AN EXPERIMENTAL TECHNIQUE FOR INVESTIGATING THE SEALING PRINCIPLES OF RECIPROCATING ELASTOMERIC SEALS FOR USE IN LINEAR HYDRAULIC ACTUATOR ASSEMBLIES

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SUMMARY
_rectangular seals are used commonly in linear hydraulic actuator systems for aerospace applications. An experimental reciprocating rig is being developed to study the contact conditions of an elastomeric seal with a hard surface. A study on the behaviour of the friction of a rectangular seal has been carried out using a reciprocating rig. The reciprocating speed is varied with a rough sliding surface and a smooth glass surface. The results show that friction is independent of speed for most of the range of the machine but at higher speeds it rises slightly with the reciprocating speed. The friction is also dependent on the roughness of the slider as a marked increase is observed when a rough surface is reciprocated against the elastomer as compared to using a smooth surface. This is in agreement to previous similar experimental studies. This high friction explains wear on the seal and wear observed in actuators. It is suggested that the mode of lubrication remains in the mixed regime to explain the high friction values recorded.

Keywords: Seal, Friction, Reciprocating, Rig, Lubrication

1 INTRODUCTION

Linear hydraulic actuators are used widely in many engineering applications. Aeroplanes use linear hydraulic actuators in flying control, landing gear retraction and other utility systems. The reliable operation of such systems and the minimisation of leaks from the seals is vital to the performance of the actuator. The contact conditions of a seal have to be studied in detail in order to improve its reliability and performance.

A common type of seal on such actuators is one with a rectangular cross section which is referred to as the rectangular seal and is the subject of study here. Relatively little experimental work has been carried out on the tribology of elastomeric seals in reciprocating motion. Extensive practical work was carried out by White and Denny [1] soon after the Second World War. Field [2] and Field and Nau [3] carried out further experiments on rectangular seals using optically smooth elastomers. Kanters and Visscher [4], and Kaneta and co-workers [5] have carried out more recent experimental work on seals. One of the key parameters to be studied is the friction between the rubber seal and the actuator dynamic surface. A simple simulation of the contact conditions on an actuator has been done using a reciprocating rig, where a slider is reciprocated against a clamped rubber seal under flooded conditions of lubrication. The high pressure arising due to fluid pressure found on a real actuator, cannot be easily replicated on a reciprocating rig and therefore the loading on the seal due to the fluid pressure is simulated by a static load on the contact. The motivation behind this study is to gain a basic understanding of the friction behaviour between an elastomer in contact with a reciprocating body in the presence of a lubricant and the factors that affect it. A dynamic numerical model taking into account the real conditions of an actuator has been developed. Some of the results calculated by this model have been used for comparison with the experimental data. An additional numerical static contact model showing the sub surface strain distribution across the contact width of the seal has also been developed and its results presented here.

The behaviour of the seal under real conditions of loading and the parameters that affect its performance such as film thickness and leakage are a subject of further detailed study.

2 EXPERIMENTAL SET UP

The test rig is powered by a DC motor, the output of which is converted from rotary to reciprocating motion via a gearbox and linear bearing assembly. A slider is connected to the linear bearing assembly, which can hold various 41 mm long × 4.5 mm thick × 13 mm wide rectangular plates. A schematic of the arrangement is shown in Figure 1. The rectangular seal is clamped on a vice and the slider assembly presses the slider plate against the seal. The contact load on the seal can be varied by attaching a weight at the end of the slider assembly. The load on the seal is worked out using the principle of moments.

Two force transducers with piezoelectric crystals measure the variation in force on the block that holds the seal. The transducers are aligned perpendicular to each other so that they can give the friction force variation in directions perpendicular and parallel to the direction of the reciprocation. However only the transducer measuring the force in the reciprocating direction is necessary for this study. A data logging device and a...
The computer interface are used to calculate the friction once the gain of the system is calculated after a calibration with a known load. The stroke length, stroke speed and the load on the rectangular seal can be varied. The reciprocating plate can also be changed so that slider plates of varying roughness can be tested.

![Figure 1: Layout of experimental apparatus](image)

For these experiments the load and the stroke length were kept constant. The seal was cut to a 1.3 mm thickness. Other parameters for the tests and properties of the rubber material are shown in Table 1.

The rig is also equipped with a microscope, light source and video recording equipment. This is being used to study the contact conditions of the seal in further detail. Initial findings are in the form of video images showing the conformation of the rough seal against the glass plate under different static and dynamic conditions.

### 3 RESULTS AND DISCUSSION

The roughness of the seal and the sliders are measured using a Talyurf machine. The rubber specimens are provided by TISPP (Dowty Engineered Seals) and are produced using a standard moulding method in industry. The roughness profile can be observed visually under strong light and shows fine grooves on the surface of the seal. The roughness of the seal is given in Table 1. The seal would normally be used in a linear hydraulic actuator.

![Figure 2: The distribution of subsurface strain on a seal of $R_a = 1.7 \mu m$](image)

The strain distribution near the vicinity of contact on such a seal of this roughness is calculated using a boundary element - finite difference model similar to that of Webster and Sayles [6] but formulated to deal with non-linear elasticity. Figure 2 shows the distribution of the maximum principal strain on the seal. The inset shows in more detail the distribution near the contact surface.

<table>
<thead>
<tr>
<th>Seal Type</th>
<th>Rectangular</th>
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<tbody>
<tr>
<td>Modulus of elasticity at 22 °C</td>
<td>5 MPa</td>
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<tr>
<td>Thickness (along reciprocating direction)</td>
<td>1.3 mm</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>ROUGHNESS ($R_a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Plate</td>
</tr>
<tr>
<td>Steel Plate</td>
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<tr>
<td>Seal before testing</td>
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<tr>
<td>Seal after testing</td>
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<table>
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<tr>
<th>TEST PARAMETERS</th>
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</thead>
<tbody>
<tr>
<td>Oil viscosity at 22 °C</td>
</tr>
<tr>
<td>Stroke length</td>
</tr>
<tr>
<td>Load on seal from the weight</td>
</tr>
<tr>
<td>Ambient temperature</td>
</tr>
<tr>
<td>Max. reciprocating frequency</td>
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<tr>
<td>Min. reciprocating frequency</td>
</tr>
</tbody>
</table>

Table 1: Seal and plate properties; test parameters
the image. The dark shade is where the black seal contacts fully with the glass plate. The greyness can be quantified to provide a real area of contact. The real area can give a value for the stress on the seal at the surface, which can then be compared to the stress value calculated by the model.

Figure 3: An image of an O-ring seal in contact with a glass plate under light load

The processed data for the friction tests is in the form of the variation of friction with time as shown in Figure 4. The velocity of the slider changes with time in a sinusoidal manner since rotary motion is converted into linear. A reciprocation frequency of 11 Hz implies an average stroking speed of 110 mm/s with a peak velocity of 346 mm/s. For frequencies of 7.5 Hz and 1.5 Hz these values are 75 mm/s and 236 mm/s, and 15 mm/s and 47 mm/s, respectively. The corresponding friction traces seem independent of this variation. The small scale variation in friction seen as small spikes along the trace shows evidence of stick-slip behaviour which is expected from rough surface interactions where there is lack of a full hydrodynamic film. A common example of such a situation is the operation of the windscreen wiper on a wet window where the rubber wiper moves in a stick-slip fashion.

The relative independence of the friction from the sinusoidal variation of velocity for the smooth glass plate is observed at both low and higher reciprocating speeds. The average friction coefficient for this lubricated glass/rubber contact is worked out to be 0.12.

A dry contact gives a friction coefficient of above 0.5. When a rough steel plate with a roughness comparable to that of the seal is reciprocated against the seal, an average rise in friction by over 70 % is observed. The friction is more influenced by the reciprocating speed and it increases with the reciprocating speed. The variation of friction in one cycle at the highest reciprocating speed is also more pronounced.

Several investigators such as Field [2] and Field and Nau [3] have observed high friction values. These observers were using smooth rubber, which they had to use in order to get film thickness values. This was also the case with Kaneta and co-workers [5]. White and Denny [1] performed detailed tests in the range of 1 mm/s - 72 mm/s stroking speeds with pressurised fluids of different viscosity. They used two surfaces of different roughness, a turned cast iron surface of $R_a = 0.6 \, \mu m$ and a honed steel surface of $R_a = 0.06 \, \mu m$. They, too, concluded that softer rubbers are generally very sensitive to the surface finish as the magnitude of the friction, at any given pressure, was strongly dependent on the surface finish. They also concluded that, beyond a certain degree of smoothness of the metal surface, there is no significant reduction of friction. The ultimate amount of total wear remained the same even though the rate of wear and wear particle size was reduced by the smooth surface. They also saw a strong dependence of friction on the viscosity of the fluid. They concluded that lubrication must have been in the boundary regime.

Kanters and Visscher [4] carried friction tests on rods of roughness $R_a = 0.01 \, \mu m$ and $R_a = 0.05 \, \mu m$. The seal roughness was $R_a = 0.54 \, \mu m$. They, too, concluded that, as long as the roughness of the rod is significantly lower than that of the seal, it does not affect the friction much. However, seals generally vary in roughness and so do the rods. The post test seal (see Table 1) is probably a seal of more realistic roughness, at least for most of the seal service life. The smoother rods in actuator applications are of $R_a = 0.05 \, \mu m$ and the rougher ones of $R_a = 0.4 \, \mu m$. If the roughness of the rod were high enough and comparable to that of the seal then it would be of concern as it could lead to high friction and wear rate.

Figure 4: Variation of friction with time for the two slider plates at different reciprocating frequencies
Evidence of wear was seen in the form of fine black debris in the oil during the experiments. This is a problem encountered in actuators where in extreme conditions the hydraulic operating fluid can become contaminated with seal debris particles. The debris particles can help to cut across the seal surface and effectively may create channels for the high pressure fluid to leak into the low pressure environment.

A complicated non-linear dynamic model of the actuator with real operating conditions has also been developed for transient numerical analysis, which will be presented in a separate publication. Changing the roughness by introducing roughness into the reciprocating piston (equivalent to changing the roughness of the plate) shows an increase in the friction in agreement with the experimental findings for the rough slider plate.

4 CONCLUSIONS

A reciprocating seal-on-plate rig, which is capable of measuring the frictional force between the seal and the plate, is described. Preliminary results show that friction is independent of reciprocating speed when a smooth surface is reciprocated with a rough seal for low speeds where conditions for the formation of a hydrodynamic film are unfavourable. This is true for speeds lower than 100 mm/s. Mixed mode or boundary lubrication is encountered over the range of testing speeds explaining high friction results by various authors and these experiments. To reduce the friction, film formation has to be encouraged. This can be achieved by higher stroking speeds, higher pressure gradients or/and the use of more viscous fluids.

After a certain quality of surface finish has been achieved, the friction is independent of how smooth the surface is. Reciprocating with a rough steel plate however increases the friction. This can be explained by the interaction of hard steel asperities with soft rubber ones. This also stresses the importance of the surface finish of the rod, cylinder bore and seals in a real actuator. If the piston rod were to be rough then it would wear the seal down significantly, which would ultimately lead to increased leakage and poor performance in practical applications.

A number of parameters affect the friction between a soft seal and a hard metal surface as is known from experiments. To gain a better understanding of the performance of the seal, tests must be performed for a wider range of speeds, pressures, temperatures, materials, with fluids of different viscosities, etc. The experimental rig described will be employed to examine many of these parameters and also to develop optical techniques to study the contact conditions. The techniques developed from this rig will be used to develop a further seal-specific rig capable of performing similar tests with seals. This eventual rig will simulate realistic conditions in an actuator of high differential pressures and extreme operating conditions.

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6 REFERENCES