

2.1 Manual Pairing Stand (Feeler gauges & dial indicators)

With the rotors mounted horizontally between pairs of test centres, measurements may be made of clearance and backlash, with visual indications of faulty contact patterns. Despite its disadvantages the method has has some attractions for use in the production environment, and is capable of revealing major problems, provided it is carried out with extreme care, and regular attention is paid to the setting of the centre distance of the test fixture.

The measurement of clearance is carried out by the manual insertion of feeler gauges.

Backlash is measured by a dial indicator placed at a convenient point one one of the lobes so that it is measuring tangential to the rotation.

If the surfaces are marked with ink, and the rotors made to rotate in contact, a quick indication of faulty contact patterns can be obtained. Typical causes might be a faulty profile, or a lead error. In the latter case, the contact band will not run the full length of the rotors.

Advantages:

1. Rotors are measured in a position which simulates their position in the compressor.
2. The method is robust, in that it does not require a special environment, e.g. it is not significantly affected by dust, temperature variations, vibrations, magnetic fields, etc.
3. The method will always detect the minimum clearance.
4. No sophisticated instruments are required, i.e. it is a relatively low cost system.

Disadvantages:

1. It is difficult to position and align the feelers, which reduces the repeatability of the results.
2. It is subject to operator ‘feel’.
3. The resolution is limited to the size interval of the feeler gauges, usually 10µm. Feeler steel has a tolerance ± 5µm.
4. Backlash is only measured in a few positions, and minima are hard to detect.
5. The method is slow, and not easily automated.

2.2 Co-ordinate Measuring Machine (CMM)

The advent of the CMM allowed the accurate measurement of a helical surface, and most CMM manufacturers now supply suitable software for screw rotor measurement. They may have between-centres mounting, with the component vertical, or horizontal, or alternatievely, a single chuck with the component mounted vertically. Interesting early examples of the former are described by Haas (1980), and by Weck, Boge *et al.* (1986).

Profile, lead and divide measurements may be made. Deviations are usually super-imposed on plots of the designed profiles, with the differences magnified to a suitable scale. Profile measurements may be placed in any desired position relative to the nominal profile, e.g. the two may be automatically 'best fitted' over part of, or all the profile, usually by rotation about the axis.

The benefits of the CMM are:

1. It can give a continuous scan of profile and helix.
2. It is accurate and repeatable.
3. It acts as a reference standard.
4. It permits the creation of master rotor artefacts.

The disadvantages are:

1. It is relatively slow and intolerant of vibrations and temperature variations, and is therefore not ideal for the shop floor.
2. Because it is not practical to scan the entire surface, no reliable measurement of clearance, backlash, contact patterns, transmission error, and the effect of misalignment on these, can be obtained.
3. Local damage is not usually detected unless clearly visible to the eye.

2.3 On-machine scanning probe

With the aid of pre-calibrated master rotors, it is possible to achieve accurate profile measurement on the grinding machine itself. This is useful for closed-loop feedback. The properties of this method are similar to those just described for the Co-ordinate Measuring Machine (see above).

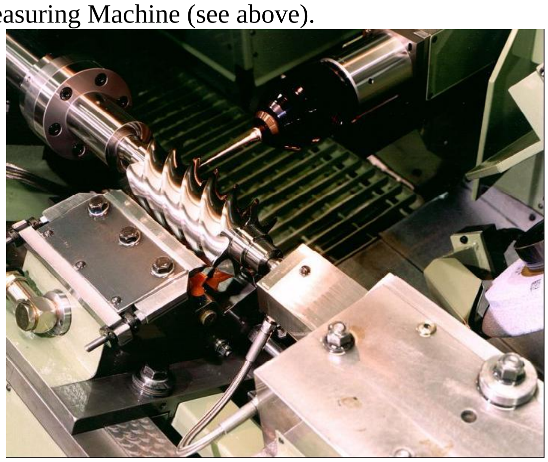

Fig. 1 Renishaw scanning probe on a Holroyd rotor grinding machine

2.4 Other methods

Burgova and Fedorov (1975) published details of an electro-magnetic multi-gauging system for screw rotors, and Xiong (1985?) developed a system for relating the profiles of rotor pairs. We have not had the opportunity to assess these devices.

3 THE HOLROYD CONJUGATE PAIR MEASURING SYSTEM

'ARAC' General Description - The optical theory of the Holroyd system has been described by Holmes and Munro (1990) in another paper, and will not be reproduced in detail here. Suffice it to say method is able to accurately measure gaps between difficult surfaces, where multiple reflections occur and no clear edge is visible. This novel approach has been integrated into a full conjugate pair measuring machine, known as the Holroyd ARAC (Automated Rotor Analysis Centre), which has world patents and has won 2 U.K. national awards. The most recent machine was installed as part of a modern manufacturing cell in the U.S.A., where it has been proven both capable and reliable. The basic elements of the system can be seen in Fig. 2. The rotors are mounted between precision spindles with their axes horizontal, one above the other. The lower spindle is powered, and both are fitted with high-resolution precision encoders.

The projector and camera are aligned on a common optical axis, and able to move together vertically, and in the direction of the rotor axes. They can also swivel about a vertical axis in relation to the rotors, to permit setting to the correct helix angle.

The projector directs white 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 (Fig. 1) and is captured and analysed according to methods developed experimentally.

The movements of the optical assembly and rotors are co-ordinated to view and measure a series of specified profile positions. The system calculates its moves from the profile and lead of the botom rotor, and the numbers of lobes on both. It automatically brings the rotors into contact on the chosen flank. (For **dry screws**, i.e. screws to be fitted with timing gears, the backlash test should be run first. The system can then be instructed to automatically park the rotors in the position of mid-backlash, thus giving a more realistic measure of the clearances.)

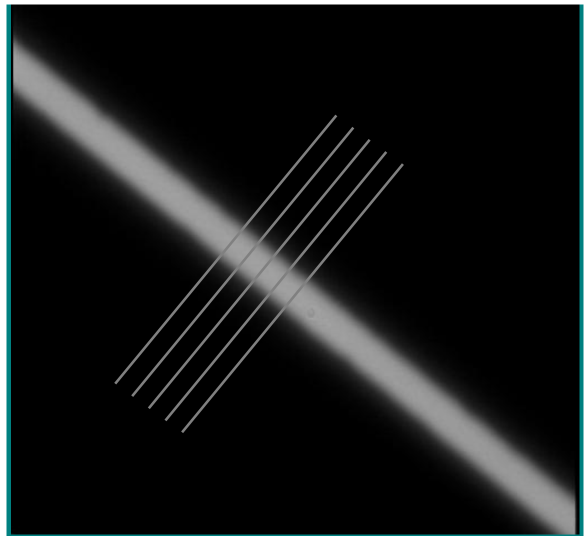

Fig. 1 Gap Measurement

Fig. 2 The ARAC viewed from the projector side

Repeatability & reproducibility (R&R) - An important property of a measuring system is the variability of readings when measurements are repeated, including the effect of using different operators. Standard statistical procedures exist for these trials. R&R results for the ARAC are shown in the box below. Note that the trials included re-loading of the rotors.

Gaps: 3 sigma = 1.4 microns.
Backlash: 3 sigma = 2.7 microns.

3.1 **Clearance Measurements**

A number of different measuring modes is available, depending on the type of investigation required. A full statistical analysis is carried out in each mode. Clearances can be measured as **pairs**, or as **individuals**. If individual measurement is specified, the user specifies which rotor is the calibrated master (calibration is done on a CMM), and inputs a file containing the calibration data. The ARAC modifies the tolerances according to the deviations in the calibrated master.

In **seal line** mode, the rotors are kept stationary, and the measurements follow the seal line (see Fig. 2). Alternatively, a **helix** test may be carried out. In this case the viewing system travels along a particular helix as the rotors rotate. This is useful to inspect the contact band on each flank.

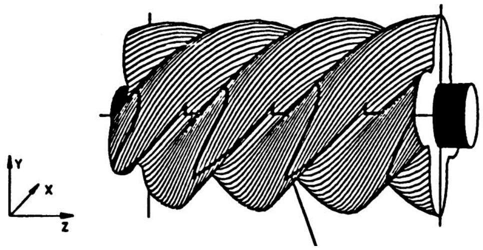

Fig. 2 Seal line on a male rotor (Diagram by courtesy of S. Jonsson (1985))

A third alternative is the **transverse** section test. In this mode, measurements are taken in a specific transverse plane, with the rotors rotated through all their engagement combinations. The viewing system and rotors move to the correct viewing position for each point. The process can then be repeated for other transverse sections along the rotor. In the graphs in Fig. 3, the base axis is the length of the seal line, from 0 to 100%, following the convention proposed by Edstroem (1992). Note the leakage area result at the left, calculated from the points available, allowing for their unequal spacing along the seal line.

HOLROYD ARAC GAPS REPORT	Sheet: OK	PAIR Test 1	PAIR Test 2	PAIR Test 3
Test Identification	Test Type:	TRANSVERSE -	TRANSVERSE -	TRANSVERSE -
Cycle start: 29 Sep 2000 09:02		Z Posn: 165.00	Z Posn: 245.00	Z Posn: 320.00
Inspector: J. Jones		C. D., mm: 109.119	C. D., mm: 109.119	C. D., mm: 109.119
First saved as: 136-2000-09-29-9-2.arf	Profile Point			

Part Identification		Num	Label	Seal Line %	Low Tol.	High Tol.	Mean Gap, microns	Seal Line %	Low Tol.	High Tol.	Mean Gap, microns	Seal Line %	Low Tol.	High Tol.	Mean Gap, microns
Part Ref:	136	1	KP/VP+	0	0.0	10.0	**5.9**	0	0.0	10.0	**6.6**		0.0	10.0	**9.1**
Pair No:	12	2	J/VI+	6	10.0	25.0	**13.1**	6	10.0	25.0	**14.9**		10.0	25.0	**17.1**
Batch No:	3	3	IM/VM	10	20.0	40.0	**34.6**	10	20.0	40.0	**32.3**		20.0	40.0	**31.6**
Top Sex & No:	F 2	4	G/U	23	25.0	55.0	**53.0**	23	25.0	55.0	**46.8**		25.0	55.0	**42.6**
Bot Sex & No:	M 1	5	EM/SM	37	35.0	75.0	**54.4**	37	35.0	75.0	**56.3**		35.0	75.0	**53.3**
Test rotor position		6	E/S	54	30.0	65.0	**53.6**	54	30.0	65.0	**57.3**		30.0	65.0	**54.7**
Description:	Variant type 2	7	DM/RM	66	20.0	50.0	**39.1**	66	20.0	50.0	**41.9**		20.0	50.0	**36.8**
		8	D/R	78	15.0	45.0	**34.0**	78	15.0	45.0	**36.3**		15.0	45.0	**26.4**
Leakage Analysis		9	CP/QP	89	15.0	40.0	**31.1**	89	15.0	40.0	**31.6**		15.0	40.0	**27.0**
Seal length per Lobe, mm:	157.0	10	M/Y	96	25.0	60.0	**52.5**	96	25.0	60.0	**50.7**		25.0	60.0	**47.5**
Leakage per lobe, Sq. mm	6.2														

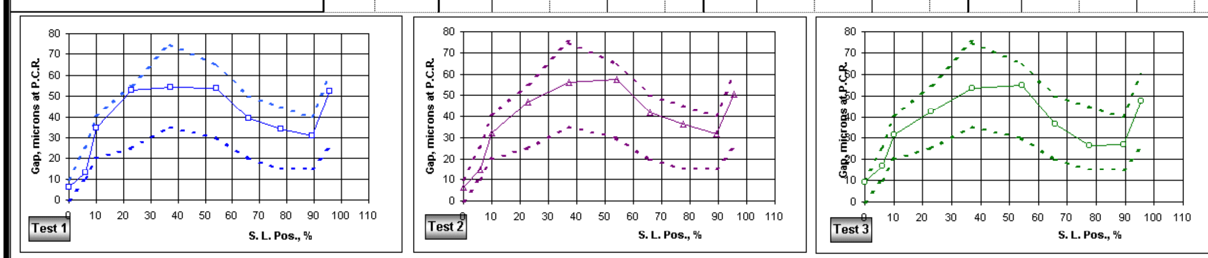

Fig. 3 Gap Report Sheet (Transverse method)

3.2 Transmission Error and Backlash

For transmission error and backlash measurments, the rotors rotate continuously through one full cycle, (or one revolution only) and then reverse. Transmission error is a composite measurement well-known in the gear industry Munro (1979), but perhaps not yet properly recognised by compressor manufacturers. It is defined as the positional error of a driven rotor/gear, with positive errors indicating an advance, and negative errors a lag. The error is expressed in microns at the pitch circle radius.

In Fig. 4, the lower line is the forward transmission error, the upper faint line is the reverse transmission error, and the upper heavy line is the backlash. In the transmission error line, the the longer waves represent the effect of run-out, the shorter waves represent tooth-to-tooth effects caused by divide and lead errors, and the shortest waves relate to errors in profile or helix form. Since the number of lobes on the male and female are usually different, it is easy to identify which rotor relates to which feature on the spectrum.

If the results of the transmission error for each flank, i.e. forward and reverse, are subtracted, a continuous measure of backlash is obtained, with the ability to extract the mean, minimum, maximum and range. The mean is plotted as a horizontal line, as are the upper and lower tolerances. The sytem can be instructed to rotate to the mesh position coresponding to the minimum backlash measured, which is useful for locating tight spots. The continuous backlash plot shows minima, which are usually missed completely by the dial gauge method. The compressor designer may need to review his tolerances! The system also reveals the effect of burrs, damage, and dirt, and the user soon realises how much these can affect the readings. This goes a long way to explaining why backlash is apparently such a difficult measurement to reproduce.

Fourier Analysis - The system converts the forward transmission error results into a spectrum using Fourier analysis, as shown in Fig. 5. This can quickly reveal the basic frequencies existing in the rotors. As with the transmission graph, the lower frequencies represent the effect of run-out, the medium frequencies represent tooth-to-tooth effects caused by divide and lead errors, and the high frequencies relate to errors in profile and helix form. Angular accelerations can be displayed in a similar manner.

3.3 **Suitability for the Production Environment**

The measurement cycle can be done in less time than it takes to finish a rotor. For the gap measurements, each frame capture takes a fraction of a second, and the reading is processed as the camera moves on to the next position.

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 compensated and effectively eliminated. Furthermore, the effect of ambient light has been completely eliminated by the use of special optical elements. Rotor temperatures are not, of course, accounted for.

Vibrations in a workshop environment are generally low frequencies transmitted through the floor, and the effect of these is totally eliminated by frame-averaging. The system is therefore extremely robust, in contrast with many other measuring devices.

In common with all optical sytems, the components must be clean. A warning of dust contamination in the gap is given by the software, which compares the minimum gap detected with the mean of all the scan lines, and warns if this exceeds a pre-selected value. A jet of clean air may be used to clear dust from the gap.

It has been observed that even small burrs at the end of the lobes can have a significant effect on the measurement results, and affect gaps, backlash, and transmission error, and these must therefore be removed before measurement.

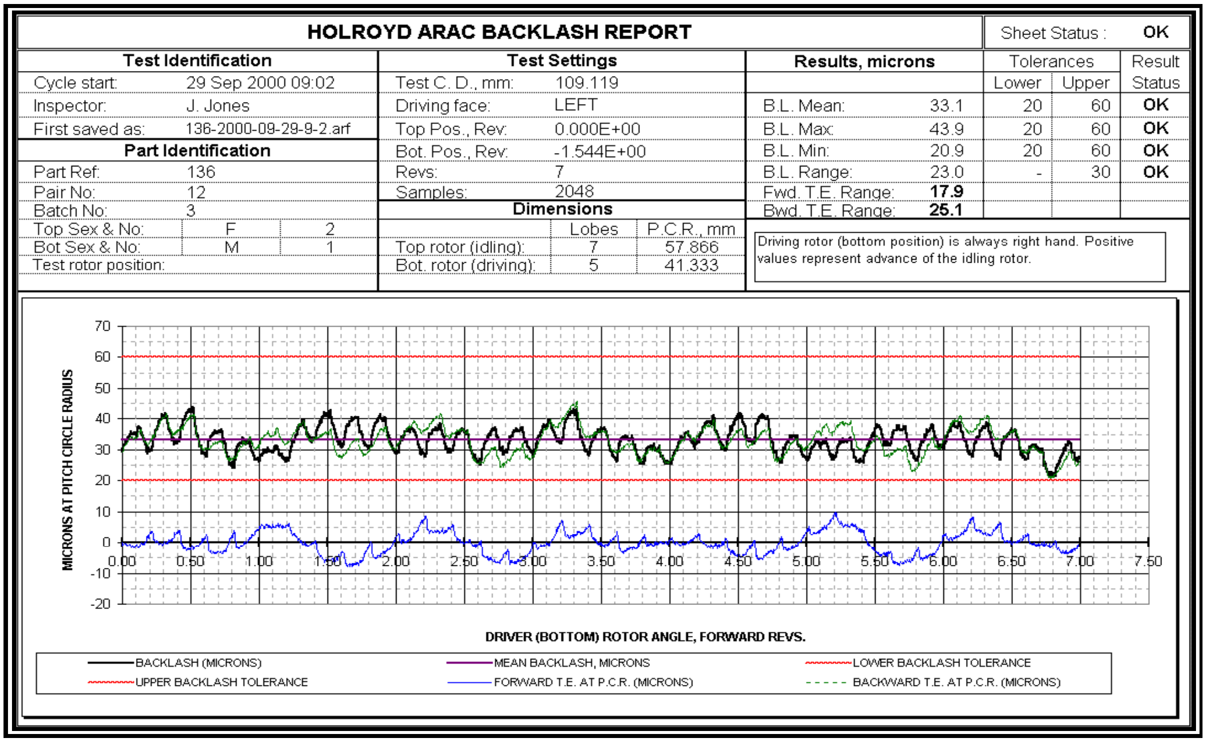

Fig. 4 Transmission Error & Backlash Report

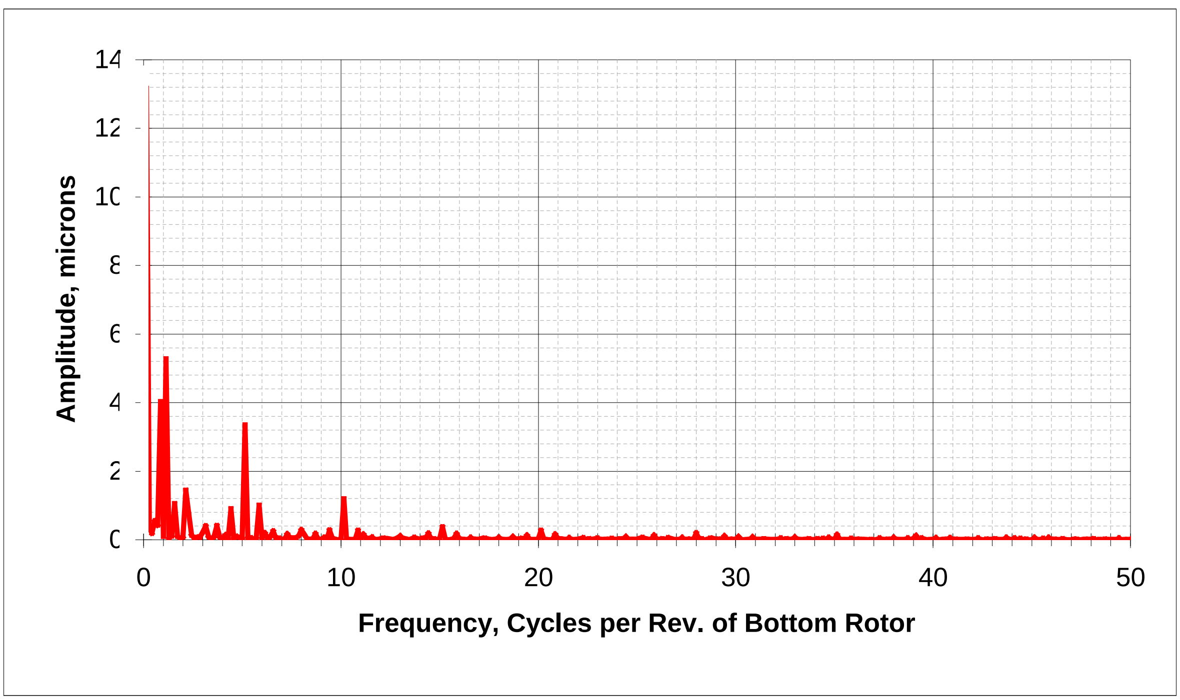

Fig. 5 Fourier Spectrum of Transmission Error

4 POTENTIAL FOR COMPRESSOR DIAGNOSIS AND DEVELOPMENT

Performance - The distribution of clearances on real rotors can now be easily measured, with an instantaneous figure for the mean clearance. Misalignments can be included to simulate the expected running conditions. Experimental correlation of these with assembly and performance data from real compressors is now a simple matter.

Reliability - Rotor dynamics within a compressor are complex. The author has seen the alarming results of root contact in rotors which showed no such contact under normal pair inspection, even with centre distance reduced by the designed amount. There was clearly more going on in the compresor than could be predicted from a quasi-static inspection of the rotors. It is our experience that small changes in the clearance distribution, and hence the behaviour of the contact bands, can have a major effect on reliability. There is an opportunity to investigate these phenomena by experimental correlation of compressor performance with the actual clearance distributions of the rotors before assembly. This should include a measurement of the effects on rotor contact of various mis-alignments.

Noise - There are relatively few publications on the influence of rotors on compressor noise. Recent publications by Yoshimura (2001) have focussed on the influence of gas forces and profile shape.

There is considerable evidence from the field of helical gears that noise frequencies can be correlated with Fourier frequencies of rotor transmission error. These accelerations can also be transformed by Fourier analysis, and this spectrum has been found to be especially relevant to noise in rotating machines such as these.

Munro (1979) has written an excellent review of the subject, which includes the effect of lead crowning on transmission error, and hence the noise produced. Work is now in progress with a major US manufacturer of refrigeration compressors to investigate these effects with a view to reducing compressor noise. It is hoped that a future paper presenting the results of this study will be produced.

5 SUMMARY - FEATURE COMPARISONS FOR THE MAIN MEASURING SYSTEMS

It may be useful to compare the features of the three main measuring systems in use for compressor rotors with reference to the following table. It will be seen that neither traditional pair measuring systems, nor those based on CMMs, are able to provide the extensive information offered by the conjugate pair measuring system.

Table 2 Comparison of measurement systems

Measurement Feature	ARAC	CMM	Feeler/ dial gauge
Leakage area *	Y		
Contact pattern *	Y		Y
Continuous backlash *	Y		
Transmission error *	Y		
Noise prediction (Fourier) *	Y		
Detect nicks, burrs *	Y		
Auto. location of tight positions (minimum backlash) *	Y		
Effect of mis-alignments *	Y		Y
Pairs	Y		Y
Individuals	Y	Y	
High accuracy	Y	Y	
High repeatability/reproducability	Y	Y	
Fast	Y		
TOTAL	13	3	3

6 CONCLUSION

An automatic system of rotor measurement has been described which has all the benefits of pair measurement with the added benefit of being able to measure individuals. With proven capability and reliability in the field, it is able to measure clearances, transmission error and backlash, and can include the effect of various misalignments and deflections. There is now the possibility of correlating these measurements with measurements of compressor performance, reliability & noise. This offers the prospect that the influence of the rotors on the behaviour of the compressor can be better understood and therefore more easily predicted prior to assembly.

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