An imaging system to analyse the behaviour of reciprocating hydraulic seals

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Abstract

The behaviour of elastomeric hydraulic seals as they reciprocate has been studied for many decades. Their friction and wear characteristics are significant for the reliability and performance of a hydraulic system. The lubricating film formed between a cylinder and the seal can be analysed by combining hydrodynamics with models of elastomer behaviour, but the resulting equations have a large number of unknowns and have yet to be resolved satisfactorily to agree with experimental results. The position of the seal within its housing while it is reciprocated is one such unknown. This paper analyses an image capture and analysis system to obtain positional information about the seal in situ with a minimum of disruption to its usual behaviour. The system uses a combination of endoscopes, CCD cameras and a stereo analysis system to determine the three-dimensional location of the seal edges. The system can accommodate a range of different seal dimensions operating with controllable stroke lengths, velocity profiles and pressures. Different lenses can be fitted to the endoscopes so that localized deformations or large scale movements of the seal can be distinguished. No images of seals have previously been obtained during reciprocation, and such images are likely to be particularly useful in the analysis of failure modes such as rolling and extrusion.

1. Introduction

Reciprocating hydraulic systems often use elastomeric seals to keep the hydraulic fluid where required within the cylinder. As the seal moves relative to the surface it is sealing against, a lubricating film of the hydraulic fluid forms underneath the seal. This film is very important for reducing friction and wear of the surfaces, and to the possible leakage of the hydraulic fluid.

This lubricating film has been studied widely since White and Denny[1] first proposed a mechanism by which it could be formed. Although the general principles of the mechanism are agreed on, the details have yet to be established. The seal appears to behave like a hydrodynamic bearing following Reynold's equation, but the pressures involved are sufficient to deform the seal significantly[2]. Any theoretical model of seal lubrication has therefore to combine a good model of elastomer deformation with Reynold's equation. A huge number of variable are involved, such as fluid temperature, seal profile, surface roughness, velocity, fluid viscosity etc., many of which are interdependent. So far, no theoretical model has been completely successful in matching practical measurements of any relevant parameters[3].

An important component of any theoretical model of the sealing process is the deformation of the seal. This will depend upon the forces acting upon it, and the elastomer's response to those forces. An important factor affecting the forces acting on the seal is the orientation of the seal within its housing. Several studies[4] have shown that seals can roll while inside their housing, so significant movement might reasonably be expected. At present, all theoretical models assume that the seal remains flush with the low pressure side of its housing at all times. Clearly this is a component of the theoretical models which could be improved by experimental data.

This paper describes a testing scheme which can determine the position in three dimensions of an elastomeric piston seal in a reciprocating hydraulic system. It is based on a stereo endoscopic optical image capture and computer analysis of the images.

2. Requirements for an imaging system

The elastomeric seals usually used in reciprocating systems are matt black, so reflect very little light. This means that any image obtained of a rectangular cross section seal in situ will contain very little data. All that can be seen with a typical flat field lens is a dark grey area representing the seal with two areas of housing either side of seal (see figure 1). If a fish eye lens is used, two faces of the seal are visible with slightly different greys.

Given this staring point, the options for obtaining three dimensional information are limited. There is no predict-

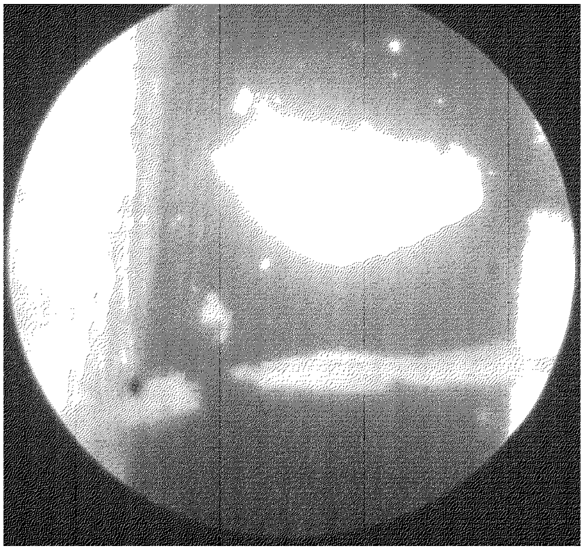

Figure 1: *Image of seal through endoscope*

able motion, no texture, no measurable variation in light intensity with position. Given the inaccessible position of the seal, structured lighting is difficult. A stereo imaging system is therefore the most appropriate means of obtaining positional data in three dimensions[5]. Even so, the only features available are the seal edges, no other information being available to distinguish many other points on the seal. This restricts the possible stereo imaging techniques to feature matching or lattice/variational techniques. Since feature matching is much more straightforward and considerably less processor intensive, it is the most sensible choice. However, the only usual features present in the images of the seal are the seal edges. This effectively limits the data obtainable from the imaging system to the location in three dimensions of the seal edge.

The seals need to be fitted between a piston and a cylinder, both of which are usually made of steel and so not optically clear. Part of the system will be reciprocating, which complicates the access problem. Clearly, the only possible way to see the seal is to replace some part of the steel piston or cylinder with an optically clear material. This will alter the behaviour of the system, however, as the tribological characteristics of the surfaces involved in the sealing are crucial to the sealing mechanism[6]. The optical window will also have to withstand the pressure of the hydraulic fluid. The influence of the high pressure oil around the seal on the images obtained of the seal also needs to be considered.

To gain useful information about the start of seal roll, it would be an advantage to be able to see as much of the seal as possible. This should make it possible to determine whether the failure mechanisms start in one place or all around the seal at the same time. Such data should help determine the causes of the failures.

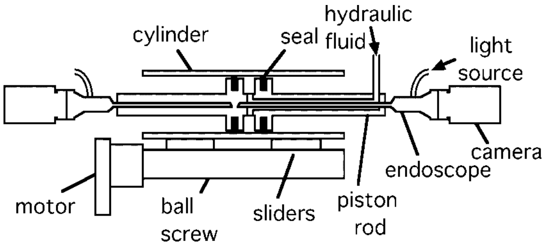

Figure 2: *Test rig*

3. Design of the test rig

The test rig needs to allow optical access to as much of the seal as possible while minimizing as far as possible any deviation in the tribological characteristics of the sealing system.

It is also desirable to have the optical components of the system stationary if possible to maintain alignment and minimize vibrations.

It would be possible to keep either the cylinder or the piston stationary, but this rig fixes the piston and reciprocates the cylinder. The optical access to the seal is then gained through the piston. This makes it possible to see the entire circumference of the seal with fairly simple optics. This arrangement means that the optical window can be fitted to the back of the seal housing, which is likely to be the least critical tribological surface involved in the sealing.

Optical access to the back of the seal seat is gained with endoscopes attached to CCD cameras. To gain stereo information, two endoscopes are used, one from each side of the piston (see figure 2). Since space is so restricted, the endoscopes use mirrors to view the seal at two different angles. A variety of lenses can be fitted to the endoscopes to change the possible fields of view. For example, a spherical field of view lens can be used to image all of the seal at once. Since this produces quite a low resolution image, a lens with a smaller field of view can be rotated to look at any points of interest.

Calibration points are marked on the piston head so that the alignment of the endoscopes in any given image can be determined from the image. These can be seen as white areas in figure 1. The calibration points can also be used to aligned the endoscopes quickly to the required position. The endoscopes can be moved along the axis of the piston or rotated, and can be locked in either or both dimensions.

The piston head is removable to allow seal of a wide range of dimensions to be fitted. The cylinder mounting and optical system can accommodate cylinders with internal diameters between 20mm and 30mm.

Use of external motor control of reciprocation removes the need for sophisticated hydraulics to provide a wide range of working regimes. This is done by mounting the cylinder on a ball screw rotated by a servomotor. The servomotor can be controlled to produce the required velocity profiles with speeds up to 1m/s, given hydraulic pressures up to 10MPa.

The endoscopes connect directly to CCD cameras Pulnix 520s with 512 by 768 pixels and 8 bit grey scale. For long test runs, the cameras can be connected to synchronized S-VHS video recorders. Images can then be captured from video or direct from the cameras in pairs by a Data Translation DT2867 frame grabber for analysis to obtain three dimensional data.

4. Image analysis

Once pairs of images have been obtained, they need to be analysed to determine the location in three dimensions of the seal edges.

The overall scheme for determining the three-dimensional position of the seal can be summarized as follows:

1. Two pictures of the seal are taken simultaneously from different known angles,
2. The pictures are analysed to identify the pixel coordinates of the seal edges,
3. The pixels in each image that represent the same point in space are matched,
4. From this the location in space of each point on the seal is determined by computer.

4.1. Edge detection

Images of seals are quite simple in that they tend to consist of a fairly uniform intensity strip with sharp edges that represents the seal, surrounded by a darker area, possibly with some of the housing in view.

When an image of the seal is passed through a Sobel filter, usually only the two sides of the seal produce strong edges, shown up by the Sobel filter as white lines of high intensity pixels (see figure 3). This filtering is done by Data Translation's Global lab package.

The area in which the seal edge can lie remains constant for a given sealing arrangement, so the processing can be restricted to just that area. Careful selection of the area will ensure that only one edge is present in each search area, and that the number of points to be considered is as small as possible to speed processing time.

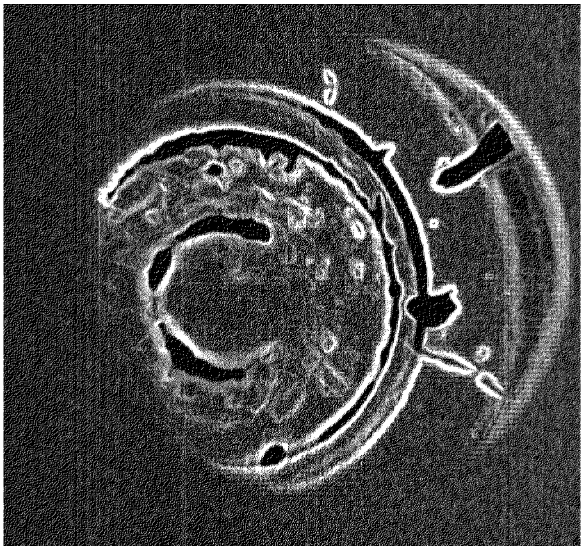

Figure 3: *Image of seal through fisheye lens*

The Sobel filtering will produce an image with the highest intensity pixels representing those pixels in the original image that were most likely to be edge points. If the maximum intensity pixel on each row is identified, a first approximation to the real location of the edge within the image can be identified. The maximum can be easily identified with the following algorithm:

```
for each point $X_n$,
if $X_n > X_{max}$,
then $X_{max} == X_n$.
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Preliminary examination of seal images showed that number of points of maximum intensity lying away from the seal edge is reasonably small and well spaced. This means that 'false' edge points can be identified simply by considering their distance from the points on the neighbouring lines. Points which are a long way from their neighbours are considered 'false' and are replaced with points nearer to their neighbours, as follows:

```
for each point $X_Y$,
if $X_{Y-1} - 2 > X_Y > X_{Y-1} + 2$,
then $X_Y == X_{Y-1}$.
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This sometimes leads to odd small scale deviations. These are smoothed out by reviewing the line again, and 'pulling in' small local deviations from a smooth curve, as follows:

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for each point $X_Y$,
if $X_{Y-1} < X_Y > X_{Y+1}$,
or $X_{Y-1} > X_Y < X_{Y+1}$,
then $X_Y == X_{Y-1}$.
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The problem of determining the pixels in an image that represent the edges of the seal can therefore be solved with a simple new algorithm, based on the idea that the pixel representing a given edge along any horizontal row must be in a vertical column very close to the pixels representing the same edge in neighbouring rows.

The extraction of the most likely edge can be summarized as follows:

1. The area in which the seal edge lies is identified,
2. The point of maximum intensity on each line of the Sobel filtered image in the relevant area is identified,
3. Points unlikely to lie on the line are eliminated,
4. The gaps are filled in, and the line smoothed.

4.2. Theory of stereo system

Once the edges in both images have been determined and their co-ordinates within the image have been extracted, the three dimensional location of the edges can be found.

The new algorithm underlying the three-dimensional part of the image analysis scheme is based on the relationship between a point in space and its image in each camera. This relationship can be found by considering the geometrical relationship between the two cameras and the seal.

Assuming that the principle planes of the two optical systems lie on the same axis, the relationship between the fields of view of the two cameras is shown in figure 4.

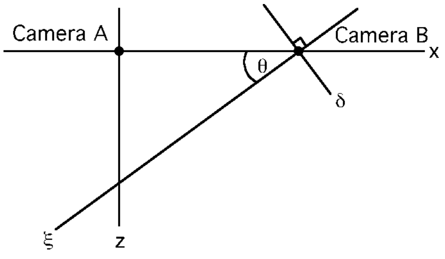

Figure 4: *Co-ordinate systems*

In this layout:

On camera A, pixel (X_a, Y_a) represents points along the line

$$\frac{f_a x}{X_a} + \frac{f_a y}{Y_a} = z \tag{1}$$

On camera B, pixel (X_b, Y_b) represents points along the line

$$\frac{f_b \delta}{X_b} + \frac{f_b y}{Y_b} = \xi \tag{2}$$

where f_a and f_b are the lengths shown in figure 4.

If (X_a, Y_a) and (X_b, Y_b) correspond to the point (x, y, z) then geometrical analysis[7] shows that:

$$z = \frac{Y_b f_a d \cos\theta}{2X_a Y_b \cos\theta + f_a Y_b \sin\theta - 2X_b Y_a} \tag{3}$$

$$y = \frac{2X_a Y_b d \cos\theta}{2X_a Y_b \cos\theta + f_a Y_b \sin\theta - 2X_b Y_a} \tag{4}$$

and

$$x = \frac{2Y_a Y_b d \cos\theta}{2X_a Y_b \cos\theta + f_a Y_b \sin\theta - 2X_b Y_a} \tag{5}$$

The three equations 3, 4 and 5 show the relationship between the three-dimensional co-ordinates of a point and its corresponding points in the two camera images. They can be used to match the pixels in each image that correspond to the same point in space and from there to find the three-dimensional location of that point in space .

4.3. The implementation of stereo analysis

The first stage of the stereo analysis is to map the co-ordinates from both images onto frames of reference with a common y-plane and a common scale. This is done with reference to the location of the calibration points within the image, and also maps the spherical field of view of the fisheye lens onto a flat field.

From here, the pairs of points in each image that correspond to the same point in space can be matched. Since only a limited number of edge points are present in each image, matches can be found using a straightforward algorithm, based on the geometrical analysis described in the previous section as follows:

Once the area in each image containing the seal edge has been identified, there is only one edgepoint on each horizontal line. So if for each edgepoint in one image, the corresponding Y co-ordinate in the other image can be found, the corresponding point can be found.

Given a point (X_b, Y_b) in one image, the point (X_a, Y_a) represents the same point in space. The relationship between Y_a and Y_b is:

$$Y_a = \frac{f_a Y_b}{2X_b \sin\theta + f_b \cos\theta} \tag{6}$$

Since there is only one point representing a given seal edge for each value of Y_a, a unique correspondence can be found.

The position of the point in space represented by each pair of points can be found from the equations in the theory section, along with some geometric measurements, such as the separation of the endoscopes. The test rig has been designed so that the endoscopes can be precisely positioned, setting their separation and the angle between their direction of view to known values. The focal length of the optical system can be adjusted on the endoscope, but the adjustment is uncalibrated. The value f_a and f_b can be found from the calibration points.

The image analysis routines are coded in C++ and can process pairs of images automatically, to produce a file of three dimensional co-ordinates for the visible sections of the seal edges.

5. Results

This system has been used to analyse the movements of a 27.8mm diameter, 4.3mm cross section elastomeric seal in an unpressurized reciprocating system. The location of the seal edge can be determined to within 0.1mm and the movement of the seal within its housing can be clearly seen. In an unpressurized system, friction will force the seal against the edge of its housing in the direction of the cylinder motion, and this can be seen.

6. Conclusions

This system provides a straightforward way of determining how a rectangular cross section elastomeric seal moves within its housing as its hydraulic system is reciprocated. This information will be used to improve current theoretical models of the elastohydrodynamic lubrication of reciprocating systems, and should help determine the mechanisms that cause seals to roll. It can be used to reproduce a wide range of working conditions, and seal dimensions. It is capable of identifying the start of a seal roll and determining how this relates to the normal working cycle of a seal. With the addition of further instrumentation, the relationship between seal position and parameters such as film pressure and thickness could be determined.

6.1. References

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