MONITORING THE AGE OF VEHICLE SHOCK ABSORBERS

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***Abstract*—Shock absorber performance is critical to the operation of military vehicles. The Australian Army is interested in implementing health and usage monitoring systems for improved maintenance and fleet management. Shock absorbers typically break down by the failure of the seal where the rod shaft enters the main body, or the seal at the end of the piston within the body. There are few practical options for monitoring the condition of shock absorbers due to harsh operating environments (temperature, dirt, shock loading and continual vibration). Instead of monitoring the change in dynamic performance of a suspension system, it is proposed that the age of a shock absorber can be estimated by measuring the cumulative work done using a calorimetry method involving temperature sensors. This paper describes a simplified thermo-mechanical model that can be used to estimate the cumulative work done by a shock absorber, which is indicative of its age.**

Keywords—condition monitoring, Health and Usage Monitoring Systems (HUMS), shock absorbers, vehicle suspension

I. INTRODUCTION

The shock absorber on an Army land vehicle is an integral part of the vehicle's suspension system. When a shock absorber failure remains undetected or is not addressed, this can lead to catastrophic failure of other suspension and steering components. The Australian Army is interested in implementing Health and Usage Monitoring Systems (HUMS) to improve equipment maintenance and fleet management, improve data integrity and reduce manual data entry burden.

Fig. 1 shows a sketch of a twin-tube shock absorber. The most common failure mechanisms of such are as follows [1]:

1. Break of rod seal in the shock-absorber.
2. Internal damages of the shock absorber: destruction, failure or natural wear of the valve assembly or piston.
3. Mechanical damage of the shock-absorber: crack, dent in a body, bent rod.
4. Destruction of the shock absorber: breaking off the rod, disengaging the mounting lug, degradation or destruction of silent blocks.
5. Inconsistency of properties or degradation of the shock absorber fluid.
6. Absence of gas in the shock absorber.

The most common event that leads to degradation of shock absorber performance is the damage or breakage of a rod or piston seal. Hence, a review of methods that have been used to monitor rubber seals, failure mechanisms of rubber, and HUMS for shock absorbers are described in the following.

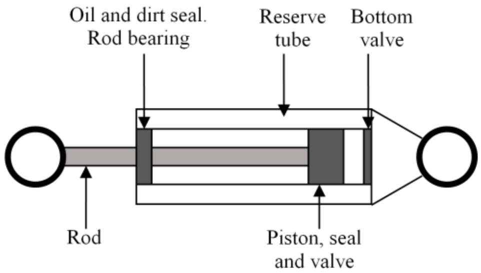

Fig. 1. Sketch of the cross-section of a twin-tube shock absorber, adapted from [2] page 16.

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II. LITERATURE REVIEW

A. *Failure of Rubber*

As noted, the failure of rubber seals is one of the most common shock absorber failure mode. Rod and piston seals operate under cyclic mechanical and thermal loading that leads to loss of elasticity and mechanical damage. The failure of the mechanical seal causes either excessive loss of fluid from the system being sealed, or excessive reduction of pressure with the system being sealed [3]. In the case of a shock absorber, the damage of a rod seal leads to deterioration or total loss of damping properties of the mechanism. Methods that have been used to monitor the condition of rubber seals include:

Embedded sensors [4], where a seal is integrated with a sensor or a microchip. Seals equipped with magnetic properties or electric conductivity may monitor their wear, measure forces and perform other functions. This technology is still at the R&D stage and is not commercially available at the moment.

Seal temperature and fluid pressure [5], where the temperature can be measured using a thermocouple or Resistance Temperature Detectors mounted close to the seal.

Acoustic emission (AE) [6] [7], as a result of stress waves generated by internal modifications such as crack growth, frictional contact, wear, bending, and corrosion. One of the limitations of Acoustic Emission techniques is that it is sensitive to the presence of process noise. There are some studies that use adaptive noise cancellation techniques to filter out background Acoustic Emission noise [8].

Ultrasonic waves [9], to measure the thickness of a lubricant film between rod seal and cylinder. Externally generated ultrasonic waves were suggested in [9] for monitoring the lubricant thickness between the raceway of a bearing and a ball bearing, and could potentially be used to monitor the lubricant thickness in the lip of a seal.

Rubber seals most likely fail due to the combined cyclic mechanical stress loading and thermal cycling. Nyemeck and Ledauphin [10] indicate that when rubber seals are exposed to a temperature rate increase that exceeds a certain value, it leads to cracking and consequentially seal failure. Researchers have investigated the failure of rubber due to mechanical loading and proposed failure model similar to Wöhler's S-N curves developed for metal fatigue around 1855. However, as rubber is cyclically compressed and unloaded, the material will heat up, and the elevated temperature can alter the fatigue life of the rubber [11], which makes life predictions difficult.

Shangguan et al. [12] used strain energy density to determine a fatigue model for rubber, where the tests were conducted at 23ºC with a cooling fan directed at the sample. A result from their fatigue testing of rubber, involving a constant amplitude of oscillating displacement (rather than force), where the axial force exerted by the compressively loaded rubber sample changes over time, showed that there was a relatively flat response for the majority of its life, followed by an extremely rapid degradation in the axial force. This rapid demise of rubber would be problematic for any HUMS system in a shock absorber, because by the time degradation of the seal is noticed, the shock absorber would likely have failed.

Zarrin et al. [13] also conducted fatigue testing of rubber, and their test results showed a more gradual "end-of-life" degradation in performance compared with Shangguan et al. [12]. Depending on the end-of-life fatigue behaviour, there could be little advanced-warning of an impending catastrophic failure of a shock absorber.

A better monitoring method would involve tracking the number of load cycles, and when say 90% of the "life" expectancy is complete, the part is replaced before entering a phase of rapid demise. However, this type of HUMS system would require continuous monitoring of damage-inducing events, whereas monitoring the dynamic performance of the system need only be done intermittently, and when the performance is not within normal bounds, an alarm can be triggered to indicate that maintenance is required.

B. *Monitoring the Performance of the Suspension*

Model-based condition monitoring techniques rely on [18]:

- a simplified model of the vehicle's dynamics;
- a limited number of sensors to be installed on a vehicle (e.g. accelerometers);
- observer-based fault detection method that identifies faults in dynamic systems through the evaluation of residuals.

A model of the vehicle's system's dynamics is created, either before use, or is adaptively developed. The difference between the model's estimate of the performance and the vehicle's actual performance is used to identify if a fault exists. Previous researchers conducted their studies using theoretical models [14] [15] [17], lab-based rigs [16] [18], and full vehicle tests [18]. In the literature review that was conducted, a commercially implemented (i.e. ruggedised robust) HUMS for shock absorbers was not found.

Condition monitoring of shock absorbers has been proposed using sensors that include:

Pressure. The shock absorber's internal pressure, together with the acceleration of the unsprung mass, can provide information about different shock absorber conditions [19], such as the transmissibility between the pressure in extension and acceleration of the wheel as a monitoring parameter.

Temperature. Damping forces and coefficients reduce as internal oil temperature increases [18] [20], and is called "damper fade" ([2], page 276). The measurement of fluid temperature (relative to e.g. ambient) could be used as a proxy for the amount of energy that the shock absorber has dissipated. This technique has been used successfully to determine the energy dissipation in rubber isolators [11] [21] [22]. A US patent was awarded to Honeywell in 2012 for a "Shock absorber health and condition monitoring device" [23]. This device uses a temperature sensor for monitoring the remaining useful life (RUL) of the shock absorber but the patent does not provide details of the algorithms used.

Force and velocity. These are the main performance parameters of a damper. A US patent [24] proposed a device that used a piezo-electric element to measure force from the damper, and suggested (without details) that this could be used to monitor the health of the shock absorber. As the transducer would need to be installed in the load path, the sensor would have to be more robust than the shock absorber, something the authors believe is unlikely. Poprawski et al. [25] investigated condition monitoring of shock absorbers on railway wagons. They created force vs velocity profile maps and defined regions of normal operation so faults could be detected when the dynamic performance was outside the "normal" range.

Acceleration. This can be measured on both sides of a damper, or on the vehicle itself. The transmissibility between two acceleration signals is a function of the damping factor and can be used as an indicator of the shock absorber condition [19] [26] [27] [28]. However, transmissibility alters with temperature, sprung mass (mass of the vehicle and payload), and the spring constant (among other things). As a result, the transmissibility would be different for the same type of shock absorber installed on different vehicles.

From the above review, there are three general approaches: monitoring the internal operations of a shock absorber to detect leaks, monitoring of the dynamic performance of the suspension system, and estimating the work done by the shock absorber. They all require robust sensors placed in harsh environments, data storage and processing to flag warnings.

Data from run-to-failure tests was not found in the open literature, making a comparison of methods challenging. Researchers have artificially induced problems in shock absorbers (e.g. [28]), but data of realistic ageing was not found.

III. THERMO-MECHANICAL MODEL OF A SHOCK ABSORBER

Shock absorber temperature affects dynamic behaviour, and should be taken into account when producing models of vehicle dynamic behaviour. However, thermo-mechanical models of shock absorbers also have the potential to be applied for condition monitoring [18] [20].the can be used to determine the cumulative work done by a shock absorber, similar to the well-used calorimetry technique, where the temperature rise of a liquid is used to determine the energy expended. The following paragraphs describe one such thermo-mechanical model, and show that by measuring temperatures, it is possible to get an estimate of the work done and hence its age.

A. Theoretical Model

The simplified thermo-mechanical model is built by applying the law of conservation of energy to two subsystems: the oil chamber and the outer cylindrical body:

$$\frac{dU}{dt} = \dot{Q} - \dot{W} \tag{1}$$

where U is the internal energy of the closed system, Q is the amount of heat transferred to the system, and W is the amount of work done by the system.

The internal energy of the oil contained in all three chambers of the shock absorber (rebound, compression, and reserve) is equal to $U_{oil} = m_{oil}c_{oil}T_{oil}$, where m_{oil} is the oil mass, c_{oil} is the specific heat capacity of oil, and T_{oil} is the oil instantaneous temperature. Convective heat transfer from the oil to the cylindrical body is given as $\dot{Q} = h_{oil}A_{cyl}^{in}(T_{cyl} - T_{oil})$, where h_{oil} is the oil heat transfer coefficient, A_{cyl}^{in} is the internal area of the cylindrical body, and T_{cyl} is the instantaneous temperature of the cylindrical body. The last term in (1) relates to the work made on the oil by the pressure forces $\dot{W} = -Fv$, where F is the shock absorber force, and v is the shock absorber velocity. As a result, the equation of conservation of energy for oil can be written as:

$$m_{oil}c_{oil}\frac{dT_{oil}}{dt} = h_{oil}A_{cyl}^{in}(T_{cyl} - T_{oil}) + Fv \tag{2}$$

For the solid cylindrical body, the energy balance equation (1) becomes the equivalence between the internal energy and the heat exchange:

$$\frac{dU_{cyl}}{dt} = \dot{Q}_{cyl} \tag{3}$$

The internal energy of the cylindrical body is $U_{cyl} = m_{cyl}c_{cyl}T_{cyl}$, where m_{cyl} is the mass of all solid parts contained in the shock absorber, and c_{cyl} is the specific heat transfer of the metal. The heat transfer term $\dot{Q}_{cyl}$ includes the convective heat transfer from the oil, and the convective and radiated heat transfer to the ambient air. As a result, the energy equation for the cylindrical body has a form:

$$\begin{aligned} m_{cyl}c_{cyl}\frac{dT_{cyl}}{dt} &= h_{oil}A_{cyl}^{in}(T_{oil} - T_{cyl}) \\ &\quad + h_{amb}A_{cyl}^{out}(T_{amb} - T_{cyl}) \\ &\quad + \varepsilon\sigma A_{cyl}^{out}(T_{amb}^4 - T_{cyl}^4) \end{aligned} \tag{4}$$

where h_{cyl} is the body heat transfer coefficient, ε is the emissivity of the cylindrical body, $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4) is the Stefan-Boltzmann constant, and A_{cyl}^{out} is the surface area of the cylindrical body.

Equations (2) and (4) constitute a simplified thermo-mechanical model of the shock absorber with known inputs to the system defined by the damper force and velocity, and temperatures as unknown dependent variables. It should be noted that such parameters as c_{oil}, h_{oil}, h_{amb} are dependent on the fluid (oil or ambient air) temperature and velocity. However, at this stage, they are considered as constants.

B. Simulation Results

It was assumed that a heavy vehicle is moving at a speed of 20 km/h on a rough road (road class E according to ISO 8608 [29]). A quarter-car model was used to synthesize velocity and force data [26], which was supplied as input into the thermo-mechanical model to generate temperatures of the shock absorber components. Small fluctuations were added to the temperatures, as shown in Fig. 2, and were then used to back-calculate the work done by the shock absorber using the extended Kalman filter, as shown in Fig. 3. The predicted values of work using the thermo-mechanical model agrees reasonably well with the actual work.

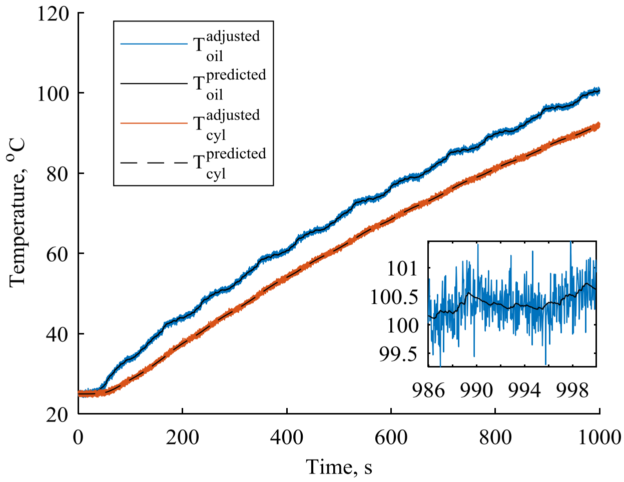

Fig. 2. Predicted and adjusted temperatures of the oil and body.

IV. CONCLUSIONS

A simple thermo-mechanical model was created based on a calorimetry method that can be used to estimate the work done by a shock absorber. The most common failure mechanism of shock absorbers is aging of rubber seals in the piston or where the piston rod enters the main body. It was shown that measurements of temperature of the oil, body and ambient air can be used to estimate the work done, which is indicative of the age of the shock absorber. A HUMS implementation would involve setting a value of energy where the shock absorber should be replaced. This can only be determined by life testing of actual shock absorbers under a range of conditions.

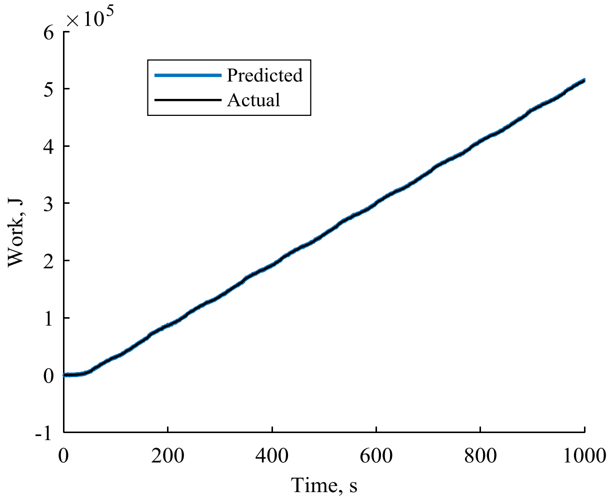

Fig. 3. Actual work and predicted work based on temperature measurements.

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