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Optimizing Shovel Dipper Design for Cutting Soft Rock and Soils

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ABSTRACT The design of dippers for cable shovels has essentially remained unchanged for the last 100 years In the past 10 years shovel manufacturers have started taking another look at dipper design, resulting m changes that have bome models from the major manufacturers that address some of the wear conditions and material retention problems that dominate maintenance and operational costs However, with the exception of added lateral curvatures to the front and corners of the dipper, the geometry is essentially unchanged This paper looks at the criteria that have resulted m the first new cutting dipper design in a century The design is based on kinematic considerations, reflected in a revolutionary geometry that matches the range of motions of the shovel, designed to minimize wear, impact loading and power required to dig, thus maximizing productivity for a minimum energy requirement The shape configuration is such that the weight of the dipper through wall thickness is reduced, enabling a larger capacity dipper to be conceived for the same shovel Benefits are reflected m reduced operational and maintenance costs and increased productivity

1. INTRODUCTION

Electric cable shovels are the most extensively used high volume excavators in open pit mining Previous work to improve the production capability of these units focused on updating mechanical and electrical components and optimizing utilization and operational approaches Little work has been done to improve dippers and their ground interactions, (ACARP, 2002) With the trend of higher production forcing the development of ever bigger, faster and smarter cable shovels there is a need to move beyond the aging geometry of dippers, relatively unchanged in the past 50 years

In the Athabasca oil sand deposits of Northern Alberta, Canada, mine opeiators employ the biggest cable shovel models with dipper capacities upwards of 44 m However, the same wear and impact associated ground-equipment interference problems plague these monster class shovel dippers, as have continually done so for the past decade Original equipment manufacturer (OEM) variations have concentrated on internal wear and retention issues, but pay no heed to the actual kinematics and high external problems that predominate

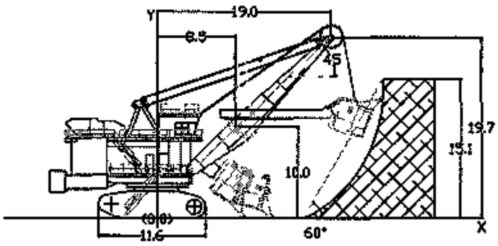
In recent years computer simulation techniques have dominated industry's approaches to system or product design These have many obvious economic and logistical advantages over physical modeling approaches, however verification remains m field application Shear size and expense of building a full scale physical prototype forces many OEM's to rely on the feedback of customers, often on an as-built basis, where failure has dire consequences on the OEM-operator relationship Consequently physical models are frequently much smaller than the full proposed design, and issues of scaling then come into question in the prediction of the full scale version Akin to this issue is one of simulation within the walls of an experimental facility versus the undisturbed virgin ground earth condition m the field It is virtually impossible to predict the performance without some scaled field testing, difficult to predict the effects of scaling and perhaps most of all to take that leap of faith on the part of both OEM and operator before any new design can make the transition to manufacture and utilization

The Alberta Equipment - Ground Interactions Syndicate (AEGIS) research group at the University of Alberta has been focusing on equipment-ground interactions for mining environments for a number of years An integrated simulation model and methodology has been developed to investigate shovel duty cycles in connection with dipper performance. This paper presents the theory and methodology used in the modeling process. This includes an in-depth investigation of cable shovel performance where an understanding of ground interactive behavior is necessary. The paper concludes with a conceptual dipper design that will be field tested in the Athabasca oil sands in the subsequent research.

2. MODELING A SHOVEL DUTY CYCLE

The current P&H 4100BOSS cable shovel in operation in the Athabasca oil sands was used as a modeling example. It was assumed that:

1 All shovel components including the dipper attachments did not change relative position except for the dipper and handle assembly relative to the main structure during any given duty cycle.
2 The shovel was operating in a homogeneous oil sand ground material environment.
3 The working face dimensions were appropriate for oil sand mining, as illustrated in figure 1.



Units in metres
Figurel. Schematic of shovel and working face.

2.1 Modeling Considerations

There are 4 main considerations related to the shovel duty cycle:

1. The means of creating the dipper cutting forces necessary at the face, via an understanding of the hoist and crowd motor operating range of current, and voltage; the hoist drum and crowd gear speed, acceleration; and the overall efficiency from the motors to the dipper in each case.
2. The geotechnical properties of the face material being excavated to evaluate the resistance to the ground engaging tools. From one cycle to the next, the dipper trajectory resulted in a new face profile which in turn was considered a function of the face resistance for the next iterative cycle.
3. The geometrical position of the dipper, defined within an x-y coordinate system for a set reference point on the dipper relative to a vertical digging plane. The velocity and acceleration components of the dipper motion were determined by derivation of the x-y coordinate position. The sum of all forces acting on the dipper gave an instantaneous acceleration.
4. The geometry of the shovel as the system through which all kinematics were referenced. The geometric constraints of the shovel components, with the boom, handle, cable and bearing tracks arranged in a 2 dimension coordinate system, figure 2, relative to the centerline swing center gave the basis through which the components acted together.

All components of shovel interacted with each other in terms of inter-force and geometrical consistency, allowing a logical schematic of the simulation process to be defined, as shown in figure 2.

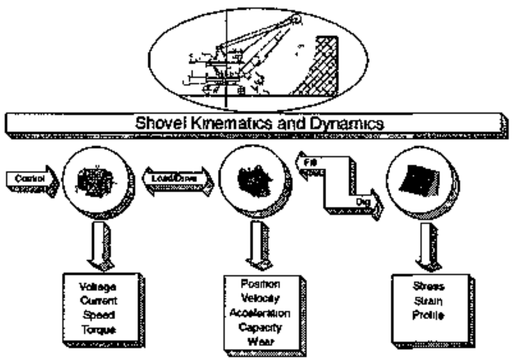


Figure 2. Schematic of the simulation process.

2.2 Subsystem Modeling

Three sub-models were developed to simulate digging duties in this research. These sub-models acted both independently and with each other. Each sub-model was based on specific equations to mathematically represent physical actions or material characteristics.

2.2.7 *Driving model*

The objective of this model is to describe the shovel response to resistance forces as the result of different digging positions or ground diggability, and vice versa. The motor output torque controls the position and speed of the dipper. The theory was based on DC motors.

2.2.2 Kinematics and dynamics model

The objective of this model is to define a correlation between the dipper position, displacement, velocity, acceleration and forces. Theory was based on Newton's first and second laws, although the combination is complicated in term of a dynamic scenario, due to of the complexity of a ground-dipper interactions and the motors real-time response of the driving motors.

2.2.3 Ground digging model

This is the crux of the model as the most operating energy is consumed in this process. This sub model predicts the force distribution to the dipper resulting from the yielding and breaking of ground.

2.3 Schedule and sequence of modeling

Tasks commence with applying an existing dipper geometry and profile to the conceptual shovel model and then the shovel digging cycle. All the information in the model was recorded and the dipper performance was reported as an important output.

2.4 **Shovel digging cycle**

A typical operating cycle consists of a digging cut, a loaded swing to discharge, a dump, and an empty return to the digging face. The shovel is propelled periodically to the face. Operating practice was taken into account in the modeling (Martin, 1982), including:

1. The digging face should not be higher than the boom point sheave.
2. Crawlers should be perpendicular to the face centre.
3. Short frequent moves are recommended to keep the shovel close to the face, maximizing the effectiveness of the crowd and hoist forces.
4. The dipper should be lowered close to the truck body or hopper during the dump cycle.

The shovel geometry determines the maximum digging profile and minimum tuck position in relation to the shovel track dimensions, to minimize interference. These were computed via a 3D solid body collision detection technique. As a result, the shovel operating profile in the vertical and horizontal orientation was determined, as shown in figure 3. As an example, the shovel incremental advance step was found to be 3.77 meters.

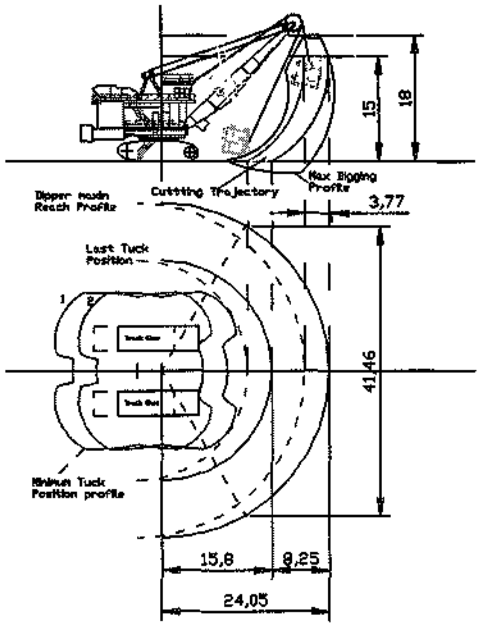


Figure 3. Digging body and cycle trajectory.

Two variations of shovel-truck loading were included in the model; double back up and single truck drive by, as shown in figure 4. This resulted in 2 alternative model swing times.

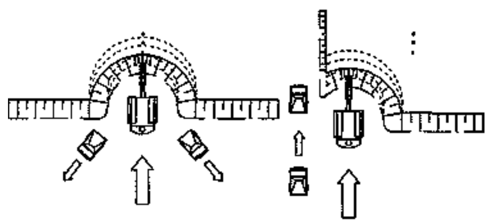
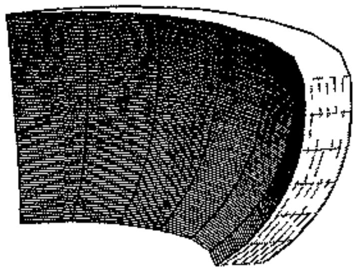
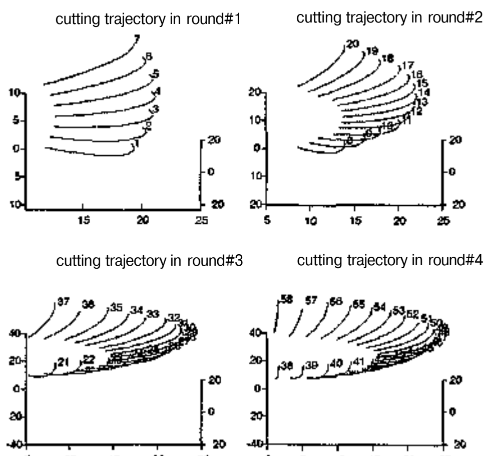


Figure 4. Shovel-truck loading variations.

Figure 5 illustrates a three dimensional digging volume calculation, and the proposal digging trajectories for a single sequence to dig this volume.



3D digging volume for a shovel move



3D digging trajectones in an idealized sequence (View point 45 degree look down with projected x y z axis)

Figure 5 3D digging body and cycle trajectones

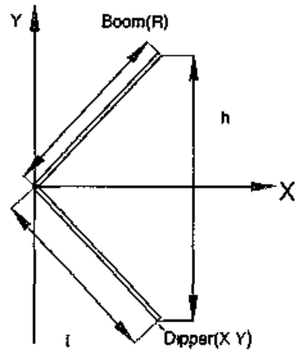


Figure 6 Simplified shovel geometry (after Daneshmend and Hendricks 1993)

Figure 7 shows the calculation variation used here

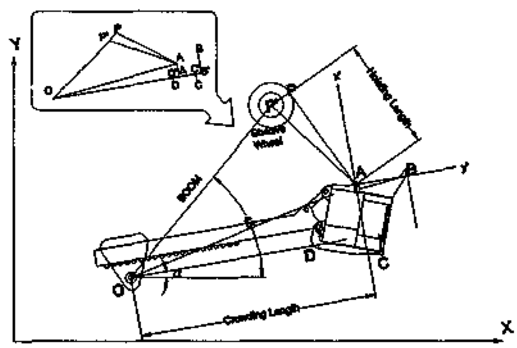


Figure 7 Shovel dipper geometry action

3. DIGGING KINEMATICS AND DYNAMICS

3.1 Kinematics

Daneshmend and Hendricks, (1993) developed a simplified kinematic model for generic shovels In their work, the position of the dipper is determined by the methodology in figure 6, m which R is the length of the shovel boom from the crowd arm attachment to its end, h ıs the length of hoist rope and 1 is the crowd arm extension

In the model, the handle is a line that is assumed to cross a corresponding connecting point on the boom The sheave wheel radius is neglected and assumed to be a point

The handle is connected to the boom via the saddle block, so that the distance (OA) from the dipper point (A) to shipper shaft, point O, is not equal to the crowd extension OA can thus be calculated via triangle OAA'

The rope is pulled or delivered via the sheave wheel, so that the tangential point (P') of the wheel and rope is not fixed, it can be determined via triangle APP'

The position of the dipper is represented by point A (the bail connecting point on the dipper) Two given variables, crowd extension and rope length, allow the dipper position in the digging plane to be determined

A local coordinate system is established, originating at point A and parallel to the handle, with X axis For any dipper position, A (X,Y) is known, and the handle angle (a) can be derived from A(X,Y) As a result, from a co ordinate transformation matrix, T can be found. Any point on the dipper in terms of local co-ordinates (x',y') can be transformed into digging plan coordinates, figure 7.

3.2 Dynamics

Figure 8 illustrates the forces acting on the dipper and handle, in which Fs is the support force tangential to the handle referenced from the saddle, Fp is the crowding force referenced from crowding motor, Fh is the hoisting force referenced from hoist motor, Gd is the gravity of the dipper plus handle acting at its centre of gravity, Go is the mass in the dipper acting at its centre of gravity, Fcx and Fey are the resistance forces in the corresponding X and Y directions, Ffe is the frictional force acting on the external front wall, Ne is the normal stress acting on the external front wall, Ffi is the frictional force acting on the internal front wall, and Ni is the normal stress due to the mass moving acting on the inside of the front wall.

It is assumed that the rope is rigid and the output motor torque is equivalent to the force acting on the handle and dipper.

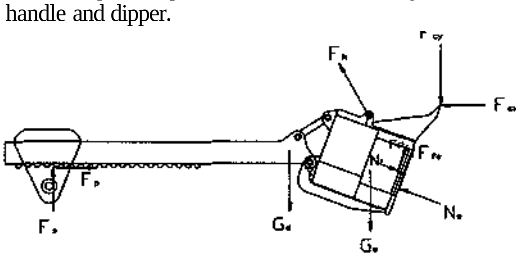


Figure 8. Dipper-handle acting forces

4. A THREE DIMENSIONAL DIPPER MODEL

The original dipper design, used over the past 50 years in industry, was first modeled in 3-D solid modeling software, illustrated in figure 9(a). Beyond the numerical simulation, several new dipper designs were also modeled, illustrated in figures 9 (b), (c), (d), and (e).

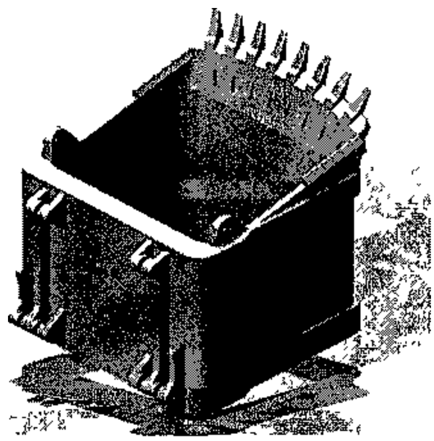


Figure 9(a). Original design with a linear front wall.

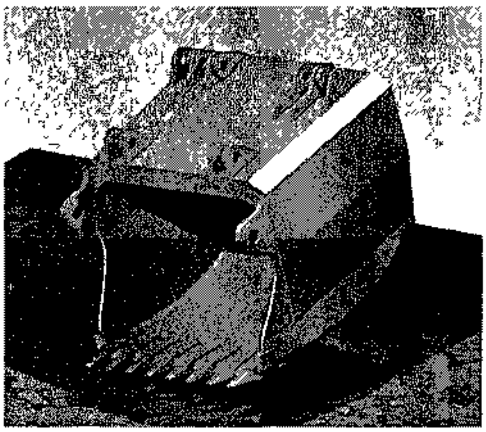


Figure 9(b). A skewed and curved concept.

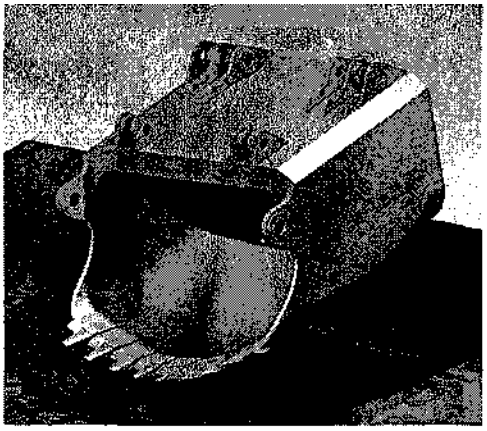


Figure 9(c). A double curve concept.

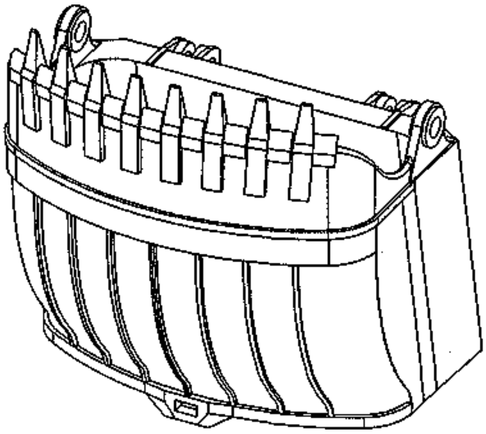


Figure 9(e) A double curve and flare concept.

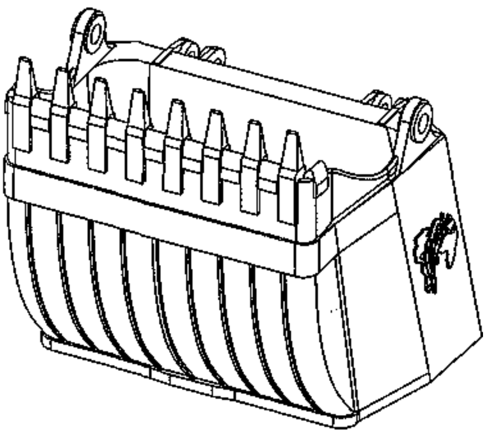


Figure 9(d). A curve and flare concept.

5. PHYSICAL MODELING

To prove the new design further, a three cubic yard dipper was fabricated to match a Dominion 500 cable shovel. This shovel was identified as having the same operating action and geometric orientation as the modern ultra class shovels at l/20th of the dipper scale. Both the new and original dipper will be tested in the field, allowing the relative performance data to be compared. Figure 10 shows this dipper and the matched door.

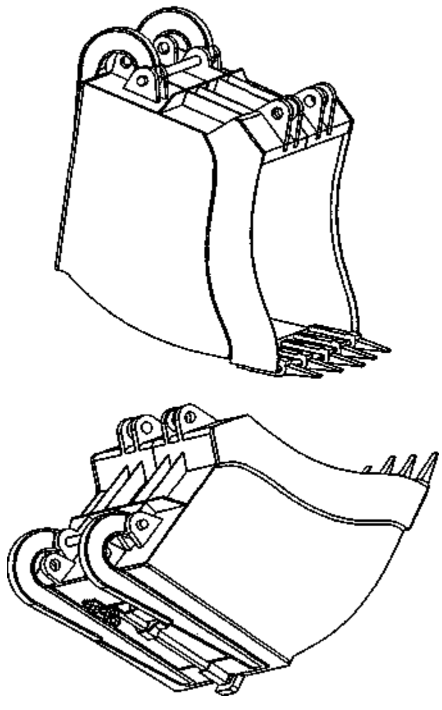


Figure 10. Scale three cubic yard dipper and door.

6. CONCLUSIONS & RECOMMENDATIONS

The dipper contribution to shovel production has not been fully investigated by OEM's and operators.

Most dippers in use are not optimally designed for specific environments Simulation and 3D computer modeling provides advantages over physical modeling, especially in terms of cost, speed and flexibility A specific model was developed based on an existing ultra-class shovel operating m oil sand conditions The simulation work of this model has led to a novel dipper design, which has a non-linear profile Three dimensional modeling has been utilized leading to the fabrication of a 3 yd^3 test model

The research in this paper did not cover the analysis of the dipper construction material, including strength and thickness issues Some in-depth work will be done in the future to optimize a section of the dipper wall to optimize the stress distribution when digging Three dimensional solid modeling makes this job much easy as long as the boundary conditions can be determined More accurate ground digging models will be developed Laboratory and field testing will verify these models

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