NUMERICAL SIMULATION OF WEAR FOR BODIES IN OSCILLATORY CONTACT

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my parents, Professor Mohamed Mukras and Bauwa Mukras, and to my siblings, AbduRahman, Suleiman, and Mariam

ACKNOWLEDGMENTS

I express my humility and utmost gratitude to Allah for his blessings in my life. Verily no success would have been achieved without his grace and mercy. I would next like to thank my parents for their support in my educational pursuits. I owe them much more than I can ever give back.

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Indeed, it would be negligent not mention the support that I have received from the members of the Masaajid in Gainesville who have enabled me to feel at home while away from home.

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When bodies are in contact and in relative motion, wear becomes an important aspect that should be considered during design. In mechanisms, wear is experienced at connections such as joints. A particular type of contact condition, known as oscillatory contact, exists at these connections and is partly responsible for wear. The objective of this study is to develop a wear-prediction procedure for bodies that experience this type of contact condition.

A prediction procedure for wear occurring in bodies that experience oscillatory contact is proposed. The methodology builds upon a widely used iterative wear-prediction procedure. Two techniques are incorporated into the methodology to minimize the simulation computational costs. In the first technique, an extrapolation scheme that optimizes the use of resources while maintaining simulation stability is implemented. The second technique involves the parallel implementation of the wear-prediction methodology. The methodology is used to predict the wear on an oscillatory pin joint and the predicted results are validated against those from actual experiments.

CHAPTER 1
INTRODUCTION

Background

Mechanical systems employ mechanisms that are used to convert one type of motion into another. These systems consist of connections such as joints where two components of the system establish contact and are in relative motion during operation. Depending on the kinematics of the mechanism, either of several contact conditions may exist at the connection. One particular contact conditions that is widely encountered is the oscillatory contacts. This contact condition coupled with other factors give rise to wear which could cause the system to fail. The importance of wear and the need for its consideration in design is dependant on a number of factors which may be either technical or economical or both. An example in which wear is of great concern is at the joints of heavy equipments such as backhoes. The joints of such equipments experience considerable amounts of wear while in operation. In order to minimize the wear occurring is such joints designers have implemented several techniques such as select materials based on material ranking or using wear resistant coating on the contacting surfaces. Although these procedures are widely used, they do not give sufficient insight or quantitative information on how a system may fail due to wear. It would thus be advantageous for designers to have the ability of predicting the wear beforehand. One way that has been used to achieve this has been the use of accelerated design verification procedures on prototypes. The procedures are generally expensive and destructive in nature but provide an abundant amount of information regarding the wear as a mode of failure.

An enormous amount of effort and resources has been placed into developing techniques that utilize computer simulations in the prediction of wear. Use of simulations for wear prediction has a number of benefits, one of which is its potential to reducing or eliminating

costly tests that may be required when considering wear in design. Simulations for wear predictions are also a versatile alternative, allowing for rapid changes in the simulation conditions with little effort.

A number of papers have been written dealing with the subject of wear prediction. A general trend that that has emerged is the use of numerical methods together with variations of Archard's wear model in predicting wear. Põdra and Andersson [1] used finite element method (FEM) in an iterative procedure to determine the wear on a pin placed over a moving disk. The simulation yielded results similar to those of an analogous experiment. In a separate paper, Põdra and Anderson [2] discuss the use of finite element analysis in wear simulation of a conical spinning contact. They compared simulation results to analytical results which showed good agreement. Põdra and Andersson [3] also used the Winkler surface model, to compute contact pressure instead of the finite element method, to simulated wear. They reported results that showed close agreement with simulations in which the finite element method was used. Yan et al. [4] predicted the wear resulting form a loaded pin contacting a rotating disc, by noting that the center of the disc wear track may be approximated as a plain strain region. They showed that the prediction results were consistent with experimental measurements. Wear simulations for a pin on disk problem were performed by Gonzalez et al. [5] using finite element method in conjunction with an incremental wear-prediction technique. In their simulation procedure, the geometry was updated at the end of each iteration. This was done to account for the worn out material. Telliskivi [6] preformed simulations to predict the wear on a disc-on-disc assembly using the Winkler mattress model. Good agreement between experiment and the simulation results were reported. Dickrell and Sawyer [7] developed a model to study the evolution of wear for a shaft and bushing assembly and ran experiment to validate the model.

A number of papers dealing with wear prediction of more complicated geometries have also been written. Flodin and Andersson [8], simulated the wear on spur gears using the Winkler model. They used an incremental wear-prediction approach in which the geometry was allowed to evolve as the simulation progressed. Flodin and Andersson [9] later extended their methodology to helical gears. They treated the helical wheel as several thin independent spur gear teeth. Brauer and Andersson [10] conducted wear simulations for gears using a combination of finite element method and an analytical approach based on Hertz theory. The FEM was used to determine the loads resulting form gear teeth interaction which were in turn used to determine contact pressure using the analytical expressions. In one paper Hugnell et al. [11] simulated the wear resulting from a cam-follower contact and in another paper [12] they simulated the mild wear in a cam-follower contact with follower rotation. They also used an incremental wear-prediction procedure and allowed the geometry to change after every simulation step. Nayak et al. [13] predicted the wear on a cam-follower and presented a guideline on designing cam followers for low wear. Fregly et al. [14] performed wear analysis to simulate mild wear on a tibial insert model. They reported close agreement between the simulation results and damage observation on actual tibial insert. Wear predictions on total hip arthroplasty were performed by Maxian et al. [15]. Bevill et al. [16] also performed simulations to determine the damage on a total hip arthroplasty due to wear and creep.

Depending on the complexity of wear mechanisms, wear predictions using computer simulations have yielded relatively reasonable results [1–3, 17–18]. The simulations, however, have been found to be quite computationally expensive. Several ideas have been implemented in an attempt to reduce computational costs associated with the wear-simulation process. Põdra and Andersson [3] attempted to minimize the computational cost by using the Winkler model to

determine the contact pressure distribution. The Winkler model was used as an alternative to the more expensive but relatively accurate FEM. Although the method was found to be less expensive it can be argued that the benefit of using more accurate results from the finite element technique outweigh the gains in computational efficiency when complicated geometries are considered. Põdra and Anderson [1] also employed a scaling approach to tackle the problem of computational costs. In this approach the incremental wear at any particular cycle of the simulation was scaled based on a predefined maximum allowable wear increment. The scaling factor was obtained as a ratio between the maximum allowable wear increment and the current maximum wear increment (maximum wear increment of entire geometry). They found that this procedure was more computationally effective. Kim, et al. [18] used a constant extrapolation technique to reduce the computational costs for the oscillatory wear problem. In their technique one finite element analysis was made to represent a number of wear cycles. Through this extrapolation, they were able to reduce the total number of analyses needed to estimate the final wear profile. A similar procedure was done by McColl, et al. [19] as well as Dickrell et al. [20]. In another paper [4], the computational costs of simulating a pin on a rotating disc was reduced by approximating the state of strain on the center of the wear track as plain strain. A less costly two-dimensional idealization was then used in place of the more expensive three-dimensional problem.

Scope and Objective

As is apparent from the literature, a number of procedures have been proposed to simulate wear. In addition several procedures have been proposed to simulate wear in more specific assemblies such as gears and cam-follower systems. One type of assembly that is encountered in numerous applications is one in which the oscillatory contact is experienced. These types of assembly are commonly found at the connections of mechanisms. Due to the nature of relative

motions at such assemblies, wear is inevitable. In this research, the objective is to develop a simulation framework for wear prediction in bodies that experience oscillatory contact. In addition to developing the prediction procedure, emphasis is made on incorporation techniques that minimize the overall computational costs and enable stable simulations.

Thesis Organization

In Chapter 2, the details of the wear model used in the prediction procedure are discussed. The simulation prediction procedure specific to bodies experiencing oscillatory contact will then be presented. A representative model to be used to demonstrate the procedure is introduced and discussed in Chapter 2. Chapter 2 will close with a discussion of a geometry updating technique that minimizes the mesh distortion.

Techniques to minimize computational costs will be presented in Chapter 3 and 4. Discussions in Chapter 3 will focus on the use of extrapolations to minimize costs. The issue of instability when extrapolations are used as well as a proposed solution is included in Chapter 3. In Chapter 4, the implementation of parallel computation as a way to reduces computational costs is discussed. In order to implement the wear-prediction procedure, a simulation program was written. The details of the program are discussed in Chapter 5.

Validation of the wear-prediction procedure is discussed in Chapter 6. Results from experiments are compared to results from the wear simulation. In Chapter 7, an example .that demonstrates how the wear-simulation program can be used to evaluate the effect of wear on the performance of a system is presented. Finally conclusions about the wear-prediction procedure will be drawn in Chapter 8 and suggestions for future research will be made in Chapter 9.

CHAPTER 2
WEAR-PREDICTION METHODOLOGY FOR BODIES IN OSCILATORY CONTACTS

Introduction

When two bodies are in contact and are in relative motion with respect to each other, wear is expected to develop on the regions of contact. The type of contact that the bodies experience is dependent on how the bodies move relative to each other. One type of contact condition that is of interest is the oscillatory contact. This type of contact condition is characterized by an oscillatory relative motion between the bodies that are in contact. The contact between a pin and a pivot in a center-link pivot joint is an example of this type contact. This example is shown in Figure 2-1 where the pin oscillates between two extreme angles. In this Chapter a procedure to predict the wear occurring in this type of contact is discussed. In this work, the assembly shown in Figure 2-1 will be used as a representative case of the oscillatory contact to illustrate the wear-prediction procedure.

Wear Model

In developing the wear-prediction methodology it is assumed that all the wear cases to be predicted fall within the plastically dominated wear regime, where slide velocities are small and surface heating can be considered negligible. Archard's wear law [21] would thus serve as the appropriate wear model to describe the wear as discussed by Lim and Ashby [22] as well as Cantizano, et al. [23]. In that model, first published by Holm [24], the worn out volume, during the process of wear, is considered to be proportional to the normal load. The model is express mathematically as follows:

$$\frac{V}{s} = K\frac{F_N}{H}, \qquad (2\text{-}1)$$

where V is the volume lost, s the sliding distance, K the dimensionless wear coefficient, H the Brinell hardness of the softer material, and F_N the normal force. Since the wear depth is the quantity of interest, as opposed to the volume lost, Eq. 2-1 is usually written in the following form:

$$\frac{hA}{s} = kF_N, \tag{2-2}$$

where h is the wear depth and A is the contact area such that $V = hA$. The non-dimensioned wear coefficient K and the hardness are bundled up into a single dimensioned wear coefficient k (Pa^{-1}). It should be noted that the wear coefficient k is not an intrinsic material property but is also dependent on the operating condition. The value of k for a specific operating condition and given pair of materials may be obtained by experiments [25]. Also worth noting, is that measured values of wear coefficients usually have large scatter and may affect wear predictions significantly. Care should thus be taken in obtaining these values. Uncertainty analysis for measured values of wear coefficients, such as those presented by Schmitz et al. [26], may be of considerable benefit.

Equation 2-2 can further be simplified by noting that the contact pressure may be expressed with the relation $p = F_N / A$ so that the wear model is expressed as

$$\frac{h}{s} = kp. \tag{2-3}$$

The wear process is generally considered to be a dynamic process (rate of change of the wear depth with respect to sliding distance) so that the first order differential form of Eq. 2-3 can be expressed as:

$$\frac{dh}{ds} = kp(s), \tag{2-4}$$

where the sliding distance is considered as the time in the dynamic process, and the contact pressure is a function of the sliding distance.

A numerical solution for the wear depth may be obtained by estimating the derivative in Eq. 2-4 with a finite divide difference to yield the depth as follows:

$$h_j = h_{j-1} + kp_j \Delta s_j \,. \tag{2-5}$$

In Eq. 2-5, h_j refers to the wear depth at the jth iteration while h_{j-1} represents the wear depth at the previous iteration. The last term of Eq. 2-5 is the incremental wear depth which is a function of the contact pressure and incremental sliding distance (Δs_j) at the corresponding iteration.

If information about the wear coefficient k, the contact pressure p_j and the sliding distance Δs_j is available at all iterations (j), the wear depth on a contact interface for a specified sliding distance s can be estimated using Eq. 2-5. Here the sliding distance is an accumulation of the incremental sliding distance for all iterations (n_iter) as is expressed in Eq. 2-6.

$$s = \sum_{j=1}^{n\_iter} \Delta s_j \,. \tag{2-6}$$

The contact pressure (p) may be obtained through numerical methods. The finite element method appears to be the most widely used method. This is probably due to its accuracy. Several papers [3, 6, 27–28] have been written in which an elastic foundation model has been used in place of the finite element method. The wear coefficient can be obtained through experiments such as this explained by Kim et al. [18, 25] where as the incremental sliding distance may be obtained from the finite element analysis or can be specified by the user.

Simulation Procedure

The most widely used procedure to simulate wear occurring at a contact interface is an iterative procedure describe by the numerical integration in Eq. 2-5. A number of papers [1,2,17–19,25,29], that demonstrate the implementation of Eq. 2-5 in predicting wear, have been written. Although the details of the various procedures differ, three main steps are common to all of them. These include the following:

- Computation of the contact pressure resulting from the contact of bodies.
- Determination of the incremental wear amount based on the wear model.
- Update of geometry to reflect the wear amount and to provide the new geometry for the next iteration.

The procedure developed for predicting wear on oscillatory contacts incorporates the aforementioned steps.

As was mentioned earlier the pin-pivot assembly shown in Figure 2-1 will be used to illustrate the simulation procedure. In this assembly the pin is fixed so that it does not translate in any direction but is allowed to oscillate (in an axis perpendicular to the paper) from one extreme to another (bounded by specified amplitude). Contrary to the conventional definition of a cycle, in this work a cycle is defined as a rotation of the pin from one extreme angle to the other (e.g. $\pm\theta^0$). The goal is to develop a procedure that can predict the wear over several thousand cycles. It is worth noting that most of the work present in the literature dealing with wear simulation does not address this type of motion but rather, that which is of a continuous nature such as in rotational contacts.

The simulation of wear at the contact interface of the pin-pivot assembly is achieved by considering each cycle separately. The wear in any cycle can be obtained by discretizing the cycle into a number of steps and thereafter applying Eq. 2-5. The discretization is such that each

step corresponds to a specific pin angle between the two extremes. In the application of Eq. 2-1, the wear coefficient k and the incremental sliding distance Δs_j are taken to be constant where as the contact pressure p_j is computes by the finite element method. The pin-pivot finite element model used to illustrate the simulation procedure will be described a later subsection.

At each step a finite element analysis is performed to determine the contact pressure over the contact region. The wear depth during any cycle and at any point on the contact surface can then be determined by Eq. 2-7 which is a modification of Eq. 2-5.

$$h_{n,i,j} = h_{n,i-1,j} + kp_{i,n}\Delta s_i \,. \qquad (2\text{-}7)$$

In Eq. 2-7, n refers to surface nodes number (of the finite element model) which may or may not establish contact with the opposing surface. The subscript i and j indicate the current step and cycle, respectively. All other terms are as defined previously.

The geometry is then updated to reflect the amount of wear and to prepare the model for the next step. Details of the geometry update procedure will be discussed in subsequent subsection. At this point the simulation progresses to the next step and the oscillating pin assumes a new position. This involves a rotation through an angle corresponding to the incremental angle. The previously described processes are repeated up until all steps in a cycle are completed. The direction of pin rotation is reversed and the simulation of the next cycle commences. The term 'step update' is adopted for this procedure since the geometry is updated after every step. The simulation process for the step update procedure is summarized in the flowchart shown in Figure 2-2.

Pin-Pivot Finite Element Model

Two methods that have been used in the literature to calculate the contact pressure at the contact surface were mentioned as the elastic foundation and the finite element method. The least expensive of the two methods, in terms of computational costs, is the elastic foundation method. This method is, however, the least preferred due to its level of accuracy especially for complicated geometries. To illustrate the simulation procedure the finite element method has be selected.

The diagram of the 2D finite element model for the pin-pivot assembly is shown in Figure 2-3. As can be seen from the diagram, three kinds of elements have been used. The eight-node quadrilateral elements were used to model the pin and the pivot. Three-node contact elements were used to represent the contact surface. It is worth noting that the contact elements coat the outer and inner surface of the pin and pivot, respectively. It should also be noted that the contact element do not add any new nodes to the model. Instead, the nodes of the quadrilateral elements that appear on the surface make up contact elements. The third type of element that was used is the link (truss) elements. This element was used to prevent rigid body motion (RBM). It was mentioned earlier that the pin is fixed from translating but allowed to rotate in a controlled manner. Specifically the rotation is allowed only once the finite element analysis has been completed. This means that the pin will not experience RBM. The pivot, however, is fixed along its lower edge to prevent any horizontal translations as well as rotation in any axis but is allowed to translate in the vertical direction. This is also the direction of loading as is shown in Figure 2-1. There is thus a potential for RBM to occur. The link element is used to eliminate this possibility. The effect of the link element is reduced by assigning it a very small elastic modulus.

Geometry Update Procedure

The process of geometry update is necessary in order to correctly simulate and predict the wear occurring at the contact interface. Indeed material removal changes the contact surface and causes a redistribution of the contact pressure resulting from the contact. These changes can only be captured if the surface is altered through a geometry update. Estimation of wear through an extrapolation which is based on the original surface has been shown to produce erroneous predictions [30]. It is therefore becoming as standard, as is evident in the literature [1–2, 17–19, 25, 29, and 31], that geometry updates are included in the process of wear simulation.

The procedure proposed to update the geometry in this research involves two steps. These steps are outlined below:

- Determine the normal direction (vector) of the contact surface at the location of each surface node (contact node).
- Shift the position of the surface nodes in the direction of the normal vector by an amount equal to the wear increment.

The normal direction of the surface nodes at the location of the contact nodes can be obtained by considering the locations of the contact elements. The contact elements at the surface have three nodes each. This element is illustrated in Figure 2-4. The corresponding shape functions for this element may be written as follows:

$$\begin{aligned} N_1 &= -\frac{1}{2}(t-1)t \\ N_2 &= -(t-1)(t+1), \\ N_3 &= \frac{1}{2}(t+1)t \end{aligned} \tag{2-8}$$

where t is the local coordinate parameter. The surface of an element can then be described in terms of the nodal coordinates and as a function of the local coordinate. The expression for the surface is given in Eq. 2-9.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_3 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \\ x_3 \\ y_3 \end{bmatrix}, \tag{2-9}$$

where x_k and y_k are the coordinates of node k ($k = 1,2,3$)for the element of interest. If the vector tangent to the surface (contact element surface) is denoted as $\mathbf{v_t}$ then its value for the element can be obtained as follows:

$$\mathbf{v_t} = \frac{\partial x}{\partial t}\mathbf{i} + \frac{\partial y}{\partial t}\mathbf{j} + 0\mathbf{k}\,, \tag{2-10}$$

where the partial differentials is given in Eq. 2-11 or 2-12.

$$\begin{bmatrix} \frac{\partial x}{\partial t} \\ \frac{\partial y}{\partial t} \end{bmatrix} = \begin{bmatrix} \frac{\partial N_1}{\partial t} & 0 & \frac{\partial N_2}{\partial t} & 0 & \frac{\partial N_3}{\partial t} & 0 \\ 0 & \frac{\partial N_1}{\partial t} & 0 & \frac{\partial N_2}{\partial t} & 0 & \frac{\partial N_3}{\partial t} \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \\ x_3 \\ y_3 \end{bmatrix} \tag{2-11}$$

or

$$\begin{aligned} \frac{\partial x}{\partial t} &= \sum_{r=1}^{3} \frac{\partial N_r}{\partial t} x_r \\ \frac{\partial y}{\partial t} &= \sum_{r=1}^{3} \frac{\partial N_r}{\partial t} y_r \end{aligned}. \tag{2-12}$$

The vector normal ($\mathbf{v_n}$) to the surface (depicted in Figure 2-4) can be expressed as a cross product of the tangent vector ($\mathbf{v_t}$) and the vector perpendicular to the plane of the surface ($\mathbf{v_p} = \langle 0,0,1 \rangle$). This cross product is expressed in Eq. 2-13.where n denotes the node number.

$$\mathbf{v}_{\mathbf{n},n} = \frac{\mathbf{v}_{\mathbf{t},n} \times \mathbf{v}_{\mathbf{p}}}{\left\| \mathbf{v}_{\mathbf{t},n} \times \mathbf{v}_{\mathbf{p}} \right\|}. \tag{2-13}$$

The resulting unit normal vector then appears as follows:

$$\mathbf{v}_{\mathbf{n},n} = \frac{\frac{\partial y}{\partial t}\mathbf{i} - \frac{\partial x}{\partial t}\mathbf{j}}{\sqrt{\left(\frac{\partial x}{\partial t}\right)^2 + \left(\frac{\partial y}{\partial t}\right)^2}}, \tag{2-14}$$

or,

$$\mathbf{v}_{\mathbf{n},n} = v_{norm\_x,n}\mathbf{i} + v_{norm\_y,n}\mathbf{j}, \tag{2-15}$$

where v_{norm_x} and v_{norm_y} are the components of the vector normal to the surface. Once the contact pressure distribution and normal vectors at all the nodes on the surface have been determined, the geometry can then be updated. The update is done by moving the surface nodes in the direction of the unit normal vector. The coordinate of the new node position at any step of any cycle can be written as follows:

$$\begin{bmatrix} x_{n,i,j} \\ y_{n,i,j} \end{bmatrix} = \begin{bmatrix} x_{n,i-1,j} \\ y_{n,i-1,j} \end{bmatrix} + kp_{n,i}\Delta s \begin{bmatrix} v_{norm\_x,n} \\ -v_{norm\_x,n} \end{bmatrix}. \tag{2-16}$$

The process of the geometry update is shown in Figure 2-5. In this diagram the wear depth is grossly exaggerated to illustrate the concept. The procedure for the geometry update has been used successfully in the wear-simulation process. A possible problem that could be encountered during model updates is mesh distortion. In the pin-pivot model, mesh distortion during model update is minimized through a carefully created finite element model. The FE model is initially created in such a way that all normal vectors at surface nodes, before any update is performed, will be in a direction parallel to the element edge. This idea is illustrated in Figure 2-6. After

several geometry updates it can be expected that the vector will no longer be parallel to the edge. The deviation is however small to be of any major consequence.

Conclusion

The procedure discussed was used to predict the wear occurring at the interface of the pin-pivot assembly. Although this was a specific problem, the general framework outlined can be extended and used to predict wear in other 2D oscillatory contact problems.

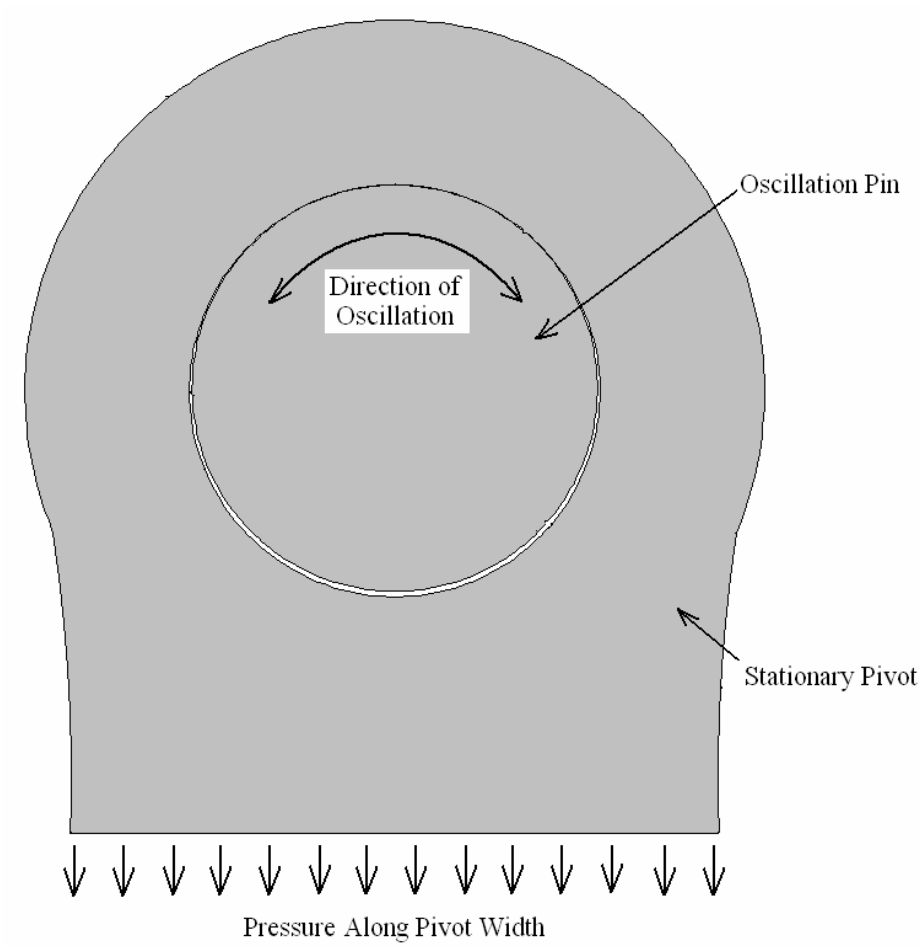


Figure 2-1. Oscillatory contact for a pin-pivot assembly.

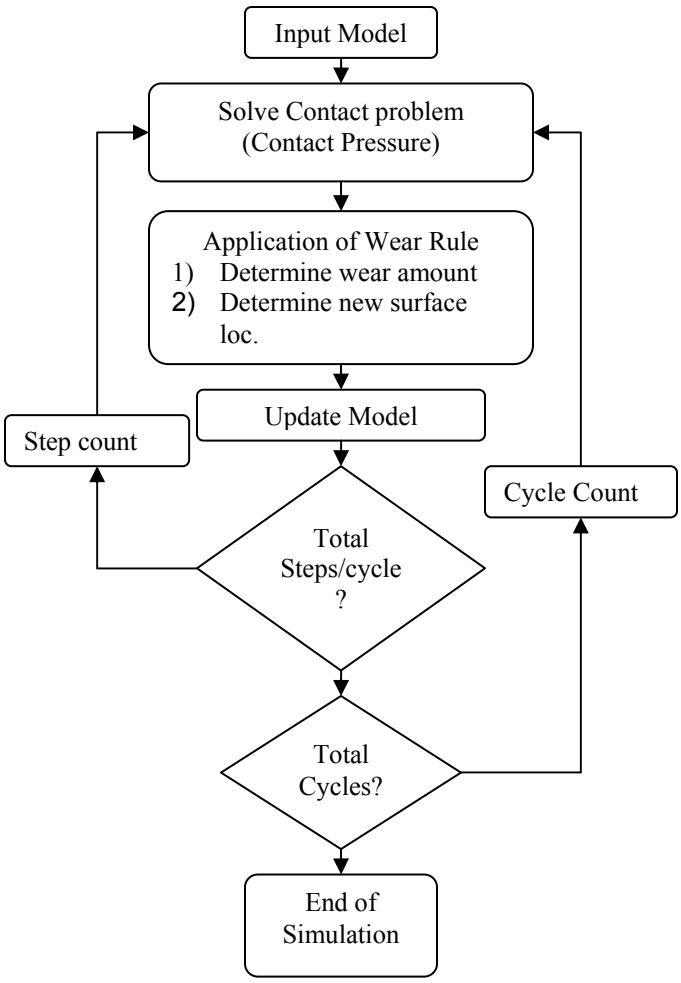


Figure 2-2. Wear simulation flow chart for the 'step update' procedure.

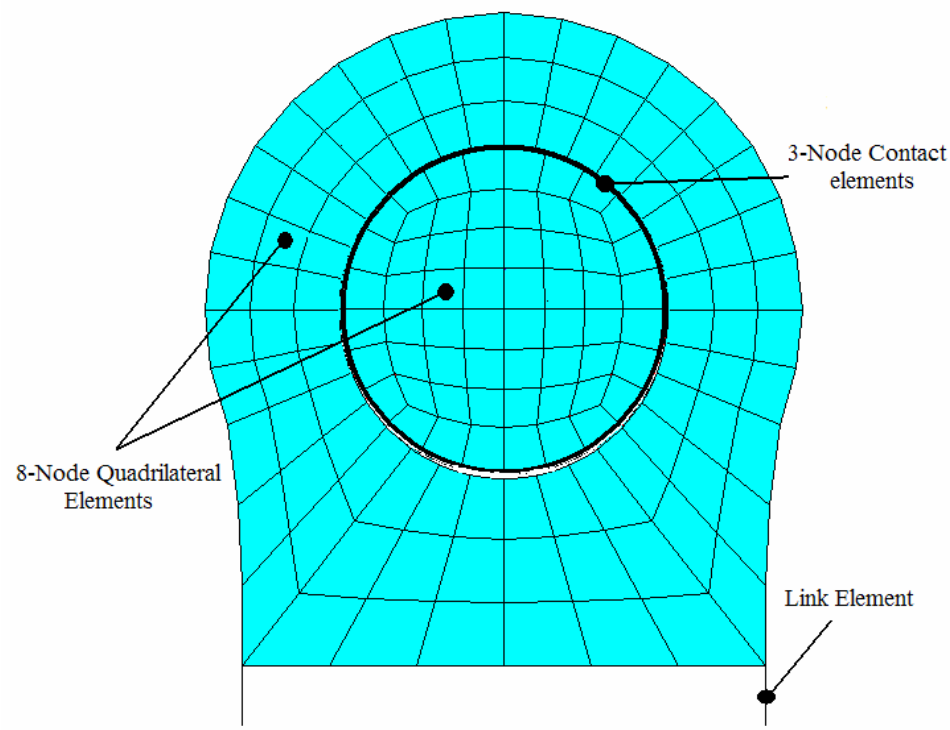


Figure 2-3. Pin-pivot finite element model.

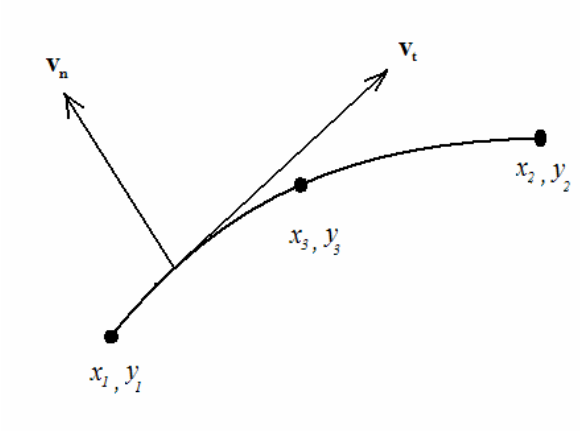


Figure 2-4. A three-node contact element used to represent the contact surface.

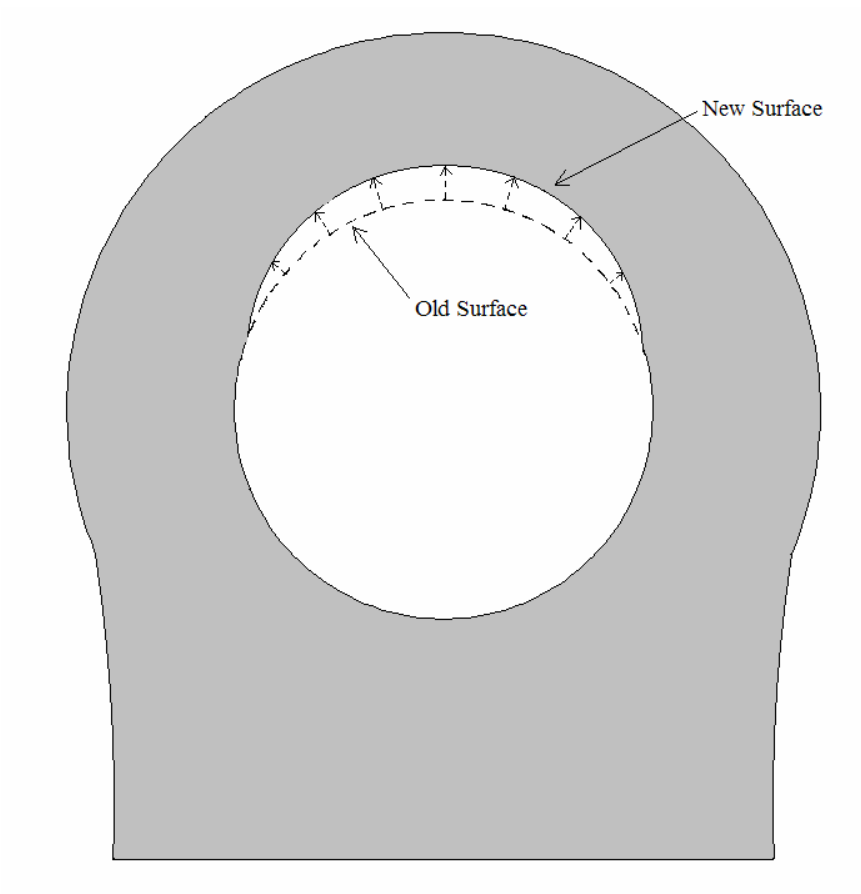


Figure 2-5. Geometry updates process.

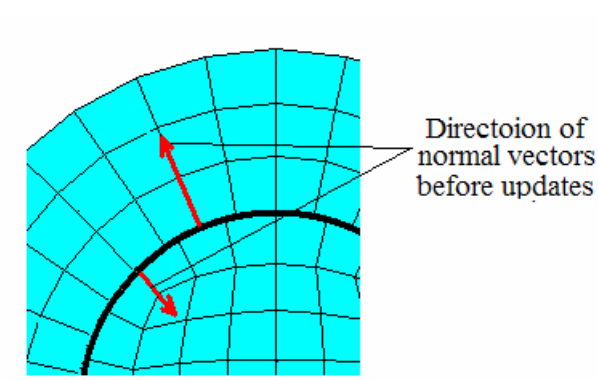


Figure 2-6. Surface normal vector for the pin-pivot assembly prior to update

CHAPTER 3
EXTRAPOLATION SCHEMES

Introduction

The procedure discussed in Chapter 2 provides a way to simulate the wear resulting from oscillatory contacts. However, the process can be quite expensive. For instance, if one desires to simulate 100,000 oscillatory cycles for a case in which each cycle is discretized into 10 steps then 1,000,000 finite element analyses (nonlinear) as well as geometry updates would be required. Clearly this may not be practical and the need for techniques to combat the computational cost becomes immediately apparent. Techniques to tackle the problem of computational costs will be discussed in the current and following Chapters.

Constant Extrapolation

Extrapolations have been used in various forms with the goal of reducing computational costs. In this work an extrapolation factor (A) is used to project the wear depth at a particular cycle to that of several hundreds of cycles. Essentially, the extrapolation is the total number of cycles for which extrapolation is desired. Thus according to this definition, the extrapolation factor can only take on positive integers values.

The equation used to determine the amount of wear at a particular node during any step in a cycle was expressed in Chapter 2 as;

$$h_{n,i,j} = h_{n,i-1,j} + kp_{i,n}\Delta s_i \,. \qquad (3\text{-}1)$$

Equation 3-1 can be modified slightly in order to incorporate an extrapolation factor. It is first noted that the first term on the right hand side (R.H.S.) of Eq. 3-1 refers to the cumulative wear depth from previous cycles whereas the last term refers to the incremental wear depth at the current step and cycle. As way to minimize computational costs, it is assumed that the next "A" cycles (as many cycles as the value of the extrapolation) will have the same amount of wear

depth as that of the current step and cycle. The total incremental wear depth for those many cycles may then be obtained by multiplying last term of Eq. 3-1 with the extrapolation factor. The resulting expression is shown in the following equation:

$$h_{n,i,j+A} = h_{n,i-1,j} + kAp_{i,n}\Delta s_i \,. \tag{3-2}$$

Utilizing the same concept, a new expression can be written to describe the position of the contact nodes during the wear-simulation process. This expression is as follows:

$$\begin{bmatrix} x_{n,i,j+A} \\ y_{n,i,j+A} \end{bmatrix} = \begin{bmatrix} x_{n,i-1,j} \\ y_{n,i-1,j} \end{bmatrix} + kAp_{n,i}\Delta s \begin{bmatrix} v_{norm\_x,n} \\ -v_{norm\_x,n} \end{bmatrix}. \tag{3-3}$$

Extrapolation and stability. As may be expected, the level of accuracy of the wear simulation is reduced when extrapolations are used. This is directly related to the assumption that the same value of incremental wear depth is maintained for several cycles. This is, however, not the case since in reality the geometry would constantly evolve which in turn would lead to a continuous redistribution of the contact pressure and thus a change in the incremental wear depth at each cycle. However the difference is small enough that it may be neglected as is evident from the overall error of simulation results.

Use of extrapolations may also cause problems in simulation stability. Here stability is defined with regard to the contact pressure distribution and hence the wear profile. An ideally stable wear simulation would be defined as one in which the contact pressure distribution remained smooth (with no sharp or sudden changes in the distribution) for the entire duration of the simulation. It is however unlikely to have smooth pressure distribution throughout the simulation process. As a result a more relaxed definition of stability is adopted where by sudden changes in the pressure distribution are allowed to occur. In Figure 3-1A, the contact pressure is seen to vary smoothly over the contact region except for small peaks at the contact edges. The

peaks are attributed to the transition form a region of contact to a region of no contact. This transition occurs at a point which can not be represented by a discrete model. The result is that there is an abrupt change in the surface curvature which causes high pressure. If such contact pressure distribution is maintained through out the simulation, the simulation can be referred to as stable. On the contrary, the diagram in Figure 3-1B is representative of contact pressure distribution that would constitute an unstable wear simulation. The two diagrams show the contact pressure distribution for a stable and unstable wear simulation consistent with the adopted definition of stability.

When very large extrapolation sizes are used, wavy pressure distributions (Figure 3-1B) are observed and the simulation becomes unstable. The shift to instability due to the use of large extrapolation sizes can be explained as follows. The contact pressure distribution (obtained from the finite element analysis) is generally not perfectly smooth. This may be due to the discretization error stemming form the finite element analysis. The use of an extrapolation factor magnifies these imperfections so that when the geometry is updated the contact surface smoothness is reduced. If large extrapolation sizes are used, the regions that experience high contact pressure in a particular step of the simulation are worn out excessively so that in the following step these regions experience little or no contact. On the other hand, the regions that did not experience high contact pressure will be worn out less and thus will experience greater contact pressure in the next step. This behavior will repeat in subsequent steps causing the surface to become increasingly unsmooth. The simulation will then become unstable. If, however, smaller extrapolation sizes are used the wearing process acts as an optimizer to smoothen the surface.

A smooth contact surface is critical for two reasons. The first reason is that a smooth contact surface is consistent with the actual case that is being simulated, and the second is that a non-smooth surface would affect the solution of the finite element problem. Due to these reasons, a condition is placed on the selection of the extrapolation size such that the selected size would not severely affect the smoothness of the pressure distribution.

Extrapolations provide a solution to the computational cost problem but as has been discussed its use may introduce other problems. The accuracy and stability of the simulation may be jeopardized by using extrapolation sizes that are too large. Using small extrapolation sizes will produce more reliable solutions but will result in a less than optimum use of resources. It may also be argued that even if an appropriate extrapolation size was selected at the beginning of the simulation it may be that at a different stage of the simulation a different extrapolation size would be required to provide optimum use of the available resources. In the next subsection a procedure is described that seeks for the largest extrapolation sized while maintaining stability during the entire simulation process.

Adaptive Extrapolation Scheme

The adaptive extrapolation technique is an idea proposed as an alternative to the constant extrapolation scheme. The idea behind it is to seek for the largest extrapolation size while maintaining a state of stability (smooth pressure distribution) throughout the simulation process. The scheme is a three-step process. In the first part an initial extrapolation size (A_0) is selected. The selection is based on experience.

In the second part of the adaptive extrapolation scheme, a stability check is performed. A single check, preferably at the center step of the cycle, is sufficient for an entire cycle. The stability check involves monitoring the contact pressure distribution within an element for all

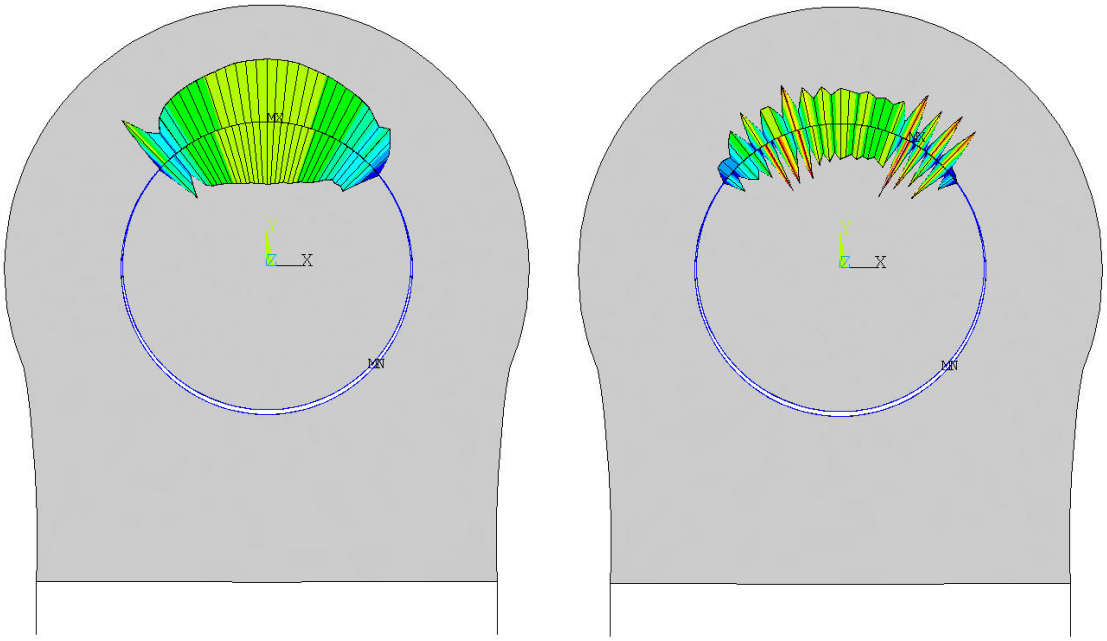
elements on the contact surface. This essentially translates to monitoring the local pressure variation. If the contact pressure difference within an element is found to exceed a stated critical pressure difference Δp_{crit} then a state of instability is noted and vice versa. In the final step of the adaptive scheme, the extrapolation size is altered based on the result of the stability check. That is, the extrapolation size is increased for the stable case and a decrease for the unstable case. This process can be summarized as follows:

$$A_j = \begin{cases} A_{j-1} + \Delta A_{\text{inc}} & \text{if } \Delta p_{\text{ele}} < \Delta p_{\text{crit}} \\ A_{j-1} - \Delta A_{\text{dec}} & \text{if } \Delta p_{\text{ele}} > \Delta p_{\text{crit}} \end{cases}. \tag{3-4}$$

It must be mentioned that in order to maintain consistency in the geometry update as well as in the 'bookkeeping' of the number of simulated cycles, a single extrapolation size must be maintained through out a cycle. That is, every step in a cycle will have the same extrapolation size while different cycles may have different extrapolation sizes. Figure 3-2 shows a graph of the extrapolation history for the oscillating pin-pivot assembly. From the graph, it can be seen that the extrapolation took on a conservative initial value of about 3900 and increased steadily up to the 12th cycle (actual computer cycles not considering the extrapolations). Thereafter the extrapolation size oscillated about a mean of about 6000.

Conclusion

The use of extrapolations is an efficient way to cut down on computational costs. Even though no way of accounting for the error involved has been developed, the results observed from simulation runs have shown acceptable error ranges. An adaptive extrapolation scheme was proposed to govern the selection of the extrapolation size during the simulation. The scheme ensures that the largest allowable extrapolation size is used during the simulation. The scheme thus provides for a way to minimize computational costs while maintaining a stable simulation.



A B

Figure 3-1. Contact pressure distribution on a pin-pivot assembly. A) The case of a stable wear simulation. B) The case of an unstable wear simulation.

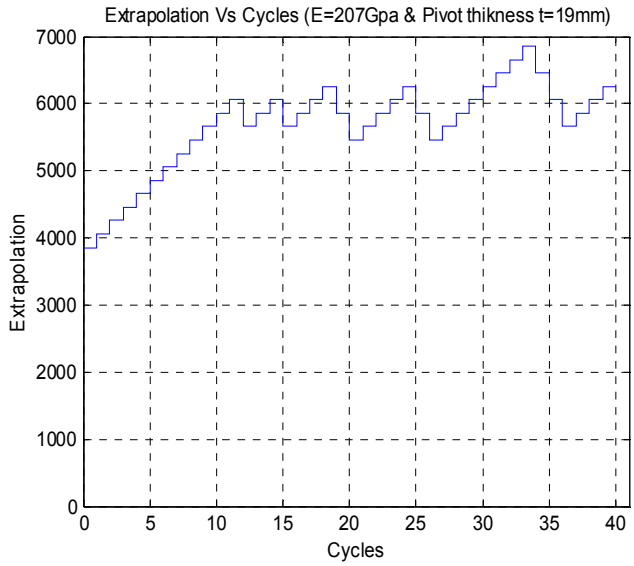


Figure 3-2. Extrapolation history for a pin-pivot assembly.

CHAPTER 4
PARALLEL COMPUTATION IN WEAR SIMULATION FOR OSCILLATORY CONTACTS

Introduction

Although the use of extrapolations is probably the most effective way to reduce the computational costs, other ways are also available. A parallel processing implementation of the simulation procedure is proposed as an additional way to remedy the problem of computational costs. This technique may be used in conjunction with the extrapolation scheme to further reduce computational costs. The discussion of parallel computation will be preceded by an introduction to the concept of 'cycle-update and intermediate cycle-update' which are central ideas in the parallel computation procedure.

Cycle- and Intermediate Cycle-Update

The wear-simulation procedure that was discussed earlier was termed as the 'step-updated' for the reason that geometry updates were preformed after every step. An alternative to the step update procedure would be to exclude all geometry updates during the entire cycle and perform a single update at the end of the cycle. We term this procedure as the 'cycle-update'. The cycle-update is a modification of the step-update where updates are performed at the end of each step/analysis. For the cycle-update, information from each analysis performed at each step is stored and later used to update the model at the end of the cycle. The equation for the wear depth at the contact interface for the cycle-update is expressed as follows;

$$h_{n,j+A} = h_{n,j-1} + kA_j \sum_{i=1}^{n\_step} p_{i,n} \Delta s_i \,, \qquad (4\text{-}1)$$

where n_step is the total number of steps in a cycle. All other terms are as defined previously. The cycle-update procedure can be summarized in the flowchart shown in Figure 4-1.

It should be noted that in both the cycle- and step-update techniques, the material removal is discrete which is at variance with the actual process of wear in which the material removal is continuous. The situation is, however, worse for the cycle-update since the frequency of material removal is much less than in the step-update procedure. The step-update therefore has a closer resemblance to the to the actual wear process. It would therefore be expected that the use of the cycle-update procedure in wear simulations would yield less reliable results in comparison to the step-update counterpart. Indeed this is what is observed when the procedure is tested. More specifically the smoothness of contact pressure distribution during the simulation is severely affected by the cycle-update than is by the step-update. A simplified explanation for this phenomenon is that the step-update, performed at each step, closely captures intermediate geometry changes within a cycle and hence the contact between two mating surface is approximately conforming throughout the simulation. The result is that the pressure distribution remains reasonably smooth. In the case of the cycle-update, the geometry is updated once in an entire cycle. This dose not allow for the contacting surface to evolve smoothly throughout the cycle and hence resulting in a less conforming contact between the mating surfaces. In this case the pressure distribution would be less smooth, putting the accuracy of the results to question.

Although the cycle-update technique may yield less than accurate results, the technique may still be used with caution. A general observation can be made regarding the accuracy when using the cycle-update procedure. It has been observed that for a fixed extrapolation size, as the total sliding distance covered through a complete cycle increases, the smoothness of the pressure distribution is affected and hence the stability and accuracy of the simulation. Based on the observation, a critical sliding distance s_{crit} is defined which if exceed, during sliding, geometry update must be performed. Determination of the critical sliding distance is unnecessary since

short simulation runs can determine if the cycle-update is the appropriate produce. Thus the mention of the critical sliding distance is purely for academic reasons rather than for practical reasons. It is concluded that the cycle-update is best suited for cases in which the total oscillation angle is small so that the sliding distance in a single cycle is less than s_{crit}.

In the event that the total sliding distance for a complete cycle is larger than s_{crit}, we may still take advantage of the idea behind cycle-update procedure. Instead of performing a single update at the end of the cycle we may perform several equally spaced updates within the cycle. This can be considered to be a hybrid of the step- and cycle-update procedure and the name intermediate cycle-update is used for the procedure. The advantage of this idea is that the number of updates in a cycle is reduced without affecting the stability of the simulation. The intermediate cycle-update procedure can be summarized as is shown in Figure 4-2.

Parallel Computation

Computers may be configured to operate in parallel mode with the advantage that results can be produced at a quicker rate. The idea proposed as a cost cutting means is a direct parallel implementation of the cycle-update and the intermediate cycle-update procedures. Since the implementation of the two procedures is similar, only the parallel implementation of the cycle-update is discussed.

The cycle-update procedure is centered on the idea that no update is performed on the geometry during the entire cycle. This means that all the analysis performed at each step within a cycle is done on same geometry. The difference between any two analyses within a cycle is the angle at with the two bodies contact during the analysis. This information may be exploited to construct the parallel computation equivalent of the wear-simulation procedure.

The parallel implementation works as follows. Several processors are dedicated to the wear analysis simulation. One of these processors is assigned the duty of a master processor. This will be the processor responsible for distributing tasks to other processors as well as consolidating the results from other process. The remaining processors will be the slave processors. Each of the processors, both slave and master processors, will represent a particular step within a cycle. In the beginning of any cycle, the appropriate model of the assembly to be analyzed for wear is fed into the master processor. The master processor then distributes the same model to the remaining processors. The master processor also allocates contact angles (each slave will have a different contact angle corresponds to a specific step in the cycle) and corresponding analysis conditions to each of the slave processors. At this point the master processor instructs the slave processor to solve their corresponding contact problem. Once the analysis in the different slave processors is done the master node collects the results and computes the wear amount for that cycle. The model geometry is then undated and thereafter a new cycle commences. The parallel implementation of the cycle-update procedure is summarized in the flowchart shown in Figure 4-3.

From the flowchart it can be seen that considerable amount of time is saved by using the parallel computational in comparison to the cycle-updating procedures. If the number of processors available is equivalent to the number of steps selected for a cycle, then the time required to complete a single cycle while using the parallel procedure is approximately equal to the time required to complete a single step in the step and cycle updating procedures.

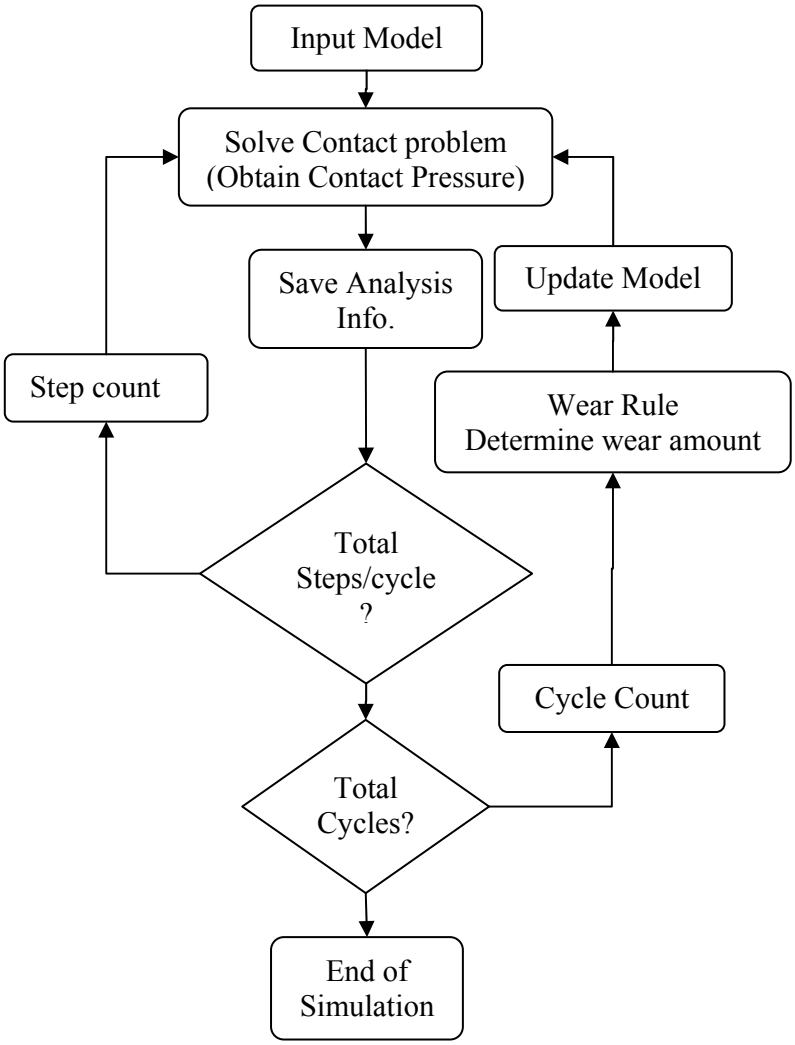


Figure 4-1. Wear simulation flow chart for the 'cycle-update' procedure.

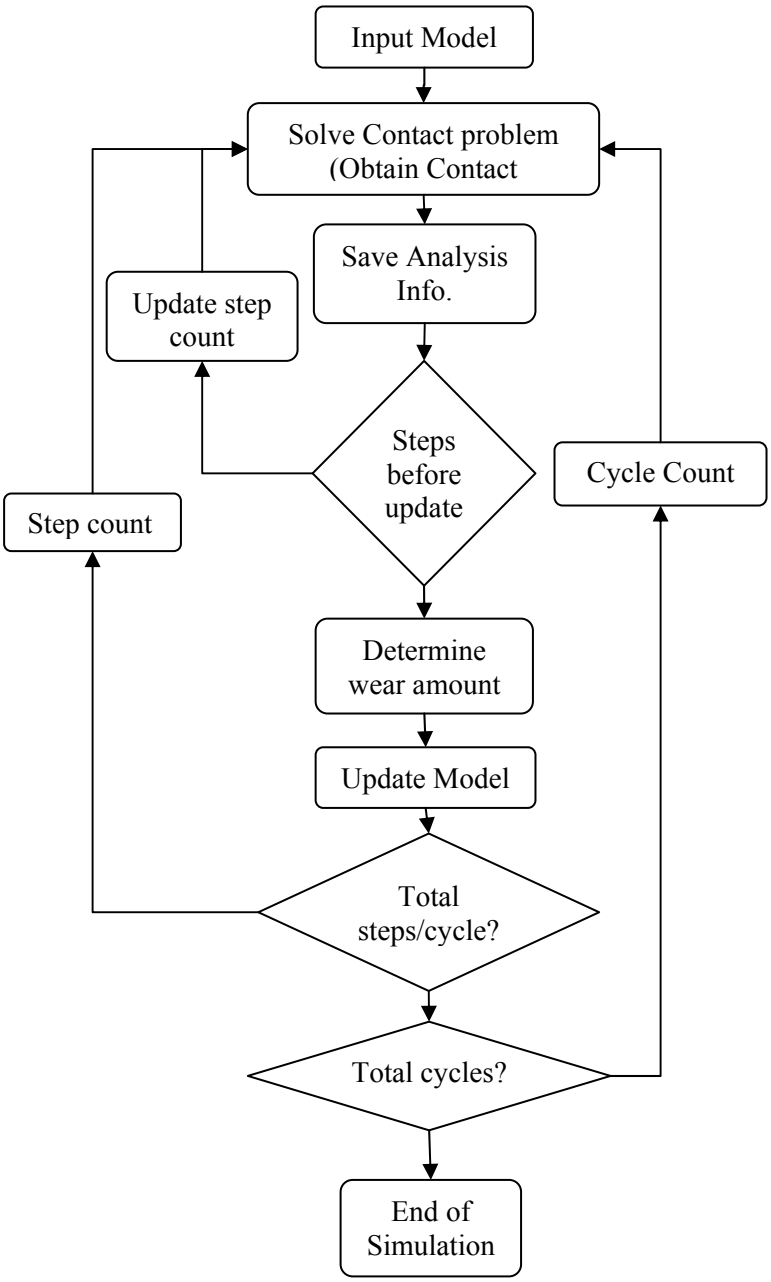


Figure 4-2. Wear simulation flow chart for the 'intermediate cycle-update' procedure.

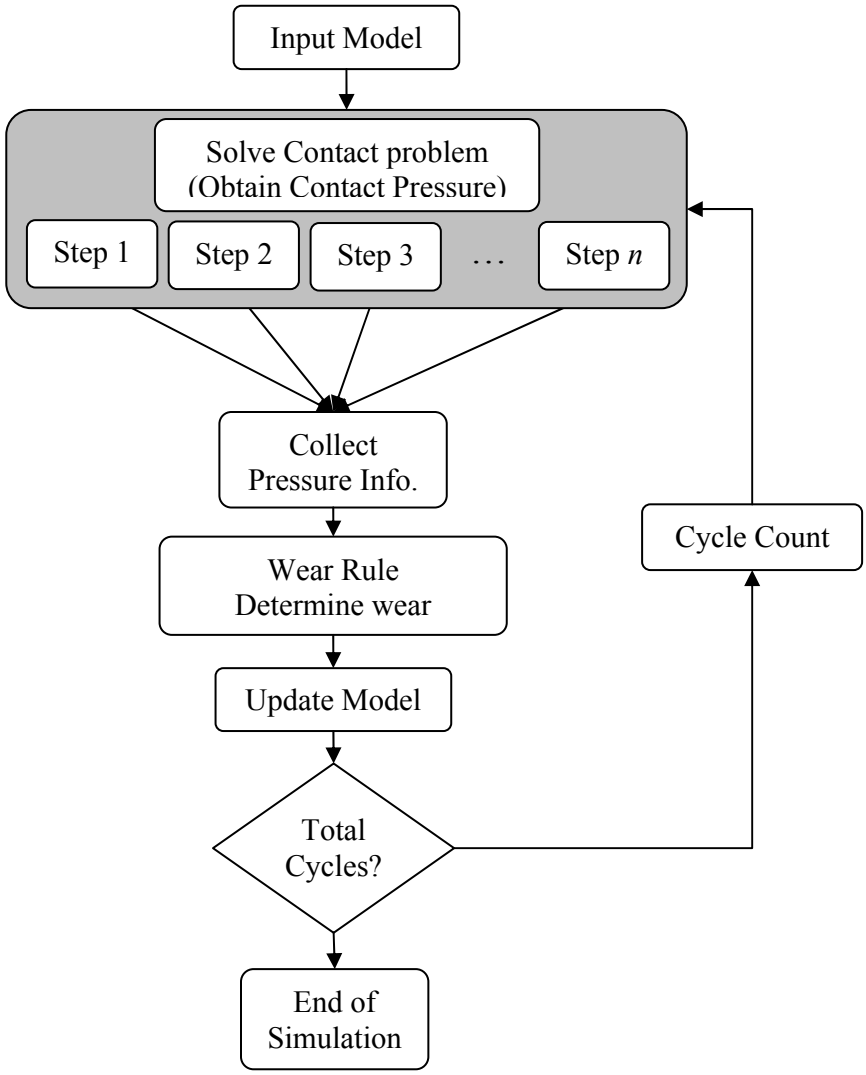


Figure 4-3. Wear simulation flow chart for the parallel implementation of the 'cycle-update' procedure.

CHAPTER 5
WEAR-SIMULATION PROGRAM

Introduction

A simulation program was written in order to execute the wear-simulation procedure that has been discussed in Chapters 2–4. The programming language used was "C" and the Finite Element Analysis software used was Ansys. Ansys Parametric Design Language (APDL) was used to write the commands necessary for the analysis. It should be mentioned that the choice of language and software for this task, was based on convenience rather than limitation. Other languages and analysis software may be used. In this Chapter the basic structure of the program will be discussed.

Wear-Simulation Program Format

The wear-simulation program is composed of two parts. The first part of the program is a C-program responsible for managing the simulation process and the second part is an Ansys analysis input file, written in APDL, consisting of a set of commands related to the finite element analysis. There exists an interaction between the two programs in which information is exchanged. The interaction is managed by the C-program. A representation of the interaction is shown in Figure 5-1. These two parts will be discussed in the following subsections.

Ansys Input Code

The Ansys input code is composed of a set of commands necessary to perform an analysis on the finite element model and output analysis results. The input code has two main functions which include performing contact analysis and extracting results from the analysis. These will be discussed in the following subsections.

Contact analysis

When the simulation program is launched, the C- program invokes Ansys and the Ansys input code is read. This will be the beginning of a step within the current cycle. The C-program also sends information to Ansys which will be read-in by the input file. This information may include the orientation of the oscillating body, the current step and cycle. Based on the information from the C-program, the input file instructs Ansys to read-in the corresponding model (the model is in a file format with extension "CDB") and prepare it for analysis. The preparation includes reorienting the oscillating body into a position consistent with the current step. Any gaps occurring due to wear in the previous step are also closed. This essentially means that contact is established between the bodies before the analysis begins. This is a necessary step since any gap may result in rigid body motion (RBM). At this point, the input code instructs Ansys to solve the contact problem.

Output of results

The solution of the contact problem yield an enormous amount of information, most of which is not of interest in the wear problem. The second task of the input code is to extract the necessary information for the wear analysis. Specifically, the contact pressure at each node is extracted from the contact analysis results. The input code also extracts the coordinates of the contact node and computes the normal vector at each contact node. This information is required for the model update.

The data extracted from the analysis as well as the model is written onto a text file in a predefined format that is readable by the C-program. Creating the text output file serves as the end of the step. Ansys software then shuts down and the C-program resumes command. A summary of the work done by the input code is shown in Figure 2-2.

Simulation Managing Code

The other part of the wear-simulation program, written in C, act as the simulation manager. The codes' main functions are to coordinating all the analysis performed by Ansys as well as performing the wear calculations.

Once the simulation program is launched the C-program reads in a set of user defined parameters that describe the desired simulation. These parameters include information such as the value of the wear coefficient, the number of steps per cycle, the total cycles to be simulated and the oscillation amplitude. The C-program then invokes Ansys, as describe in the previous section, and stays dormant until the contact analysis is done. Results from the contact analysis stored in the text output file are then read in by the C-program. Stability check and extrapolation modifications are then performed as was outlined in Chapter 2. The wear rule is then applied. This determines the amount of wear increment at each node consistent with the contact pressure form the analysis and the wear coefficient. Base on the incremental wear depth geometry update is updated and a data file in text format is created. Information such as the contact node number and the corresponding contact pressure and wear depth are appended to the file as the simulation progresses. At this stage a cycle is completed and a new cycle commences. The structure of the simulation program is depicted in Figure 5-3.

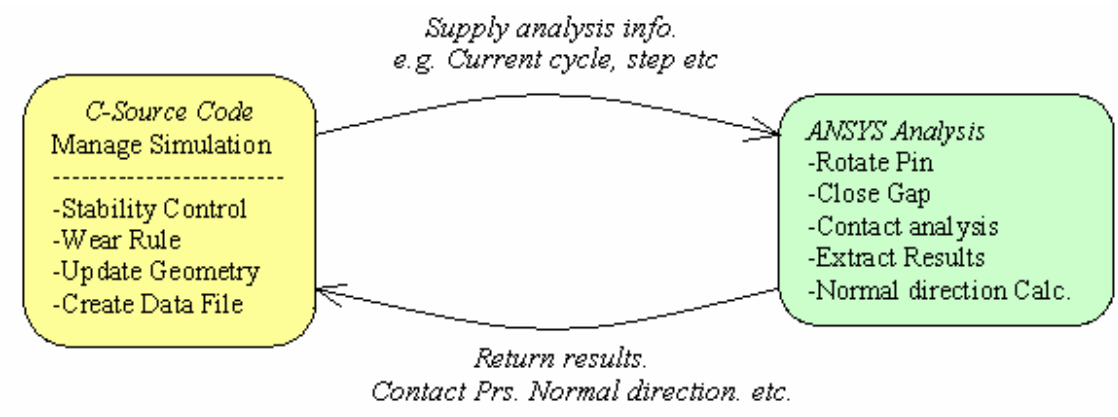


Figure 5-1. Interaction between the C code and the Ansys input code.

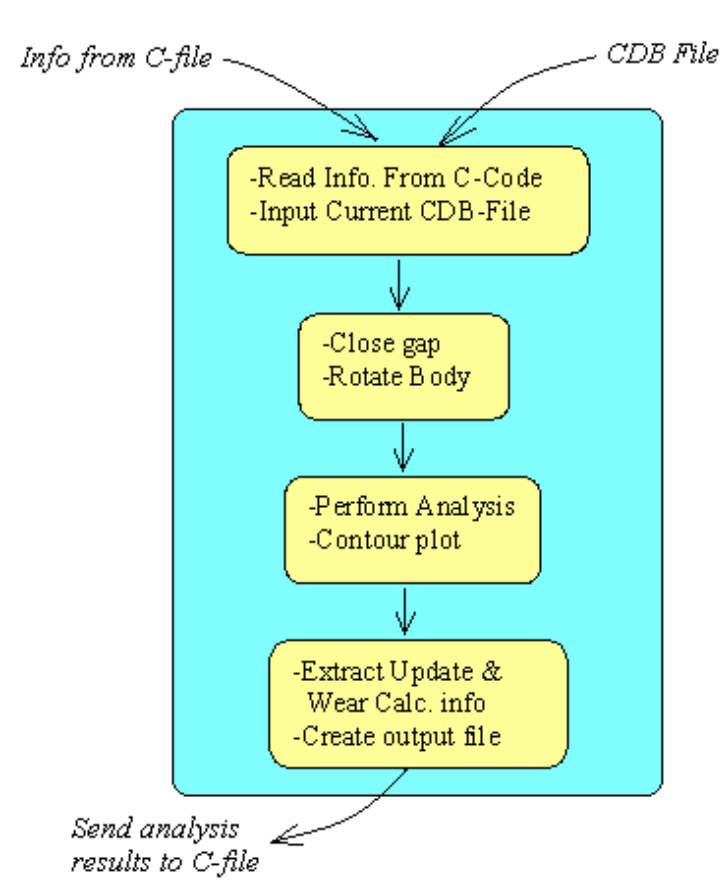


Figure 5-2. Function of the Ansys input code.

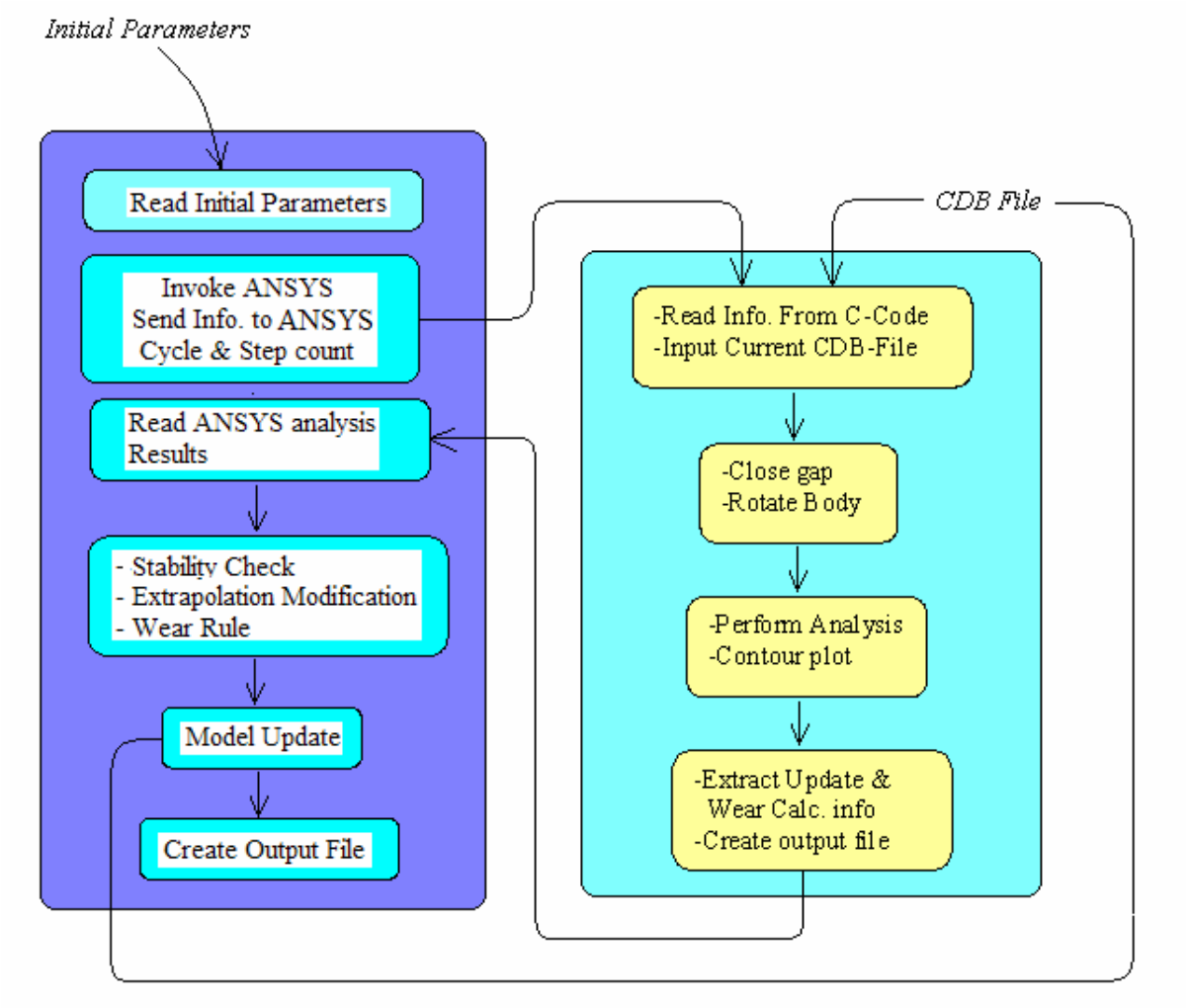


Figure 5-3. Structure of the wear-simulation program.

CHAPTER 6
EXPERIMENTAL VALIDATION OF THE WEAR-SIMULATION PROCEDURE

Introduction

Probably the most convincing way to validate the results of a simulation is to compare them against those from an actual experiment. In this work the simulation procedure is validated by comparing simulation results to results from a wear tests performed on an oscillating pin in pivot assembly. The simulation procedure is then used to simulate the wear occurring at the pin joints of a backhoe (construction equipment). The effect of wear on the performance of the backhoe is then demonstrated.

Wear-Simulation Validation

The wear simulation is validated through a comparison of simulation and test results. The wear test consisted of a fixed steel pin inside an un-lubricated oscillating steel pivot. The pivot was set to oscillate with amplitude of 3^0 and was loaded in the direction of its shoulder as shown in Figure 6-1. The resulting pressure at the cross-sectional of the pivot was 60MPa. The pressure was kept approximately constant through out the test. A total number of 408,000 cycles were completed during the test to yield a maximum wear depth of about 2mm. It should be noted, for the sake of comparison, that the definition of the test cycles is different from that of the simulation cycles. Here a test cycle is defined as a complete rotation from one extreme to the other and then back to the starting position (in this case -3^0 to 3^0 and back to -3^0). The test information is summarized in Table 6-1 for convenience.

Three simulation experiments were performed to mimic the actual tests performed on the pin and pivot assembly. The three simulations experiments were as follows:

- step-updating procedure
- intermediate cycle-update procedure

- parallel implementation of the intermediate cycle-update procedure

All three simulation tests were performed with the model shown in Figure 6-1. A wear coefficient of 1.0×10^{-5} mm^3/Nm (typical on un-lubricated steel on steel contact) was used. This value is obtained from pin-on-disk tests results reported by Kim et al. [18]. In all three cases the cycles were discretized into 10 steps. Both the step- and intermediate cycle-updating simulation tests were performed on the same computer (for time comparison), however, the parallel implementation was performed on a parallel cluster. The following is a brief discussion of these simulation test and the corresponding results.

Step-Update Simulation Test

The step updating simulation test was performed with oscillation amplitude and loading identical to that of the actual wear test. The simulation test was run for 100,000 cycles (considering the extrapolation). The simulation test parameters are summarized in Table 6-2 below. In Figure 6-2, the history of wear for the pin and pivot nodes that experienced the most wear is shown. From the figure, a transient and steady state wear regime can be identified as discussed by Yang et al. [32].

The transient wear regime corresponds to the beginning of the simulation until the contact between the pin and the pivot is conforming. Thereafter the wear transitions to the steady state wear regime. The steady state wear regime in marked by an interesting phenomenon where by the contact pressure distribution is observed to be approximately constant over the region of contact. This is in contrast to the transient wear regime during which a range of contact pressure values is observed over the contact region. This concept is illustrated in Figure 6-3.

Within the steady state wear regime, the wear is approximately linear with respect to the cycles as can be seen in Figure 6-2. This information may be exploited to determine the wear on

the maximum wear nodes after 408,000 cycles. Noting that one test cycle has twice the sliding distance in comparison to that of the simulation test, an extrapolation within the steady state can be made to predict the wear depth at the 408,000th cycle. The expression for the predicted wear depth is a follows;

$$h = 2\left[(h_{FEM_2} - h_{FEM_1}) \left(\frac{n_{\text{test}} - n_{sim_1}}{n_{sim_2} - n_{sim_1}} \right) + h_{FEM_1} \right], \qquad (6\text{-}1)$$

where, h is the predicted wear depth, n_{sim_1} and n_{sim_2} are the total simulated cycles at two points within the steady state regime whereas h_{FEM_1} and h_{FEM_2} are the corresponding simulate wear depths at these cycles. In this equation the experiment test cycles is denoted by n_{test}.

A value of 1.867mm was predicted as the maximum wear depth on the pin. Although this value underestimates the wear depth it is a reasonable prediction considering that the wear phenomenon is a complex process. The variation of the extrapolation size is depicted in Figure 6-4. The simulation took approximately 206 minutes.

Intermediate Cycle-Update: Parallel Computation

The Intermediate cycle-update procedure and its parallel implementation were performed with the same parameter values as were used in the step-updating procedure (see Table 6-2). However, in this procedure, the update was performed after every 3 steps so that 3 updates were performed in each cycle. This is in contrast to the step-update procedure where 10 updates were performed, one at the end of every step. The result for the intermediate cycle-update and the corresponding parallel implementation are identical. The plot of the wear on the pin and pivot nodes that experience the most wear is shown in Figure 6-5.

A maximum wear depth (on the pin) of 1.854mm was obtained from the intermediate cycle-update procedure and its parallel implementation. A plot of the extrapolation during the

analysis is shown in Figure 6-6. A simulation time of 450 minutes was noted for the intermediate cycle update procedure. This is slightly more than twice the time it took to complete the step-update simulation test. This time difference can be explained by examining the extrapolation history plots (Figure 6-4 and Figure 6-6) for the two procedures. The average extrapolation for the step update is slightly greater than twice that of the intermediate cycle update procedure. This is because the step update is a more stable procedure than the intermediate cycle updating procedure. The stable characteristic of the step update allows for the use of larger extrapolation and thus few simulations cycles are required to predict the wear depth. In the present case, only 19 cycles were required to complete the step-update simulation test whereas 49 cycles were required to complete the intermediate cycle update simulation test. The parallel implementation of the intermediate update procedure only took approximately 135 minutes to complete. Clearly this procedure provides a time advantage. A comparison of the results form the simulation tests and the actual tests are shown in Table 6-3.

Conclusion

The discussion in this Chapter focused on validating the wear-simulation procedure that was presented previously. The validation is done by comparing the results from the simulation to that of an experimental counterpart. The wear occurring at the contact interface of an oscillation pin-pivot assembly was simulated. The predicted wear depth deviated from the actual experimental wear depth by approximately 7%. Even though this deviation appears to be large the predicted results is able to give a good insight into the wear occurring at the interface. Indeed like any other approximation technique, errors are inherent. A number of factors contribute to this discrepancy including the wear model, which is not an exact representation of wear and the finite element analysis, which is an approximation technique.

Another contributor is the wear coefficient. The wear coefficient is obtained experimentally and as was mentioned has a large scatter. Errors in the wear coefficient considerably affect the results of the simulation. For instance, if instead a wear coefficient of 1.2×10^{-5} mm^3/Nm was used the new predicted wear depth would be 2.028mm. The new wear coefficient, which is still within the range of scatter according to Kim et al. [18], has a deviation of about 1.4% from the experimental value. This is indeed a large improvement from the previous predictions. It is thus concluded that even though the procedure does not accurately predict the wear the results obtained are of the correct order of magnitude and can be used for preliminary design.

Table 6-1. Wear test information for the pin and pivot assembly.

Test Parameters	Values
Oscillation amplitude	$\pm 3^0$
Load (cross-sectional pressure)	60MPa
Test condition	Un-lubricated steel on steel
Total cycles	408,000
Max wear depth on pin	~2.00mm

Table 6-2. Simulation parameters for the pin in pivot simulation test.

Simulation Parameters	Value
Oscillation amplitude	$\pm 3^0$
Load (cross-sectional pressure)	60MPa
Wear coefficient (k)	1.0×10^{-5} mm^3/Nm
Total cycles	100,000
Steps per cycle	10

Table 6-3. Comparison of results form the simulation tests and actual wear tests for the pin in pivot assembly

	Max. wear depth (pin) (mm)	Simulation time (min.)
Actual test	2.000	--
Step update	1.867	206
Inter. cycle update	1.854	450
Parallel	1.854	135

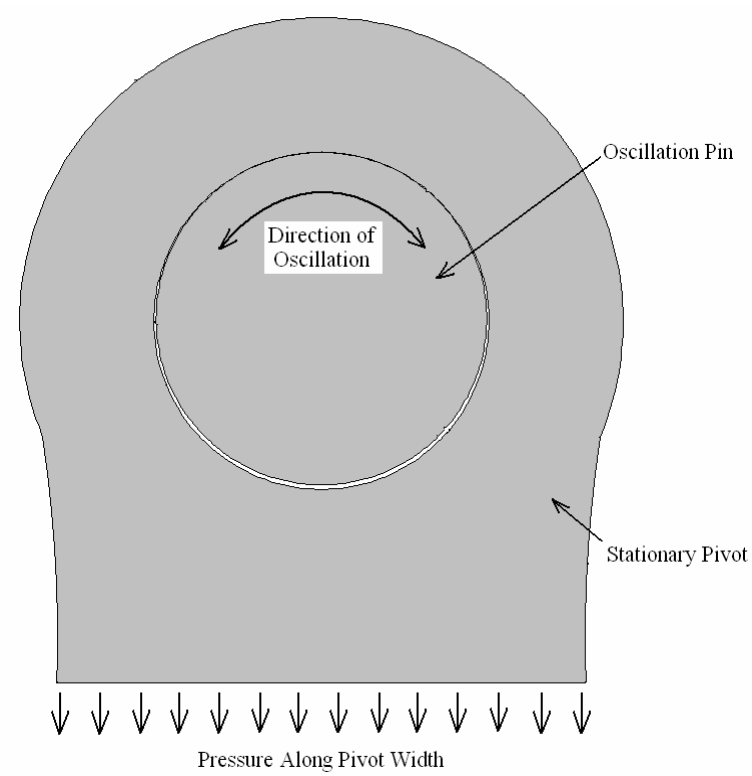


Figure 6-1. Pin-pivot assembly for the wear test.

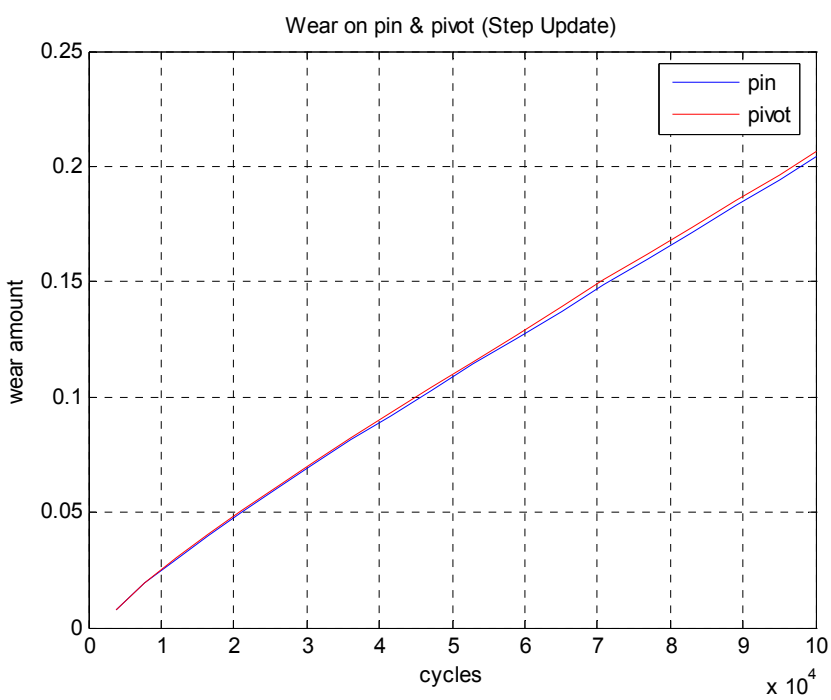
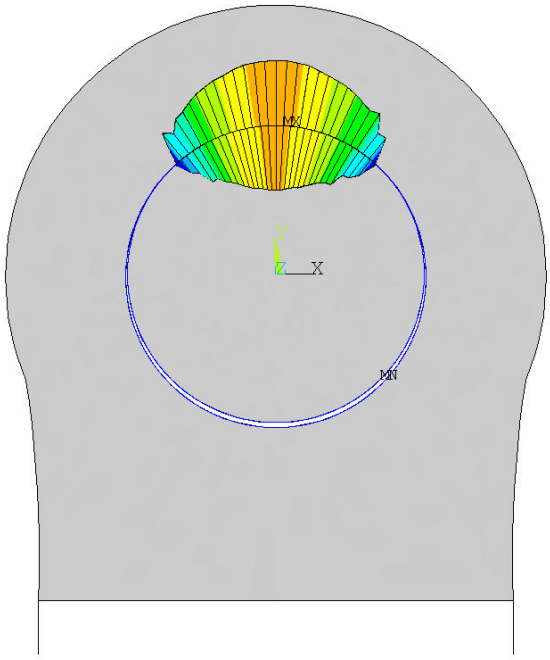
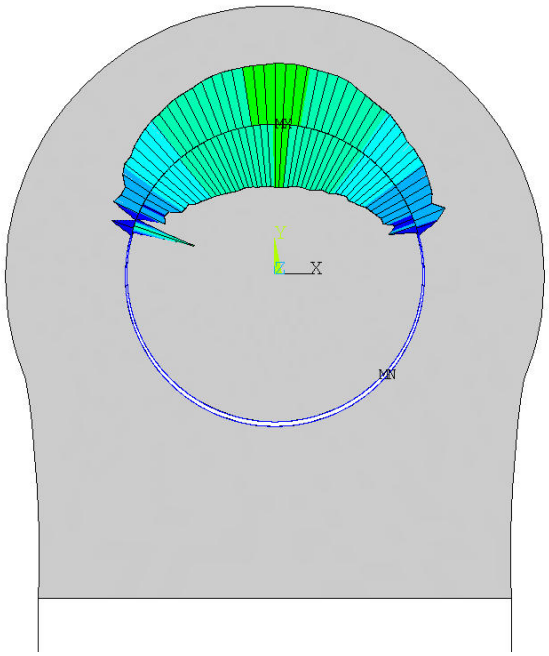


Figure 6-2. Cumulative maximum wear on pin and pivot.



A



B

Figure 6-3. Contact pressure distribution on the pin and pivot during wear analysis. A) Contact pressure distribution in the transient wear regime. A range of pressure values is observed. B) Contact pressure distribution within the steady wear regime. The pressure distribution is approximately constant over the region of contact.

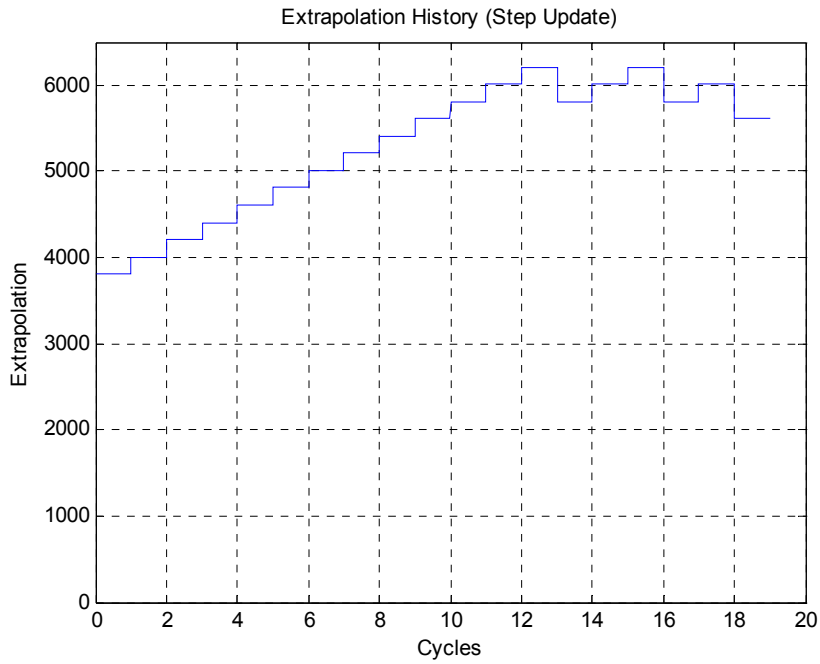


Figure 6-4. Extrapolation history plot for the step updating simulation procedure.

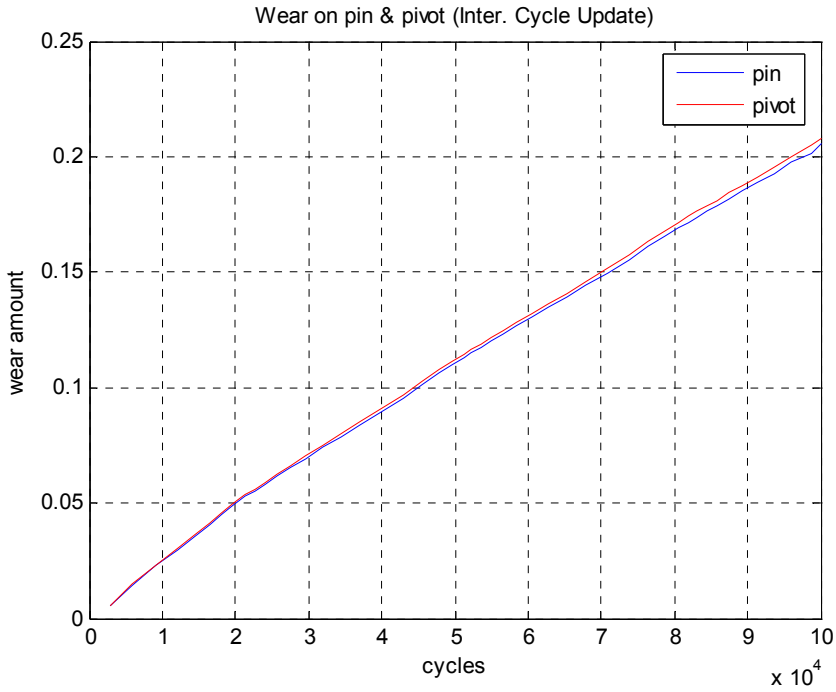


Figure 6-5. Cumulative maximum wear on pin and pivot for the intermediate cycle updating procedure and the parallel implementation.

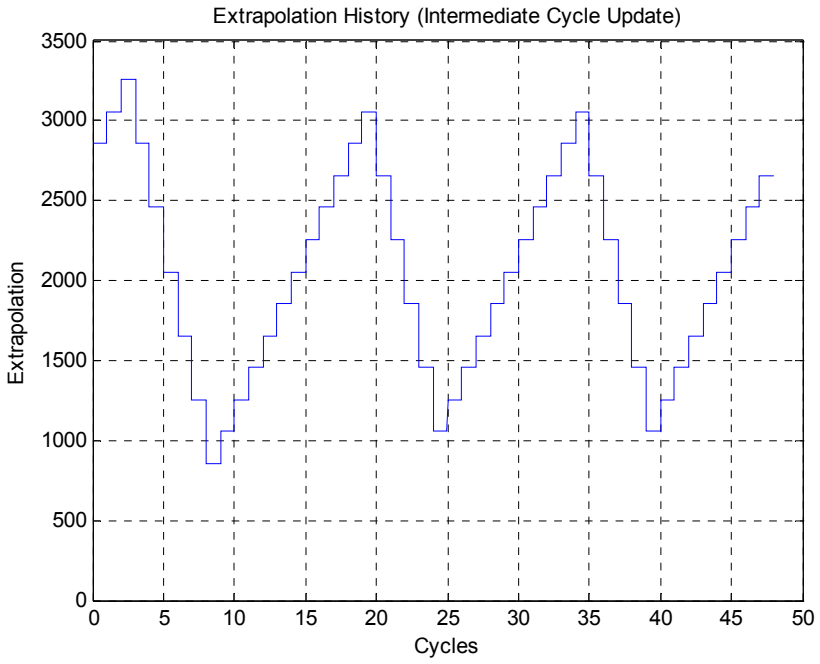


Figure 6-6. Extrapolation history plot for the intermediate cycle update procedure and its parallel implementation.

CHAPTER 7
WEAR-SIMULATION EXAMPLE: ESTIMATION OF BACKHOE BUCKET TIP DISPLACEMENT

Introduction

In Chapter 6, the wear-simulation procedure for oscillatory contact was validated through experiments. It was found that the method can reasonably predict wear occurring at such interfaces as long as accurate wear coefficients are obtained. In this Chapter, the usefulness of the procedure will be demonstrated through an example. The example involves determining the erroneous displacement at the tip of construction equipment due to wear at various joints.

Estimation of Tip Displacement

A backhoe system will be used to demonstrate how the simulation procedure can aid in determining the effect of wear on the performance of a system. The system is a part of a construction vehicle used in excavation work. The particular backhoe system to be used in this example consists of three major parts (boom, dipper and bucket) as shown in Figure 7-1. The system consists of three joints; two connect the three parts together while the third one connects the backhoe system to the vehicle (not shown in Figure 7-1). Each joint consists of two components that are in contact and experience relative oscillatory motion when the backhoe undergoes a cycle of digging and loading. The contact at these joints can be considered as oscillatory and as may be expected, large amounts of wear occur at these joints. The goal in this example is to estimate the amount of control of the bucket tip that is lost due to wear at these joints. The loss in control is quantified as the magnitude of the unwanted bucket tip displacement that occurs when the backhoe is rotated about the rotation axis. The tip displacement is shown in Figure 7-1.

The diagram in Figure 7-2 shows a pivot joint before and after wear has occurred. In Figure 7-2A diagram no wear has occurred and the pin sits snugly in the pivot hole. In such a

case the tip displacement is negligible. However, once wear has occurred at the joints, the pin is able to rotate through an angle as shown in Figure 7-2B. This kind of rotation propagates through all three joint and eventually causes a bucket tip displacement. The magnitude of the tip displacement is dependent on the amount of wear.

In this example the tip displacement will be obtained assuming that the backhoe has been in operation for a period of one year. This corresponds to a total of 90,000 cycles of digging and loading dirt. This is obtained by assuming that the backhoe executed 60 cycles an hour, 5 hours a day for 300 days in a year. The tip displacement is obtained by first determining the amount of wear at each of the joints. In this case the joints are represented by a pin and pivot assembly similar to that used in the previous Chapters. The loading at each joint is taken to be constant throughout the entire cycle. A list of the loads applied at each pivot is shown in Table 7-1. Also listed in Table 7-1, are the oscillation amplitudes of the each pin at each their corresponding joint. It is worth noting that an assumption is made that no other factors contribute to the tip displacement and that the initial tip displacement is zero.

The three joint are assumed to be made of steel and that no lubricant is used. A wear coefficient with a value of 1.0×10^{-5} mm^3/Nm is thus used in the analysis. This choice is consistent with experiments performed by Kim et al. [18]. A wear analysis is performed on all the joints for the specified parameters. Only 52440 cycles are simulated and the final results are linearly extrapolated. The wear depth at the joints obtained from the simulation is shown as a function of the cycles in Figure 7-3. It can be seen from Table 7-2 that the wear on joint 3 is greatest. This is consistent with the fact the oscillation amplitude for the third joint is the largest. The maximum wear depth on the pin and pivot at 20,000 cycles and the extrapolated wear depths at 90,000 cycles for the three joints are reported in Table 7-2. The wear depth at 90,000 cycles is

used to determine the bucket tip displacements of all the component parts from the centerline. The component displacements as well as the overall backhoe tip displacement are listed in Table 7-3 and are depicted in Figure 7-4.

A maximum bucket tip displacement of 149mm is estimated. This can be interpreted as the additional distance, from the desired position, that the bucket tip will travel be for coming to a halt when the backhoe is rotated.

Conclusion

The value of the simulation procedure was demonstrated through an example in which the erroneous bucket tip displacement, attributed to wear, for a backhoe system was estimated. Although the input values for the backhoe system and thus the tip displacements are not from an existing case, the example demonstrates how the performance of a system can be affected by wear and how the simulation procedure can aid in quantifying the loss in performance.

Table 7-1. List of loads and relative rotation angles at the joints of the backhoe.

	Load (MPa)	Oscillation amplitude
Joint 1	10.75	-15^0 to 15^0
Joint 2	10.40	-22.5^0 to 22.5^0
Joint 3	12.15	-35^0 to 35^0

Table 7-2. Summary of the wear depth at the joints after 20,000 cycles as well as the extrapolated wear depth at 90,000cycles

	Initial diameter (mm)		Wear depth at 20000 cycles (mm)		Wear depth at 90000 cycles (mm)	
	Pin	Pivot	Pin	Pivot	Pin	Pivot
Joint 1	74.47	75.44	0.114	0.128	0.516	0.576
Joint 2	75.13	76.11	0.139	0.168	0.626	0.758
Joint 3	54.48	55.19	0.161	0.216	0.724	0.974

Table 7-3. Displacement of the boom component parts from the center line.

Part	Angle deflection		Distance from center (mm)	
Boom	Θ_{BM}	1.688^0	L_{BM}	73.64
Dipper	Θ_D	0.426^0	L_D	55.34
Bucket	Θ_{BU}	0.432^0	L_{BU}	20.00
Tip displacement	148.98mm			

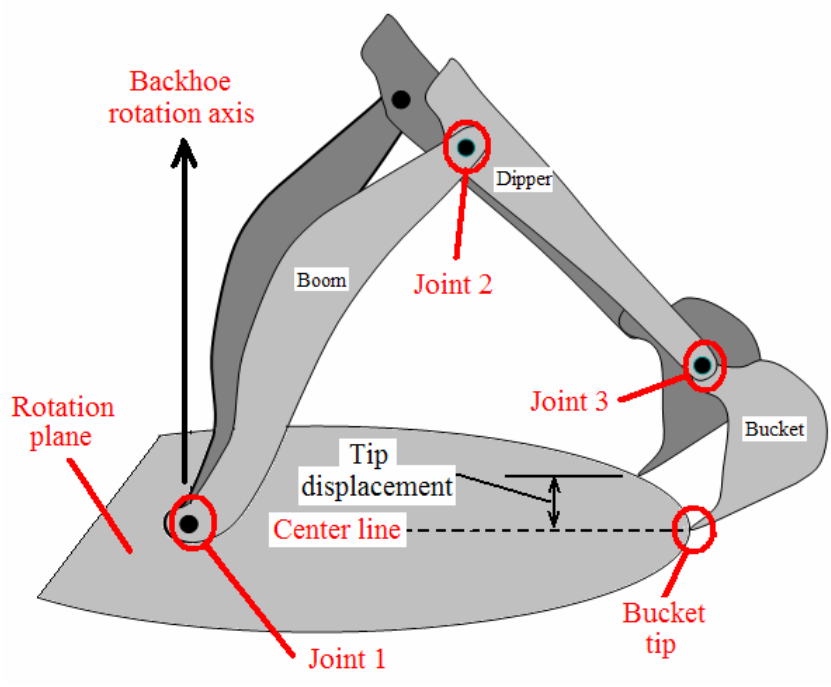
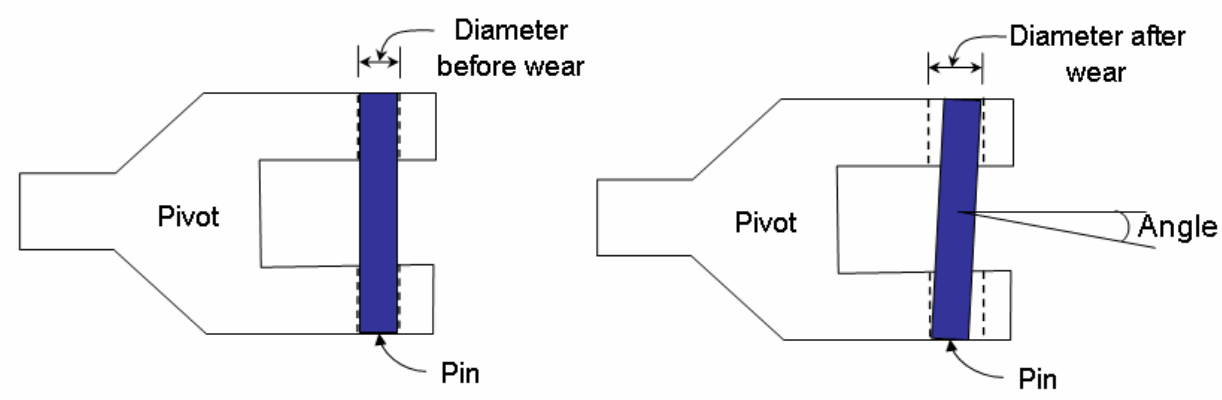


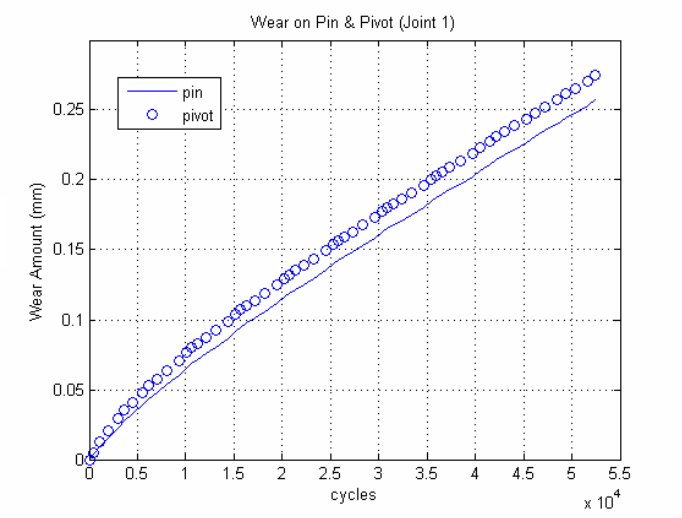
Figure 7-1. Pin-pivot assembly for the wear test.



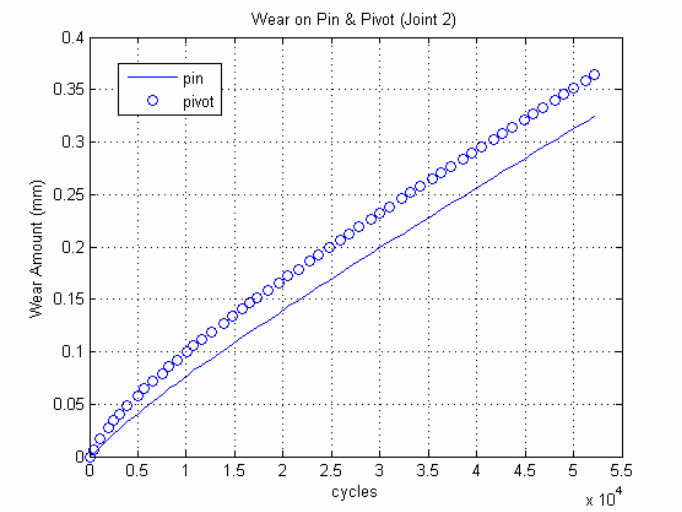
A B

Figure 7-2. Joint consisting of a pin and pivot: A) Joint before wear has occurred on both components. B) Joint after wear has occurred on both components.

A



B



C

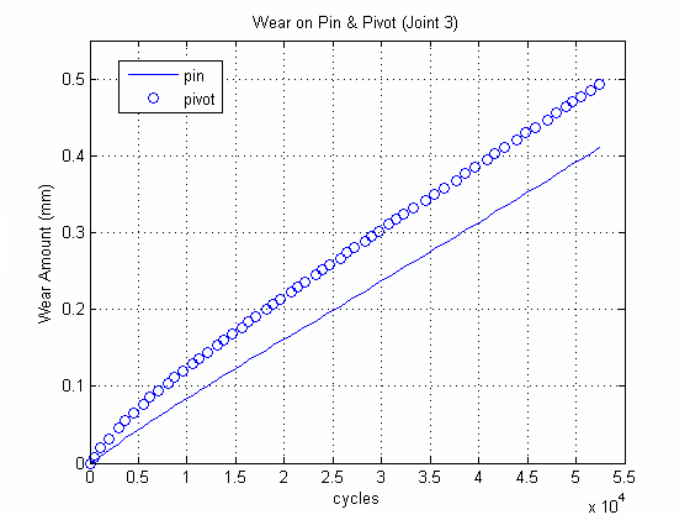


Figure 7-3. Wear on the pin and pivot at the backhoe Joints. A) Wear at joint 1. B) Wear at joint 2. C) Wear at joint 3.

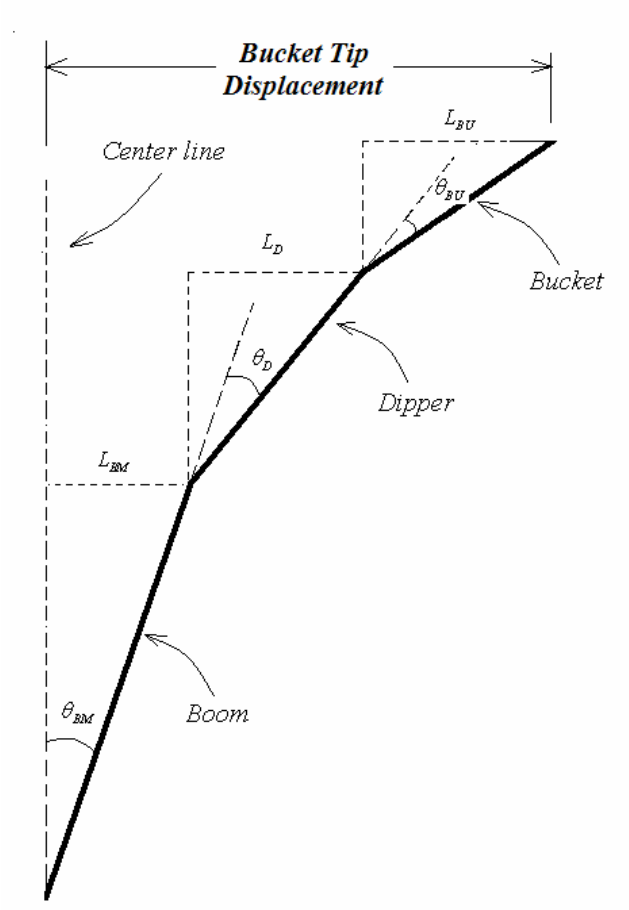


Figure 7-4. Backhoe component displacement from the vehicle centerline.

CHAPTER 8
CONCLUDING REMARKS

The objectives in this work were two fold. One goal was to develop a wear-simulation procedure to predict wear occurring on bodies experiencing oscillatory contact. The second goal was to incorporate into the wear procedure, techniques that would minimize the associated computational costs of the simulation process while ensuring stability through out the simulation process.

The wear-prediction procedure was developed based on a modified form of Archard's wear law. It involves determining wear at incremental steps within a cycle for the total number of cycles to be simulated. At the end of every step the geometry is updated to reflect the evolution of the surface and thus account for changing contact conditions. This update procedure, termed as step update, is a more stable procedure than the cycle and intermediate cycle update procedures in which updates are delayed to the end of the cycle or after several steps have been simulated.

Two techniques were proposed to minimize the computational costs of the simulation. The first technique was an incorporation of an adaptive extrapolation scheme into the wear-prediction procedure. The purpose of scheme was to optimize the selection of the extrapolation factor for the best use of the available resources while ensuring stability in the simulation.

The second technique is a parallel implementation of the cycle and intermediate update procedures. With no parallel implementation, step update approach is computationally cheaper than the intermediate cycle update procedure. The reason for this is that the intermediate cycle-update procedure is a less stable procedure (due to the reduced number of geometry updates in a cycle) and thus requiring the use of smaller extrapolation sizes. This results in a longer simulation time. When parallel computation is used, the intermediate cycle update procedure is a

cheaper alternative in terms of computational cost. It is deduced that in the absence of parallel computing resources, the most reasonable simulation procedure to use is the step-updating procedure where as the intermediate cycle updating procedure is best when parallel computing is available.

In the simulation validation process, it was found that the wear depth on the pin predicted by the simulation procedure was under predicted but within a reasonable range. This under prediction is largely attributed to the wear coefficient used. The wear model used is a phenomenological model in which the wear coefficient is determined through experiments. Hence an inaccuracy in this coefficient has a great effect on the prediction process as was shown in Chapter 6. Based on the results it is concluded that the procedure is a reasonable way to predict wear on bodies experiencing oscillatory contact

CHAPTER 9
RECOMMENDATIONS FOR FUTURE WORK

The wear-prediction procedure presented in this work provides a way to determine the wear occurring on bodies that experience oscillatory contacts. In the procedure, the changing contact condition or evolving surface was accounted for by updating the surface as the simulation progressed. This ensured for a more realistic simulation of the wear process.

The prediction process can be made even more realistic by considering how the wear affects the kinematics and dynamics of a system and in turn how the kinematics and dynamics of the system affects the wear process. In mechanisms, once wear has occurred at connection, the initial paths through with components of the mechanism travel are no longer preserved. The loads involved may also be affected. These changes occur due to the gap or change in geometry that is introduced at the connections as wear occurs. It should also be noted that the changes in the motion of the components, as well as the loading, will affect the wear process.

The procedure that has been presented is an idealized case in which the changing system does not affect the wear process and vice versa. Essentially wear predicted by isolating the region in which the wear occurs and thus neglecting any changes that the wear would have on the overall system. A recommendation for future work is to study the effect of a continuously changing system (changing due to wear) on the wear process itself.

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BIOGRAPHICAL SKETCH

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