SAG 2006

DEPARTMENT OF MINING ENGINEERING

UNIVERSITY OF BRITISH COLUMBIA

A STRUCTURED APPROACH TO MODELLING SAG MILL LINER WEAR – NUMERICAL MODELLING OF LINER EVOLUTION

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ABSTRACT

A numerical framework to predict the three-dimensional evolution of the liner profile within a rotating industrial SAG mill is presented. The need to understand the manner in which the lifter profile develops is emphasised by comparing two discrete element method (DEM) simulations with measured new (i.e. unworn) and worn lifter profiles. The DEM informs the subsequent wear model as to the loading conditions on the shell of the mill. The wear model relates the loading conditions on the shell to material loss. The lifter profile is then evolved and forms the input for the next DEM simulation step in the wear analysis cycle.

INTRODUCTION

Predicting the optimal spacing between the lifters and the evolution of the lifter profile during the course of the lifters' useful lifespan will greatly assist in the design of industrial mill. Numerical methods, such as the discrete element method (DEM) (Cundall & Strack, 1979), coupled with powerful modern computers allow the dynamic behaviour of the mill charge to be approximated subject to various assumptions regarding the shape of the charge particles (usually assumed spherical) and the manner in which they interact. Predicting the evolution of the lifter profile is a far more complex task than predicting the charge profile as the

underlying wear mechanism is not completely understood. In addition, component wear in industrial mills is not a well characterised process, and appropriate and accurate data to calibrate and validate numerical models is sparse. In spite of these complications, the outputs of the DEM have been coupled with relatively simplistic wear models with promising results.

This paper addresses two major issues: the influence that the lifter profile has on the charge behaviour within an industrial mill and the development of a structured methodology to evolve lifter profiles within the framework of the DEM.

The influence of the lifter profile on the motion of the charge has been investigated by several authors (see e.g. Cleary, 2001a). The current authors and co-workers compared the trajectory of a single particle within the bulk charge of an experimental mill with DEM predictions for a wide range of lifter profiles at varying mill speeds (Govender, 2005). The small experimental scale of this investigation renders it questionable to extrapolate all the results to a full scale industrial mill. Cleary (2001a) investigated the influence of lifter shape on charge motion for a 5m diameter SAG mill. The current work uses a well characterised 8m diameter industrial SAG mill, treating competent silicate ore, as the base case for the investigation. Considerable lifter profile and charge size distribution data has been gathered over the useful lifespan of the lifter. The details of the mill and charge are given in Table 1. An in-house sampler was used to collect a 1000kg representative sample of the mill charge. This measured size distribution provides the charge size distribution for the DEM simulation.

DEM SIMULATIONS

Due to the large computational overhead (i.e. the amount of processor time it takes) of DEM simulations, it is necessary to truncate the size distribution to reduce the particles to a manageable number whilst still attempting to capture the salient features of the bulk motion. As the small particle sizes are orders of magnitude less in size than the larger ones, they are probably too small to contribute in any significant manner to the forces giving rise to liner wear, and they are removed from the size distribution. In addition, the stable time-step size (the theoretical maximum time-step required to accurately integrate the individual particle's motion) is directly related to the smallest particle size. Truncating the size distribution at 22mm was seen as acceptable as the packing of the particles between the lifters, and the cataracting stream is still accurately represented. In Table 1 the total number of particles per one m^3 is converted to a number per 0.25m slice of the mill length. Truncating the size distribution reduces the number of particles from over ½ million to less than 40 000, thereby significantly reducing the computational overhead. To put this in perspective, a 3.6GHz processor

with 2Gb of RAM takes approximately 3 weeks to conduct a full simulation (4 revolutions) of this truncated charge. It is thus critical to truncate the mill load but without adversely affecting the charge kinetics and energy distribution profiles significantly. Assessing the influence of charge size truncation is part of the ongoing scope of this study of liner wear prediction.

Table 1 Mill parameters.

mill diameter, m		shell	8.00	inside liner		7.801
speed, rpm		rpm	11.4	% crit	75	
mill filling, %		total,ave.	40	balls	14.9	
number of rows of lifters			52			
feedrate, tph			230	(average)		
ore	gold, quartzite		sg	2.7		
size distribution, % retained			number of balls		number of rocks	
size, mm	balls	ore	exp./m^3	sim.	exp./m^3	sim.
212		0.00				
180		0.10			5	9
122		0.10			5	9
90	39.9	0.46	12	121	4	7
63	47.3	1.46	39	247	31	60
45	9.4	6.06	22	328	370	708
31.5	2.6	15.17	17	290	2623	5014
22.4	0.8	21.22			10446	19972
16		21.87			29740	0
11.2		15.66			60223	0
8		6.98			75911	0
5.6		3.52			114453	0
total numbers			90	986	293812	25779

Two measured lifter profiles are simulated. Figure 1a and b depict the new lifter profile while Figure 1c and d shows the measured profile after a period of 211 days. The resulting DEM representation of the mill was directly generated from the CAD model of the mill that took as its input the measured lifter data. It was seen as important to capture the significant detail of the measured profile in the DEM model, as is evident in Figure 1.

The profiles were obtained using the UCT profiler gauge, Chandramohan & Powell (2006). An image of the mechanical gauge in use and the measured profiles over the life of a lifter are shown in **Figure 2** (see next page).

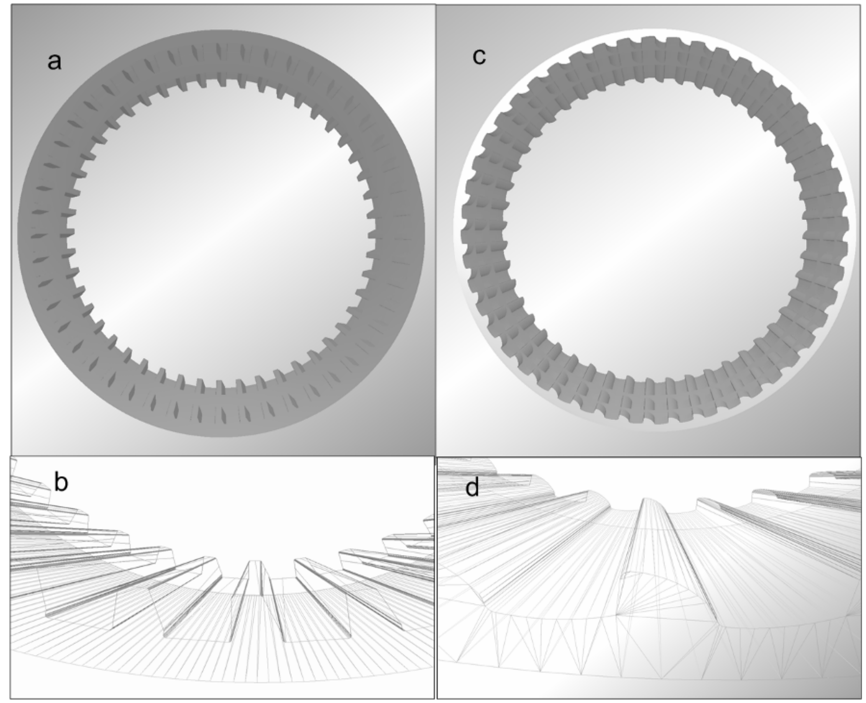

Figure 1 a) Mill with new lifters. c) Mill with worn lifters. b&d) Close up of DEM model of new lifter profile. d) Close up of DEM model of worn lifter profile.

A 0.25m slice of the mill containing approximately 38 000 particles was simulated using the commercial DEM package EDEM from DEM Solutions. Periodic boundary conditions in the longitudinal direction (i.e. parallel to the axis of mill rotation) were implemented. These boundaries allow the particles that cross through the boundary to ‘reappear’ at the opposite boundary. Thus, the natural three-dimensional packing, as opposed to the altered packing that would occur if a rigid boundary was used, and the particle population is preserved. Utilising a periodic boundary, the 0.25m slice can accommodate the largest particles, but should ideally be wider than this. A wider slice, with the resulting larger number of particles, will be simulated using a parallel processing environment in the near future. A three-dimensional slice has been shown to be a far better approximation to the full three-dimensional behaviour and in particular the particle packing than the associated two-dimensional model (Cleary, 2001a).

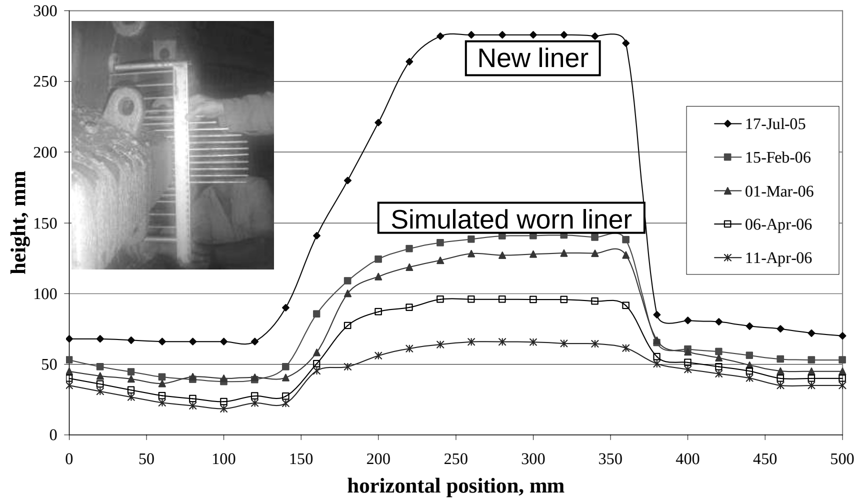

Figure 2 Liner profiles a) the gauge in situ b) progressive profiles.

The primary DEM input parameters are listed in Table 2. The widely used simplified Hertz-Mindlin contact model is employed to approximate the contact between the spherical DEM particles (see e.g. the review article by Mishra, 2003). The magnitude of the shear modulus for both the ball and ore particles has been decreased by a factor of 100 to increase the minimum critical time-step size, whilst attempting not to invalidate the assumptions of the contact model. The time-step duration of approximately 6.2e-5s (30% of the Rayleigh time-step duration) is fixed for the duration of the analysis. The correct number of particles to generate the required filling corresponding to the measured particle size distribution is “placed” in the mill and two complete revolutions simulated in order to mix the charge and allow the mill to enter a pseudo-steady state. Thereafter, another two revolutions are simulated in order to assess the effect of lifter profile on charge behaviour.

Table 2 DEM simulation parameters.

	Steel		Steel-Rock		Rock	
Shear modulus, N/m2	G_s	$7.752\text{x}10^8$			G_r	$7.550\text{x}10^7$
Poisson’s ratio	μ_s	0.29			μ_r	0.2
Coefficient of rolling friction	Φ^r_{ss}	0.001	Φ^r_{sr}	0.002	Φ^r_{rr}	0.005
Coefficient of sliding friction	Φ_{ss}	0.3	Φ_{sr}	0.5	Φ_{rr}	0.8
Coefficient of restitution	α_{ss}	0.3	α_{sr}	0.5	α_{rr}	0.5

INFLUENCE OF LIFTER PROFILE ON CHARGE BEHAVIOUR

Outputs from the DEM simulations for the new and worn lifter profiles are shown in Figure 3 (see next page). Figure 3a and d show time-exposure (streak) images of the charge motion, coloured by the magnitude of the velocity. Streak images give a far more detailed overview of the charge motion than conventional “snapshot” images of the charge at an instant in time (see Figure 3b and e). The new, more aggressive lifters increase the angular position of the shoulder causing more particles to enter the cataracting stream. The velocities attained by these particles are higher than for similar particles in the reduced cataracting stream produced using the worn lifters. Figure 3a clearly indicates however that many of these high velocity particles in the cataracting stream impact with the shell of the mill in the toe region.

These high velocity impacts with the shell damage the liner of the mill, resulting in peening, cracking, and sometimes fracturing of the liners. The charge profile attained using the worn lifter is less damaging as no particle impacts occur directly with the shell in the toe region. The milling action has changed considerably as the liner wears. Not only has the impact point dropped down onto the charge, but there is clearly a smaller fraction of the charge undergoing cataracting and impacting. The consequence of this is a shift from impact breakage to abrasion grinding. This will result in a lowered throughput, but finer product. To recover the throughput this variable speed mill can be sped up to 80% of critical speed as the liner wears to this profile. In order to link this information into the liner design, a milling model that utilises DEM outputs is required. At the University of Cape Town a Unified Comminution Model (UCM) is being developed that does just this, Powell (2006).

An ability to predict the manner in which the lifter profile evolves with time is clearly required for the proper design of lifters. Measurements, such as those given in **Figure 2** and Table 3, indicate that the new lifters wear at a lower rate initially and then the wear rate accelerates as they wear below a critical height that allows excessive slip of the charge. Thus, it is critical to understand the manner and rate at which the lifters evolve in order to optimise the mill design process.

Figure 3c and f show close up images of the particle packing structure against the lifter. A component of this research is to investigate the effect of lifter spacing on mill performance. The spacing between lifters is too close in the current design resulting in the charge “packing” into position between the lifters, as shown by all the balls between the lifters in Figure 3c all having the same velocity – corresponding to the mill’s rotational velocity.

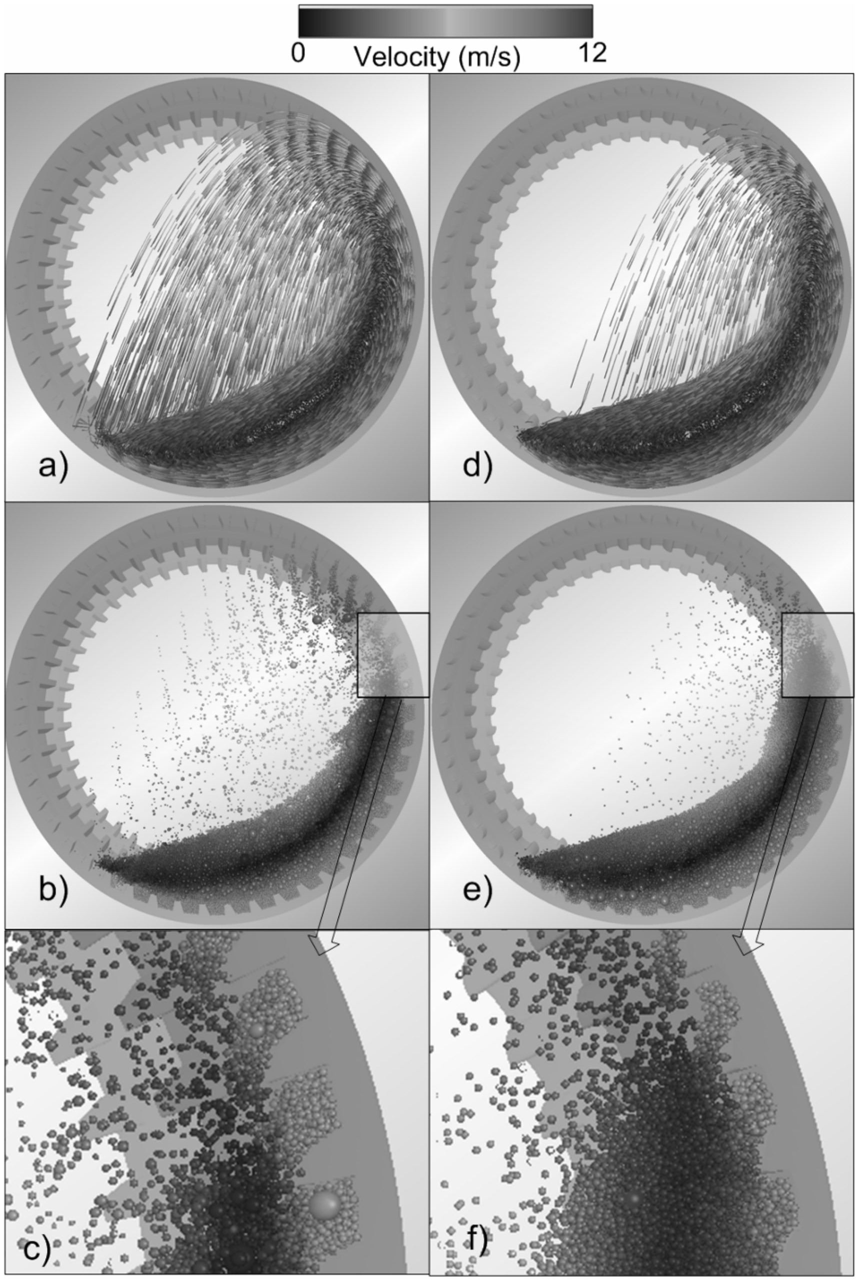

Figure 3 Images of DEM trajectory data. (a–c): the outputs for new lifters and (d-f) for worn lifters. (a & b): - Streak images. (b & e): Snapshot images of velocity profile. (c & f): Close-up of particle packing between lifters.

Table 3 Liner wear rates of test mill.

Date	days	height	lifter wear, mm/kt	lifter wear, mm/day	liner plate wear, mm/kt
17-Jul-05	0	215			
15-Feb-06	213	88	0.106	0.595	0.070
01-Mar-06	227	84	0.103	0.579	0.101
06-Apr-06	263	56	0.108	0.606	0.106
11-May-06	298	30	0.111	0.622	0.111

This forms a dead zone of zero grinding action. For the worn lifters it is evident that there is relative motion right down to the shell plate between the lifters, so this remains an active zone. A considerable portion of the grinding action takes place in the shear zones between layers of charge as the mill draws the charge upwards, so locking up 18% of the ascending charge will have a considerable influence on the grinding rate of the mill. In related work conducted on the mill that is simulated in the current work, van der Westhuizen and Powell (2006), it was found that the mill throughput was severely limited when new lifters were installed in the mill.

This worn lifter simulation is at the point at which the liner wear begins to accelerate, see **Figure 2** for the profiles. Below this there should be considerable sliding action extending onto the liner plate, and leading to accelerated lifter and liner plate wear.

A series of simulations for different lifter spacing ratios is currently underway and results will be presented in a forthcoming publication. This will present the collision energy spectra and power draw of the various mill configurations so as to provide the first stage of the link between liner evolution and mill performance.

PREDICTING THE EVOLVED LIFTER PROFILE

A method to predict the evolution of the lifter profile for the full scale industrial mill described in the previous section is presented. The prediction of lifter evolution has been considered by several authors. The following serves as a summary of several key contributions; others have been omitted for the sake of brevity. The essential components to consider when assessing the relative merits of a wear methodology are: the manner in which the lifter profile is discretised and whether this approach is valid in three dimensions, the wear model applied, and the smoothing algorithm used to average the wear across the lifter to prevent the formation of local depressions.

Cleary (1998) discretised the profile of the liner into equal sized divisions, henceforth referred to as bins. A two-dimensional DEM mill model was considered. The kinetic energy of the particles impacting with the mill shell was accumulated in the bins. The Finnie wear model (Finnie, 1972), a variant of the widely used Archard's model (Archard, 1980), was used to relate the bin data to liner wear (i.e. material loss). The wear across all lifters was then accumulated to a single representative lifter and the amount of wear in each bin averaged using a cubic spline smoothing algorithm.

The later work of Cleary (2001b) extended his earlier work (1998) to three-dimensions. The surface of the lifter was tessellated into triangular elements (i.e. decomposed into a set of non-overlapping triangular facets). The data accumulated in each of the elements was then averaged over the length of the mill and smoothed. The elements were constructed to be smaller in diameter than the smallest particle in the charge. The amount of wear was now assumed to be due to impact and abrasion. Impact wear was estimated using two measures; namely the energy dissipated in the normal direction at the contact and a measure of the excess kinetic energy. The abrasive wear was likewise estimated using two measures; namely the energy dissipated by the tangential (to the contact surface) and the kinetic energy of each particle involved in the collision. As such, the Cleary (2001b) model is the most flexible (and complex) model in the current literature. Other notable contributions include the work of Qiu *et al.* (2001) and Glover & de Beer (1997). Unfortunately, a complete understanding of the wear mechanisms in a mill that can conveniently utilise the outputs of the DEM in a relatively simple manner and that is parameterised using well constructed experiments, is not available at present.

The approach taken in the current work resembles that of Cleary (1998). Each collision event with the mill shell is recorded during the simulation process. The resulting data file is post-processed to map all the collision events in the mill to a representative master lifter. The master lifter is then decomposed into a series of rectangular elements (bins) that extend the length of the mill. The width of the elements is selected to be significantly smaller than that of the smallest particle in the mill. The discretised profile of the master lifter is shown in Figure 4 (see page after next), wherein 100 bins have been used. It should be noted that in this and subsequent images of the lifter, the horizontal and vertical scale shown are not equal. The units are in m, but are only shown to represent scale and do not correspond to a specific position in the mill. The curved shell of the mill between the lifters is in addition represented as a straight line segment. Any possible contact data can be accumulated in the bins. The normalised variation in the number of contact events and the normal

energy dissipated across the profile of the lifter are shown in Figure 5 (see next page) and Figure 6 (see page after next) . Archard's law is used to relate the contact data to material loss in the direction normal to the bin. The relatively short duration of the DEM simulation (approximately 0.5s wherein 40 000 collision events occurred) and the finite size of the bins produces data less smooth than one would expect in an actual mill wherein the data would be accumulated (if this were possible) over a period of weeks to months. The procedure to smooth the data is as follows. A cubic spline function is first used to smooth the data profile prior to applying Archard's law. Archard's law is then applied and the updated lifter profile obtained. A least squares smoothing spline is then used to smooth the resulting worn lifter profile. The worn lifter profile so obtained then forms the basis for further wear simulations. The profile is exported in a CAD compliant format and forms the input for the next DEM simulation.

The iterative nature of the simulation process required to predict the wear process, coupled with the computational expense of the individual simulations, necessitated the development of a procedure to maximise the amount of wear predicted by each simulation without introducing significant errors. The approach taken in this work is as follows. The amount of wear as a percentage of the lifter volume is determined. If this amount is below a defined threshold, the updated lifter profile is determined but the simulation not restarted. The loading on the previous geometry is now applied normal to the updated lifter profile and a successive updated lifter profile determined. This process repeats until the amount of wear exceeds the specified threshold.

CONCLUSIONS

The effect of the lifter profile on the behaviour of a full scale industrial mill has been investigated using the DEM. Considerable changes in the response of the mill are predicted as the lifter profiles moves from an unworn to a worn one. It is obvious that the liner should be designed to maximise output over the working lifespan of the liners and that a knowledge of the worn lifter profiles would be of considerable value. The liner wear procedure developed in this work resembles that presented by other researchers. The primary difference in the current approach is that the system is not binned a priori and the manner in which the collision data and worn profiles are smoothed.

The focus of future work will be on calibrating the wear model to the measured lifter profiles, this is being conducted in related work

(Chandramohan & Powell, 2006), and determining a means to critically assess the performance of the numerical model. In addition, procedures to expedite the simulation of the wear process need to be investigated. The longer term goal is to use laboratory wear data, such as that being developed by Radzisewski (2001), to fully predict the wear and evolving profile for a greenfields application.

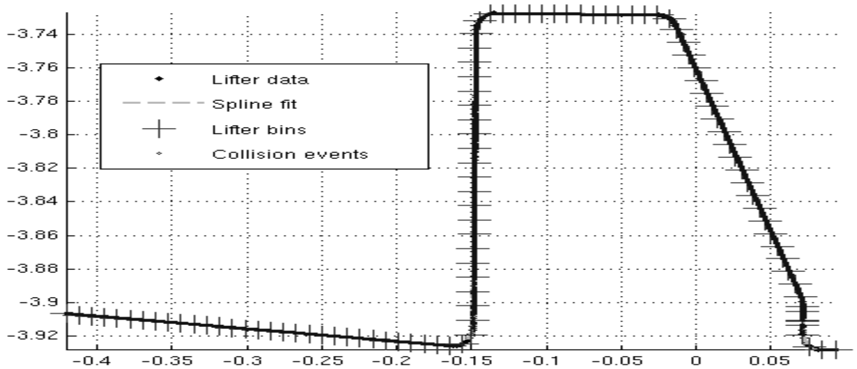

Figure 4 Discretised new master lifter profile (scale in m).

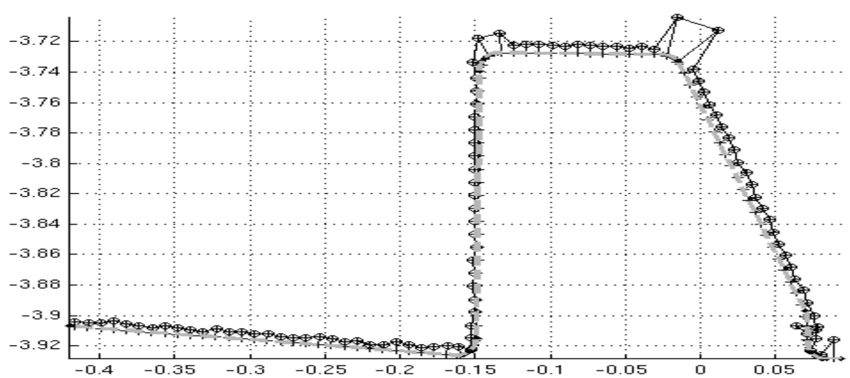

Figure 5 Normalised distribution of the number of contact events occurring with the master lifter (scale in m).

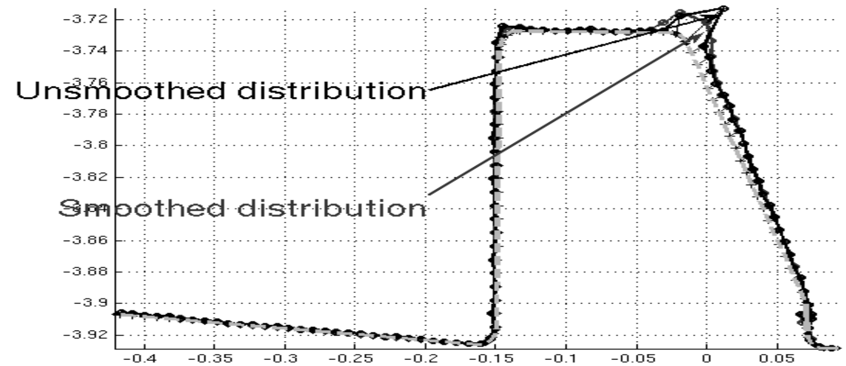

Figure 6 Normalised distribution of the normal energy dissipated during collision events with the shell. Both smoothed and unsmoothed collision data is shown. The smoothing is performed using a least squares smoothing spline algorithm (scale in m).

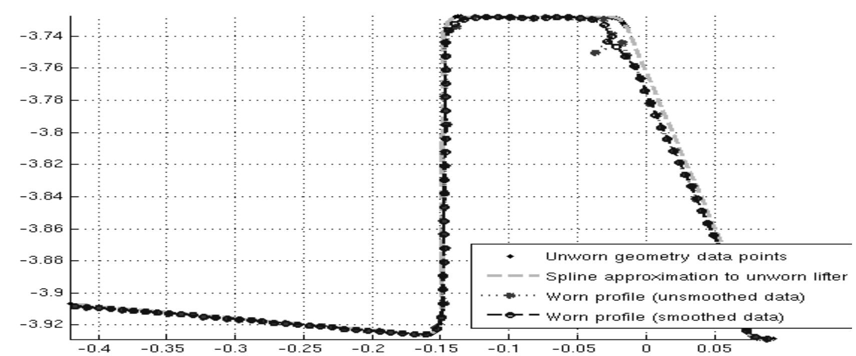

Figure 7 Updated original and worn master lifter profiles (scale, m).

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